ARLON

TECHNOLOGY ENABLING INNOVATION

Everything You Ever Wanted to Know About Laminates... but Were Afraid to Ask

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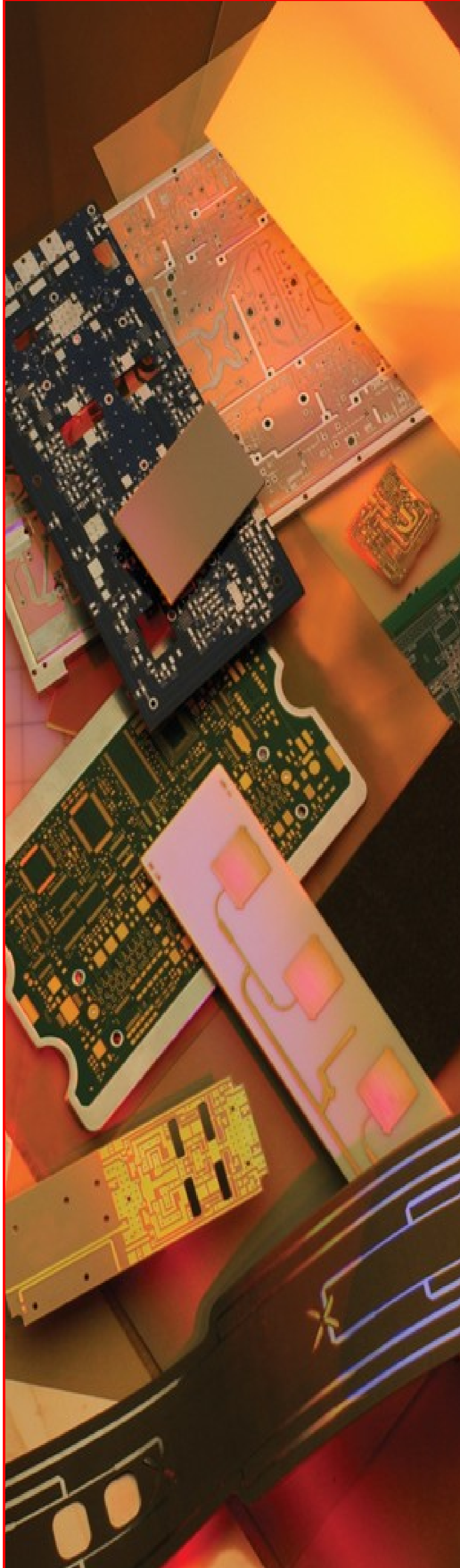

Introduction to the 9th Edition

Dear Reader,

It has been over 25 years since the earliest edition of "Everything You Ever Wanted to Know About Laminates…but Were Afraid to Ask" was pounded out on an old TRaSh-80 Computer. It has undergone periodic review and editing, including adaption for use on our website. (When I entered the industry Al Gore had not yet invented the internet.) Before I "retired" in 2004, we did another minor revision, but it was largely cosmetic, removing most references to the old military specification and introducing IPC-4101, the "new" specification for laminate and prepreg materials.

When I entered the laminates industry in 1983 (when Arlon acquired Howe Industries) I knew almost nothing about the industry or the application of its products. It was a high intensity learning curve for me, with a lot of help from internal gurus and from our customers, who were always willing to share their knowledge and experience. I had to ask a million questions (usually several times) before I started to feel comfortable with it all. The original idea behind Everything…" was to answer the many questions our customers asked about high tech materials – which in large part turn out to have been the same ones I had asked for myself in my first few months in the industry. It wound up being a "best seller" and we "sold out" several early print editions. (The price was right, of course!)

The present revision has involved a total review and rewrite. There are fundamentals which have not changed in 25 years, but the industry has moved a long way and Arlon has a much more diversified line of high performance products serving a marketplace with very different needs and priorities. Yes, we still are the premier manufacturer of polyimide laminate and prepreg -- and still supply a variety of materials for CTE control. But we also make a family of low flow materials, a line of thermally conductive materials, have entered the arena of lead-free and "green" products, to mention a few. What would have been considered a "high tech" multilayer board 25 year ago is being produced routinely now, and high tech has become altogether different and more complex. We have tried to reflect a changing world in this present edition of "Everything…"

It would be impossible to thank everybody who has contributed to "Everything…" through the years, but in particular I want to mention Vince Weis, my mentor when I first entered the industry, and still the "go-to guy" when there is a question to which I don't have an answer.

I dedicate this 9th Edition of "Everything…" to my many co-workers, industry peers and customers, so many of whom have been generous with their advice throughout the years, and without whom there would never have been an "Everything…"

Chet Guiles, Rancho Cucamonga, CA

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I. MATERIALS

Introduction

Although this book is entitled "Everything You Ever Wanted to Know About Laminates, But Were Afraid to Ask," the real subject matter is Printed Circuit Boards, the materials that are used to manufacture them, and how you as a designer or manufacturer of MLB's can benefit by a better understanding of what we, as laminators, do and supply. Multilayer printed circuit boards are complex composite structures comprising a series of layers of reinforced resin and copper foil all put together in a multi-level operation that involves an electrical and electronic design team, and at the PWB shop level, the integration of a variety of physical and chemical processes. The starting point for the manufacture of those PWBs is the copper-clad laminates and prepregs that you purchase from Arlon.

What are those materials? How are they manufactured? What are their key properties, and how are they processed to give the best results? By the time you're finished, I hope you'll have a better appreciation of the finer points of your raw materials, and through clever use of subliminal technology, an irresistible urge to buy them from Arlon.

General Discussion of Resin Systems

The popular names of the materials which comprise the majority of printed wiring board laminates have often been generalizations of the chemical names of the principal resin systems used in each such as "Epoxy," "Polyimide," "PTFE" and the like. In recent years the search for products suitable for evolving high performance applications have resulted in the use of new materials and combinations of materials that make the generalizations of the past somewhat more difficult to sustain. For instance, reference to "Epoxy" or "FR-4" is too general to accommodate the diverse requirements that characterize Low Flow, Multifunctional, Lead-Free, CAF Resistant, High Speed Digital and "Green" epoxy products. This diversification is reflected in the proliferation of slash sheets in IPC-4101, the laminate and prepreg spec currently in effect in the industry. (IPC-4101 is discussed in some detail in section III, "Laminates.") Products can also be characterized in terms of intrinsic properties, resin system, end application or even substrate type.

Some of the newer products, such as those based on laser drillable fiberglass, woven Kevlar®, Thermount® nonwoven aramid substrate or woven quartz reinforcement are frequently referred to by the generic name of the substrate rather than by the resin utilized, and of course all laminators including Arlon would like to have you all use our by trade names rather than generic resin designators! (Naturally that would preclude your referring to them by our competitors' trade names...)

Many of the resins in use in the electronic laminates industry are thermosets (which means that they "cure" into a hard final product) rather than thermoplastics (which may be melted and re-melted). The most notable exception of course is the use of PTFE, or polytetrafluoroethylene (also known by its Dupont trade name as Teflon® although DuPont is not the only manufacturer

of PTFE) in laminates for microwave and RF, where its dielectric properties are ideal for high frequency applications.

Is there an "Ideal" PWB Material or system? If not, what would be the key elements of such a system?

Because of the diversity of materials available and the wide range of applications, the concept of an “ideal laminate” has become fuzzy, to say the least. A material ideal for a high temperature application may be impractical in a microwave or high speed digital design, for instance. As a result, while we can list properties that are potentially important, each design team needs to establish a prioritization among them because no one material will have the optimal value for all the properties which might be considered important. Your laminate “cookbook” does have some common “ingredients” (i.e. properties) from which designers will be making choices during the design phase:

Glass Transition Temperature (Tg): The highest temperature systems are polyimides (such as Arlon’s 35N, 33N and 85N) with Tg’s of 250°C or above. Tg is a rough indicator of total Z-direction expansion and hence is considered a proxy for plated through hole reliability. A wide variety of epoxy systems with Tg’s in the 170°C range have found application where either process temperatures or in-use temperatures (or both) are less demanding. While Tg is a good frame of reference for traditional epoxy and polyimide materials, it is less reliable for reliability characterization of highly filled systems and for many of the non-traditional resin systems used in high frequency/low loss applications whose properties are composites of their various components.

Example: Polyimide Thermount MLB’s will survive 2-3x the thermal cycles of standard polyimide glass despite having identical resin and Tg because there are no stress concentrators caused by fiber bundles intersecting the walls of the plated through holes.

Example: A filled PTFE product such as Arlon’s CLTE-XT microwave material does not even have a Tg in the range of 50 to 260°C, yet has a low and consistent Z-direction expansion in that range by virtue of which it will have excellent plated through hole reliability.

T260, T288 and T300 values represent the length of time that a clad laminate will survive a particular temperature (respectively 260°C, 288°C and 300°C) before it begins to delaminate or blister. The test is performed in a TMA (Thermo-Mechanical Analyzer) and these values are considered good indicators of the short term resistance of products to solder processing; as such they have become part of the Lead-Free minimum requirements as defined by IPC.

Thermal Decomposition Temperature (Td): This property varies greatly with the chemical composition of materials, from the mid 300°C range for many epoxy systems to over 400°C for some polyimides. Td is the temperature at which a material begins to degrade thermally. Some data sheets will list a Td as the temperature at which a material has lost 5% of its original weight due to decomposition. A better indicator of performance would be the onset temperature, at

which significant weight loss begins to occur. By the time a material, has lost 5% of its weight to decomposition it may well be unusable in many applications.

Dielectric Constant and Loss Tangent: Dielectric constant determines the speed at which an electrical signal will travel in a dielectric material. Signal propagation speed is expressed relative to the speed of light in a vacuum, which is roughly 3.0×10^{10} cm/sec. The dielectric constant of a hard vacuum (space) is defined as 1.00. Higher dielectric constants will result in slower signal propagation speed. Loss Tangent is a measure of how much of the power of a signal is lost as it passes along a transmission line on a dielectric material.

These are determined by the inherent properties of the components of any specific resin system, although we normally refer to a "relative dielectric constant" because it is dependent on test method and frequency as well as material per-se. No one value of Dk is "ideal" for all applications. For many high speed digital applications, modified epoxy systems with dielectric constants in the range of 3.0 to 3.5 have been found to offer good cost-performance value. In other applications such as critical antennas, low noise amplifiers, etc., a very low loss material such as PTFE is optimal. Choice of specific material is as much an issue of loss characteristics under use conditions as it does of Dk per-se. For microwave and RF applications, pure PTFE on a fiberglass substrate, with a Dk of 2.1 and Loss of 0.0009, is the best available in wide commercial use. Consistency of dielectric constant is important for maintaining designed characteristic impedance (Zo) values.

Registration (aka "Dimensional Stability"): All laminate materials shrink to some degree on etching, and the key to proper registration is consistency both of product and process. The most suitable material would be one that moves minimally when it is etched, and has consistent and reproducible movement that would allow predictable factors for artwork compensation. The "ideal" material would not require artwork compensation at all, and would always register properly so as not to require drill compensation. The IPC test referred to as "dimensional stability" has at best a tenuous connection to the actual registration of a specific board design. Registration continues to be a key fabrication concern for high layer count and HDI designs.

Coefficient of Thermal Expansion (CTE, expressed in ppm/°C): Should be roughly matched to the expansion requirements of claddings, devices to be mounted on the surface and thermal planes buried in the interior. Current thinking says that for leadless ceramic chip carrier attachment, 6.0 ppm/°C is ideal. (At present, Arlon's 45NK woven Kevlar® reinforced laminates with relatively low resin contents come closest to the 6.0 CTE ideal.) Other materials such as quartz reinforcement, Copper-Invar-Copper distributed constraining planes and nonwoven aramid reinforcement achieve values as low as 9-11, a substantial improvement over 17-18 for conventional epoxy or polyimide laminates and have proven acceptable and consistent in a variety of SMT designs.

Thermal Conductivity (Tc): As the density of components on a board increases due to demand for increasing functionality, and the overall surface areas of PWBs decrease, the watt-density of power being generated on a PWB increases. Critical devices exhibit failure rates that double for every 10°C of temperature increase, and so there is a push to have the thermal conductivity of the PWB materials themselves be high enough to help remove heat from devices on the surface of

the board, without at the same time suffering in terms of electrical and dielectric properties. Target thermal conductivities to achieve significant reduction in board surface temperatures near active devices fall in the 1.0 to 3.0 W/m-K range, significant when compared with values of 0.25 to 0.3 W/m-K for traditional epoxy or polyimide systems.

Z-Direction Expansion: Ideally the Z-direction expansion should match that of the copper in the plated through holes (about 17 ppm/^{o}C) to avoid damaging the plated copper during thermal excursions resulting from process steps such as solder reflow. Most standard materials have CTE's of 50-60 ppm/°C below the Tg, and roughly 4x higher above the Tg. High Tg materials such as polyimide have less overall Z-direction expansion (about 1.1% from 50°C to 250°C) than typical epoxy systems (with about 3 to 4% from 50°C to 250°C) due to their higher Tg.

Lead-Free Compatability: Lead-Free materials are materials able to withstand the higher soldering and reflow temperatures of lead-free solder systems. These may be anywhere from 30°C to 50°C higher than traditional lead-tin systems. Lead-free systems are usually characterized in terms of Tg (>155°C), T288 and T300 thermal resistance, Td (>330°C to 5% decomposition) and overall CTE (<3.5%). Materials such as polyimide have always been "lead-free" compliant, but newer generations of epoxy systems have had to be developed to meet the newer requirements. Lead-free is more complex than it might seem, since many current laminate materials will survive in "lead-free" applications, while some of the devices that are mounted on the boards have not even been tested at the higher lead-free temperatures. The overall thrust is to provide materials that will have a "margin of safety" across a range of higher lead-free solder temperatures.

CAF Resistance: Copper Anodic Filament (CAF) growth between adjacent plated through holes can cause electrical shorts and intermittent performance in PWB's when a combination of ionic residues, physical pathway (such as a separation between resin and an individual fiberglass fiber) and a steady voltage differential between holes drives the deposition of electromigrated copper along a glass fiber. CAF is of particular interest to designers making large high performance boards that will be in use continually for long periods of time such as in high end servers. Realistic "specifications" for Pass-Fail have been difficult to define, and CAF issues can be as much related to board fabrication as to material choices. Laminators have found that proper resin formulation, engineered glass finish technology, and optimized processing can increase resistance to CAF formation.

"Green" Laminate and Prepreg: The "green" requirement is driven more by market considerations than by "good science." Green materials are broadly defined as materials with UL-94 V0 flammability ratings achieved without the use of brominated flame retardants. Even though the brominated bisphenol-A that is used in most conventional FR-4 systems is NOT "banned," non-governmental organizations (NGO's) such as Greenpeace, are pressuring to have "green" systems become the norm and hence are trying to force a move to non-brominated systems wherever possible. Some like to refer to non-brominated systems as "environmentally friendly," although little long term work has been done to-date to assess the actual health or environmental impact of phosphorus compounds and other non-brominated systems.

Meeting "Environmental" Regulations

Modeled on the European Union's RoHS (Recycling of Hazardous Substances) and WEEE (Waste Electrical & Electronic Regulation), many other countries (and even individual states) have enacted or are in the process of developing similar regulations concerned with the content of electronic materials. To some degree this is a sort of technical minefield, because even if the various regulations are "normalized," the cost of compliance to multiple independent and different regulations may become a significant part of the cost of a finished PWB.

Uncomplicated Processing: The "ideal" laminate and prepreg system should be able to be processed using conventional photo-imaging methods, etching and wet chemical processing and lamination techniques. High process yields and process and design flexibility should be such that the material can be used in multiple designs with high probability of success. Unfortunately much of the industry still defines "normal process" as being that for conventional FR-4 and has tooled for that. Use of advanced materials in high performance MLBs will require some rethinking of what is "ideal" processing.

Epoxy Resins

By far the most common resin systems used worldwide in making PWB's are based on epoxies. Epoxies are relatively low in raw material cost, yet are capable of a wide range of formulation variations, Tg values from 110°C to as high as 170°C, and are very compatible with most PWB fabrication processes. Briefly:

Difunctional Epoxies (FR-4) begin with brominated bisphenol-A epoxy resins and are formulated with accelerators (i.e. 2-methylimidazole, aka 2MI), hardeners (dicyandiamide, aka "dicy") and fillers (talc is cheap and improves drilling, silica and hollow glass spheres lower dielectric constant, etc.). There are a variety of epoxy products, distributed roughly by Tg into three basic categories:

1. Low end traditional difunctional systems (Tg range 110-130°C)

2. Modified Difunctional systems blended with tetrafunctional or multifunctional resins; (Tg's range 135-160° C.)

3. Pure Multifunctional epoxy systems; (Tg's 170°C or above.)

Tetrafunctional modified systems offer somewhat higher Tg due to the enhanced crosslinking, as well as better resistance to many of the solvents and chemicals used in board manufacture. Midrange difunctional modified systems offer improved performance in higher layer count designs, and multifunctionals ("Pure Multifunctionals") result in improved yields on high layer count designs where PTH reliability as well as resistance to measling are problematic.

Low-Flow epoxy systems are designed with restricted flow for applications such as heat sink bonding and rigid-flex PWB manufacture. Low-Flow systems are available in various Tg and flow ranges. Arlon manufactures several epoxy low-flow materials:

- 47N (130oC Tg) is used primarily for heat sink bonding;
- 49N (170oC Tg) is used in rigid-flex applications; and
- 51N (Tg 170oC) is a “Lead-Free” Low Flow based on a thermally enhanced epoxy system for use in a wide range of applications.

Thermally conductive epoxy systems are designed to have substantially higher Tc values than traditional epoxy systems. Typical values for thermally conductive epoxies range from 1 to 3 W/m-K compared to 0.25 W/m-K for traditional epoxy systems. Filled with thermally conductive fillers and based on lead-free resin technology, Arlon’s 91ML (1.0 W/m-K) and 92ML (2.0 W/m-K) are examples of second generation thermally conductive products. Thermally conductive systems promote heat transfer both through the laminate and laterally within the laminate, to reduce temperatures at the board surface (i.e. device temperatures) by anywhere from 10 to 20°C compared to traditional systems.

Blended Resin Systems

Blends of different resin systems are also available, such as BT-Epoxy, BT-bismaleimide, Epoxy-Polyimide, Epoxy-PPO, etc. It is often wrongly assumed that blending will result in properties halfway between the two primary blend components – this assumption is not "scientific," and can lead to trouble.

Note: The IPC Resin Technology Task Group has available a "Terms and Definitions" guide to assist in understanding the terms used in naming and describing resins and resin systems. Besides the names and definitions of common resins and additives, it also addresses such concepts as "blend", "cure", "crosslink", "filler", etc. The use of standard definitions might help us all be more precise in referring to various materials, avoiding a Pandora's Box of possible mix-and-match chemistries to assail the PWB designer.

Polyimides

Polyimide resins are used where high temperature is expected either in process or in application. The high Tg of polyimide (>250°C) makes it the optimum material for use in any of several applications or environments:

- Where high process temperatures may result in latent defects in plated through holes (PTHs) the use of polyimides reduces the overall strain in a hole due to thermal processing, solder reflow, and the like.
- Where the product will be subject to periodic field repair, or where devices will be repeatedly removed and re-soldered, polyimide resists pad lifting and other damage caused ~~to~~ by repeated application of temperature.
- Where the product’s application requires exposure to severe temperature conditions, such as in the case of “burn-in” testing of IC’s or PWBs used in down hole drilling in oil exploration or geothermal projects.

POLYIMIDES begin with addition polymerization of bismaleimides and maleic anhydride or other similar chemistries containing imide structures. There are three broad types of polyimides in common use today:

1.) "Pure Polyimides" including 2nd generation polyimides, such as Arlon's 85N, which do not have brominated flame retardants or other additives which reduce thermal stability, represent the ultimate in thermal stability and temperature resistance.

2.) 3rd Generation Polyimides, based on Kerimid 701 (Arlon 33N and 35N) provide tougher resins with improved flammability resistance (33N is UL 94 V0, and 35N is UL 94-V1). Accelerated polyimide cures in Arlon’s 33N and 35N systems have enabled somewhat lower temperature and shorter cures (as low as 90 minutes) than traditional “pure” polyimides.

3.) Filled polyimide systems such as Arlon’s 84N are used where clearance holes are needed in boards with, for example, heavier metal cores or ground planes. The filler (usually about 25-30% by weight) serves to reduce resin shrinkage, thus minimizing crack formation in filled areas either during cure and when the clearance holes are subsequently drilled.

4.) Low-Flow polyimides consist of bismaleimide resins, epoxy resins and the necessary catalysts, flow restrictors and accelerators appropriate to their formulation. Arlon's 37N and 38N No-Flow polyimides are examples of blended polyimides with Tg’s around 200°C, used primarily in rigid-flex applications where polyimide materials are required for reliability, typically in commercial aerospace and military applications.

5.) 4th Generation advanced polyimides with improved adhesion to copper foil, reduced sensitivity to ambient moisture, reduced Z-direction expansion and improved registration stability are currently under development.

Non-Traditional Resin Systems

The requirement for improved dielectric and loss properties has resulted in the development of a variety of blended products and the use of resin systems that are “non-traditional” in that they may use entirely different cure mechanisms (such as peroxide cures). Such systems may be based on materials that historically were not considered for traditional PWB’s (such as polyolefins, blends with polyphenylene oxide/polyphenylene ether, etc.). Systems such as Arlon’s olefinic based 25N and 25FR offer improved electrical properties, but require a modified lamination process because of their peroxide cure system.

Other systems are under development, some based on unique patented technology and aimed at the transition market between traditional systems and those requiring enhanced dielectric properties, as well as modified systems that enhance traditional materials in terms of performance and cost.

Remember -- no matter what the name of a resin may be, or how sophisticated it may sound, it is the actual in-use properties of the material, your ability to purchase consistent product over a

period of time and its ability to be processed successfully into MLBs that you are counting on when designing. There are dozens of properties which we can use to differentiate between one material and another, and trying to make material selection based on too many of these can actually confuse the issue of what is really important for an application.

Select materials based on the properties you really need, and don't get suckered into the game of supplier "specsmanship" that provides a plethora of non-critical property values that make a product look "better" while in reality not contributing real value for the specific application. Such properties as chemical resistance, dielectric constant and dissipation factor, thermal coefficient of expansion, flexural strength (at various temperatures), thermal conductivity, tensile modulus, Poisson's Ratio and others are often tossed into the properties "pot" when writing specification sheets and making design decisions on laminate materials.

Remember also that based on historical specification standards such as IPC-4101, data sheet properties are often based on 0.062" rigid laminates and while they may be used as the basis for a first pass comparison of materials, may not be good predictors of actual properties in all laminate thicknesses, prepreg resin contents or MLB constructions. Data sheet data alone should not be taken as proxy for evaluation of a design in actual use environments. Discussions with your laminator's technical people about your application and requirements will help you avoid getting into the "Specsmanship" trap and will enable you to make better selections of the specific materials for your designs.

Typical Polyimide and Epoxy Products (Arlon Systems)

The following table illustrates the variety of different laminate and prepreg systems that can be made using various epoxy and polyimide base resins with selected reinforcements. The examples are based on Arlon standard products, however many of these and other variants on the basic theme are made by a number of suppliers worldwide.

Laminate and Prepreg Materials and Typical Properties

	Tg °C	UL-94	Key Feature(s)	Td (5%)	Z-Expansion 50-260°C (%)	Tc W/m-K
Polyimide						
85N Pure Polyimide	250	HB	Best Thermal Stability	407	1.2	0.20
84N Filled Polyimide	250	HB	Crack-resistant Fill	407	1.0	0.25
35N GP Fast Cure	250	V1	General Purpose Poly Fast Cure	407	1.2	0.20
35NQ Quartz Reinforced	250	V1	Low Dk and Loss Tangent	407	1.1	0.20
33N GP UL-94 V0	250	V0	Best Flame Retardant Polyimide	389	1.2	0.20
37N Low Flow	200	V0	Low Flow For Polyimide Rigid-Flex	340	2.3	0.30
38N Low Flow	200	V0	Enhanced Process Poly Low Flow	330	1.5	0.30
85NT Non-woven Aramid	240	HB	CTE Control for SMT Application	426	2.3	0.20

Epoxy						
45N Multifunctional	170	V0	General Purpose Epoxy	311	2.4	0.25
44N Filled Multifunctional	170	V0	Crack-resistant Fill	311	2.3	0.30
45NK Aramid Reinforced	170	V0	Lowest X-Y CTE (~5-7 ppm/^oC)	311	3.5	0.20
55ST Non-woven Aramid	170	V0	High Bond Strength SMT Product	309	4.6	0.20
55LM Non-Woven Aramid	170	V0	Reduced Moisture Absorption	337	4.7	0.20
47N Low Flow	130	V0	General Purpose, Heat Sink Bonding	314	3.5	0.25
49N Low Flow	170	V0	General Purpose, Rigid-Flex	302	2.6	0.25
51N Lead-Free Low Flow	170	V0	Lead-Free Low Flow for Rigid-Flex	368	2.6	0.25
99ML Thermal Conductive	170	V0	Thermally Conductive General Purpose	311	2.6	1.20
91ML Thermal Conductive	170	V0	Thermally Conductive High Tc	368	2.6	1.00
92ML Thermal Conductive	170	V0	Thermally Conductive Economy Grade	361	2.4	2.00

What is High performance?

The term "High Performance" has been used to mean various things at different times and clarification is in order. In general a “high performance” laminate is one that performs a function that can’t be achieved using traditional FR-4 materials. There are several areas (at least) which demand "High Performance" PWB's:

1.) Boards that have special thermal requirements, either because they will operate continuously or intermittently in high temperature environments or because they will have to handle high concentrations of power in small areas.

2.) High Speed Digital applications often require large or high layer count multilayers that are extremely complex to manufacture and may have need for enhanced electrical properties such as reduced dielectric constant to improve signal propagation speeds; this includes such jobs as mother-boards with complex etched patterns requiring precise registration;

3.) Boards requiring Controlled Thermal Expansion characteristics for SMT technology;

4.) Boards with special or tightened electrical requirements, especially those requiring precise controlled characteristic impedance. (Note that impedance can be controlled using traditional materials as long as laminate “variables” such as resin content and glass construction are specified and held to acceptable tolerances.)

5.) Boards which will operate at microwave/RF frequencies and therefore require materials with low loss or low dielectric constant. Especially as materials are now handling high frequency, high volume digital data, these characteristics have become increasingly important and in many cases trump traditional properties in terms of overall importance.

6.) Boards which require high density interconnection (HDI) and for which materials are required to be able to be laser-drilled for the formation of microvias from the surface to layers 2 and 3.

With some thought, many of these can be subcategorized and there may be others that are considered “high performance” that we have omitted. In any case the term generally implies that the PWB’s themselves must perform beyond the ability of traditional designs and materials, and hence that the raw materials used in their manufacture have to exhibit some properties set that is “beyond the norm.”

Define Glass Transition Temperature (Tg) and discuss its significance. What are the Tg's of the common laminate materials?

The simplest way to define Glass Transition Temperature is to call it "The temperature at which the mechanical properties of a laminate begin to change rapidly." Glass Transition Temperature is just what its name suggests: it is that temperature at which a material changes from a hard, brittle "glass-like" form to a softer, rubberlike consistency. Technically, we can relate this phenomenon to changes in "free volume" and the relative mobility of individual molecular segments within the crosslinked lattice. With a highly crosslinked thermoset polymer the transition is not dramatic like the sharp melting point of a pure crystalline compound or the extreme softening of a thermoplastic.

Nevertheless at the Tg there are significant changes in the physical properties of many resin systems which can, and will, affect its performance as part of a PWB.

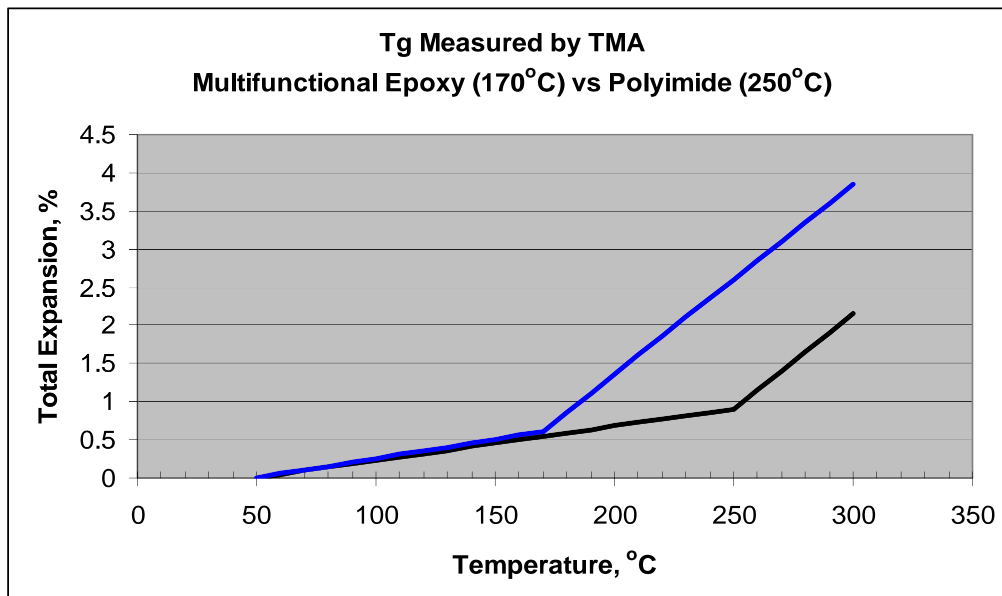
There are a number of ways to measure Tg (Thermo-Mechanical Analyzer, Quartz Tube Dilatometer, Dynamic Mechanical Analyzer, Surface Strain Gauges, Differential Scanning Calorimetry and maybe others). The values obtained with each will be different, because each measures a slightly different property or combination of properties. There is no "right way" or "wrong way" to measure Tg, but because of the wide availability of Thermomechanical Analysis (TMA) equipment within the PWB industry, it has become the method of choice, and gives good and reliable results when performed by a well-trained technician using careful sample preparation techniques. (More on this subject in Section V. Analytical Methods)

The reason TMA is our method of choice is that in the process of determining Tg, the test method measures CTE and expansion properties (see chart below), which are a direct indicator of the stresses on a plated through hole (PTH). While there are indeed material properties transitions measurable by other methods, none of them look at actual Z-direction movement, and may give a misleading idea of the impact of temperature on your PTH's by giving you a higher Tg number, but one based on some other property. If your supplier provides Tg by DSC for example, as is common for epoxy systems, try to understand the difference between that number and the value for TMA -- often as much as 5-7°C. Given that, you can make better decisions on expected material performance.

One of the most common results of the softening of the resin at its Tg is that it becomes easily smeared during drilling. With conventional FR-4 the heat generated at the cutting surfaces of the drill is often sufficient to cause smearing. In addition, when we heat a resin above its Tg, either in use or during processing, it may cause substantial reduction in bond between the resin of the

laminate and its copper foil cladding, resulting in pad or line lifting and other problems with surface features. Materials such as polyimide with high Tg's are much less affected by phenomena such as smearing and pad lifting.

The out-of-plane coefficient of thermal expansion (Z-direction) changes dramatically above the Tg. It is typical for the Z-direction CTE to increase about four-fold, from 50-60 ppm/ °C below the Tg to 180-250 ppm/°C above it. Because Z-direction expansion causes strain on the copper



plated in holes, the extra expansion above the Tg is often responsible for PTH copper cracking during processing or rework. It may also result in "latent defects" that will show up later during normal in-service use.

This is especially evident in thick boards with small holes (and high aspect ratios) such as large backplanes. The effect of Z-direction expansion is also critical in flex-rigid boards where flex materials (acrylic or other thermoplastic-containing adhesives) with low Tg's and high inherent Z-direction expansion coefficients can result in boards with overall expansions of as much as 500 ppm/°C which can result in plated through hole barrel cracking, lifted pads and even cracking of surface resin caused by excessive stresses during heating and cooling cycles.

Typical Tg's for common resin systems are as follows:

Conventional Polyimides 240-260°C
Epoxy Modified Polyimides 200-220°C
Epoxy-PPO Blends 150-170°C
BT/Epoxy Blends 160-200°C
Pure Multifunctional Epoxies 160-180°C
Tetrafunctional Modified Epoxies 140-160°C
FR-5 (High "Hot Strength" Epoxy)130-140°C
FR-4 (Standard Epoxies) 115-125°C

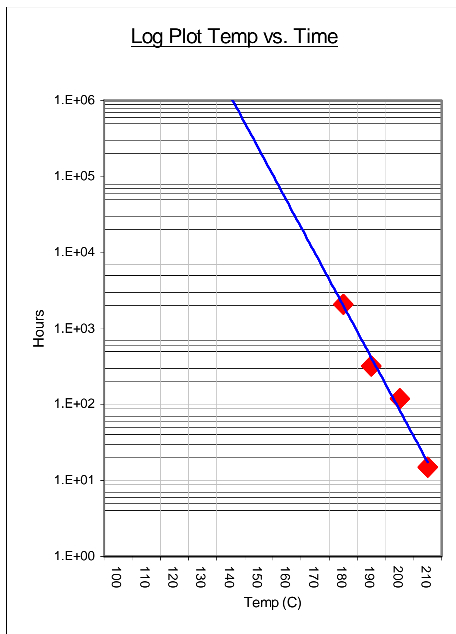
TROUBLESHOOTING TIP: Know your resin system thoroughly before making a commitments to its use. Blends of materials can probably produce almost any desired Tg. While this may appear to be a neat continuum of Tg's that can be tailored to any application, there are some concerns about mixed or blended systems, which may exhibit dual Tg's, with each resin component acting as a discrete distributed phase. In such cases, the tendency to smear and an early increase of Z-direction expansion may occur despite high published values for the Tg. Additionally, papers have been published indicating that blended (as opposed to true copolymer) resin systems may tend to exhibit microcracking during thermal cycling, in a polymeric equivalent to "work hardening."

The resin system is the "heart" of any laminate. Know what you are using, and seek assurances that it will be consistent over time.

What determines "Continuous Operating Temperature" of a system and how does that differ from Tg? What are the Continuous Operating Temperatures of common laminate systems?

The 5th Amendment might allow one to say, "On advice of Counsel I respectfully decline to answer on the grounds that it might tend to incriminate me." The truth is that no answer to this question will ever totally satisfy a designer with specific conditions in mind, and only some kind of accelerated testing of an actual board or assembly will give a meaningful answer.

Continuous operating temperature is the temperature at which a particular material can operate without undue deterioration during its normal and expected service lifetime.



There are many ways to evaluate this. Underwriters Laboratories develops a thermal index (Arrhenius plotting of time vs. temperature) for materials which is the mathematical extrapolation of data from a four temperature accelerated aging evaluation to a temperature at which the material will operate for 100,000 hours and still retain at least 50% of its original physical or electrical properties.

Typical properties tested by UL are tensile strength, dielectric breakdown resistance, etc. Remember, however, that the maker of a PWB wants his entire board to operate for a long period of time, and most data available on materials was specifically developed on the unclad laminate composite (resin and glass). Moreover the internal structure of the board itself (amount of heat sinking capacity, density of power generating components) and the intended use environment will also

affect the service life of a board.

While the UL RTI (Relative Thermal Index) may not represent the ultimate use temperature of a material, it is a good starting point guideline, and use above that temperature will result in increasing rate of failure (the rate of any chemical reaction roughly doubles for every 10 degrees C, so you can see how much effect additional temperature will have).

Oxidation is the principal mechanism by which epoxies and polyimides embrittle and turn brown as they sit or operate at high temperatures over a period of time. Above the Tg this process occurs more rapidly because of greater diffusion rates and more molecular motion. With polyimide, for example, although it turns brown fairly quickly, this is mostly a surface oxidation and not a deep deterioration of the material. Lower temperature materials, epoxies with fairly labile bromine and the like, will deteriorate substantially at temperatures which are relatively innocuous to polyimide.

Oxidation is also a major cause of long term failure of copper bonds on PWB's. Copper traces oxidize not only on the top side (where they turn purple or black) but also underneath due to diffusion of oxygen. When the treatment that bonds the copper to the surface oxidizes sufficiently, the bond will fail, and the line will fall off with relatively little handling.

Prolonged temperatures over 250°F will eventually deteriorate copper bonds on any PWB surface. This is a primary mechanism for failure of copper bonds on PTFE boards which otherwise are almost entirely resistant to normal oxidative (or almost any chemical) attack on the resin itself.

Thermal properties are not only a function of long term thermal stability of a polymeric material, but relate to interactions between material and design, quality of fabrication, use conditions such as thermal cycling, and environmental effects such as humidity and temperature that can aggravate such issues as CAF formation, volume resistivity, etc..

Use of designs with "Pads Only" surfaces, or employment of high temperature conformal coatings may significantly extend the service life of a board under oxidative conditions.
Td, thermal decomposition temperature, is often cited in product literature as an indicator of a material's ability to withstand long exposure to elevated temperatures. Td values are typically cited as that temperature at which the material has lost 5% of its weight due to thermal decomposition. In this writer's opinion, a better value to use is the value defined as the "onset" of decomposition, usually several degrees lower, but to be honest, once a material has decomposed to the point that it has lost 5% of its weight, it will probably look like a blistered, charred mess and have long since failed. Since PWB's are almost never used at temperatures that approach or exceed the Td (at least not on purpose) these values are used as relative indicators of short term stability (resistance to high temp solder processing, etc.) rather than defining "Continuous Operating Temperature" limits.

Why do epoxies and polyimide turn brown when we expose them to elevated temperature?

Almost all organic materials turn yellow, then brown or red-brown and finally black on thermal aging, due to oxidation or other thermal degradation which produces sequences of allylic double bonds (a sequence of seven or eight alternating double bonds will cause noticeable yellowing in a polymer long before any actual properties degradation may occur). This is often simply the result of surface oxidation and represents no significant problem.

Polyimides turn dark brown on the surface after a fairly short exposure in air to elevated temperatures. We are aware of no deterioration of physical or electrical properties associated with this initial darkening. Standard FR-4, under the same conditions, may start to debrominate and suffer embrittlement, delamination and discoloration throughout the laminate. Prolonged exposure to high temperature and oxygen will, of course result in a deepening of the oxidized layer, and eventually severely oxidized resin will start to flake off. The best protection against excessive oxidation is to use a good high temperature conformal coating, which will protect the resin surface, and copper traces from direct exposure to air. Alternatively a “pads only” surface will provide protection for the embedded circuitry at a modest increase in product cost.

Do resins require a postcure after laminating?

In the distant past some laminators shipped "green" epoxy (referring here to undercured resin rather than bromine-free chemistry) due to pressure to shorten cycles and increase throughput. Most laminators today fully cure rigid laminate materials since they will not receive subsequent cure. Polyimide laminates designated for multilayer use are cured to about 85% of full cure in our lamination process in order to leave some chemistry “alive” for enhanced interlayer bonding in the MLB process. Years ago, poor interlaminar bond in polyimide laminates could be – and sometimes was -- caused by post curing all laminates to a degree that there was no reactivity left for reaction with prepregs in MLB lamination.

Some PWB manufacturers subject their laminate to an automatic 4-6 hour prebake at 325 to 350 °F. In addition, panelized laminate materials may be "stabilized" somewhat by a short prebake process in terms of registration since the bake temperature goes over the Tg and allows for some stress relief. (Note: this is only known to be helpful when the laminate has been panelized -- full sheet baking may complete an under cure, but won't noticeably "stabilize" a material in terms of registration.) Since polyimide laminate has a Tg higher than the normal bake temperature, it has not been found necessary for polyimide materials and generally won't have any impact.

Polyimides cure in a two-step chemical reaction. The first step involves the addition reaction of a bismaleimide with an aromatic diamine or other reactive intermediate which occurs at 350-360°F. This step results in a linear polymer which is brittle and has poor interlaminar bond. The second step of the reaction for polyimide, which takes place at 400-425°F is a crosslinking reaction in which double bonds on the maleimide end blocks of the molecules open and react with one another. This cross linking reaction occurs more slowly, which is why uncatalyzed polyimide requires longer time for cure completion. This final cure step builds cross-link density, brings Tg to its full development and improves the physical properties of the material.

Can we cure polyimide at 360 °F without a postcure?

Postcure generally refers to either a second temperature step in a curing process or an off-line cure in an oven rather than a press. In that sense a single temperature cure such as is now recommended to cure polyimide materials does not constitute a "postcure" in the traditional sense. Polyimides do and will continue to require a high temperature cure to develop their properties fully, but off-line oven postcuring is rarely done. Because of limitations of press temperature capabilities, many PWB manufacturers would like to process polyimides at epoxy cure temperatures. This will not achieve a full cure, and a commitment to use high performance materials may require investment in high temperature steam or electric presses.

Cure temperatures below 415°F may not advance the cure of polyimide resins acceptably, regardless of the time. It is not reasonable to expect that 10-12 hours (or any amount of time) at 360-370°F will take the place of 2 to 4 hours of cure at 400-425°F.

TROUBLESHOOTING TIP: It is important to remember that the properties of polyimides are not fully developed at low temperatures. Among other things, Kerimid 701 polyimide laminate that has only received a 360 °F cure will have a low Tg (less than 200°C), poor interlaminar bond, may delaminate or fracture during shearing, drilling and routing operations and will probably exhibit cracking in cross-sections.

All polyimide resins are not the same and it is important to review manufacturers' recommendations for the specific resin system you are using to be sure it is properly cured. Arlon's 85N resin, for instance, requires a slightly higher temperature and longer cure than its 33N and 35N systems to give optimal properties.

Blatant Commercial Message: The best available laminate resin for long term high temperature applications is Arlon's 85N, which is a pure polyimide with no flame retardants or other thermally unstable additives. Where the best thermal performance is needed, 85N exceeds any other commercially available material, with superior property retention at high temperature.

TROUBLESHOOTING TIP: It is always important that a designer test the materials he is choosing to ensure that they will actually perform acceptably in their intended use. This is not a cop-out to avoid responsibility for the performance of our materials. Neither we, nor any laminator, can ensure that our material will perform in conditions that are out of our control or in every potential application of the product. There needs to be a good early dialogue between the designer and the laminator to discuss needs and specifications and make sure they select the best available material for the job. This will minimize the risk of designing boards that will fall short of expectations.

What are Dielectric Constant and Loss Tangent?

Dielectric Constant (aka permittivity, DK, Er, etc.) is the property of a material that determines the relative speed that an electrical signal will travel in that material. Signal speed is inversely

proportional to the square root of the dielectric constant. A low dielectric constant will result in a high signal propagation speed and a high dielectric constant will result in a much slower signal propagation speed.

A good analogy is to imagine yourself running along the beach with your feet six inches deep in the water. The dielectric constant is analogous to the viscosity of the water. If the tide goes out you are running in air on hard sand (dielectric constant lower) and you can run faster. If the water suddenly turns to molasses, or you are in deep soft sand you are going to be running in slow motion (dielectric constant higher).

Dielectric constant is not an easy property to measure or to specify, because it depends not only on the intrinsic properties of the material itself, but also on the test method, the test frequency and the conditioning of samples before and during the test. Dielectric constant tends to shift with temperature.

Note: Dielectric constant is not a "constant" in the sense that the speed of light in a vacuum (to which the relative Dk of other materials is referenced) is a constant. Dielectric constant and loss of materials depend on a variety of factors including test method and frequency at which the test is performed. In general higher frequencies (with more "energy") will result in higher loss values, yet result in a shift downward in dielectric constant. Example: polyimide with a Dk of 4.3 at 1 MHz may have a value as low as 3.8 to 4.0 at 2-4 GHz.

We determine the characteristic impedance of a PWB based on the thickness of the laminate (spacing between copper layers) and its dielectric constant as well as etched line height and width. Impedance control, and impedance matching of critical linked functional modules is especially important in high speed devices and designs.

Note: dielectric constant and dissipation factor have not always been considered critical except in high speed digital or microwave applications. As the quest for improved impedance control continues, interest in control and consistency of dielectric constant (regardless of absolute value) will grow. Since dielectric constant of a glass/resin composite is proportional to the volume ratio of glass to resin, the specification of laminate constructions and prepreg styles will be a necessity.

Typical dielectric constants of materials as measured at 1 Mhz are as follows:

Material	Dielectric constant
Hard Vacuum (~air)	1.0
Pure Teflon®	2.1
Type GY Teflon®-Glass	2.2 - 2.3
Type GX Teflon® Glass	2.55
Filled PTFE (CLTE-XT)	3.0
Polyimide-Quartz	3.5 - 3.8
Polyimide-Glass	4.0 - 4.6
Epoxy-Glass (FR-4)	4.4 - 5.2
BT-Epoxy	3.8 - 4.0
Non-woven Aramid Epoxy	3.8 - 4.1

Woven Aramid Epoxy	3.8 - 4.1
Ceramic-Filled Teflon®	6.0 - 10.2
Water	70.0

Related to dielectric constant (or "permittivity") is dissipation factor (aka loss, loss tangent, tan beta, etc.). This is a measure of the percentage of the total transmitted power that will be lost as power dissipates into the laminate material. A wide range of dielectric loss is available depending on material choice: Traditional FR-4 may have loss values of as high as 0.025, while polyimide is closer to 0.015. Lower loss materials such as Arlon's 25N will have intermediate looss values in the range of 0.0025 to 0.003. As a reference, laminates based on PTFE and reinforced with woven glass can be manufactured with low Dk (2.17) and loss as low as 0.0009 at 10 GHz (i.e. Arlon's DiClad 880).

System loss is often expressed in dB (decibels), defined as the negative log to the base ten of the ratio of the Power In to the Power out in the system, and as a reference point a -3 dB value means that exactly half the power is being lost in the system.

In an actual board, transmission "line loss" will be caused by several factors: conductor loss is due to resistance in the copper traces due to copper's inherent (albeit low) resistivity and the geometry (cross-sectional area and roughness of the copper treatment in contact with the substrate) of the transmission line; radiation loss is caused because part of a signal in a transmission line is "broadcast" as though from an antenna; and finally, dielectric loss is a result of loss in the substrate itself. Hence actual losses will depend on line length, geometry, material and design – again, there is a need to look beyond published "loss" values for laminates to determine real system losses.

What is Impedance?

Webster's 9th Collegiate Dictionary defines impedance as "the apparent opposition in an electrical circuit to the flow of alternating current that is analogous to the actual electrical resistance to a direct current..." We who are not electrical designers often use the words "controlled impedance" without giving serious thought to their meaning. What variables affect it and what, if anything, can we do about it? If you are building "impedance controlled" MLB's, you are probably hounding your laminator for tightened tolerances on laminate thickness and on dielectric constant.

Dielectric constant has something to do with impedance, but maybe you're not sure not exactly why. Additionally, when you struggle with inner layer spacing or etched line width you are affecting the impedance.

Characteristic Impedance is of considerable importance in a high speed, high frequency environment, and has become a matter of daily discussion for those designing and making sophisticated printed wiring boards. When impedances are not "matched" between elements of a system, reflected waves can result in surge currents (which cause spurious activation of devices) and significant power losses (which result in slow voltage rise rates and critical timing

problems). Impedance should not be confused with signal propagation velocity, which is a function of dielectric constant.

How do you calculate impedance?

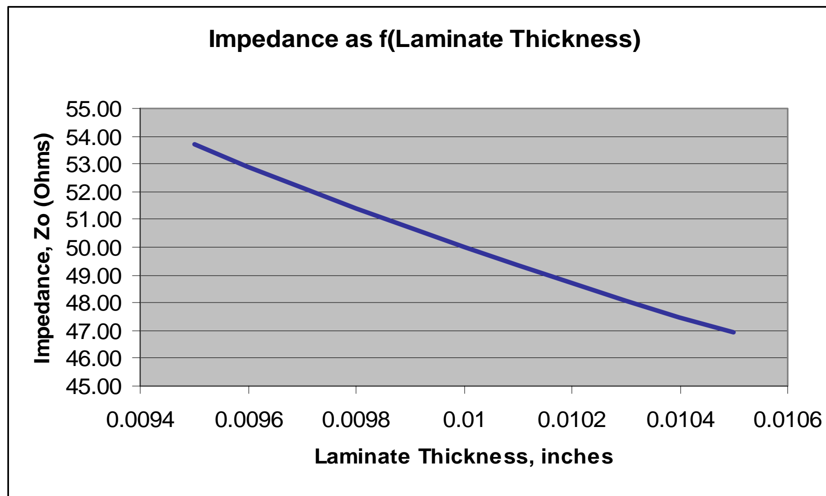
Impedance can be estimated as a function of laminate thickness, dielectric constant and etched transmission line thickness and width based on published equations. As an example, the following is a simple stripline formula:

Impedance = (2*G1*G2)/(G1+G2)

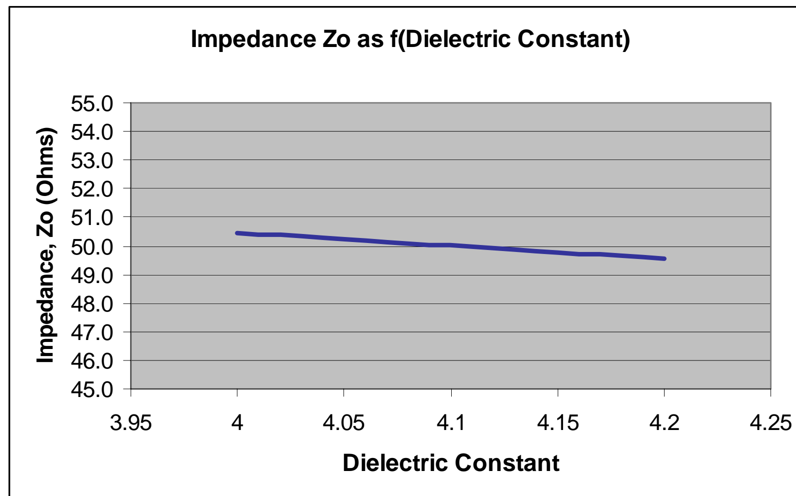
Where:

G1 = (60/SQRT(Er))*ln(8*H1/(0.067*PI*(0.8*W+th)))
G2 = (60/SQRT(Er))*ln(8*(H1+H2)/(0.067*PI*(0.8*W+th)))
H1 = Laminate Thickness
W = Copper Line Width
H2 = Distance to Opposite Copper Plane
th = Copper Foil Thickness
Er = Dielectric constant: of the Laminate

This and similar widely published equations for stripline, and microstrip designs lend themselves readily to "what if" calculation using Excel or equivalent spreadsheet programs. The accompanying graphs, generated using this equation illustrate a simple sensitivity analysis on the Polyimide-Glass system, looking at the key variables which affect impedance: laminate thickness, dielectric constant and line width (assuming copper thickness remains constant).



The effect of either, laminate thickness (Note: this is equally true for inner layer dielectric spacing!) or line thickness and width, is greater than that of dielectric constant, which is an inverse square root function. (see charts below showing impedance as a function of normal



variation in dielectric constant and impedance for as typical polyimide product with nominal Dk of 4.1 and thickness of 0.010") These relationships will always be similar when considering the sources of impedance variation within a given system, regardless of the absolute values of the variables.

What is an acceptable variation in impedance? Can it be met with a particular system? These are questions that only the designer can answer for his particular project. The issue may not be "What do we want?", but "Can it be met with the tolerances possible using commercially available laminate and prepregs? And can it be met within the capabilities of our PWB manufacturing process?"

Given the normal variability in materials and process, can you design around the laminate dielectric properties you can get from your PWB manufacturer?

The impedance of most multilayer PWB's, when determined by stripline or microstrip methods, behaves as though the dielectric constant is lower than when determined by the 1 MHz MIL-S-13949 two-fluid cell method. Two factors are be involved: first, transmission lines themselves have more resin around them (they are partially encapsulated by the resin from the prepreg bonding layers) than the overall average for the laminate product, and second, at higher frequencies, dielectric constant shifts downward. In either case, Caveat designer!

Suggestion: make and test a prototype and do a "what if" analysis based on the expected normal variability of your laminate thickness (and/or pressed prepreg if that determines the critical spacing), of the etched traces on your board and the dielectric constant of the laminate. Hint: the normal variability of the dielectric constant, assuming you specify the construction of your laminate, will usually have less impact on final variation in impedance than laminate thickness and etched line width (and undercut) control.

What is the importance of the copper foil used on laminates?

On the surface this sounds like an almost silly question. Copper foil is used to carry signals from one part of a PWB to another, serve as ground and power planes, interconnecting the various devices, inputs and outputs that make the finished board work in its application. But there is a whole world of technology implied in the use and application of copper foil, and as we look at the various kinds of copper foil, the morphology and treatments used, and the effects they all have on performance, we will see that we can't treat this superficially. And you as a user of PWB materials, need to understand these differences so you can order material that will perform to your needs, and be consistent in properties.

What is the difference between "rolled" and electrodeposited foil? How do you know which one to use for a given job?

Electrodeposited copper foil is the standard copper used in the laminate industry. ED foil is deposited from solution at specific voltage and current conditions onto a moving titanium or steel drum, from which it is subsequently stripped. The grain structure formed by this process forms the dendritic "tooth" of the copper foil on the "bath side" of the copper. The drum side takes the smooth texture of the polished drum surface onto which it is plated.

Rolled copper is made by running a copper strip through successively smaller and smaller gaps in a rolling mill until it reaches the desired thickness. Rolled copper is smoother and can be made very flexible by annealing. Because it is smooth, its bond to laminates is totally dependant on the quality of the treatment it receives and the "adhesive" or mechanical properties of the resin system to which it is being bonded. Rolled copper also has a different grain structure than ED copper and will etch at a different rate.

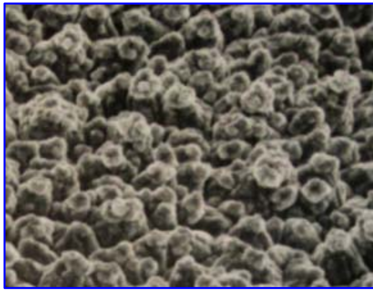
Much of the rolled foil in the laminate industry is used in flexible circuitry, typically bonded to a polyimide film with an acrylic adhesive, where its ductility is essential to the application, such as the flexible connection to the print head on a typical ink-jet printer.

Another significant application of rolled foil is in microwave and RF applications where its very smooth surface permits the production of PTFE fluoropolymer (and other) laminates with very low loss tangent (dissipation factor). Dissipation factor is lower in rolled foil than in ED foil because of a phenomenon called "surface effect" -- the electrical signal traveling at microwave frequencies acts as though it follows the profile of the copper at the interface with the dielectric. The rougher ED copper has a longer "pathway" than the smooth rolled foil and hence usually exhibits greater loss.

Note: There are a variety of low profile copper foils which provide cost advantages over rolled while offering a significant benefit vs. standard ED in terms of copper adhesion to various resin systems, faster etch rate, potential reduced dielectric loss etc.

What is Copper Foil Treatment?

What are the various treatments used on copper foil? What are the real differences in terms of properties and performance?



The "standard" copper treatment consists of microscopic copper nodules deposited over the copper "teeth" on the bath-side of the foil (see photomicrograph below). To reduce oxidation and make a more thermally stable treatment, brass, zinc or sometimes nickel is plated lightly over the deposited copper nodules. A further treatment in the form of a very light zinc chromate or other antioxidation treatment may be used to prevent oxidation of the drum or smooth side of the foil.

Copper adhesion is achieved by a combination of physical and chemical bonding. ED copper foil has a natural "tooth structure" formed during electro-deposition and the nodular treatment (see above) provides a locking mechanism when the resin coats and encapsulates the copper teeth/treatment. Chemical treatment of copper foils can also enhance bonds. Many of the foils in use today have proprietary silane or other treatments which chemically enhance bond to a variety of resins.

Note: All copper finishes will not work equally well with all resins. Optimization of lamination process and selection of the foil finish for each resin system is critical to achieving good bonds.

When the copper foil is treated on both sides it is called double treat copper. Double treated copper (sometimes also called Drum Side Treated Foil, or DSTF) does not give equal bonds on each side, but has a lower profile and lower bond on the drum (smooth) side since that side has not got a base of columnar copper crystal structure to build on as the bath side (rough side) does. Nevertheless most believe that DT copper gives a much better inner layer bond than black or brown oxide with standard ED foil, and when used drum side down, has a very low profile that enhances loss and also makes it possible to do precision etching without excessive etch back.

What is Ohmega-Ply®? What is its application?

Ohmega Ply® and related products designed for embedded resistors in MLB's, is a plated copper foil product in which a very thin layer of a proprietary nickel alloy is plated on the bath (rough) side of the copper foil before lamination. The nickel and copper can be individually and selectively etched to produce "planar resistors", in certain cases eliminating the necessity of soldering or otherwise mounting large numbers of resistors on complex boards. Circuit boards requiring many resistors and in which real estate is critical (terminating resistor networks, computers, and certain burn-in applications) are obvious markets for this technology.

Resistance foils are normally supplied in one of two grades, 25 ohm/square and 100 ohm/square to provide ability to produce resistors of almost any required value.

TROUBLESHOOTING TIP: Planar resistors – especially the 100 ohm/square products whose nickel layers are very thin -- are very delicate. The value of the resistors generated will depend

at least in part on the cure temperature of the laminate and the handling of materials (to prevent damaging the delicate resistor layer) as well as the quality of etch process of the resistors themselves. Not only is it necessary to customize laminating cycles to produce the basic clad product, but it is essential that the designer and fabricator understand the special chemistries and processes used in etching inner layers, and the importance of process control and verification testing at every key step in the process.

What is Copper-Invar-Copper (CIC)? Why do we use it? What are its limits?

Copper-Invar-Copper is a sandwich of Invar, a nickel containing iron alloy, bonded between two layers of copper. It is metallurgically bonded in the rolling process which also reduces the thickness to as low as 0.006" which is the grade Arlon uses in its CIC products. Typically the ratio of copper to Invar is 12.5%/75%/12.5% which gives it a CTE of about 5.5 ppm/°C. Since CIC, thanks to the nickel-iron core, has a very high modulus, it is effective in constraining the overall movement of PWB's in which layers of CIC are embedded. CIC may be used as combined heat sink, ground and restraining layers in multilayer PWB's for surface mount applications.

Bonding CIC to polyimide laminates is somewhat difficult because of the shear forces caused by differences in thermal expansion during heating and cooling. Special treatment of the CIC surface and proprietary press cycles are required to bond it to polyimide. Until this treatment was developed, practical use of CIC with polyimide had been severely limited, and only a limited number of suppliers have been able to manage the treatment with any consistency. The application of CIC will be discussed in more detail in the section on CTE Control.

What is HTE Copper? Why do we use it?

HTE copper (IPC-CF-150, Class 3), also known as "High Temperature Elongation" copper, has a greater nominal elongation at elevated temperature than standard ED copper foil. This value, typically 2-5% vs. 1% or less in standard ED foil, correlates to reduced cracking of inner layer foil at PTH interfaces during thermal cycling. The use of HTE copper foil is most critical in thicker epoxy MLB's which may experience severe Z-direction expansion during thermal processing or repair operations.

While HTE copper foil may not always be necessary in polyimide MLB's, Arlon and some other laminators now use HTE foil exclusively, there being no downside to its use, and benefits in terms of PTH reliability regardless of the resin system used.

What is Release Copper? Why do we use it?

We manufacture polyimide products in presses that operate up to 425°F and cannot use the traditional polymeric release material which tends to degrade, outgas and “scum” at that temperature. Instead we use copper foil with the drum side down (shiny side against the

laminate) when making unclad materials. A number of multilayer board manufacturers also find it convenient to use copper release foil in this application to avoid analogous problems with polymeric release materials.

How is copper affected by Tg, operating temperature, etc.? What factors contribute to copper bond longevity?

Copper bond is important both during PWB fabrication and in use. If copper traces or pads lift off the board or become detached, they are easily damaged and can cause board failure. In some applications such as boards for mobile phones, there is a requirement that the board resist a 1 meter “drop test” and if peel values are too low, devices will pop off the board, pads and all, due to the G-shock of the drop.

Materials such as polyimide and Teflon® are in themselves resistant in varying degrees to both heat and chemicals. They can withstand temperatures as high as 500°F for prolonged periods of time and have excellent tolerance to the attack of various etching and plating chemistries. The bond between the laminate itself and the copper foil that will become the circuitry on the finished PWB is somewhat more fragile. The major causes of copper bond failure are thermo-mechanically induced (shear) forces and oxidation under the foil.

During prolonged exposure to high temperature, oxygen diffuses under the foil at the base of an etched line and starts to further oxidize at the treatment interface which is the path of least resistance. Eventually the original treatment will largely be displaced by a very weak black cupric oxide layer which will fail when thermally or mechanically stressed. When we examine a copper trace microscopically after peel, it will show the reduction in bonded width caused by prolonged thermal exposure.

How hot? How long? We honestly don’t know, although material used under inert gas blanketing will last longer than when exposed in air and the use of pads-only surfaces on burn in boards that will see long exposure to elevated temperature can greatly extend service life, as will use of conformal coatings that additionally act as oxygen diffusion barriers.

Above the Tg, thermosetting polymers such as epoxies may soften measurably and can start to lose their bond. Copper pads can be easily lifted off an epoxy board during rework or field solder repair, while polyimides, which rarely exceed their Tg temperature during soldering, do not normally exhibit this problem. The use of newer, lead-free solder systems only serve to exacerbate this issue which is often critical when attempting to remove and reattach devices on the board.

Various copper treatments are available which both enhance bond and attempt to reduce the effects of secondary oxidation attack. Copper foil is treated by the growth of copper nodules which provide bonding "tooth" in addition to the normal grain structure. These nodules are lightly oxided and then treated with a deposition of brass, zinc or even sometimes nickel along with chromate conversion treatments and other oxidation inhibitors to reduce subsequent oxidation attack.

What governs the choice of which copper foil type or weight to use in a particular laminate?

The copper foil used on a PWB serves several functions. The primary use is as a circuit line to carry signals from one point to another to permit interconnection of various components on the board. Copper also serves as power and ground layers. And copper layers can help carry away unwanted heat from power devices.

All that being said, the designer of a PWB must determine several characteristics of his board which will determine what type and thickness of copper to use:

1. The power handling requirements of the board (thin copper won't handle as much power as thicker copper, and too much power routed through a small cross section could result in overheating and burnout -- almost as though it were a fuse);

2. Characteristic impedance and line loss are affected by the cross sectional area of the copper foil used as well as the thickness of the laminate and its dielectric constant. This needs to be included in design calculations.

3. The size and spacing of the copper traces that must be etched on the various layers (very fine lines and narrow spacing will generally require thinner copper or DSTF foil to minimize undercut during etching);

3. How much heat dissipation must be handled by the copper, especially in inner layers (the heavier the copper, the more capacity it has to dissipate heat);

4. Other factors such as inner layer bonding, etc. which might require special copper properties or finishes? And…

5. In microwave/RF applications, the surface roughness of the foil will impact the loss characteristics of a transmission line, so that lower profile copper foils are often preferred where loss is critical.

6. If copper foil is used for foil lamination the finish on the copper is critical and must be compatible with the resin system employed.

Reinforcements

Reinforcements, sometimes called substrate materials, are the medium on which resin is cast or coated to produce the prepreg building blocks of a product line. The reinforcement contributes significantly to both physical and electrical properties of the finished product and may need to be cleaned and/or treated to ensure proper and intimate bonding to the various resin systems with which they will be used. We will discuss primarily standard E-Glass materials since they are the bulk of the reinforcement used in epoxy and polyimide laminates. Other substrates are available

and used in specialty materials. Nonwoven aramid, woven Kevlar® and woven quartz fabric in addition to several chemical composition variations on the standard glass will be considered.

What are the differences between the common fiberglass fabric styles used in laminates? What is the basis for their choice and selection?

We use a number of fiberglass fabric styles in the manufacture of prepreg and laminate. Their selection is most often based on the thickness they will contribute to the finished laminate or printed wiring board or on the amount of resin they hold for filling and bonding. Specific choices often depend not only on building thickness but also on secondary properties such as stiffness, dielectric constant, CTE control, dimensional stability (registration) and (as is always an issue) cost.

Fiberglass fabric starts out on a "warp beam" containing thousands of individual strands of yarn rolled onto a master beam, or roll. These yarns will compose the machine direction of the fabric, or more correctly, the "warp direction". The warp yarns are then "slashed" -- run through a solution of sizing agents and lubricants which protects them from damage during weaving.

In the actual weaving process the warp beam is mounted at the back of a loom and the "fill" yarns are inserted as the warp yarns are passed through from back to front. In the older style Draper looms, a wooden shuttle containing the fill yarn was slapped back and forth from side to side of the loom to insert the fill yarns and alternating warp yarns moved up and down in a mechanical frame to create the traditional "plain weave". This resulted in a woven, or "Drapered", edge. In the newer air jet or water jet looms, the fill yarns move across the loom on jets of air or water and are cut off individually leaving a fringed edge. A single warp beam may contain several thousand yards (several miles!) of warp yarns and may represent as much as a week's weaving time for a single loom.

After weaving, electrical grade glasses must be "scoured" (think aggressive hot water rinse, not some torture process with steel-wool) to remove excess sizing from the warp yarns and then heat cleaned (a lengthy stay in an oven at elevated temperature) to remove the rest of it. After scouring and heat cleaning the weaver treats the fabric with organosilane finishing agents to provide a fabric surface which can be wet by and bonded to various resin systems. Glass manufacturers apply high temperature finishes such as amino-silanes to glass intended for polyimide manufacture so that the bonds will survive the use conditions that the polyimide will see. The finish on a fiberglass fabric represents only a very tiny amount of material (a fraction of a percent of the raw weight) but vitally affects how the resin will wet the surface during prepregging. Prepreg with repellent spots or streaks (which often show up on heating even if they are not evident initially) is generally a result of either poor scouring and heat cleaning or inadequate silane treatment. There are a variety of finishes offered by the glass weavers, and the correct choice of finish for each resin system is critical to its performance.

Historical Note: Some of you who are relatively new to the industry may wonder about the reason why so many epoxy resin systems are green in color. It goes back to a previous generation of fiberglass finishes based on chromium chemistry and with the trade name Volan. The Volan

finish was green in color, and when the industry went away from Volan (there is still a little bit used, but concentrations are much lower and it's not so obviously green any more) and started using organosilanes, end users complained about the change in appearance of their product. Virtually all the suppliers started dying their FR-4 green so it would look “normal.” It is still common to see green epoxy PWB’s. We hope it works better with the green dye in place!

The most commonly used glass styles are as follows:

Style	Threat Count	Wt (oz/yd^2)	Resin Wt %	Ply Yield (mils)
104	60x52	0.55	75	1.1
106	56x56	0.72	72	1.3
1080	60x47	1.38	63	2.4
2313	60x64	2.38	55	3.3
2116	60x58	3.01	50	3.7
7628	44x32	6.03	40	6.8

Lightweight fabrics with high resin contents tend to give smooth, resin rich surfaces, and provide better fill for internal copper etched patterns. Heavier fabrics are less expensive, tend to provide enhanced dimensional stability (registration) and permit building of greater thickness at less cost per mil. The use of heavier fabrics, especially 7628, can affect surface smoothness and drilling characteristics. Heavy fabrics (especially 7628 and thicker fabrics occasionally used in rigid laminates to cut costs) can deflect small drills or cause them to break.

What are "Warp" and "Fill?" What other terms are used to describe the direction of weave in fabric? Why is this important to our customers?

In a roll of woven fabric we use the term "Warp" to designate the direction of the length of the roll and "Fill" to designate the direction of the yarns which "fill in" from side to side in the weaving process. (See above for discussion of fiberglass fabric manufacture) Some people refer to warp as "Machine Direction," "Grain" (erroneously, since fiberglass fabric does not have a grain or granular structure) or "Strong Direction" (accurate technically, but confusing). Some refer to fill as "Woof," "Weft" or "Cross Direction." The number of yarns and their tension are not evenly balanced in many of the commonly used fabrics and their effects on such things as registration can vary. Normally if a PWB fabricator knows which direction is Warp and which is Fill he can orient them in the same way each time and adjust his processing to compensate for predictable effects.

Normally the Warp is parallel to the 48" direction of a 36" x 48" laminate. By convention the Warp is in the longest direction of a piece of cut prepreg or panelized laminate unless specific customer request or cutting efficiencies dictate otherwise. When warp is not in the long direction, or when our customers order square panels, we mark the warp direction clearly by an arrow on the material or the package.

TROUBLESHOOTING TIP: When specifying warp direction, we suggest the phrase "Warp Direction Parallel to the . . . " required dimension of the panel as the clearest expression of this

requirement. Such phrases as "Grain to the long direction" or "Strong direction across the panel" can be confusing.

What is "Weave Distortion?" What problems can it cause?

Weave distortion occurs when some of the fill yarns in a fabric are out of true (they should be at a 90 degree angle to the warp yarns, which are normally under tension and remain straight during handling). When some of the yarns are distorted it is possible for a laminate or multilayer to develop a twisted or rippled condition. Not only is it necessary to have undistorted yarns in the raw fabric, but the laminator has to take care that the yarns are aligned in one sheet of prepreg relative to another, or warpage can occur.

What is S-Glass and why would we use it?

"S" Glass, more accurately, S2-Glass is a "high strength" glass fiber originally developed for the structural field. It differs in both composition and properties from E-Glass.

Compositionally, S2-Glass has a higher percentage of both Silicon Dioxide and Aluminum Oxide than E-Glass. It is more difficult to manufacture than E-glass because it has a much higher melting point and requires special tooling in the drawing operation. Exotic tooling means that it is expensive, and also means that nobody will have an "extra" die on hand. Relatively small amounts of S2-Glass are woven for electrical grade applications each year and relatively large minimum purchases are required (relative to most PWB program requirements).

S2-Glass has a lower dielectric constant and dissipation factor than E-Glass because of the higher silicon dioxide percentage. It also has a slightly lower CTE than E-Glass (same reason). In practical terms it will knock off about 1-2 ppm/°C in CTE value in a typical MLB with an average 50% resin content. Likewise, for equivalent constructions, it will reduce dielectric constant by about 0.2.

Finishes can be put on S2-Glass the same as for E-glass, which means that it will be essentially compatible with all the basic resin systems. When to use S2-Glass? When incremental improvement in dielectric constant and/or CTE (preferably both at the same time) is worth a significant price increase, because, at least as of this writing, S2-Glass costs several times as much as E-glass and requires large minimum purchases.

What is Kevlar®? Where do we use it?

Kevlar® is a polyaramid fiber produced by the Dupont Company. It is lighter and stronger than fiberglass and has a lower dielectric constant. Its principal claim to fame for our industry is a thermal coefficient of linear expansion of -4 ppm/ °C which makes it an excellent fabric to use in CTE (Controlled Thermal Expansion) applications where very low expansion coefficients are needed in the laminate. (Kevlar’s strength and resistance to being cut makes it an ideal

reinforcement for laminated personal armor for law enforcement and military applications, which is where most of the woven Kevlar fabric is used.) Kevlar's use and benefits will be discussed at length in the section under Controlled Thermal Expansion.

What are the differences between quartz and standard E-glass? Why is quartz so expensive? When would we use it?

Quartz is nearly pure silica fiber, compared to E-glass which is a complex silica-alumina. It is a much higher temperature material (requiring special processing to draw and make fibers from it -- hence its much higher cost), with better electrical properties and a lower dielectric constant than E-glass. It also has a Lower CTE than glass (0.5 ppm/ °C vs. 5-6 ppm/ °C for glass) which makes it interesting for programs wanting lower expansion coefficients. It also has a very low dielectric constant and loss -- allowing a polyimide-glass product to have Er 3.65 and loss as low as 0.005. Most of its applications to-date to relate to its dielectric properties rather than its CTE.

Quartz is a much more frangible fiber than glass which results in problems with handling including quality issues such as picks and broken filaments. Although the quality of quartz fabric improved dramatically in the late 1980's, it is still not up to the standard of the electrical grade E-glass. Drilling quartz is much more difficult than drilling glass. The higher crystallinity of pure quartz results in much higher drill wear than compared to E-glass.

Financial Advice: If Quartz reinforced laminate achieves any volume, buy stock in "Drills-R-Us.com."

What is Thermount®?

Thermount® is a nonwoven (i.e. paper) product developed by DuPont from a mixture of Para-aramid fiber and amorphous meta-aramid as a binder. Laminates based on Thermount® offer many of the advantages of Kevlar® product, with improved dimensional stability, ease of drilling and reduced cost. While it is not possible to bring the CTE values down as low with Thermount® as with woven aramid fabric, they are low enough (9-10 ppm/°C in a finished board) to be very attractive to SMT designers.

Polyimide on nonwoven aramid --Arlon's 85NT -- became a successful commercial product, having completed life-cycle testing at various OEM's and board shops for inclusion in various military and commercial avionics board designs. In many cases it replaced the much heavier CIC in SMT boards, for tremendous weight savings in electronics hardware.

Epoxy Thermount(R) has found a home in extending the SMT marketplace into many commercial applications as well as offering "economy" SMT technology for conversion of military programs. Arlon has been one of the leaders in Thermount® applications offering both a polyimide product (85NT) and several variations on epoxy systems including a high strength bond (55ST), and an improved moisture resistance grade (55LM).

Unfortunately in 2005 DuPont announced that it would discontinue manufacture of Thermount®. Arlon in conjunction with its OEM customers, procured a substantial supply of Thermount before manufacturing was discontinued to ensure the availability for existing ongoing programs, and is actively seeking, at this writing, to find alternative materials that will meet the particular needs of the SMT marketplace for the longer term.

Return to TOC

II. PREPREG

What is Prepreg? Briefly, how do we produce it?

Prepreg is a shorthand expression for "pre-impregnated." It is fiberglass or other fabric reinforcement which we have saturated (imPREGnated) with a polyimide, epoxy or other resin system, which has been partially "cured" (or reacted) during the coating operation. Prepreg is also called "B-Stage", "Bonding Sheet" or, commonly, simply "Preg."

The substrate fabric is coated with resin on a coater (or treater) in which it is pulled through a pan filled with a solution of resin in one or more solvents and then through a sequence of "metering bars" to accurately control the amount of resin that is deposited on the fabric. The resin saturated fabric is then pulled through a series of temperature-controlled oven zones in which solvent is removed and the resin is caused to partially react, or "B-Stage."

What is gel time? Why does IPC-4101 make gel time an "optional" test?

Gel time is the time (usually expressed in seconds) at a given temperature which it takes a resin to go from a free flowing melt stage to a gelled, or semisolid, condition. The gel time for epoxy is a rough relative indicator of the "process window" -- the period of time -- during which the prepreg will flow during lamination. Pure polyimides have higher melting points and often, poorly defined gel points (unless the temperature at which the gel time is performed is changed higher than 171°C).

The gel test still depends on a well trained operator with a calibrated toothpick or coffee stirrer and a hotplate rather than a sophisticated instrumented system for testing. The determination of endpoint is somewhat subjective (". . . and when the resin forms little balls that pick off the surface when you stir them around, that's the gel point . . .") and will vary with operator. The more gradual the actual endpoint, the more operator bias will be seen in the results.

Interestingly, the lack of a well defined gel point makes the coating of polyimides more difficult than the coating of epoxy. In an epoxy system there are three "controllable" variables: resin content, flow and gel. With polyimides there are only flow and resin content. This means that sophisticated control of coater parameters and the implementation of rheological testing methods are vital to ensure that prepreg is consistent from batch to batch. Moreover with epoxy systems the measurement of gel before and after coating provides a good idea of the degree of B- staging achieved. A 250 second solution gel may result in a 125 second prepreg gel, indicating that about half its cure has occurred in the coater. Polyimide solution gels are unduly affected by the reactive and high boiling solvents used and do not fit well in this type of comparison. For this reason scaled flow and rheology are often more reliable indicators of product and process consistency.

What is resin content? Why is it important? How do we test for it and control it?

Resin content is the percent of the total weight of a prepreg which is resin. The standard method of test for resin content in fiberglass reinforced prepregs (and laminates) is a "burn out" in which the final weight after a burnout at 1100°C is subtracted from the original weight. The difference, expressed as a percentage, is the resin content.

In systems using organic reinforcements such asThermount™ or Kevlar™, resin content must be determined by a "basis weight" method, in which we measure the original fabric weight (and assume it to be constant through a roll of fabric) and determine the resin content by the difference between the coated weight and the basis weight.

Resin content, and to a lesser extent, flow, determines how thick a piece of laminate will be when we press it and how much resin will be present to fill inner layer copper in a MLB. The resin content also has significant effects on properties such as dielectric constant (permittivity), coefficient of thermal expansion (X-Y CTE), dimensional stability (registration), drilling and etching quality.

The ability to control resin content depends on the variation in weight of the base fabric, the consistency of the coater operation and the batch-to-batch variation in resin solution rheology. Normally we produce prepreg within a ± 3% tolerance.

Over time we have seen more PWB processors request the "treated weight" method of resin content control for prepreg. The advantage to this is that it tends to compensate for any slight variations in the fabric basis weight and provides a finished product that is tighter in thickness control. The reason for this is straightforward – the density of glass is twice that of resin (in other words it contributes only half as much per unit of weight to the finished thickness) so if there is a small change in the glass weight, if we are controlling resin content by weight %, we have to add twice the volume of resin to compensate to keep the weight percentage the same. That means we can have a wider variation in pressed thickness (which is what you as a customer want to remain constant) when we control resin by weight % than when we control treated weight.

Arlon uses treated weight for control of its prepregs for internal use, and IPC-4101 permits the use of either a Treated Weight or Burn-Off method for resin content specification for purchased prepregs.

What is flow? How do we test for and control it? Why is it important?

When you heat prepreg under pressure the resin melts (liquefies) and flows. Both the pressure and the rate of heatup of the resin impact the amount of flow that occurs. (More under the subject of Rheology in the Analytical/Testing section of this book.) There is a finite period of time during which the resin remains fluid enough to flow freely, after which its average molecular weight advances to the point at which we say it has "gelled." This is the basic principle underlying the lamination process. "Flow" is a semi-quantitative measure of how the resin melts and flows during the lamination process.

Actual flow of the resin is critical to the lamination operation and can be affected significantly by laminating conditions, therefore IPC flow test values should be used as a guideline and not worshipped with excessive reverence. The amount of actual flow achieved will impact such properties as interlaminar bond, bond to oxided inner layer copper foil, bond of laminate to ED copper foil used in laminate manufacture and the overall effectiveness of prepreg as a "bonding sheet." The PWB laminator must have consistent flow characteristics if he is to ensure repeatable manufacturing performance.

There are several methods of measuring flow in IPC-4101 that represent different approaches to flow.

1.) The standard 4-ply flow test is designated MF -- probably for Mil Flow (a carry back to the old military standard). The standard 4-ply flow test involves cutting pieces of prepreg to a specific size, weighing them and pressing them at a controlled temperature and pressure. The resin flows under the test condition and afterward a smaller section is cut from the center, reweighed and normalized to the original area. The loss in weight between the original material and the final weighed "flow biscuit," expressed as a percentage, is the "Flow."

We strongly advise standardization on the methods actually spelled out in IPC-4101 where possible. More plies result in higher flow values, all else being equal. Any effort to make and stock standardized prepreg is complicated by the possibility that different end users will impose different requirements on the same material.

2.) Scaled Flow (SC) and Delta-H (DH) need to be considered together to get the real benefit out of the test. The original work intended that these two parameters taken together would provide a good indication of both the finished ply thickness yielded by a prepreg and the amount of flow that occurred to get there. We will discuss Scaled Flow in more detail below.

3.) Low-Flow (NF) is a separate test method that is used to measure the amount of flow of materials designed for heat sink bonding and rigid-flex applications where the prepreg needs to bond layers together, but can't be allowed to flow excessively into cutout areas or areas where flex material needs to remain unconstrained. This test involves the measurement of the amount of flow of resin into 1" diameter holes that represent a cutout area in a board.

4.) Rheological properties (FR) are measured by any of a number of pieces of equipment (most commonly used in production environments is the ViscoPlot) that measure the fluidity (or viscosity) of the resin when it is melted or during the melt process. ODR (Oscillating Disc Rheometry) is a more sophisticated test that yields information on change of rheology as a function of time, temperature, heat up rate, etc., and will be discussed in the section on Analytical methods. Many PWB process engineers use rheological data to give them an idea of how the material will flow during processing.

What is Scaled Flow? How do we measure it? What does it tell us?

Scaled flow has been in use by most laminators for a many years. In the scaled flow test we press a standardized number of plies of fabric (18 for thin prepregs 104, 106, 1080, and 10 for heavier glass such as 2313, 2116, 7628) at 310°F (340°F for polyimides) and 31 psi and measure the change in thickness instead of the change in weight. The basic output of the scaled flow test is a measure of the thickness per ply of prepreg actually yielded by the test as well as a "delta H" factor, which is the change in thickness from the theoretical value (determined by weighing the original 18 (or 10) plies and applying a factor to it which accounts for resin and fabric densities.) Scaled flow is felt to be a reasonable indicator of the yielded thickness per ply of prepreg in board layup.

Note: "Delta H" values are valid for standard FR-4 systems because all the factors set up for the system were derived for FR-4. If there are significant differences in resin or fabric density (Highly filled resins may have a density of 1.6 or more vs. 1.25-1.3 for standard materials; Thermount® fabric has a density of 1.44 vs. 2.54 for E-glass, etc.) these may be invalid and will have to be individually calculated. Also the standard factors do not account for small variations in fabric weight within a lot or roll.

There is controversy as to the effectiveness of any single currently used flow test to predict performance in the multilayer MLB process. At best we have trouble reproducing these tests with precision, and even with well calibrated equipment (a 5-10°F variation in temperature will make a substantial difference in test results) the element of operator skill remains significant.

Are there other flow test methods that may be more useful than the traditional Mil and Scaled Flow tests now most widely used in the industry?

The real question as we see it is how to define "flow" in such a way that the test used for it gives us the most information pertinent to its intended end use. It is apparent that the current tests, including the IPC-4101 4-ply and scaled flow methods, deal only with the "state" of the prepreg after the test vs. the "state" of the prepreg before the test and do not adequately address the issue of what happens in between.

We think that an understanding of the changes in chemistry and rheology of the resin during melt, flow and gelation are critical to this issue. There are several approaches to the testing of prepreg that have had some attention.

1.) Dynamic Mechanical Spectroscopic methods are under investigation as ways of characterizing prepreg. Use of an oscillating disc rheometer (ODR) capable of measuring loss and storage modulus of materials can give us much information about the change in viscosity of a resin as it melts and flows. When testing is done in the presence of a fabric reinforcement, the fabric itself becomes a more significant part of the system as the resin cures, obscuring the resin dynamics. Use of an ODR on neat resin removed from prepreg may partially overcome this deficiency.

2.) Dielectric Spectroscopy, measuring the change in dielectric properties as the resin mlts, flows and cures has also been investigated as a means of controlling lamination conditions. It has not

been well established how good the correlation is between this measurement and the rheology of the resin itself. The approach may also be skewed by ionic conductivity or impurities on a batch-to-batch basis. As with DMS, the equipment is relatively costly and the test methods are too lengthy to be compatible with real-time testing during prepreg manufacture.

3.) Dynamic Scaled Flow (aka Parallel Plate Rheometry), an attachment to the standard TA Thermal Analyzer, -- distinctly separate from the Oscillating Disc Rheometer (ODR) -- is a source of potentially useful information on the rheology of a resin in a prepreg. This method (like the ODR) involves placing a pressed pellet of resin (removed from the glass reinforcement) between parallel plates under low pressure and heating it at a fixed rate. The measurement of the rate at which the plates close when the resin melts gives information about melt point, relative viscosity and gel or cure time. Because theoretical modeling of viscosity often involves parallel plates, calculation of a complex viscosity value is theoretically possible from these tests. The test is not well-suited as a real-time process control test.

4.) Oscillating Disc Rheometry (ODR), now in common use in the industry as a developmental tool, is becoming accepted as the most accurate and scientific way to characterize resin flows. Like the dynamic scaled flow (parallel plate) method, it looks at the resin separate from the fabric, and thereby is not fooled by fabric geometry factors. More about ODR is presented in the Analytical section of this handbook.

5.) Parallel Plate Rheometry or Cone and Plate Rheometry are a production type pieces of equipment that permit a quick test to be performed of the melt viscosity as a real-time production control tool. It overcomes the difficulty of the ODR (fairly lengthy preparation and running time) for real-time testing of prepregs. These tests are sensitive to operator technique, and equipment setup, but can be useful in establishing a flow characteristic in real-time.

What is ODR Used for?

The oscillating disk parallel plate rheometer (ODR) permits the resin development chemist to characterize the melt viscosity of various resin systems dynamically. We can look at the changes in viscosity as a function of heat up rate as well as time at temperature. By programming the heat up rate, the real-time thermal profile of a press cycle can be duplicated on the rheometer and the manner in which that resin melts and flows can be characterized.

What is Rheology?

What does rheological characterization mean to you? Among others:

1.) You can compare the flow characteristics of the resin system you are going to use with standard materials with which you are already familiar.

2.) You can look at the effect of rate of rise of temperature on fluidity of your selected resin system. Sometimes you can make major improvements in MLB lamination by achieving slightly more or less flow.

3.) You can determine the "open time" available to you in your standard press cycle by modeling the cycle on the rheometer.

What are "No-Flow" (more accurately “Low-Flow”) Prepregs?

Low-flow prepregs are prepregs which are modified to limit their flow where it is undesirable for there to be a "bead" of resin at the bond line. The largest usages of no-flow prepregs are in the areas of HEAT SINK BONDING and RIGID-FLEX LAMINATION, where various cut-out areas cannot tolerate resin flowing in. In some cases an IC die will be placed in the cut-out area. In other cases resin beads interfere with secondary operations.

The term "No Flow" is a misnomer, since the resin must melt and flow to a limited and controlled degree in order to "wet out" the bonding surfaces and achieve adhesion. The trick is to control the flow so that over a reasonable range of normal process variation it does not flow either too little (poor bond, voiding, etc) or too much (flowing into cutout areas where it has to be painstakingly removed by someone with an Exacto knife and awesome eyesight). We prefer to call them “Low-Flow” products.

“No-flow” prepregs were historically produced using epoxy systems modified with thermoplastic rubbers, or have been composed of partially crosslinked acrylic compounds. These have been troublesome, because their degree of "No-Flow" has been hard to control. Compounds with thermoplastics tend to "creep" on aging, and some bonds have failed unexpectedly after storage.

In newer generation products, the low-flow characteristics are achieved by a combination of controlled B-staging and chemical composition of the resin, which may include high molecular weight flow restrictors as well as cure systems designed to control the length of “open time” in the system. The IPC Low-Flow test uses a sample in which two 1” diameter holes are punched and the amount of flow measured under test conditions as the amount of flow into the hole, measured as reduction in diameter of the hole. Typical specifications ere expressed in mils of hole diameter reduction, i.e. 60 to 90 mils. Low-Flow testing is one of the most difficult of the prepreg tests, and there is cumulative variability in measurement, test sample preparation and process variability that in many cases approaches or exceeds the range of flow desired in specifications.

Arlon has pioneered the use of improved computerized measurement techniques for Low-Flow testing. The method we use, instead of taking a limited number of individual diameter measurements of the resin flowing into the 1” diameter holes in the samples, uses an optical system to take in excess of 1000 individual readings and calculates a statistical best fit hole diameter. The use of such methods has greatly reduced the variability of results due to measurement technique and operator bias and has permitted us to concentrate on reducing variability due to sample preparation and process.

Arlon has several epoxy and polyimide Low-Flow products, optimized for various applications and end user requirements:

- 37N Polyimide Low-Flow (Tg > 200oC) for polyimide rigid-flex applications

- 38N Polyimide Low-Flow (Tg >200oC) is a second generation polyimide low flow with enhanced bond capability to polyimide films, and modified rheology to broaden its process flexibility.

- 47N Tetrafunctional modified epoxy No-Flow (Tg = 130oC) for heat sink bonding
- in a variety of applications

- 49N Multifunctional Epoxy No-Flow (Tg = 170oC) for high temp epoxy rigid-flex
- applications including those employing the newer adhesiveless flex materials.

- 51N Lead-Free Epoxy Low-Flow (Tg = 170oC) is based on an enhanced resin system that meets the IPC suggested requirements for Lead-Free solderability applications.

In addition there are thermally conductive epoxy prepregs, which, because of their high filler loading, can be readily adapted to serve in a low-flow application with minor process variations in pressure and heat-rise.

- 91ML is a Lead-Free system with a 170oC Tg and Tc of 1.0 W/m-K.

- 92ML is a Lead-Free system with a 170oC Tg and Tc of 2.0 W/m-K.

What are the most common problems customers will encounter with prepreg? What do we need to know to help resolve those problems?

The most common problems we encounter with prepregs are those dealing with flow specifications and the correlation of flow test data between laboratories. Because some of the test methods for prepreg flow are relatively imprecise and somewhat operator, equipment and technique sensitive, a few percentage points of difference often result in rejections and frustration on both ends trying to reconcile the differences.

Other possible prepreg problems include random bits of particulate matter (no matter what anybody tells you, the inside of a coater will accumulate and occasionally release minute bits of burned or oxidized resin, incinerated insect parts and other minor detritus), wrinkles and creases within rolls of material and miscounts (I've tried it myself and occasionally it is possible to count 100 pieces of prepreg and miss by 1 or 2.).

Whenever there is a problem with any of our prepreg, we need to know the lot number of the material, the exact nature of the problem encountered and a sample of the prepreg taken from the part of a lot or roll deemed defective. We always make an attempt to correlate our original data with a retest and compare that with the results obtained by our customers. Our objective is always to ship 100% good material, but if we occasionally slip, our wish is to find out why, and plug the gap for the next time.

How do we know what the "Shelf-Life" of various prepregs should be? What are the shelf life requirements for polyimide prepregs?

Shelf life is the length of time that you can store a particular prepreg under specified temperature and humidity conditions before it ages to the extent that it will not flow and laminate properly.

All Arlon prepreg is certified to IPC-4101B or IPC-4103 and meets the shelf life requirements stated in these documents in paragraph 3.17. In essence prepreg supplied shall be capable of and certified to meet all the requirements specified when stored per condition 1 or condition 2 for the specification sheet requirements. These conditions are applicable to the date the prepreg is received.

Condition 1: Six months (180 days) when stored at <5ºC (41ºF)
Condition 2: Three months (90 days) when stored at <23ºC (73ºF) and <50% relative humidity

Prepreg should be stored in the absence of a catalytic environment such as UV light or excessive radiation. Prepreg should be allowed to equilibrate at processing conditions before use.

After the initial storage period, we recommend retesting prepreg for flow to make sure that any changes are noted and compensated for. You can use process changes (adjustments in heat-up rate, pressure, etc.) to adjust for minor changes which occur. Arlon will retest out-of-age prepreg if a sample is provided and report test results.

TROUBLESHOOTING TIP: Once the original flow value (MF) has decreased by more than 15% of the original value you should assume that the material has exceeded shelf life and any decision to use it should be based on actual in-use tests. Older prepreg has been used with success, however there is a risk entailed in doing so and that decision should be made on an informed basis.

Arlon can't warrant performance of out of shelf-life material.

Tell us more about moisture issues in prepreg?

With most high temperature, multifunctional epoxies, the effect of moisture is to reduce Tg by reacting with the resin (hydrolysis). The same rules that apply for polyimide may be applied to high temperature epoxies. While moisture technically doesn't reduce the Tg of polyimide (or interfere with crosslink density), it can hinder the press and product from reaching the desired cure time and temperature profile, which ultimately can interfere with proper Tg development.

Cyanate esters are especially sensitive to moisture, and if there is water present during high temperature processing, carbamates may be formed by the reaction of water with the basic cyanate chemistry. Carbamates are "blowing agents", used commercially to make plastic and rubber foams, and are NOT desirable in MLB lamination as they may cause delamination or

blistering during high temperature cures. For this and other reasons (especially an inherent propensity to resin cracking), Arlon discontinued the use of Cyanate ester systems.

What about polyimide prepregs? Is moisture really a bigger issue with polyimides than with epoxy systems?

Polyimides are more moisture sensitive than epoxies in the sense that they will absorb water from the air more quickly. Moisture which is in the prepreg does not do the prepreg itself any harm, but may result in voids, delamination and other defects in laminated boards. Foamy flow is an indicator of moisture in prepreg. It is not exclusively a phenomenon associated with polyimide, but because polyimide picks up moisture faster than FR-4, it is seen as a problem more often. Drying any prepreg by storing at low humidity with desiccant, or vacuum drying before use will minimize this effect.

Moisture can cause additional problems in finished PWBs – the integrity of a multilayer board under high temperature stressed conditions (such as are simulated by the T288 or T300 test for materials designated "Lead-Free") can be compromised by excessive moisture. Thus it is important to control moisture even in finished bare boards prior to solder reflow or assembly processing, and even in finished boards of they are going to be subsequently exposed to high temperatures, such as when they are to be repaired, or when devices require replacement or re-soldering. Obviously this is exaggerated with lead-free solder systems due to their higher temperatures.

We recommend vacuum drying prepregs for several hours at 29" of Hg, and this will be discussed at length in the Processing section. Vacuum desiccation at room temperature is preferred over any kind of oven drying for standard epoxy or polyimide prepreg, even when you believe the oven drying is under controlled conditions and the temperature low enough not to hurt the prepreg. Oven drying may tend to advance the prepreg, and may result in marginal or insufficient flow or bond that can result in delamination or other failures on subsequent thermal processing.

The only exception to that might be for non-woven aramid polyimide where a vacuum oven temperature of no more than 90°F (32°C) for 4-5 hours at 29" of vacuum may be helpful in removing excess moisture.

Arlon recommends vacuum desiccation of all prepregs prior to use.

Prepreg stored under refrigeration at ≤ 5ºC (41ºF) must be allowed to stabilize at ambient temperatures prior to use. This time can be included as part of a vacuum desiccation process. Vacuum desiccation of Arlon's prepreg is recommended to remove moisture. Moisture trapped in a multiplayer PCB can cause excess resin flow, measles, delamination and depressed Tg values. Store the dried prepreg in either a nitrogen dry box or chemical desiccation box. Control the temperature and humidity in these chambers per the conditions stated above.

Vacuum times:

Epoxy Prepregs:	44N, 45N, 45NK, 47N, 49N, 51N	= 8–12 Hours
Polyimide Prepregs:	33N, 35N, 37N, 38N, 84N, 85N	= 8-12 Hours
Thermount® Prepregs:	55NT, 55RT, 55ST, 65GT, 85NT, 85RT	= 24 Hours
25N & 25FR Prepregs:		= 4-6 Hours

Return to TOC

III. LAMINATE

What is a Laminate?

In the broadest sense a laminate is a composite comprising one or more plies of prepreg with copper (or other metal) foil on one or both sides, that is formed into a final product by the application of heat and pressure. Laminates may be produced from any of the resin systems, reinforcements and metal foils discussed in the Materials section. The details of the composition of various laminates, the differing press cycles required to produce laminate with proper cure and finished properties, are all part of the "art" of the laminator. We hope that what we have to say here will clarify some of the reasons for the choices we (and you) make regarding laminate materials.

How Are Laminates Classified?

As is discussed in detail in the Materials section above, many standard E-Glass reinforced laminates are designated by the name of the resin used: polyimide, epoxy, etc. Some of the old NEMA names persist as well. Many users refer to all epoxy-glass systems as "FR-4" and there are some residual designations from obsolete mil specs as well, often built into drawings from older military/aerospace designs. Other laminate systems may be referred to by a combination of the resin and the reinforcement used (such as Copper-Invar-Copper Polyimide or Epoxy-Kevlar) or even reduced generically by "short-hand" to the name of the reinforcement ("Thermount," for example). Documents such as MIL-S-13949 (now obsolete) and IPC-4101 use slash sheets and detailed line callout systems to classify laminate systems.

What are the Most Important Laminate Properties?

This is a little bit like asking an artist what is the most important color. It will depend on the subject matter and the particular effects he is trying to schieve. Without trying to do a complete rehash of the discussion of the designer's "palette" of key properties, which are covered in considerable detail in the Materials section, the "most important" laminate properties will vary depending on the intent of the designer and the constraints of the design.

There are some "givens" however. All laminate, regardless of the material or application needs to meet certain inspection level criteria including laminate thickness, copper foil adhesion, internal cleanliness and copper surface quality. These are all properties that are more or less independent of the resin system selected, but are critical to MLB design, manufacture and basic product function – they are part of what we call "form, fit and function."

Glass transition temperature, which is an indication of the state of cure, is one important factor for a rigid laminate that will receive no additional cure, as in MLB manufacture. For thin laminates that will be relaminated with bonding sheets, Tg is not normally tested since it is an inherent property of the resin (assuming it will eventually receive a full cure) and will be a property of the finished MLB. It is also difficult to get a good reading of Tg on polyimide

systems on thicknesses much below 0.025" since the TMA works best on thicker samples. The process should be checked periodically by measuring Tg on finished boards to verify lamination conditions.

Other properties such as dielectric properties, thermal properties, flammability characteristics and mechanical properties may be tested periodically in compliance with schedules in IPC-4101, or as scheduled by UL in the case of flammability rating, to ensure that the resin system is consistent and the lamination process is in control. Most of these properties are uniquely determined by the ratio of resin to reinforcement and the intrinsic properties of each, and are not something that the laminator "controls" independently.

Particular properties that are critical to a design or application can always be specified in a purchase document or customer specification, and additional conformance testing done as agreed upon between user and supplier.

What is MIL-S-13949?

MIL-S-13949 is the now discontinued military specification which defined the minimum properties required for qualification and maintenance of qualification for laminates and prepregs for use in military printed wiring board applications. Defense Electronics Supply Center (DESC) in Dayton, Ohio, prepared and maintained MIL-S-13949 and as of this writing there are still military specifications in force for actual PWB's which are to be supplied to the military, but those specifications now require "best commercial practice" for laminate and prepreg selection. Many of the test methods formerly called out in MIL-S-13949 were written and updated by the IPC or ASTM and most have been moved over into the new IPC 4101 specification. IPC-4101is now almost exclusively used in the industry for both military and commercial programs and for all practical purposes has replaced MIL-S-13949 as the specification of choice for laminate and prepreg materials. While customers with older prints will refer occasionally to MIL-S-13949 (with some degree of nostalgia) the specification to be used today is IPC-4101.

Note: Occasionally a customer will ask us to specify material to MIL-S-13949 because it is referenced on an older drawing. DESC has advised that this spec is no longer in force and we are prohibited from specifying to it, however Arlon can cross-index the old MIL-S-13949 specification to the IPC-4101 slash sheet and certify to compliance with the appropriate slash sheet in the IPC document. In all but a very few oddball instances, this has proven satisfactory to the designers.

What is IPC-4101?

IPC-4101 is the industry standard for defining the properties of materials and specifying products. The basic laminate definition in IPC-4101 is supplied in the form of the "Slash Sheet" in which the specific materials are named, and minimum critical property requirements defined. IPC 4101 incorporates a line call-out system which permits the type of laminate or prepreg to be spelled out, and defines the basic properties of that material. The line callout system for

laminates includes information about base material, base thickness, type and weight of copper foil and other key properties. It does not call out specific constructions nor does it set specific values for many other properties that must be worked out between buyer and seller.

How Do I read an IPC-4101 Slash Sheet?

The IPC-4101 Slash Sheets for some of Arlon's products will give a good indication of how this system works. The top of the slash sheet contains the basic information about the material designation including reinforcement type, resin system, nominal Tg, Mil-S-13949 designation etc. The balance of the slash sheet contains actual product specifications for particular properties. Most of the slash sheets attempt to differentiate between thin laminates (<0.020") and rigid laminates (>0.020"). Properties are given in English and Metric Units and are referenced to test methods, either from IPC-650 or others, such as UL-94 for flammability. The term **AABUS** will appear in the slash sheet whenever a property value is to be "As Agreed Between User and Supplier." Both laminate and prepreg requirements are incorporated into the same slash sheet which can result in some misunderstandings, since many prepregs have much higher resin contents (and hence different properties) than the laminates by which the specifications are established. The best bet is to discuss your specific needs with Arlon.

- /41 -- Pure Polyimide System Minimum 250oC Tg (85N, 35N, 33N)

SPECIFICATION SHEET #: IPC-4101/41
REINFORCEMENT: *1:* Woven E-glass — *2:* N/A
RESIN SYSTEM: *Primary:* Polyimide
Secondary 1: N/A — *Secondary 2:* N/A
FLAME RETARDANT MECHANISM: N/A — *Minimum UL94 Requirement:* HB
FILLERS: With or without inorganic fillers
ID REFERENCE: *UL/ANSI:* GPY — *MIL-S-13949:* /10 - GIL, GIP
ANSI: GPY/41
GLASS TRANSITION (T_g): 250°C minimum

Keywords: (For Search Only)
NOT Grade Requirement
See Section 7
Polyimide / Woven Glass
High Reliability
GPY

- /42 -- Modified Polyimide System Minimum 200oC Tg (Note that all Arlon's standard polyimides also meet /42

SPECIFICATION SHEET #: IPC-4101/42
REINFORCEMENT: *1:* Woven E-glass — *2:* N/A
RESIN SYSTEM: *Primary:* Polyimide
Secondary 1: Epoxy — *Secondary 2:* N/A
FLAME RETARDANT MECHANISM: N/A — *Minimum UL94 Requirement:* HB
FILLERS: With or without inorganic fillers
ID REFERENCE: *UL/ANSI:* GPY — *MIL-S-13949:* /10 - GIJ
ANSI: GPY/42
GLASS TRANSITION (T_g): 200°C minimum

Keywords: (For Search Only)
NOT Grade Requirement
See Section 7
Polyimide / Epoxy / Woven Glass
High Reliability
GPY

- /129 – Epoxy System, Lead-Free Applications, Minimum Tg 170oC (Arlon's 51N Lead-Free Low Flow meets the requirement of /129

SPECIFICATION SHEET #: IPC-4101/129
REINFORCEMENT: *1:* Woven E-glass — *2:* N/A
RESIN SYSTEM: *Primary:* Epoxy
Secondary 1: Multifunctional epoxy — *Secondary 2:* Modified Epoxy or Non-epoxy (max. wt. 5%)
FLAME RETARDANT MECHANISM: Bromine, RoHS Compliant — *Minimum UL94 Requirement:* V-0
FILLERS (≥5%): N/A
ID REFERENCE: *UL/ANSI:* FR-4/129
GLASS TRANSITION (T_g): 170°C minimum
UL MAX. OPERATING TEMP: 130°C

Keywords: (For Search Only)
NOT Grade Requirement
See Section 7
Epoxy / Woven Glass
Lead-Free FR-4
Low Z-axis CTE
High Decomposition Temperature

The slash sheet requirements must be read carefully, since there is sometimes some question about which systems fall into which category. Normally a resin system with 5% or less of filler, including those with no filler at all, will either be referred to as unfilled, or (somewhat confusingly) as “<5% filler” while systems filled to a greater extent will be designated as “Filled” systems.

Note: The IPC-4101 specification does not differentiate between metric and English callouts, and so it is critical that the buyer of laminate specify which product he is trying to order. Example: a thickness callout of 1600 might either be 1.6 mm (0.060") or 0.1600" (4 mm+).

IPC 4101 also has provisions for qualification of vendors by requiring a qualification assessment of the supplier's facilities and of products by performing periodic required quality conformance testing of materials. All products which were on the QPL for MIL-S-13949 as of November 1998 were considered to be qualified under IPC-4101 so there was no discontinuity of supply caused by the conversion. The major difference between IPC 4101 and MIL-S-13949 (and a significant concern to some military PWB users) is that this system does not have or require a government systems audit, although in most cases this function is partially achieved by the implementation and maintenance of the appropriate ISO-9000 system which does have as a condition an independent audit process.

How does our part number relate to the IPC-4101 line callout? Why can't we just use that callout as an internal part number?

The IPC-4101 line callout system for Laminates includes information about base material type and governing slash sheet, base thickness, type and weight/thickness of copper foil, Thickness, Tolerance Class and Surface Quality Class. Arlon's part numbers are "smart" part numbers that provide us with information about our specific resin system as well as basic thickness, copper cladding and specific laminate construction. Additional designators are required to indicate the sheet or panel size.

The IPC-4101 Prepreg callout specifies base material type, governing slash sheet, reinforcement type, resin content, resin flow parameter method and any optional prepreg testing. Arlon's part numbers provide our specific resin designation, reinforcement style, and nominal resin content and flow values. Additional designators are required to indicate the size of sheeted material.

It is always a struggle to maintain part numbers that are descriptive in nature because they take up so much space. The 15 character alphanumeric part number field in our manufacturing computer system is not really large enough to take in the entire IPC-4101 line designator plus our specific resin code and laminate construction suffix. Data Processing advises that they are a headache to whoever has to keypunch data and would best be replaced by a 6 digit number able to be entered entirely from a numeric keypad. What we are now using remains a reasonable compromise that aids our customers in seeing that they receive the correct resin and construction each time and permits both us and our customers to look at our part number and quickly identify what's in the box.

Typical Arlon Part Numbers might be:

- **35G0050CTTD** (**35**N resin on woven **G**lass, 0.**0050**" thick core, one ounce HTE copper both sides (code **T** = 1 oz. HTE copper), using a "**D**" construction which calls out 1 ply of 106 + 1 ply of 2313 glass)

- **35N8065** (**35N** prepreg on 10**80** glass reinforcement, **65**% resin content)

Note that these do not include tolerance specifications, resin flow values, or any other detail, but would immediately identify the resin system, the thickness, copper cladding, the construction in the case of laminate, and the resin system, glass style and resin content in the case of prepreg. The part number uniquely defines the product although it does not contain all the same detail that might be in an IPC-4101 line callout.

The IPC line callouts for the above would be as follows:

- **L40 0050 H1/H1 B C** (for the 5 core laminate) The particular product is certified to Slash Sheet /40. Thickness and copper type and weight are called out. The suffix letters refer to the copper surface quality and to the thickness tolerance requirements.

- **L40 E1080 RC SC 00** (for the 1080 prepreg) The particular prepreg is certified to Slash Sheet /40. E1080 refers to Style 1080 "E", or Electrical Grade, Glass. The suffix terms refer to test methods to be applied, here "Resin Content" and "Scaled Flow." The 00 term could refer to a normal flow test if it were required. Note that the Arlon part number contains the actual resin content (65%) but no flow value.

Since many of these properties are as agreed upon between supplier and user, the callouts do not include all the specification details, which would require much more space and are covered in detail as required in the cert or test report.

Also worth noting is that many of the laminate properties listed in IPC-4101 slash sheets are based on rigid laminate construction (usually assumes laminate greater than 0.020") which results in properties listed that may be significantly different than those in the thin laminate and prepreg used to make a multilayer PWB. For example if slash sheet 40 refers to a Dielectric Constant as "Maximum 5.4," don't be surprised if the actual value for an 0.005" or 0.006" laminate is closer to 4.2, or at higher test and use frequencies, as 3.8 to 4.0. One of the weaknesses of a general specification is just that – it is sometimes too general, and does not provide all the information needed for a specific application. Suppliers' data sheets tend to conform to the slash sheet in terms of test results. Ask Arlon what your key properties will be in the configuration you plan to use in your designs. You may be surprised with some of the values you'll be given, but it's better to be surprised before you design or build your boards than after.

What testing does IPC-4101 require us to do?

There are different groups of tests required by IPC-4101. Qualification testing and Qualification Retention testing require us to perform or have performed at an approved outside laboratory, all the tests spelled out in IPC-4101 at frequencies as indicated. For initial qualification of a product, all tests must be carried out and a report prepared.

Retention of qualification requires periodic testing to be done in all areas. The frequency of such testing varies and may be required on every lot (See below for definition of lot test), monthly, or quarterly. The supplier is required to have such test results available for review by buyers on request. Such testing may be done in-house, or by a qualified outside test laboratory capable of testing to the appropriate IPC, UL or ASTM test methods.

For laminates the IPC-4101 specification includes requirements on surface finish (pits and dents, wrinkles, scratches), solderability, base material condition after etching off copper, bow and twist, thermal stress resistance, peel strength, volume and surface resistivity, dimensional stability, water absorption, dielectric breakdown (parallel to laminate), dielectric strength (perpendicular to laminate), permittivity (dielectric constant) and loss tangent (dissipation factor), Q resonance (when required for microwave applications), flexural strength (and flexural strength at elevated temperature where required), arc resistance, flammability (if required), fungus resistance, chemical resistance, pressure vessel thermal stress, glass transition temperature and average CTE (where specified).

The slash sheets spell out requirements for individual products. For prepregs the specification calls for testing for the presence of dicyandiamide crystals (for epoxy systems), woven reinforcement to the provisions of the glass reinforcement specification, IPC-4412, volatile content, flammability and other “prepreg properties” AABUS -- tests for standard resin content, flow, scaled flow, delta-H and "no-flow" systems as well as options for measuring rheological properties, electrical strength (laminated), dielectric constant and loss tangent, chemical resistance and flammability (if required) may be included if needed on a lot basis.

Lot Acceptance testing is that testing which must be done on every lot of material. The definition of a lot varies somewhat but is essentially all the material made at the same time using the same lots of raw materials. Lot tests include basic prepreg tests such as resin content, flow and volatiles, and laminate tests such as thickness, copper peel, resistance to thermal shock and visual examination of copper surfaces for scratches and inclusions. These are normally the tests that are needed by an end user to verify that the material is what he ordered and that might be required to ensure process consistency (such as prepreg resin content and flow).

What is a QPL?

QPL-13949 was the Qualified Products List for MIL-S-13949 and was a listing of all manufacturers and products which were qualified to that specification and maintained that qualification by periodic reporting of data to DESC and by passing DESC audits of quality systems. IPC-4101 does not have a QPL. Qualified products are defined by the process of qualification testing and ongoing product qualification retention testing, but this is not

maintained by a third party such as DESC which maintained a QPL for the old 13949 specification.

Historical Note: Howe Industries (now Arlon) was the first laminator to receive MIL-P-13949 QPL approval for Type GI, polyimide laminate (before the government spent heaven knows how much money and intellectual brainpower to change it from MIL-P for "Plastic" to Mil-S for "Sheet").

Historical Note: Art Howe was an industry pioneer and visionary, who made a commitment to polyimide as a laminate material years before the industry as a whole recognized and accepted its broad value and began to specify it into military and commercial programs. After a successful career at GE Coshocton, OH, and Mica Corporation in Culver City, CA, Art started his prepreg business in his garage (literally), staked everything he had on its success. And won. (Art's untimely death in an automobile accident in 1983 was a loss to the industry and a personal tragedy to those of us who had the privilege of working with him.) With the fusion of Howe Industries into Arlon and the commitment of a new facility to polyimide production in 1984-5, Art Howe's dream came to fulfillment.

What determines the thickness of a laminate? What do we mean by "buildup"?

The thickness of a laminate is a function of the number and type of prepreg layers, or plies, which it contains. Each style of fabric, when coated with resin to a particular weight, has a characteristic thickness which we can determine mathematically based on the fabric weight and density and the resin weight and density. Because the fabric weight can vary by as much as ±5% roll to roll, it is felt that controlling total weight is more accurate a method of ensuring total laminate thickness than simply measuring resin content. It is possible to have a single fabric with several different finished weights (resin contents) which will yield different finished laminate thicknesses when plied. "Buildup" is the term used to describe a specific combination of plies of prepreg that goes into the construction of a laminate.

It is possible to build up most laminates in any of several different ways. As a matter of fact, when a laminate is 0.020" or more in thickness there are almost an infinite variety of buildups we can use. We govern normal production by the principle of lowest cost -- the buildups selected are those which yield the desired thickness at the lowest cost. In rigids we use all 7628 (no 7642 or other heavier glass styles which are cheaper, but make what we consider to be inferior laminate) and in thinner laminates use the heaviest fabric combinations consistent with achieving the desired thickness.

For the common prepregs the buildup thickness per ply can be given roughly, but the actual thickness yield depends on processing as well as resin content or ply weight.

Fabric Style Typical Thickness Per Ply

106 E-glass 0.0018"-0.0023"

1080 E-glass 0.0025"-0.0033"
2313 E-glass 0.0032"-0.004"
2116 E-glass 0.0042"-0.005"
7628 E-glass 0.006"-0.0078"
503 Quartz 0.005"-0.0055"
120 Kevlar® 0.004"-0.005"
E 210 Thermount® 0.0017"- 0.0020"
E 220 Thermount® 0.0030"-0.0032"
E 230 Thermount® 0.0037"-0.0039"

For a two-ply laminate yielding 5 mils overall, we use 1 ply of 106 and 1 ply of 2313, or 2 plies of 1080 prepreg with low resin content (54-56%). For a similar 6 mil laminate we use 1 ply of 106 and 1 ply of 2116, or 2 plies of 1080 with a higher resin content (60-62%). In a similar way we have established buildups for each standard laminate. Alternative constructions are available for many laminates, reflecting varying opinions within the industry as to what is the "right" construction for each individual product. Buildups affect both electrical properties (a function of resin content) and physical properties (mechanical strength, etc.) as well as having an impact on registration in the PWB manufacturing process.

What thicknesses can we build and what buildups are typical of standard products?

We build laminates in thicknesses ranging from 0.002" to 0.500", and have built laminates as thick as 6.00", but these require very costly lamination techniques which make them expensive to produce. Applications for laminates above about 0.125" are often mechanical rather than electrical/electronic. The most common thicknesses and constructions are thin laminates for multilayer manufacture.

Typical laminate thicknesses and constructions are as follows:

- 0.005" 2-1080 (lowest cost), or 1-106/1-2313 (improved registration)
- 0.006" 2-1080 (lowest cost), or 1-106/1-2116 (improved registration)
- 0.008" 1-2313/1-2116
- 0.010" 2-2116
- 0.012" 1-7628/2-1080
- 0.014" 2-7628
- 0.021" 3-7628 Lightweight plies added as required to meet thickness
- 0.031" 5-7628 Lightweight plies added as required to meet thickness
- 0.062" 10-7628 Lightweight plies added as required to meet thickness

As a matter of general principle we historically favored "balanced" buildups. More recent work indicates that in many thin laminates (0.005" through 0.008") better inner layer registration can be achieved during multilayer lamination with unbalanced buildups which incorporate one or more heavier fabrics such as 2313 or 2116 along with a ply of 106 or 1080. Although balanced buildups minimize any risk of warping of laminate, control of lamination process will minimize this in multilayers regardless of specific constructions used.

TROUBLESHOOTING TIP: Do not rely solely on construction of the laminate to solve registration problems. It is only one of many factors. See the comments on dimensional stability and registration in the Process section.

Why don't we recommend the use of single side clad laminate for use as cap sheets on multilayer boards?

We use a copper foil release sheet when we laminate single sided sheets. This means that the unclad side will have a very smooth surface, quite unlike that under the treated side of the regular foil after etching, which is in fact a "mirror image" of the tooth structure of the foil. Smooth surfaces are harder to bond than etched surfaces. Moreover, single sided laminates tend to curl due to the differences in expansion and shrinkage of the laminate and the copper during lamination and cool down. This means possible problems in photo processing and etching the other side.

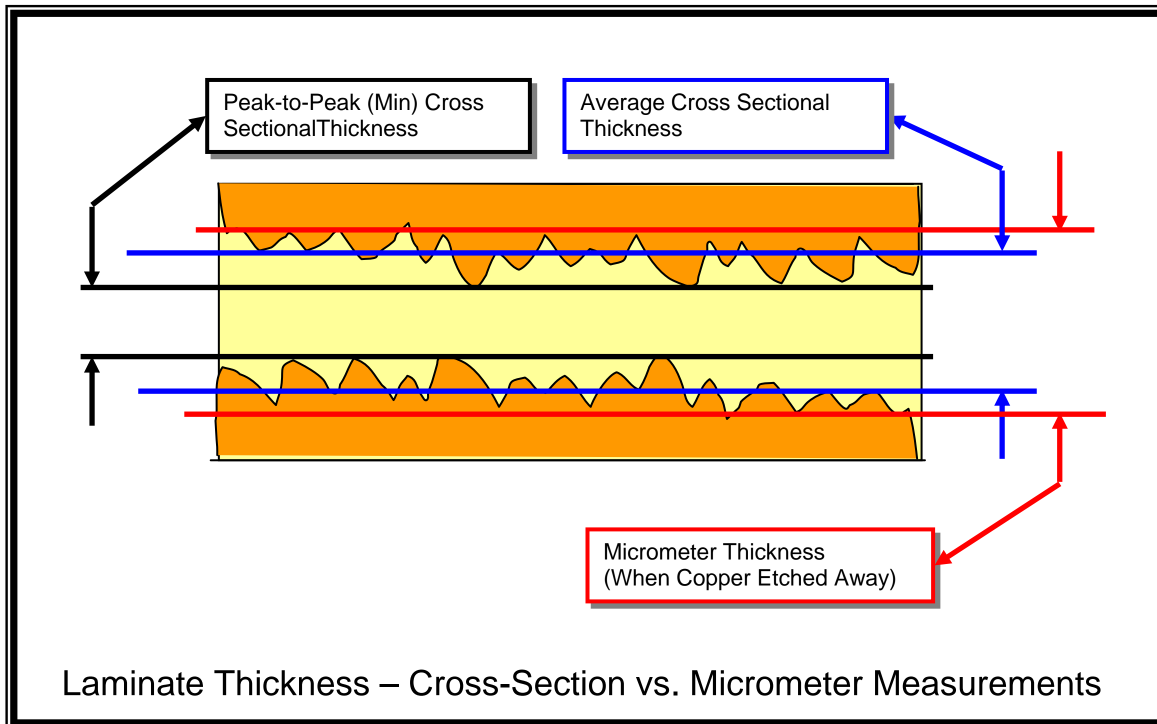
We recommend against the use of thin single sided polyimide laminate because it tends to curl when removed from the press and because the smooth surface tends to cause marginal interlaminar bond in the MLB process.

TROUBLESHOOTING TIP: The preferred approach is to use two sided material and etch off the copper on the second side. The removal of a layer of copper foil by etching is good insurance against delamination or blistering. The etched off surface has a texture which is suitable for bonding without reliance on sanding, steel wool or other dubious methods of surface preparation. The best approach is to design boards using two-sided laminate for all layers.

How does measurement of thickness by cross-section differ from measurement of thickness by micrometer? What difference does it make?

Measurement by micrometer gives a direct thickness value of the laminate, either by taking the overall thickness including copper, or that of the laminate after the copper has been etched off. It is important to know which measurement the customers require, because the difference between the etched thickness (most common) and the overall thickness (often required on rigid laminates 0.031” or greater) will vary depending on the weight of copper foil used on both sides.

Minimum thickness as measured by cross-section gives the minimum distance between the "teeth" of the copper foil on the two sides of the laminate. (The included diagram adapted from IPC 4101 shows how this measurement is taken.)



Measurement of the capacitance of the laminate, and its characteristic impedance, depends on laminate thickness. The actual measurement obtained will depend on the surface morphology of the particular copper foil as well as the actual weight/thickness of the prepreg that makes up the laminate. A relatively few scattered large copper dendrites can result in lower values for peak-to-peak thickness than for a more uniform copper treatment such as found on DSTF (as discussed under Materials, above). And Murphy's Law states clearly that: "In any random sampling of laminate the largest copper dendrites will occur in those areas selected for cross-sectioning."

An "average thickness" measurement can also be made by cross section, in which we measure the tooth height of the copper iabout a third of the way doewn the “teeth” rather than at the nearest peaks. Such a measurement will still be lower than that determined by micrometer, which measures the total thickness of the core including the peaks and valleys developed by the copper dendrite structure.

All these measurements of thickness will give different results. For our discussion, thickness by cross-section (IPC 4101 Class D Thickness measurement) will always give the lowest value and be the most critical, because the copper tooth can result in a reduction of thickness over micrometer values of as much as 0.0004"-0.0005" per side, or about 0.001" on a double clad laminate.

Cross-Sectional Thickness Requirements

While the old MIL-S-13949 minimum cross sectional requirement for thickness is now gone with that spec, there are still customers who require a minimum cross section value for various products in addition to a normal micrometer thickness value.

TROUBLESHOOTING TIP: Even when specifying laminate thickness of 0.005", be careful about tolerance if you also require a minimum cross-section. An 0.005" laminate to IPC-4101 Class B tolerance will allow 0.0041" to 0.0059" (+/-0.0009"), but that 0.004" material you'd like to have to reduce the overall thickness "just a bit more" won't meet a cross-sectional minimum of 0.0035" (if that's your requirement). In some cases special thickness tolerance requirements will result in the need to "sort and select" material, and thereby impose an increased cost.

What are the IPC-4101 requirements for thickness tolerance? How do we define them? Can we meet them all?

IPC-4101 contains several classifications of thickness tolerance for laminates. Normal thickness measurement is made using a micrometer, and there is special provision made for a class of thickness which will be measured by microscopic cross section.

As mentioned above, thickness by micrometer may be measured either as an overall thickness including the copper foil (Classes K, L and M) or measured on the laminate core, not counting the copper foil thickness (Classes A, B and C). Thickness by micrometer is called class D and is measured between the copper teeth of the foil. This type of measurement is often important where capacitance is critical.

As an example, for a standard 0.012" laminate clad both sides, the thickness would have tolerances as follows:

Class A/K +/- 0.0015"
Class B/L +/- 0.0009"
Class C/M +/- 0.0007"

Note that the tolerance is the same whether thickness is measured overall (with copper) or on the core only, BUT the tolerance of a laminate may be different depending on which thickness you measure.

Example: an 0.010" core laminate with copper C1/C1 measured overall would nominally be 0.010" plus 2 pieces of copper each of which is nominally 0.0013 for a total thickness of 0.0126". The 10 mil core measures 0.010" and a Class B tolerance is 0.0007".
The 12.6 mil overall thickness has a tolerance of 0.0009". Be sure what you are ordering and testing!

Special Thicknesses, Tolerances

Suppose a customer wants a special thickness, construction or tolerance? Arlon makes an effort to be as flexible as possible in terms of copper cladding, panel sizes and the like. And it is sometimes (though not always) possible to "sort" for tightened tolerance, albeit that has an increased cost associated with it.

In general "specials" are more complicated to make for several reasons: there is a true economy of scale in prepregging and laminating for standard laminate thicknesses, while short runs of special items are costly to make, even if they seem "similar to" standards; the overhead cost of creating and maintaining engineering documentation on materials is the same whether we produce 10 sheets or 1000 -- the same is true of cost accounting, order entry and processing; and often the raw materials needed for specials are not in stock, resulting in long lead times – and potential frustration.

The point of all that is that we recommend that designers work as much as possible with standard Arlon products to ensure best delivery, lowest cost and assurance of long term availability.

What are the "X", "Y" and "Z" axes of a laminate? What is their significance to our use of laminate?

The X, Y and Z axes of the laminate are the "Cartesian Coordinates" of a piece of laminate. By convention the X direction corresponds to the warp direction of the prepreg used to manufacture the laminate and the Y direction to the fill direction of the fabric. The Z direction, as is the convention in analytical geometry, is the direction perpendicular (or "normal") to the plane of the laminate defined by X and Y. We refer to the X and Y axes of the laminate when we are referring to the orientation of the prepreg in the laminate for layup purposes, when we are making measurements of dimensional stability or when we are measuring the in-plane CTE of the material. The Z direction is always the direction of drilled holes, and critical issues of plated through hole reliability often revolve around the thermal expansion properties of the laminate in the Z-direction.

What is the significance of UL Recognition of polyimide laminates?

Underwriters Laboratories recognizes laminate materials as a part of their overall program of ensuring that systems and components of systems meet applicable safety standards. UL's primary focus has always been that of public safety, and their focus is on those materials properties which, in failure, might contribute to a fire or other definable hazard. Fire safety is a major UL consideration and much of our work with UL centers on UL-94 which is the basic standard for flammability. Because they have extensive test facilities, Underwriters is perceived to be an unbiased source of test data and results, and as a result they have branched out into the testing of various functional properties of products which may or may not be directly related to safety. Most commercial and industrial electronics and electrical systems cannot be sold or installed in this country and many others unless they have the UL label.

Arlon was the first US laminator to receive a UL listing for polyimide laminate and all of our commercial polyimide products are recognized. UL developed (with the IPC) a generic rating (designated GPY) for polyimide laminates which will permit any polyimide material that is classifiable as a generic polyimide, by comparison with infrared spectra (see Infrared under Analytical Methods) of the materials considered generically as polyimides, to receive a listing as

long as the flammability, flex modulus and ash content of their samples are also in line with the generic samples.

The issue of "V0" vs. "V1" arises occasionally. Most equipment people must have at least a V1 rating on their product. Historically many "V0" materials sometimes managed only to get "V1" when they were fabricated into PWB's and coated with solder masks that burn like napalm. As PWB producers now want to use more exotic materials, which are not as inherently flame retardant as brominated FR-4, they cannot always count on the laminate to compensate for the flammable solder mask. This has resulted in development of flame resistant mask materials, which in turn has broadened the applicability of laminates with the "UL-94 V1" rating.

We are often asked to define the difference between UL 94 V0 and V1. This is detailed in IPC-4101, but in summary the test consists of the application of a flame of known BTU energy at the bottom of a strip of material for ten seconds, withdrawal of that flame and then reapplication of the flame. The requirement for UL 94-V0 and V1 is as follows:

	UL-94 V0	UL-94 V1
• Flaming Combustion after each flame application:	<=10 sec	<=30 sec
• Total Combustion Time (5 samples, 2 per sample):	< 50 sec	< 250 sec
• Glowing Time after second removal of flame:	<= 30 sec	<= 60 sec
• Complete flaming or glowing combustion up to the		
• holding clamp (sample entirely burned up):	None	None
• Dripping flaming particles to ignite tissue paper:	None	None

Another classification, HB, means that the sample burns at a finite rate, and the test has to be performed on a horizontally supported sample. Some pure polyimide products such as Arlon's 85N are classified HB. By not using brominated flame retardants the highest level of long term thermal stability can be obtained in polyimide products.

What is a Cert?

A "cert" is a Certificate of Compliance. It is a piece of paper that says, in effect, "The material we are selling you meets the requirements of your purchase order." Generally a cert either contains some basic test data or certifies that test data exists to back it up. A cert is the most common, and lowest level of a "Test Report." When appropriate, test data and certs are combined in a single form which makes record keeping and handling easier and less prone to error.

What do we include in a Cert/Test Report?

A test report contains details of the actual testing done to a material prior to shipment. The test report includes our part number, the IPC line callout for the appropriate slash sheet, and a summary of the IPC-4101 Lot Acceptance Tests and inspections as well as any other specific

tests required by our customers. Test reports generally indicate the specification to which the product is being tested, the value required and the actual test value as applicable. We keep test reports on file for review and have traceability back to basic documents such as shop travelers, etc. in conformance with established procedures. In most cases the test report and Certificate of Compliance ("Cert") are combined in a single document which accompanies the shipment of material.

How do we control traceability?

Our QA system is set up to conform to ISO-9002. Traceability is required by most customers and is achieved as follows:

1. Resin batch mix cards include the lot number of each batch of raw resin used in their mixing and the measured weights of each component added to the mix.

2. Treater run sheets include reference to the mix cards as well as listing the manufacturer, lot and roll numbers of all rolls of fabric used during the run. Treater run sheet data includes all actual test data generated during the run.

3. Shop Travelers (for laminate) include the lot numbers of all lots of prepreg used to make the laminate (traceable to the treater run sheets), and the manufacturer and roll numbers of all copper foil used. The shop traveler becomes a part of the basic quality record for the laminate.

The lot number is the key to traceability. Given the lot number of any roll of prepreg or any laminate we can trace back to the raw materials from which we manufactured it and the complete equipment setup and conditions under which it was run.

What is IPC-4103?

IPC-4103 (Specification for Base Materials for High Speed / High Frequency Applications) is an IPC specification document similar to 4101 which we have discussed at length above, but which deals specifically with materials intended for microwave and RF applications which do not fit well into the traditional set of slash sheet properties. The defined Scope of 4103 is stated thusly: "*This specification covers the requirements for high speed/ high frequency base materials, herein referred to as laminate or bonding layer, to be used primarily for the fabrication of rigid or multilayer printed boards for high speed / high frequency electrical and electronic circuits.*" As you can see in the slash sheet header for IPC-4103 /10, below, critical properties are defined in terms of Permittivity (Dielectric Constant) and test frequency (in this case 10 GHz).

Specification Sheet

Specification Sheet #	**:**	**IPC-4103/10**
Reinforcement	**:**	**Woven E Glass, Ceramic**
Resin System	**:**	**Hydrocarbon**
Permittivity Range	**:**	**3.25 – 3.43**
Permittivity Test Frequency	**:**	**10^{10} Hz**
Nominal Permittivity	**:**	**A – 3.38, X – AABUS***
ID Reference	**:**	**N/A**
Glass Transition Range	**:**	**N/A**

Other properties such as laminate thickness and cladding, inspection criteria for surface quality and internal cleanliness are also covered as in the slash sheets for 4101, on which they are modeled. Many properties are similar in both sets of specifications, but as noted the emphasis of 4103 is high frequency application.

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IV. PROCESSING OF HIGH PERFORMANCE MULTILAYERS

How can a laminator be of assistance to its customers in defining processes or providing process information?

As producers of laminate and prepreg we are in many ways partners of those who design and manufacture circuit boards. Over a period of time, through working with problems, helping customers who are new at the business of fabrication using high performance materials, and acquiring a thorough knowledge of our own materials, we are able to provide guidelines and information on some aspects handling and processing of polyimides and our other high performance laminates. We try to maintain people on our sales/technical service staff who have had board shop or mass lamination experience so that they will "speak your language."

Where possible, we try to act as a clearinghouse for technical and process related information. We freely pass along information that we know to be "in the public domain" or that we have developed by in-house testing and evaluation. In many cases, however, we work with customers whose processes are proprietary in nature, and we can't be effective partners if we can't be trusted -- so please don't ask us to pass along information about your competitors' plants and processes. And be assured that we won't do that with any proprietary information we might learn from working with you.

What are the limitations of laminator-supplied processing recommendations?

No process guideline can anticipate all the possible variations on a theme that will eventually be encountered by the products we produce. Even if all else is equal (which is will never be) there are regional differences that can affect product use and performance. Consider that Arizona and Israel will have different climatic conditions than Taiwan and Florida. Handling of materials will be different depending on what the potential exposures to temperature and humidity might be. Every shop has a slightly different combination of processes optimized for their particular business.

Permit us a moment of "straight talk" at this point. Processing high performance laminates, and manufacturing complex multilayer boards is not a simple business. Those of you who embark down that road can expect to make a significant commitment in capital and engineering talent to make it work. You are running complicated chemical as well as thermal and mechanical processes over which you must maintain tight control. Tight process controls require expenditure of management and engineering time and commitment. The right equipment and process for high performance materials may be more complex and take more time than for conventional high volume FR-4 boards, and if that commitment is not made, your laminate supplier will not be able to make high performance materials run smoothly in a low performance process.

Some of you, some of the time, we will not be able to help. You will undertake to manufacture boards that are outside the capabilities of your process. You will expect our material to work in your existing processes without being willing to make changes, or if you are an OEM, you will design boards that are just plain hard to manufacture. In other instances we will simply not have

the answer that you need. We will not know how to adjust your copper plating bath to give you 30% elongation. We will not know what power dial setting will make your IR reflow system stop burning up your boards. We will not be able to make our material pass UL-94 V0 in combination with your flammable solder mask. And so forth . . .

The point of this all: we provide technical assistance and make recommendations to the best of our ability, but evaluation of any material should involve not just an understanding of its basic properties, but should include engineering and manufacturing trials to ensure compatibility of the material both in the specific board design and in the existing equipment and process of the PWB manufacturer.

What are the "critical" process parameters that we need to be aware of?

There are 5 specific areas particularly related to choice of laminate and prepreg raw materials to which PWB manufacturers should pay particular attention in the process of building up and laminating MLB's. These points are critical regardless of the material, although specific recommendations may be different for polyimides vs. epoxies or for low-flow or filled systems.

1. Maintaining prepreg and processed inner layers dry prior to lamination.

2. Control of heat up rate in the laminating press to ensure consistent melt flow.

3. Assuring the correct lamination temperature for the material being used.

4. Assuring that the cure time at temperature is adequate to develop Tg.

5. Controlling cool down to prevent warpage.

At what points in the manufacturing process must changes be made in handling high performance resins (i.e polyimide) vs. FR-4?

The basic process of making multilayer boards is the same for polyimide and most other high performance resin systems as for FR-4. The differences relate to the specific characteristics and properties of high performance materials which are different from those of standard epoxies.

There are several areas in which you should employ special precautions or different procedures:

1. Polyimide, and most multifunctional epoxy prepregs are more sensitive to moisture than are FR-4 prepregs. This requires special handling and/or drying.

2. Conventional black oxide (treated weight about 1 mg/cm^2) treatment of inner layer copper will not always give a good uniform bond with polyimide. Use a brown oxide (0.2 to 0.3 mg/cm^2) or even a reduced oxide. This will help with other materials as well. The esthetic value of a dense black appearance is not worth the risk of blistering and delamination.

3. Lamination cycles must be tailored to the melting temperature and higher
melt viscosity of the resin. This is true of polyimides as well as low flow and other filled or modified materials whose melt viscosities are inherently different than traditional high flow materials.

4. In special situations such as for Arlon's 25N and 25FR low dielectric constant systems, the flow is lower than normal and the cure system is different, so a lower heat up rate (about 3°C/5°F/minute) is recommended to ensure adequate flow prior to cure.

5. For processors using conventional FR-4 processing: You cannot achieve good etch back on the high performance polymer systems with traditional concentrated sulfuric acid, which works well with low Tg FR-4. Use plasma, or a good alkaline permanganate for performance systems.

What special precautions must be taken with regard to moisture in high performance polyimide and multifunctional epoxy prepregs?

Polyimide prepregs are more sensitive to moisture pickup from the air than conventional epoxy prepregs. The presence of moisture in prepreg, as is also the case in epoxies, can cause any of a number of process and product quality problems including foamy flow, voids, delamination and uneven thickness. In the case of polyimide, it also has an established link with poor bond to inner layer treated copper foil.

Grannells and Lamm (United Technologies) determined that as little as 0.2% moisture in a polyimide prepreg may result in some blistering and delamination, and as little as 0.4% can result in frothy flow and significantly deteriorated inner layer bonding. It is possible for polyimide prepreg to have this much or more water in it just from sitting around in an uncontrolled humidity environment.

TROUBLESHOOTING TIP: Other volatile components of the prepreg include low molecular weight resin fractions and some traces of retained high boiling solvents which serve as process lubricant and actually react during prepreg cure, so measurement of total volatiles is not necessarily a good measure of retained water. Proactive removal of moisture by desiccation is important.

Although desiccant boxes have been used with some degree of success to remove water, the process is slow and unless you use dry desiccant and change it or "recharge" it regularly, it is often unreliable for critical jobs. Polyimide will eventually start to compete with desiccant for water if the desiccant is not dry and changed regularly. If you use a dry box, it is extremely helpful to use a slow bleed of dry nitrogen (use a bubble type flow meter to ensure that the flow is adequate) over the material. This will remove any ambient moisture and by reducing the partial pressure of water over the material, aid in the diffusion of residual moisture out of the product.

The relationship between dry prepreg and quality of inner layer bond is a most important aspect of this phenomenon. The one method which has reliably removed water from prepreg down to the 0.2% level is vacuum desiccation. Roughly 12 to 16 hours (overnight) at 29 inches of mercury will remove essentially all the water that is not chemically bonded. "Hydrogen bonded" water at the surface of the fiberglass fibers, for example is not volatile under normal conditions although it can over time affect the degree of cure and the flow. Keeping prepreg in a dry environment prior to use will minimize the risk, but proactive drying is always recommended.

There are several ways to remove water effectively using vacuum:

1. Use a plasma unit during its "time off". The plasma unit is capable of pulling a hard vacuum and unless it is in use 24 hours a day, it should be free overnight. Vacuum pumps are made for continuous duty and this will not hurt them.

2. If you are using vacuum assisted hydraulic presses or autoclave presses, prepreg can be dried in these units (without heat and pressure, of course!) during their off time at night.

3. Prepreg can be "turkey bagged" or placed into an improvised tool (made for example from silicone rubber sheeting designed for structural mold tooling) and held overnight in a vacuum.

TROUBLESHOOTING TIP: The purpose of vacuum drying and vacuum lamination is the removal of volatile elements in the system to prevent their interfering with the process or product. While vacuum drying at room temperature or slightly above will largely remove only water, vacuum lamination may release low molecular weight resin or other trace materials at cure temperatures that over time can build up in the vacuum system and contaminate vacuum pump oil. Coalescing type filters collect this type of volatiles, but may become plugged up quickly, negating the effect of the vacuum. Cold trap filters, while they are less common and require continuing attention, do not plug up as readily. Valves and fittings in the system need to be cleaned periodically so they perform optimally. Be sure the vacuum pump has an oil return line and change vacuum pump oil on a regular preventive maintenance schedule to prevent damage to the pump.

Talk to me some more about oxides? Why shouldn’t we use the traditional black oxide? The lighter red or brown oxides don't look right?

The use of brown (sometimes called red or bronze) oxide is strongly recommended for bonding polyimide inner layers. The larger the area of copper remaining on an inner layer, the more critical this bonding effect becomes. Narrow lines and small features are encapsulated by the resin during lamination and are less sensitive to failure during subsequent thermal stress. The needle-like structure of a conventional black oxide often does not survive the layer-to-layer thermally induced shear stresses. In the case of large features or copper planes, delamination can occur. Circuit designers should consider "cross hatching" large copper areas such as ground and power planes whenever possible to increase the encapsulation of the copper with the prepreg resin.

Grannells and Lamm suggested that lap shear testing may be a reliable indicator of the quality of an oxide bond, with a rough estimate that says values below 1800 psi indicate failure in the oxide itself and values over 2200 psi indicate actual resin failure with values in between indicating a mixed failure mode. Examination of an actual delaminated board will quickly show whether you have adhesive or cohesive failure, although it will not necessarily indicate a specific mechanism.

Although aesthetically the heavy black or dark brown oxide makes the board appear more uniform, actual measured bond strengths are usually higher when the oxide is a lighter brown color without the velvety look and texture typical of black oxides. Heavy oxide growth results in a weaker bond to the resin, which may further weaken during drilling operations, thereby creating a path for subsequent chemical attack during the electroless copper process.

This will contribute to the once notorious "pink ring" problem. In numerous cases, bonds have improved dramatically after dilution of oxide bath chemical concentration, reduction of bath temperature, and/or use of a “reduced” black oxide. It is always desirable to have sufficient bath time to permit a reasonable process window. If ten seconds of bath time will make the difference between good and bad results, you should drop the temperature to stretch out the time.

What will be the biggest problems with oxiding?

Preparation of the copper surface before oxiding is critically important. The use of an aggressive chemical etch is recommended. A relatively unaggressive etchant such as sulfuric acid/peroxide, removes the tarnish well, but leaves a smooth surface that may not be best for bonding. A ferric chloride or ammonium persulfate pre-etch gives the best results. In United Technologies work, bonds with lap shear values of 2200 psi were most easily obtained with ferric pre-etch.

Aggressive hot water rinsing after oxide treatment is also critical to the process. Polyimides are sensitive to alkalis and may tend to "hold" them at any exposed resin surface. Alkalis will also "hide" in the structure of the oxide itself. Excessive alkali residue will not only result in ionic contamination but may also contribute to later moisture pickup and delamination. Hot water spray rinsing to remove alkali residues from the oxide bath is essential. Immediate hot water bath rinse (with plenty of agitation) followed by subsequent cool water and deionized rinses will usually work fairly well. Inadequate rinsing will almost always cause downstream problems. One of the most frequent problems with users new to polyimide is unwillingness to make the commitment to additional adequate hot water rinsing.

Hint: a final deionized water rinse with a low concentration of acetic acid (1%) will neutralize any residual caustic and promote enhanced bonds to polyimide. The acetic acid is totally volatile and will not remain as a contaminant.

TROUBLESHOOTING TIP: A word of caution here regarding tap water rinses, particularly in colder climates. Tap water may be too cold to provide thorough rinsing and can “set” any caustic residues in the polyimide surface or the oxide structure.

What Are "Oxide Alternatives"?

The use of traditional brown oxide treatments applied from a caustic solution has been supplanted in many cases today by any of a series of products referred to as "Oxide Alternatives" that are regarded as easier to use, have better resistance to acidic environments, and provide generally better inner layer adhesion than even the best of the traditional systems. Alternative oxide systems claim better adhesion of solder mask and of dielectric materials to processed layers by providing a higher surface area for bonding, and marked reduction in the notorious "pink ring" phenomenon because of their acid resistant nature. Most of the alternative systems are based on a series of individual baths, and hence are easily adapted into the flow of conventional PWB inner layer processing.

Most of the alternative oxide systems in use involve a sulfuric-peroxide system that provides a cuprous oxide (Cu_2O) with much better physical properties than the dendritic black oxide (CuO) of the traditional system. Reduced black oxides did produce cuprous oxides, but it was an added step, and the new systems are considered to have lower cost and to be easier to use according to Arlon's technical service group.

The recent move to more lead-free technology, as we have discussed under Materials, demands a total system that is more resistant to thermal shock during PWB processing, reflow and assembly. The alternative oxides provide inner layer bonds as high as 4 lb/in for high performance materials (polyimides et. al) vs. a "best effort" of 2.5 lb/in for a reduced brown oxide. Because the new systems are not based on strong caustics, the issues with rinsing of polyimides to prevent swelling and delamination are reduced dramatically.

The alternative oxide systems have found especially warm welcomes in the rigid-flex area, where the polyimide films were prone to serious attack by the strongly caustic traditional black oxide systems.

What press cycles should we use for MLB lamination?

After proper baking of the inner layers to remove moisture (90 minutes at 250°F seems to be adequate for thin polyimide layers), lamination may proceed. The key elements of lamination are rate of rise, pressure, cure temperature and sequence. These must be adjusted to ensure that the resin melts and flows properly to wet the bonding surfaces and fill inner layer copper, remove any minor entrapped volatility that might cause voiding, and, of course, properly cure the resin.

Oxide layers are the weakest physical link in the bond of prepreg to inner layer copper foil during the multilayer process. A higher melt viscosity prepreg such as polyimide, if it is not allowed to reach a proper melt rheology, may damage the oxide layer mechanically, resulting in subsequent lack of cohesive strength in the bond, in effect building in a mechanically induced fault structure which can fail under later thermally induced shear stresses.

Specifically, we recommend a controlled heat up rate to ensure a consistent melt rheology in the resin during processing.   Between the “critical temperatures, we suggest a heatup rate controlled at abvout 10oF (5oC) per minute Too fast -- or too slow -- could cause you flow problems or result in inadequate bonding. Perhaps the most important reason for controlling heatup -- the need for consistency of process on an overall basis.

Lamination pressure will vary depending on many factors including panel size (larger panels may require higher pressure to achieve equivalent flow), amount of heavy copper, especially on signal layers and the type and number of plies of prepreg used.

The following table indicates some “starting point recommendations for lamination of typical Arlon laminate/prepreg materials:

	Poly (85N)	Poly (35N)	Multi (45N)	LoFlo (38N)	LoFlo (51N)
Nom Tg	250°C	250°C	170°C	200°C	170°C
Crit Range	150-250°F	150-250°F	130-230°F	130-230°F	130-230°F
Heat Rate	10oF/min	10°F/min	10°F/min	10°F/min	10°F/min
Cure Temp	425°F	415°F	365°F	365°F	365°F
Time@Temp	120-180 min	90 min	90 min	90 min	90 min
Cooldown	<10°F/min	<10°F/min	<10°F/min	<10°F/min	<10°F/min

What do we have to do to ensure that our product is properly cured?

A total cure time of at 3 hours at 425°F will be required to fully crosslink the pure polyimide products such as 85N. Polyimide resin is toughened and rendered less brittle by proper cure process. A properly cured multilayer polyimide board should have a Tg of 250°C -- or above. Board shops do not always achieve this, and the reason is usually not enough cure.

Newer accelerated polyimides such as Arlon’s 33N and 35N with shorter cure times take advantage of a chemical “booster” to permit cures at slightly lower temperature and significantly reduced cure times. Nonetheless attention needs to be paid to ensuring that the materials are at the cure temperature for the desired time.

No matter what the material, a certain amount of time at temperature is required to achieve proper cure, and shortcutting that will usually result in low Tg.

TROUBLESHOOTING TIP: The degree of cure will depend to some degree on the total mass of material in the press at one time and a board with a lot of heavier metal ground and power planes will often require an extended cure cycle to reach full Tg because the heat capacity of the copper will absorb some of the BTU’s that would otherwise kick-start the resin cure earlier in the cycle. The presence of moisture, especially in epoxy systems, may result in lower than desired Tg due to hydrolysis of the system, which in effect takes away from the available bonds for cross linking.

Use of TMA (Thermomechanical Analysis) can be of great help in determining the cure cycle required to achieve proper Tg in polyimide MLB's. (DSC is more conventionally used in

determining cure of epoxy boards.) The change in Z-direction coefficient of thermal expansion which occurs at the Tg is usually easy to see, especially on a thick board. As you develop the correct cure cycle, that Tg will approach the 250°C level. Tg's of 180 - 220°C indicate under cure and that the process needs to be adjusted somewhere.

Why is the rate of heatup critical?

The rate of heatup of all resin systems is critical. One of the classic keys to making good multilayers is to control the rate of rise of temperature through the critical flow period which occurs between the time the resin begins to melt and the time it "gels" or reaches a viscosity too high to allow significant additional flow. In polyimide this range runs from around 190°F through about 320°F. This range should fall around 10°F (5°C) per minute.

Note: I am frequently told that "We can't control it that tightly." Try! And if you can't hit the exact numbers, do whatever is possible to ensure that it will be the same every time. If heatup is too slow, the resin may not flow properly. If too fast, uneven flow (and thickness) may result.

Slow heat rise (insufficient resin flow) can result in high melt viscosity (low flow) in which resin is unable to flow around oxide crystals or copper structure (in the case of double-treated or DSTF foil) and/or create local voids. Either can provide a pathway for chemical attack of the oxide deposit and contribute thereby to "pink ring". Fast heat rise (higher than expected resin flow) can result in resin starvation leaving fabric fibers directly against inner layer copper. This too can provide a pathway for chemicals to leach along glass bundles in a wicking (capillary) action.

TROUBLESHOOTING TIP: In determining the rate of heatup in a MLB package, placement of the control thermocouple is critical. In a typical book there might be three laminates, 0.090"-0.130" thick each. The thermocouple should be placed about two thirds of the way between the center of the book and the outside (nearest the press platen). If the thermocouple is placed at the center of the middle lam, the outside might shoot past the gel point while the inside is waiting to catch up. If pressure is applied too late, there will be too little flow, and voiding and delamination can occur.

What issues might I encounter with out-of-norm pressure?

If lamination Pressure is Too Low, then boards may exhibit poor interlaminar adhesion and show voids in low pressure areas where resin does not flow sufficiently. The usual fix may involve slight increases pressure, or adjustment in heating rate to open up the lamination window.

If Lamination Pressure is Too High, Cross sections may show evidence of distorted inner layers along with glass knuckles crushed against inner layer traces. Boards may have a "football" shape with thin edges due to excess flow. The problem is usually corrected with reduced pressure or if needed, heat rate reduction.

Heat up rate is critical, since total flow is dependent not only on pressure, but on melt viscosity of the resin system. Both the melt viscosity and the "open time" are dependent to some degree of the heat up rate. As indicated above, we normally recommend a base-line rate of about 10°F/minute.

There is a good method for approximation of starting point pressure that allows modification for resin type and for panel size. Larger panels require higher pressure to achieve equivalent flow. It has to do with the relationship between board area and pressure:

P = k * sqrt(A)

Where:

P is pressure in psi
K is a constant defined for the resin system, usually determined by experience
A is the area of the PWB in square inches (panel length times panel width)
("sqrt" is "square root" in Excel formula shorthand)

Example: If we have found that 300 psi is a good pressure for polyimide in an 18" x 24" panel, what pressure would we use for a 12" x 18" panel of the same resin system?

350 = k * sqrt(18 x 24) = sqrt(432) = 20.8

K = 350/20.8 = 16.8

Pressure (for a 12 x 18) = 16.8 * sqrt(12 x 18) = 16.8*14.6 = 247 psi (round to 250)

Good starting point "k" values are 15 for polyimide, 10 for standard flow epoxies and 20 for low flow epoxy systems. Each user will have to determine optimal values for his own system and individual board designs may vary somewhat. More inner layer heavy copper circuitry may require higher pressures to flow and fill adequately, etc.

How do I control prepreg flow?

Quite often a process tweak is necessary to get prepreg to flow just right for a particular board design. Let's face it – even an optimized process has to be based on historical experience. It's like trying to steer a car looking out the rear window. So when you do have a job that doesn't flow exactly right, what options do you have?

1. Adjust the lamination pressure. Slight changes in pressure will result in a little more, or less, flow and may allow you to come up with the right conditions for that tricky board.

2. Adjust the press heat up rate. This requires more of a change than pressure adjustment and shouldn't be used unless you can't fix the process by pressure alone. When heated up more slowly, resins tend to have lower melt viscosities and flow more slowly. I have found reduced heat up rate (by adding one or two pieces of kraft paper or padding

material) to be a good fix for boards that tend to have a “football” shape after lamination. This seems to work when pressure reduction may result in poor fill in low pressure areas adjacent to heavy copper.

3. In some cases when the prepreg is a “low-flow” the prepreg has to be cut back slightly to prevent the flow bead for coming out into a cutout area. Changing the cutback can often fix a minor flow issue without otherwise having to tweak the process, and has the advantage that it can be done for one or two specific cutouts that for whatever reason are flowing too much without having to touch others or modify the lamination process. Changing pressure or heat up rate affects the whole board more or less equally.

Why is vacuum lamination superior to conventional press lamination for high performance multilayers? How does it differ?

Vacuum lamination is now the norm in most high end MLB facilities, although in some high volume FR-4 facilities, non-vacuum presses are still in use. For many reasons, vacuum lamination is highly desirable for MLB manufacture as it has become for the laminators themselves. Both enclosed vacuum presses and autoclave systems are in use. The biggest difference is that autoclave systems are slower in heat up rate and so consideration needs to be given to using prepregs with sufficient resin content to flow and fill at lower heat rate, hence higher melt viscosity.

In any vacuum lamination system reduced lamination pressures are possible since the vacuum itself helps with resin flow around traces and into via holes. Normally we look to reduce pressures to about 60-70% of the pressure used in a non-vacuum press.

The reduced pressure also seems to help with registration, especially on complex PWB’s.

We have heard a lot about dimensional stability. How can we get materials that are dimensionally stable?

We prefer to talk about Registration rather than Dimensional Stability because it is what really hits the MLB producer. Registration problems which occur during lamination of MLB's seem to defy meaningful correlation to the laminate characteristic often called "dimensional stability." In my opinion there is no laminate property we define or for which we test at present that will accurately predict movement in a MLB, although it is probably a function of both the stress relief movement in an etched board and the CTE of the materials in the entire package. We depend on feedback from our customers who use the materials in a wide variety of designs to characterize material movement in actual process conditions.

As you are may or may not be aware, an IPC task group long ago tossed in the towel on an attempt to develop a "Lamination Simulation Test" which might have been an advance over the existing d.s. test. Their conclusion was that there are too many variables to reasonably be able to expect precise replication of test results within one manufacturer's facility over a period of time,

let alone achieve the meaningful correlation between multiple test facilities that would permit the establishment of a standardized test method.

That does not mean, however, that there is no way to make improvements, only that the particular combination of actions which makes sense for one MLB producer might not, for any number of reasons, work equally well for another board manufacturer (or even for a different type of board design).

Dimensional Stability Characterized

All laminates have some stresses built in when they are manufactured. This is due to resin flow combined with the natural differences in thermal expansion of the components of the system (resin, reinforcement and copper foil). When foil is etched off a laminate, there is some stress relief that occurs, usually in the form of shrinkage. If artwork has not been compensated for this movement, then inner layer features will be off to some degree from the nominal of the artwork.

Note: film type artwork may also exhibit dimensional changes due to temperature and humidity conditions where it is stored and used.

When the final multilayer package is put together all inner layers expand to some degree due to the increase in temperature, and then when the package has been cured and cooled, all the layers try to come back to the place where they started, but since all the layers are now locked together, they will not come back to a zero-base.

The result is that buried board features may not line up exactly with the theoretical locations, and drill offsets based on x-ray measurement of the boards are needed to achieve proper alignment of drills with internal features. If the artwork compensation factors are properly established, then the final board will meet specifications and drilling will be acceptable.

This is an oversimplification, of course, but every manufacturer of MLB's has to deal with registration on a daily basis, so an understanding of some of the factors that affect it is useful and necessary.

Does Laminate Construction Affect D.S.?

Laminate construction affects the amount of nominal movement of the laminate after-etch as well as the consistency of movement from panel to panel. Constructions based entirely on lightweight glass (106, 1080, for instance) will have higher resin content and more absolute amount of shrinkage when cured. Constructions which have at least one ply of heavier glass have been determined to be more stable and more consistent. Therefore a 5 mil laminate made of 1 ply of 106 and 1 ply of 2312 glass is more stable than a 5 mil laminate made of two plies of 1080. And so forth.

The use of heavier glass plies in prepreg layers also helps stabilize the system. The use of unbalanced constructions, while potentially at risk due to "warpage" has been shown over the years to significantly improve inner layer registration in MLB's.

What Methods are Available for Enhancing Registration

In summary:

1. Use the most dimensionally stable materials consistent with board thickness requirements.
2. Use heavier weight prepregs (2313, 2116) whenever possible to help stabilize the entire system.
3. Based on your own experience, establish starting point artwork compensation numbers for the resin systems you use the most. Typically for thin polyimides these will be 0.4 to 0.6 mils/inch for the warp (long) direction and 0.2 to 0.3 mils/inch for the warp (cross) direction. For traditional epoxy systems the values are about half that of polyimide.
4. Be sure that all artwork is handled in a controlled temperature/humidity environment.
5. Be sure that boards are designed with registration in mind. Avoid inner layers with a lot of copper on one edge or the other, which may result in skewing. Use of copper borders (even if they are not solid) helps stabilize the board against distortion.
6. More pins may help up to a point, especially if there are solid copper borders.
7. Laminate at the lowest temperature appropriate for your resin system. Higher temperatures result in more X-Y movement during lamination and more stresses when the boards are cooled.
8. Cool boards at or less than 10°F (5°C) per minute to avoid "locking in" unbalanced stresses.

What determines drill speeds and feed rates? What are the best drilling conditions for use with polyimides?

It is necessary to drill polyimide so as to avoid fracturing the resin at and around drilled holes. It is inherently a harder resin than epoxy (some of the newer modified polyimides are less susceptible to fracturing, but nonetheless are harder and more frangible than epoxies, and must be treated with respect) or they will fracture when abused.

TROUBLESHOOTING TIP: If you have not properly cured your polyimide material, it is likely that you will encounter drilling problems, including the possibility of drill smear.

There are numerous ways to abuse material during drilling. We have not attempted to disclose all these methods here, as we are afraid somebody might read about them and try some of them out.

TROUBLESHOOTING TIP: We recommend starting out with a drill surface speed of 400-500 surface feet per minute (you will have to calculate RPM for each drill diameter) at a 1 mil chip load for polyimide. Higher chip loads are common for epoxy. You may be able to modify this as you develop experience with the resin systems you use, but to ensure generally good drilling, we suggest starting with a low chip load.

Because polyimide has a relatively high Tg, temperatures reached at the drill tip during drilling (in excess of 425°F has been measured by non-contact IR measuring methods at the instant of drill withdrawal) do not normally cause smearing. Smear results from softening of the resin and subsequent dragging of that resin across the hole wall and inner layer copper lands. Proper entry and backup material will also help in preventing excessive burring, clear the drill bit of resin picked up during drilling and even, with some specialized entry materials, cool the drill.

Drill geometry is critical. The drills should have margin relief to minimize heating, which is one cause of nail heading.

Small diameter holes (less than 0.020") have been drilled successfully without entry material. In cases where entry material is necessary (due to topography of the MLB surface) Micro-Entry (0.006"-0.008") aluminum clad material works well. Peck drilling, making a series of entries and withdrawals, also helps clear the drill and keep it cooler during drilling. This is especially useful in fairly heavy boards stacked two or three high.

TROUBLESHOOTING TIP: One caveat -- beware of drilling with a "peck" method into boards with heavy metal cores, which may break bits if they "peck" too hard.

Why can't I punch my polyimide boards?

TROUBLESHOOTING TIP: Punching polyimide boards will have the same effect as Oscar De La Hoya punching my jaw -- they are both likely to shatter. The resin is simply not flexible enough to survive the impact. In the best case the edges of the punched piece will delaminate and fracture. In the worst case a whole section may delaminate from the impact. If it isn't obvious immediately it may become so during subsequent thermal operations.

Although polyimides are toughened by proper Tg development during curing, no cure is enough to make standard polyimide really suitable for punching. We have not seen any evidence that the newer "modified polyimides" are good enough for this operation. Plan on routing out your multiple imaged polyimide boards.

TROUBLESHOOTING TIP: Do not punch out your pieces for microsectioning of polyimide. If you do so you will likely encounter "fracturing" in your section that wasn't there before sample preparation. Rout out sections and grind carefully down past the initial cut line.

We hear a lot about Lead-Free Solder processing. What effect will higher solder temperatures have on my MLB's?

The issues with lead-free soldering are the same as for any solder or reflow process, but they are exacerbated by the higher soldering temperatures, the melt points of which can be anywhere from 15 to 30°C higher than traditional solder temperatures. The critical difference will be in

total Z-direction expansion, because the temperature that a board will reach will be proportionally higher than with tin-lead solder.

Additional caution will need to be observed in any post-processing such as device removal and reattachment where the higher temperatures may significantly exceed the Tg of even the high temp multifunctional epoxies and could result in resin softening, pad lifting and other issues normally associated with lower Tg "standard" epoxy systems. The difference in solder temperatures offsets the benefit of going from 140 to 170°C Tg in the material itself.

There remain some concerns about the lead-free solders themselves, and while we have only anecdotal evidence to-date, there are concerns about tin whisker formation having an effect (shorting between traces) not dissimilar to CAF.

The lead-free solder temperatures themselves are not high enough to result in significant material decomposition during PWB manufacture. The minimum Td (Decomposition Temperature) recommended by IPC for a Lead-Free system is 330°C which is well above the potential solder temperatures that will be encountered. On the other hand there are large numbers of devices that have not yet been tested and qualified for lead-free soldering temperatures. This is one of the remaining open issues with full implementation of lead-free technology.

The table below provides an estimation of temperatures that will be encountered with some lead-free solder systems. As of this writing there does not seem to be a real consensus as to the selection of one over another but there is no doubt that lead-free is here to stay, so expect any or all of these to be required at one time or another.

Commonly Used Lead-Free Solder Alloys vs. Standard Tin-Lead

Solder Alloy	Melt Temp	Reflow Range	Industry/Application
Tin-Lead	183°C	200-235°C	Historic Standard
Tin-Silver-Copper	217°C	230-250°C	Telecom, Automotive
Tin-Silver-Bismuth	206-213°C	225-240°C	Military, Aerospace
Tin-Copper	227°C	230-260°C	Telecon, Consumer
Tin-Zinc	198.5°C	215-230°C	Consumer

Data from IPC Lead-Free forum at http://leadfree.ipc.org/ . Reflow Ranges estimated.

How about processing Woven Kevlar® Materials? Are there any special precautions to take while processing aramid fiber reinforced boards?

There is only one "killer" process issue which really separates Kevlar® from other materials. Moisture pickup. Kevlar® prepreg MUST, MUST, MUST be vacuum dried immediately before use. Aramid materials (Kevlar® and Thermount®) are the only materials which vacuum dry in our facility before pressing into full sized sheets of laminate. We suggest a full 24 hours of vacuum drying at 29 inches of mercury. Desiccant boxes will not get the moisture level down low enough and will only result in frustration sooner or later. Fail to properly dry aramid materials at your own peril!

Woven aramid reinforced boards also have a tendency to be inconsistent lot to lot in terms of drill registration due to variability in the as-received woven product. We strongly advise making a test board from each lot of material (laminate and prepreg) to establish proper artwork compensation, and to take all the precautions listed above to minimize misregistration. Experience has been that once a lot of material has been "calibrated" it will then process with reasonable consistency.

Are there any problems drilling Kevlar®?

Woven Kevlar® fabric is used to make a variety of composite body armor, knife and bulletproof vests and the like. It is hard to cut. It is a pain to drill. Your routed edges and drilled holes may be filled with "frizzies," strands of fiber that did not cut as cleanly as fiberglass. Fiberglass actually shears cleanly off in a well drilled hole -- Kevlar® is partly cut and partly torn apart. Before electroless processing, Kevlar® boards should be etched back with plasma. This will remove the frizzies both in the holes and on the routed edges of the boards. Subsequent electroless deposition and plating can be done as with any epoxy board. If plasma makes too smooth a hole, permanganate can be used as a secondary step to microetch the inside of the hole just as with polyimide boards.

Note: Use of glass etch will NOT do anything with Kevlar® boards and may wick into fiber bundles. Bypass the glass-etch baths in your Kevlar process.

How about Thermount? What are the process issues we will encounter with Thermount reinforced laminate systems?

Arlon has been the primary supplier of Thermount based laminates for many years. While DuPont has discontinued manufacturing Thermount and the supply is dwindling, there are still designs using Thermount and the processing of Thermount has some critical issues.

Moisture pickup, especially in polyimide Thermount products (which are our largest selling nonwoven aramid products) is the major risk factor to be considered, and residual moisture over 0.22% will almost certainly result in blistering. Prepregs and laminates MUST be dried according to process recommendations made in the literature prior to lamination or blistering and delamination will be expected.

Drilling is slightly more difficult than with woven glass, since the aramid fibers are high modulus and will tend to leave "frizzies" in drilled holes and along routed edges. Optimizing drill and rout processes is important. Frizzies can be removed by plasma treatment prior to plating.

Thermount materials can be laser drilled with hole diameters as small as 25-50 microns (1 to 2 mils). Lased holes tend to taper slightly, so an aspect ratio of 1:1 is recommended when lasing holes in Thermount layers.

Registration is more consistent with polyimide Thermount product on E-Series Thermount reinforcements than with woven glass. Minimal artwork compensation is usually required, on the order of 0.1 to 0.2 mil/inch in the warp direction and none in the fill. This is due to the nonwoven construction, since the fibers are discontinuous and don't exert the same overall effect that they do in woven products.

Thermount systems use low resin content to ensure controlled CTE values, and in some cases higher laminating pressures may be needed to ensure flow into copper detail and inner layer via holes.

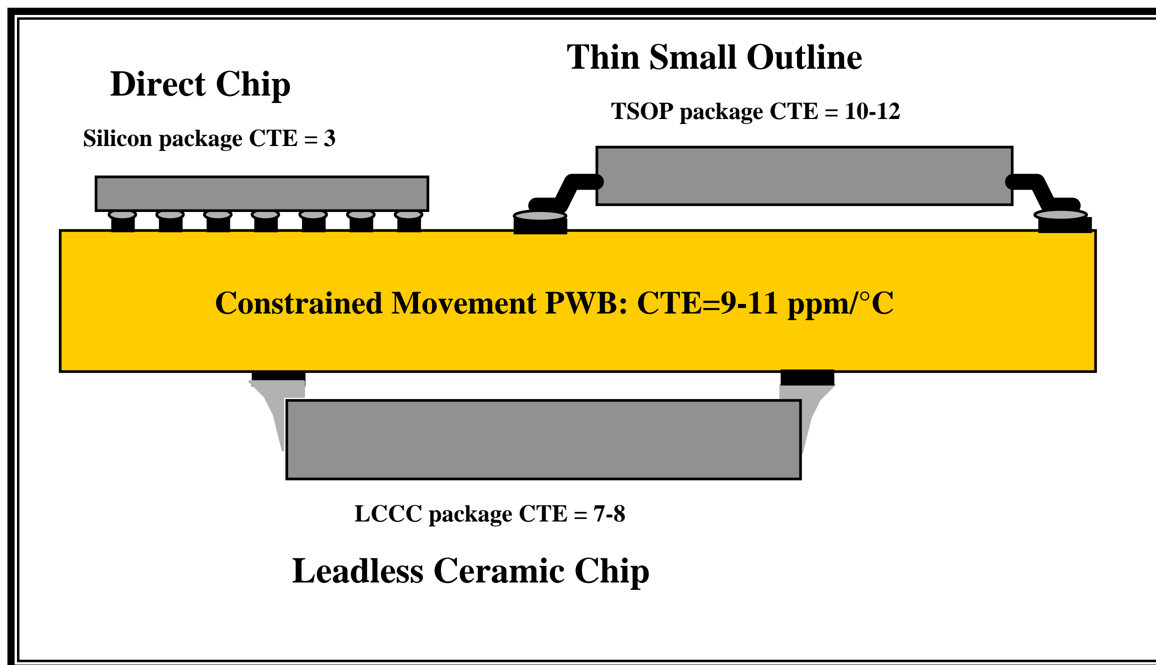
Return to TOC

V. CONTROLLED CTE

Why is the CTE of a MLB so important?

In the case of the ceramic chip carrier (CTE 6 ppm/°C) mounted on a conventional printed circuit board (CTE 17-18 ppm/°C), when the chip carrier is large enough, the mismatch in expansion will cause shear stresses within the solder joint that mounts the device on the board. A sufficient number of thermal test cycles (typically -65°C to +125°C) will eventually lead to work hardening of the solder and cracking of the solder joint itself. The resulting intermittent electrical discontinuity is entirely unacceptable in high reliability electronics applications regardless of their application.

In the case of stacked dies and direct chip attach, the requirements become even more critical since CTE values for die materials can be between 3-4.5 ppm/^{o}C and the mismatch is even more critical than for leadless ceramic packages. The diagram below illustrates the expected average movement in ppm/^{o}C for various kinds of surface attached devices compared with the movement of a typical constrained movement PWB. A normal laminate with a CTE of 17-18 ppm/^{o}C could result in excessive strain on solder joints and subsequent work hardening and cracking.



What is CTE (Coefficient of Thermal Expansion)?

Coefficient of Thermal Expansion (CTE), aka Thermal Coefficient of Expansion (TCE), is a characteristic thermomechanical property of a material or a composite. It is the tendency of a material to expand as it is heated.

The expansion of materials is volumetric in nature, but the laminate construction is such that we need to separately consider in-plane expansion (X and Y direction) and out-of-plane expansion (Z-direction). If there were no restraining fabric in the laminate, the neat resin would expand isotropically (the same in all directions) at about 30-40 ppm/oC.
Reinforcing fabrics used in laminates (glass, quartz, aramid) have lower coefficients of thermal expansion than the resin and high modulus values (Glass at about 12 million psi, aramid fibers at about 19 million psi, as examples) which restrain the in-plane expansion of the system. The volumetric resin expansion, however, is essentially incompressible, which means that to the extent that the resin is constrained from moving in the plane of the laminate by the high strength fiber reinforcement, that resin will expand in the relatively unconstrained Z-direction.

The Z-direction coefficient of thermal expansion increases by as much as fourfold, above the glass transition temperature of the resin system. In typical systems this means going from 50 to 200 ppm/ °C above the Tg transition.

The CTE in the X and Y directions usually decreases slightly above the Tg because the resin modulus decreases and the constraining ability of the reinforcement becomes stronger since its modulus is relatively unaffected by temperature changes.

Can we find CTE-Controlled Products in all Resin systems?

The answer to that question is a qualified "Yes." It is qualified in that not all resin systems are available with all possible constraining methods and Arlon does not offer all possible resin systems with constraining substrates or foils. Arlon offers a number of combinations of materials that are used in constrained CTE situations, covering a range of resin systems and reinforcements that should provide options for most applications.

1. Polyimide resin (Tg = 250°C) is available in a nonwoven aramid reinforced product (Arlon's 85NT) or as 0.005" or 0.006" glass reinforced laminate with distributed 0.006" Copper-Invar-Copper (CIC) layers. Polyimide on woven quartz substrate (low dielectric constant) is also available on special order.

2. Multifunctional Epoxy (45N) is available on a woven Kevlar® reinforcement with very low CTE values (as low as 5 ppm/oC) and is available as thin glass reinforced laminate with distributed 0.006" CIC layers.

3. Non-woven aramid reinforcement is available in a standard low CTE epoxy product (55NT) and as well is available with a number of specialized epoxy resin systems, offering improved moisture resistance (55LM) and excellent bond and cohesive strength (55ST). The 55-series resins are specially formulated for use with nonwoven aramid.

4. Arlon also offers several low CTE products based on polytetrafluoroethylene (PTFE) such as its CLTE product line, TC-350 and TC-600, all of which have reduced CTE values due to the inclusion of low expansion filler technology.

What are the CTE's of the materials used in making MLB's?

Typically:

Copper foil 17-18 ppm/°C
Fiberglass Fabric 5-6 ppm/°C (X and Y will differ in most cases)
Epoxy Resin 35-45 ppm/°C (volumetric isotropy)
Polyimide Resin 30-40 ppm/°C (volumetric isotropy)
Aluminum Sheet 22-23 ppm/°C
Kevlar® Fabric -4.5 ppm/°C (in-plane only – fibers expand radially when heated)
Quartz Fabric 0.5 ppm/°C
Copper-Invar-Copper 5.5 ppm/°C (in-plane)
Alumina-Ceramic 6.0 ppm/°C
Silicon Chip 3.0 to 4.5 ppm/^{o}C

Note: While these are the CTE's for the "pure" materials, the effective CTE's in a composite will depend on many factors, including the effective tensile modulus of each component in the form in which it is used. For instance aramid fibers have a nominal tensile modulus of 19 x 10^6 psi, but because it is used in the form of a woven glass, the effective modulus may be much lower. When we do modeling, as with the Schapery Equation (See below) we need to use empirical values based on actual testing to establish "effective" values for the various properties involved.

What is the CTE of a typical multilayer board?

The final CTE will depend on the modulus of each of the components of the composite structure, the effectiveness of the chemical and physical bond of the components to one another, the degree of transfer of the modulus of the stiffer materials into the resin (for example a woven fabric will have an out-of-plane component at fabric crossovers) and the volume ratio of each material in the composite.

A typical multilayer printed circuit board has a CTE of 16-18 ppm/°C. A rigid 2-sided printed wiring board may have a CTE as low as 12-14 ppm/°C. The lowest CTE for any resin/fiber system will almost always be that with the lowest resin content. It is possible, and we have learned this from painful experience, to make laminates with CTE's that are very low, but that will not make an acceptable MLB due to resin starvation, lack of resin to flow and fill inner layer copper patterns, etc. The key phrase to remember is "minimum acceptable resin content," which will differ for various reinforcement materials. Only if the system makes a good MLB which will meet the requirements of applicable specifications will the low CTE be of any real value to the design.

What are the available solutions to the CTE mismatch problem?

Numerous solutions to this problem have been addressed over the years. One approach is the use of an inherently low CTE laminate system such as those we produce with Thermount® non-woven aramid systems, Kevlar® woven aramid fiber reinforcements, or quartz fabric reinforcements.

Another approach is to use a low expansion layer within the structure of the printed wiring board itself whose high modulus will dominate the system and reduce the effective CTE. Metal cores such as CIC, and carbon fiber composite cores have both been used with varying degrees of success. Metal foil with low expansion such as 6 mil CIC can also be incorporated into MLB's, with the advantage that distributed thin layers of CIC typically at layers 2 and 3, have as much impact on surface CTE as a heavier single layer buried at the center of a board.

An attempt was made some years back to use a compliant layer at the surface of PWBs to which the devices could be mounted without resultant stress. Problems with drilling holes through these compliant layers and subsequent plating and processing issues have largely relegated this once-promising approach to the back burner.

Woven aramid fiber reinforced laminates, Thermount nonwoven aramid reinforced boards, metal core boards and metal foil layer boards all are in ongoing programs at present. Because it offers the opportunity to use a pure polyimide resin system, quartz fabric reinforced materials offer both reduction in CTE and enhanced dielectric properties – typically with a Dk of 3.65 and a loss of 0.005.

Is there a "correct CTE" for a board designed for surface mounting of LCCC's?

There is a correct CTE for every design which uses direct surface mounted devices, including LCCC's. Unfortunately, we have only scratched the surface of understanding exactly what that is, and it will differ from design to design. If we make our laminates with a CTE of 6 ppm/°C to precisely match that of ceramic LCCC's would that be "correct"? Maybe, if we were not going to leave any copper foil on them after we processed them into layers. Copper expands at 17-18 ppm/°C and drives the CTE upward. If we start at 6 ppm/°C the effective CTE of the board may be 8 ppm/°C. If we start at 4-5 ppm/^{o}C, the finished PWB may be at 6-7 ppm/oC. (Which is why 45NK woven aramid reinforced material is almost "ideal" for LCCC mounting.)

This does not even begin to touch on the tricky issue of heatup and cooldown rate. In normal power cycling the powered mounted device will warm up first and expand faster than the board (unless the board's CTE is sufficiently greater than that of the devices). At power down, the device will probably cool at a different rate than the board, and they will not move together then, either. Nor do we yet have available a thermally variable CTE material which will continuously monitor and match the movement of the surface mounted devices.

The issue is additionally compounded by the use of hermetically sealed plastic chip carriers, whose expansion coefficients are often closer to 10-12 ppm/^{o}C, and so a material that really was 6 ppm/^{o}C would actually have a reverse effect where the chip carrier expansion would be more than that of the board. Can you say "tailorable CTE"? In an opposite direction, direct chip on

board attachment may require even lower expansion coefficients to “match” silicon’s expansion of about 4.4 ppm/^{o}C. And as in all cases, the heat-up rate of the device and the board will not be the same.

Further effects will be experienced depending on the ability of the board design to carry heat away from the board surface – thermally conductive materials may have less net expansion because they don’t get as hot (it is temperature, not rate of heat flow, that determines expansion). Once again there is a complex board design issue here in which a designer needs to take into account several variables in addition to CTE.

The question of whether there is a "correct" CTE remains unanswered definitively, but significant power cycling studies at several military/aerospace OEM’s using differing methods of constraint (Kevlar® reinforcement, Copper-Invar-Copper constraining core) seem to suggest that a net board CTE of 8-10 ppm/°C will permit over 1000 cycles without failure using LCCC’s.

Why is the coefficient of thermal expansion of the laminate always greater in the Z-direction that in the X and Y axes in the plane of the laminate?

Neat resin expands isotropically when heated. That is, if unconstrained it will expand equally in the X, Y and Z axes with a volume coefficient of thermal expansion about three times that of the linear coefficient of expansion in an unconstrained system. For example the volume coefficient of thermal expansion of polyimide resin might be about 35 ppm/°C. Fabric reinforcements which are an essential part of the laminate composite have much lower expansion coefficients than the resin itself, and that, combined with high in-plane modulus in the direction of the fibers, results in a constraint of the X and Y movement. Because the resin expansion is incompressible, the expanding resin has to go somewhere. The path of least resistance is the Z-direction. (Nothing is ever simple.) The net effect is that for an unclad polyimide laminate the X and Y CTE turns out to average 15-16 ppm/°C (depending on resin content) and the Z direction 55 ppm/°C.

In highly filled systems with no discrete Tg in the range of 50 to 260°C – such as PTFE – the expansion in all directions may be reduced significantly, both due to the effect of the filler, and the reduction in actual resin in the system. CLTE-XT is a good example of a low CTE product whose CTE properties are largely governed by the use of a microdisperse proprietary filler system.

Discuss the issue of total Z-direction expansion 50 to 260°C

In a constrained CTE material or in standard glass-polyimide (or epoxy) material, the Z-direction movement determines the relative strain (and hence stress) on a plated through hole. Because the CTE is normally reported “below the Tg,” that value does not give a complete indicator of the expansion that can be expected at solder reflow temperatures, so we have adopted the use of a “total expansion” value from 50 to 260°C which will give an indication of the relative strain on a PTH at “working” temperatures. Given the hoop strength of copper, the elongation of the plated copper and some idea of work hardening with cyclic stress, etc, it is possible to determine a

value of expansion that could be problematic based on board thickness, soldering temperature, etc.

To give a rough example, a polyimide system with Tg of 250°C will have a total expansion of about 1 to 1.1% (10,000 to 11,000 ppm) between 50 and 260°C. Multifunctional Epoxy, whose high Z-direction movement starts at a much lower Tg (typically 170°C), may have a value of 3 to 3.5% (30,000 to 35,000 ppm). IPC has established a maximum total CTE of about 3.5% for Lead-Free systems. With few exceptions, the expected cycle life of PTH's (all other things being equal) will be roughly proportional to the total Z-direction expansion of the system.

Note: An interesting phenomenon was noted by some British aerospace researchers in the early days of the use of Thermount as a constraining core material. PTH life was roughly 3 times as great for polyimide Thermount systems as for polyimide glass, even though they have the same Tg and even though the Thermount actually has a higher Z-direction expansion due to the constraint of the X/Y CTE. That runs counter to expectation if Tg and total Z-expansion are the only factors involved. Analysis indicated that the nonwoven aramid material did not concentrate stresses within the PTH the way glass fiber bundles do where they intersect the surface of the PTH. The result of a more uniform stress distribution was extended time to mean PTH failure.

What is The Schapery Equation?

The final CTE of any composite product will depend on the modulus and coefficient of expansion of each of the components of the composite structure, the effectiveness of the chemical and physical bond of the components to one another, the degree of transfer of the modulus of the stiffer reinforcement materials into the resin (for example a woven fabric will have a significant out-of-plane component at fabric crossovers) and the volume ratio of the components of the composite.

One common mathematical model (the Schapery Equation) that is used to calculate CTE values is based on the modulus, the CTE and the volume fraction of the components.

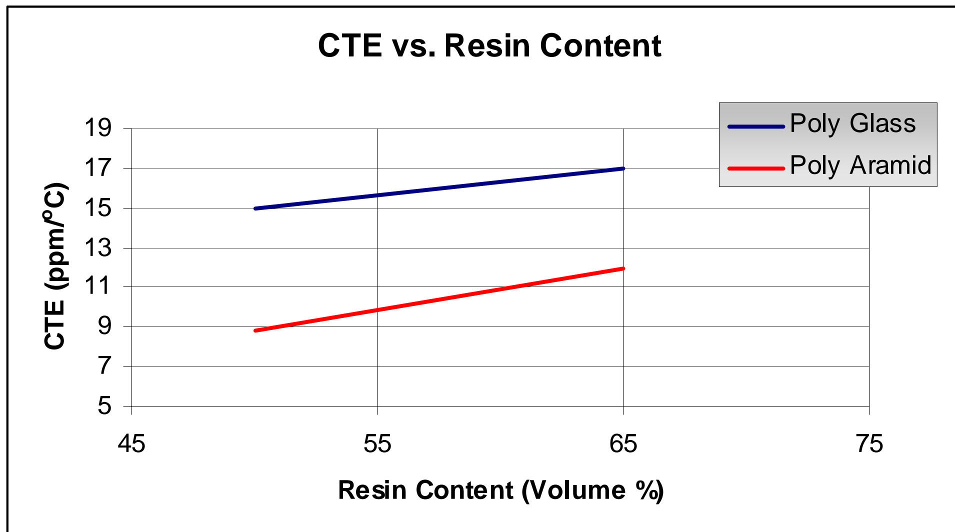
A(composite)= [a1*m1*v1+a2*m2*v2....+an*mn*vn]/[m1*v1+m2*v2....+mn*vn]

Where:

a1, a2, etc. are the effective CTE's of the components
m1, m2, etc. are the effective moduli of the components
v1, v2, etc. are the volume fractions

The effective modulus and CTE values for calculation purposes may not be the same as the theoretical value. For instance, while aramid fibers have a modulus of 19×10^6 psi, as a woven fabric that value is reduced to about 14×10^6 psi, and while individual aramid fibers have a CTE of about -4.5 ppm/°C the effective value is about 1.0. These values must be determined empirically for the systems being used.

The graph (below) shows the effect of resin content (volume %) on nominal CTE for polyimide laminate based on woven glass vs. nonwoven aramid reinforcement.



You mentioned an 0.006" CIC product. Tell us about that. How do we use it? Are there any limitations?

Although there are various thicknesses of CIC available, Arlon exclusively uses 0.006" thick product with a composition of 12.5% Copper/75% Invar/12.5% Copper. This is supplied in the form of CIC foil laminated both sides on a thin laminate (typically 0.005" or 0.006"). This approach permits designs that use distributed CIC layers (typically at layers 2 and 3 and 10 and 11, for example, in a 12 layer design) to achieve CTE control without using a heavy metal core.

One of the most common failures in boards built with internal CIC foil planes is delamination at the CIC foil surface. Some of our customers have preferred in past to use CIC with no treatment on the outside. Any problems with pre-etch or oxide treatment of the CIC can result in poor bonding. The difference in expansion coefficient between the CIC and the underlying laminate will result in significant shear forces that will cause delamination if the bond is not sufficient or is spotty in quality.

The only satisfactory way to achieve adhesion to this surface is to use a supplier-applied treatment which deposits a nodular copper "tooth" structure. The surface morphology of this treatment gives reasonable mechanical adhesion and transfers most of the shear force to the bond line between the metallic deposit and the CIC, which is strong enough to withstand the stresses. We manufacture as a standard product a laminate with the best available "double treat" CIC for either polyimide or epoxy. The CIC comes with treatment on both sides so you need do no risky secondary bond processing. Just keep the treated side clean, and it will give you the bond strength you need for your CTE applications using the normal prepreg as a bonding adhesive.

Clearance holes in 0.006" CIC foil can cause some problems as well. Resin from prepreg can fill these holes, but you will wind up with an 0.006" section of pure resin. This may result in cracking as well as problems with plating and Z-direction expansion. Arlon offers 84N and 44N

filled prepregs that are used against these clearances to fill then with a resin that contains microdisperse ceramic filler. The filler reduces shrinkage and inhibits crack formation. There is also a Howefill® product (Howefill® 50) which can be sifted on during layup to provide the proper fill for clearance holes in 0.006" or thicker CIC planes.

We do not recommend use of laminate with CIC on one side and standard copper on the other. We would caution that this will result in a warpage or curling phenomenon that will probably take place inside your etcher -- where it will make a mess and jam the feed. We do not make single sided CIC laminate (unclad the other) because it will curl like a
scroll as soon as we take it out of our own press.

How is Copper-Invar-Copper used?

We manufacture thin laminate with 0.006" CIC foil clad on both sides. Like copper foil clad products, these laminates may be printed and etched and laminated within a multilayer board. The CIC layers constrain expansion and serve as power and ground planes. It is felt by some that distributed thin CIC planes near the surface of the board may provide CTE control better than a single much thicker central core. Their copper content makes them good electrical conductors, although, as we will discuss later, connecting to them can be a problem. The 0.006" foil is not as good a good thermal conductor as pure copper because there is too little mass of copper -- its purpose is basically to provide expansion control.

Designers can use thicker CIC pieces (0.020" or more in the center of the MLB) for thermal management (i.e. as a heat sink) in addition to CTE control. Frequently two complete multilayer PWB's are bonded to the two sides of a solid piece of CIC. The two boards are fabricated using conventional materials and processes and then bonded to the CIC with some form of adhesive. The ideal adhesive would be thermally conductive, electrically insulating, non-flowing, with high modulus to transfer the expansion characteristics of the CIC to the multilayers and tough enough to withstand the shear forces that want to tear it apart. Does that seem like too much to ask?

Howefill 50 is a powder compound designed specifically for filling clearance holes in thick CIC or other metal core boards where use of filled prepreg won't provide enough resin to flow into the clearance holes.

Is CTE the only reason for the use of a metal core in a PWB? Does the use of metal cores raise other issues?

A constraining core to control in-plane expansion is designed into many PWB's that are intended primarily for surface mounting of leadless ceramic chip carriers. The essential requirements for a constraining core are that it must have a low coefficient of thermal expansion (CTE) in the X-Y plane of the board and that it must also have a sufficiently high modulus in tension to prevent the rest of the board from expanding at its characteristic rate of 14-18 ppm/°C (or 14-18 x 10^{-6} in/in/^{o}C). There are a number of ways to accomplish this including the use of graphite

composites, copper-molybdenum-copper layers, grappling hook and cable come-along, Kevlar® reinforced composite layers and Copper-Invar-Copper (CIC) layers. Other properties of a constraining core such as heat transfer, electrical conductivity and weight are important as are processing characteristics such as ability to be etched, drilled, copper-plated and bonded to other materials.

There is an effect of constraining the in-plane expansion that is less intuitively obvious but potentially more risky that the shear issue discussed above. The resin systems used in conventional laminate systems (polyimide, epoxy) expand isotropically if they are not constrained. Non-reinforced resin will expand about 35 ppm/°C in all directions. Glass fabric has an inherent expansion coefficient of about 5 ppm/°C. When resin and glass are combined in a laminate (depending on the styles of glass used and the actual resin content of the composite) the in-plane CTE is about 16 ppm/°C and the Z-direction expansion (the resin exhibits incompressible volumetric expansion for a given temperature change) becomes 55 ppm/°C. When CIC further constrains the in-plane expansion to 7-8 ppm/ C is that the Z-direction expansion increases still more (the resin expansion has to go someplace). It can wind up significantly more than what it was before you added the CIC -- as much as 90 to 120 ppm/°C.

The copper in a plated through hole has to have some ductility to it or it will crack during normal thermal cycling. Additionally copper has a CTE of about 17 ppm/°C. But when plated into a board expanding and contracting at 120 ppm/°C this may be too little. After a few cycles, the copper will start to work harden and its ductility will begin to be affected. The result -- cracked plated through holes, pad lifting, crazing and laminate cracking. Copper cores with CTE's of 17 ppm/°C or Aluminum with 23 ppm/°C expand more than the board does so they do not force extra expansion in the Z direction. If you have no experience working with CIC, these problems may pop up unexpectedly and you may look to the wrong places for their causes, while your boss fumes about the yield losses and what they are doing to his bottom line.

The use of CIC in thin foil form which may act both as a constraining layer and as power or ground plane presents other problems. Several concerns exist in trying to process this material in a standard production line. The common copper etchants will not effectively attack the Invar portion of the foil. A special process line (Ferric Chloride or the like) is needed to attack the Invar if it has to be pattern etched. We may have to change drilling parameters in order to produce satisfactory holes without damaging drill bits. (It may be necessary to drill the holes which connect to CIC planes differently than the rest of the holes in the board.) Once we drill the holes in the CIC, plating through is still a potential hassle, since most plating systems, by design, plate to copper, resin and glass. They do not bond well to Invar and special chemical and/or mechanical processes may be needed to optimize plating to Invar.

Sounds like a lot of issues with CIC. Are there solutions for any of them?

There is no obvious answer to dealing with the large difference between the CTE of the CIC and that of the circuit boards being bonded to it. Use of an inherently

low CTE system based on woven Kevlar® reinforced laminate and prepreg or nonwoven aramid reinforced systems is a design alternative that has found considerable favor over the past ten years or so.

It is possible to make selections of materials that go into those boards to minimize their CTE. The basic principle is this: more glass and less resin means lower CTE. Any multilayer board may be constructed a number of ways (the earlier in the design stage that we recognize and address this, the better) and those alternatives can have widely differing CTE's. The lowest in-plane CTE possible consistent with the design requirements of the board should be selected. In addition, a material with the highest Tg (Glass Transition Temperature) possible should be selected for the application. This will minimize the additional Z-direction expansion that occurs above the Tg which can create serious problems with through-hole reliability, especially in thick boards with high aspect ratios.

Bonding to laminated-in metal cores with clearance holes presents similar problems, but different approaches must be taken to deal with them. The first problem you will encounter is drilling through the Invar. Do not expect long drill life, and change drills often enough to ensure consistently good hole quality. Once you have drilled the holes in the CIC you may have to fill them back up with dielectric material. The selection of fill material is critical to the eventual success of this approach. The hole fill material should closely match the expansion characteristics of the CIC. If the hole fill compound has a higher expansion coefficient than the CIC (and most of them do) it will shrink back into the hole after filling and curing, causing a dimple effect on the surface and, worse, tending to cause the fill compound to pull away from the drilled hole wall of the CIC. If the hole-wall adhesion is adequate, then watch out for cracks within the hole fill compound itself.

What is Howefill 50®? How do we use it?

We have developed a product called Howefill 50® that we specially designed for this application. Howefill is closely matched to the expansion characteristics of the CIC, and the ceramic filler helps to drill it cleanly using the same parameters as for drilling the laminate itself as well as helping it to plate uniformly with good hole wall adhesion. The low CTE puts little or no additional stress on the plated through hole, thus producing enhanced reliability during thermal cycling or the repeated thermal stresses that may be encountered during rework operations.

Howefill® is a free-flowing powder that is a blend of powdered polyimide resin and inorganic ceramic fillers which result in properties compatible with the electrical and mechanical properties of our laminates.

Typical properties of Howefill® 50 (after cure) are as follows:

Tg (°C) 250
CTE (ppm/°C) 17
Thermal Conductivity 0.5 w/M-k

Density (g/cc)1.9
Water absorption (%) 0.3
Resistivity (ohm-cm) 10^{13}
Electrical strength >1000 (volts/mil)

When Would I use a Ceramic Filled Prepreg?

84N (ceramic filled polyimide prepreg) and 44N (its multifunctional epoxy analog) are used for clearance holes in MLB's with distributed CIC layers. The prepregs have nominally 28% finely dispersed ceramic filler which reduces resin shrinkage during cure, and inhibits radial crack formation during subsequent drilling operations.

These products are in use world-wide and have proven to be an effective way to reduce the risk associated with trying to fill clearance holes with pure resin (i.e. from standard unfilled prepreg). In fact, Arlon has determined in its polyimide product that lower levels of filler, preferred at one time by some customers, are significantly less effective in preventing shrinkage and cracking than the current 28% material. As a result we discontinued making the lower % filled product and have converted all our customers to the better material.

Talk to us about woven aramid reinforced PWB's. What are the advantages of this system?

The use of woven aramid fiber reinforced PWB's is the best way currently available to achieve a very low CTE for mounting large LCCC's or for direct mounting of silicon chips (whose CTE is about 4.4 ppm/^{o}C)on boards. The high fiber modulus of the Kevlar® combined with its low effective X-Y coefficient of thermal expansion gives this system the "horsepower" to control in-plane CTE.

Woven aramid reinforced laminate has a CTE of about 4-57 ppm/^{o}C. They are exceptionally light in weight, as aramid is an organic fiber material with much lower density (1.44) than conventional E-glass (2.54). The finished laminates have lower dielectric constant (3.6) than E-glass (4.5) which translates to higher signal speeds in finished board designs. Arlon's 45NK multifunctional epoxy product reinforced with woven aramid meets IPC-4101 /50.

Does Use of Woven aramid Reinforced Laminates have any disadvantages?

Or you might ask, "Why isn't everybody using Kevlar® reinforced MLB's?" (If we're so smart, how come we ain't rich?)

There are a few issues in using Kevlar® reinforced substrates. We alluded earlier to the fact that we cannot simply use any resin system that is available, and that because of CTE constraints, we have to be selective in resin contents. Polyimide resin systems have not historically bonded well enough to woven aramid to make them viable systems. That means that a Tg of about 170 is the best we have achieved to-date. Resin content has to be minimized (while maintaining enough for

adequate flow and fill) to keep CTE low. These are not so much negatives as natural constraints on the system.

Three issues continue to be raised in the use of Kevlar® which, even if they do not seem to be causing material to fail, are worth noting:

1. The question of resin microcracking occurs frequently. Kevlar® has a negative coefficient of thermal expansion in the X/Y plane because the fibers themselves shrink longitudinally when heated and expand radially at the same time. At fiber crossovers, therefore, a substantial stress concentration occurs where cracks can initiate and from which they can propagate. To date it is doubtful whether these microcracks actually cause product failure. The fear, that they may propagate to the surface and cause trace failure has not been substantiated in use. Epoxies are inherently flexible enough to resist cracking, but at sufficient magnification and after enough thermal cycles, the phenomenon can be seen in any Kevlar® reinforced system.

The use of thin polyimide face layers helps alleviate any concern about crack propagation, and also helps with repairability without significantly increasing the CTE of the overall system.

2. The second issue is thermal management. Kevlar® reinforced laminates transfer heat at about half the rate of conventional glass reinforced laminates. The heat transfer coefficient for a typical epoxy or polyimide-glass laminate is around 0.3 BTU/hr-°F-ft, while Kevlar, in the same system of units, is about 0.15. Since conventional laminates are not especially good heat conductors, and numerous strategies are employed to remove heat, those techniques will simply need to be applied with even more vigor with Kevlar® laminates.

3. Because of the constraint of the X/Y expansion and the contribution to Z direction expansion of the Kevlar® itself (expanding radially when heated), the net Z direction expansion of Kevlar® reinforced laminates is greater than for equivalent epoxy or polyimide glass reinforced materials. This can affect things such as pad-lifting in thicker designs.

4. Experientially we have found that registration is not as easy with aramid woven products as with glass or Thermount (see below) systems. This seems to be a matter more of lot to lot variation in the woven fabric, since most users have determined that once they have made a test board to fine tune the artwork compensation needed, that those factors will work well for the balance of the lot of material.

There is still interest in quartz fabrics for CTE control. Why?

In most respects quartz fabric behaves like glass, which permits us to treat it with virtually any resin system which is available today. Requirements which might be difficult or impossible for an epoxy-woven aramid system can be easily met with quartz polyimide. This means we are able to manufacture a full 260°C Tg quartz polyimide product with CTE of 8-10 ppm/°C. A second critical factor is that the low dielectric constant of quartz allows us to produce quartz polyimide laminates with dielectric constant (composite) of 3.5 to 3.8 at X-Band, with dissipation loss in

the 0.008 area. The reduced dielectric constant and low loss make it attractive for some microwave applications such as radomes or microwave polarizers.

Are there disadvantages of quartz fabric?

Quartz fabric is expensive. It is hard to drill. Nearly pure silica, quartz eats conventional carbide drills in 25 or less hits. After those 25 hits, the drill will be so badly damaged that it will not be able to be resharpened. If conventional bits are the only way to drill quartz and quartz takes off as a laminate material, we can all make some extra cash by buying stock in drill suppliers. The introduction of diamond drills may minimize this issue, although they, too, will be expensive. Finally, the 8-10 ppm/^{o}C CTE achievable by quartz may not be low enough to meet the system requirements for high reliability mounting of some very large outline leadless ceramic chip carriers.

Talk to us about Thermount? It looked like the ideal balance of cost/performance for Surface Mount PWB's. Where does that all stand?

Thermount® is a nonwoven aramid composite material comprised of short para-aramid fibers (with high tensile modulus) with a meta-aramid binder that holds the strong fibers together. Thermount is supplied in the form of yellow paper (it is made using a conventional paper-making process) that is engineered to provide a good X/Y balance of CTE. Available in several thicknesses, Thermount offers several benefits for SMT design:

1. Lightweight, especially when it replaces CIC-containing systems
2. Good registration stability
3. CTE values in the range of 8-10 ppm/^{o}C
4. Compatible with both epoxy and polyimide resin systems
5. Excellent Plated Through Hole Reliability
6. CAF resistance due to the random fiber orientation
7. Proven reliability in systems such as the Tomahawk Cruise Missile guidance system.
8. Thin laminates available (2, 3, 4 mils)
9. Able to be laser drilled – holes to 50 microns.

And the downside if any?

Like any aramid system, Thermount will absorb more moisture than woven glass, and hence there will be need for extra care in drying the inner layers (and prepreg) prior to lamination. More than about 0.2% moisture may result in blistering, especially in polyimide systems which are cured at 425°F/215°C.

A bigger "downside" has been that DuPont and their licensed producers elected to discontinue manufacturing Thermount at the end of 2006. While Arlon and several of our OEM customers arranged to make significant purchases of Thermount to support ongoing programs, and while

there are substantial supplies of most grades still on hand, Thermount as such will eventually be gone and no more is going to be manufactured.

So what is Arlon doing about that?

Arlon has a large scale R&D effort underway to find a suitable replacement for Thermount. Good progress has been made in finding nonwoven aramid products with acceptable physical properties that can also be coated on our equipment. At least two viable candidates are under evaluation in scale-up trials as of Q3 2008 with some customer sampling expected in 2009.

This has been a challenge because Thermount was a versatile product, both having proven excellent for SMT applications, and as well, being a good vehicle for laser drilling for high density interconnect designs.

We will keep our customers closely advised of progress in this program.

Return to TOC

VI. ANALYTICAL METHODS AND TESTING

What is Thermal Analysis?

Thermal analysis is the general term given to the analytical methods (and pieces of equipment) which measure the physical, mechanical and/or chemical properties of materials as they are heated or cooled. Properties may be measured directly, such as the Heat of Reaction by DSC; or indirectly, such as Tg (Glass Transition Temperature) which is determined from the rate of change of CTE in the TMA.

Over the years, thermal analysis equipment has served as the "workhorse" in the printed circuit industry. Thermal analysis has also been very important as a process control tool.

Instruments such as the DSC, TMA, and TGA have been used to determine degree of cure, rates of cure, thermal stability, melting points, Heats of reaction, and moisture content among other things. These techniques will be discussed more fully in this section.

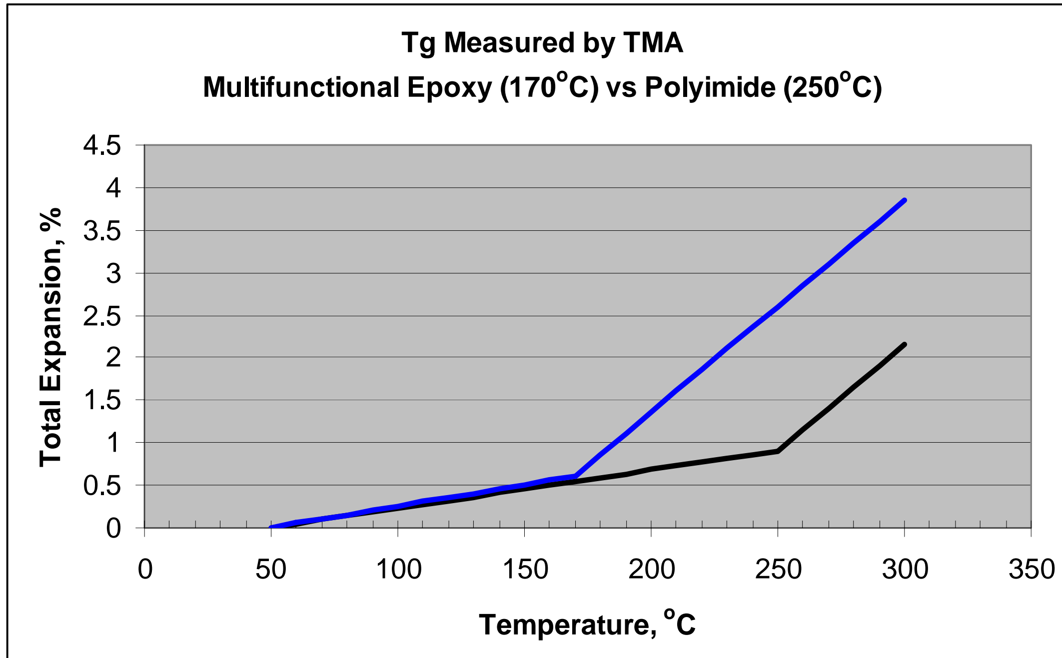
Define Glass Transition Temperature Tg and discuss its significance. What are the Tg's of the common laminate materials?

One simple way to define Glass Transition Temperature that relates it to actual use is to call it "The temperature at which the mechanical properties of a laminate begin to change significantly." Glass Transition Temperature is just what its name suggests: it is that temperature at which a material changes from a hard, brittle "glassy" form to a softer, rubberlike consistency.

Technically, we can relate this phenomenon to changes in "free volume" and the relative mobility of individual segments within the crosslinked lattice. Tg is the temperature at which polymer segments start to slide relative to each other. Greater long range molecular motion and increased rotational freedom leads to more segmental movement of the polymer chain. With a highly crosslinked thermoset polymer the transition is not a dramatic one such as the precise melting point of a pure crystalline compound or the extreme softening of a thermoplastic. It does not change from “hard as a rock” to “silly putty” and hence the need for analytical methods to determine the Tg.

Nevertheless at the Tg there are significant changes in the physical properties of any resin system which can, and will, affect its performance as part of a PWB. There are a number of ways to measure Tg (TMA, Quartz Tube Dilatometer, Dynamic Mechanical Analyzer, surface strain gauges, Differential Scanning Calorimetry and maybe others). The values obtained with each will be different, because each measures a slightly different property or combination of properties. There is no "right way" or "wrong way" to measure Tg, but because of the wide availability of Thermomechanical Analysis (TMA) equipment within
the PWB industry, it has become the method of choice, and gives good and fairly reliable results when performed by a well trained technician using careful sample preparation techniques.

DSC has been used for epoxy/FR-4 systems, perhaps largely because of its ease of use and the minimal sample preparation required. TMA has been used for polyimide, first, because the polyimide does not have a sharp transition detectable by DSC, and second, because the Z-direction expansion can be directly related to the expected reliability of plated through holes in a PWB. The graph (below) illustrates the effect of the change in CTE at the transition temperature as measured by TMA.



One of the most common results of the softening of the resin at its Tg is that it becomes easily smeared during drilling. With conventional FR4 the heat generated at the cutting surfaces of the drill is usually sufficient to cause smearing. In addition, when resin is heated above its Tg, either in use or during processing, it will cause substantial reduction in bond between the resin of the laminate and its copper foil cladding, resulting in pad lifting and other problems with surface features.

The coefficient of thermal expansion in the Z direction changes dramatically above the Tg. It is typical for the Z CTE to increase by fourfold, from 50ppm/°C below the Tg to 200ppm/°C above it. Because Z expansion causes stresses on the copper plated in holes, the extra expansion above the Tg is often responsible for PTH copper cracking during processing or rework. This is especially evident in thick boards with small holes (high aspect ratio) such as backplanes.

The effect of Z expansion is especially critical in flex boards where flex materials (acrylic or other thermoplastic adhesives) with low Tg's and high inherent Z-expansion coefficients can result in boards with overall expansions of as much as 500 ppm/°C which can result in plated

through hole barrel cracking, lifted pads and even cracking of surface resin caused by excessive stresses during heating and cooling cycles.

Typical Tg's for common resin systems are as follows:

Conventional Polyimides 250°C
BT/Epoxy Blends 220°C
Pure Multifunctional Epoxies 170°C
Multifunctional- and Tetrafunctional- Epoxy Blends 145°C
Tetrafunctional Blends 130°C
FR-5 140°C
FR4 (Standard Epoxies) 115°C

TROUBLESHOOTING TIP: You should know your resin system thoroughly before making major commitments to its use. Blends of these materials can probably produce almost any desired Tg. While this may appear to be a neat continuum of Tg's that can be tailored to any application, there are some concerns about mixed or blended systems, which may exhibit dual Tg's with each resin component acting as a discrete distributed phase. In such cases, the tendency to smear and an early increase of Z axis expansion may occur despite published values for the Tg. Additionally it has been reported that blended resin systems that do not fully copolymerize tend to exhibit microcracking during thermal cycling, in a polymeric equivalent to "work hardening". This is likely due to shear forces between lower Tg segments that did not get incorporated into the polymer network, leading to low Tg/high CTE segments adjacent to high Tg/low CTE segments, hence microcracking occurs due to shear between the segments.

One other comment on resin systems: the cost/price of a finished laminate relates to the costs of all its raw materials (glass fabric, resin, copper foil) plus labor and overhead and small changes in resin formulations which may look attractive to purchasing people at laminators may not make dramatic or even significant changes in prices to the end user once resin specific gravity (how much resin does it take to make a piece of 1080 glass yield 0.0025"?), increased time and problems with mixing and other changes in process downstream are taken in consideration. Blended systems can create financial-based pressure to modify the blend incrementally to improve profits without adequate consideration for what the effect will be on the product two or three years down the road when it is in service.

The resin system is the "heart" of a laminate. Know what you are getting, and seek assurances that it will not change from time to time without your knowing it.

What is DSC and what does it tell us about prepreg and laminate?

DSC is Differential Scanning Calorimetry. It is one of a number of so called thermo-analytical methods which can be used to evaluate various physical and chemical properties of laminates and prepregs. DSC measures change in heat flow through a resin system compared to that through an aluminum reference. Samples are heated at a controlled rate from room temperature (or below) to a point sufficiently above the expected Tg to identify the transition point.

Key features of a DSC scan include a resin melt point (an endotherm, indicating that energy is absorbed by the system when it melts) and a cure exotherm (indicating that once the necessary energy is supplied to initiate the reaction, heat is generated by the system as it cures). Combining DSC data with standard flow and resin content data, we can make a judgment as to whether a prepreg is "out of age," over staged, etc. While DSC has not become a standard QA method in evaluating polyimide prepreg, it can be a valuable troubleshooting tool.

TROUBLESHOOTING TIP: Consider carefully any use of DSC as a "tool" for evaluating polyimide prepreg. After over a year of doing routine DSC scans on incoming resin and B-stage, Arlon scientists concluded that neither set of data has been helpful in controlling the process, evaluating the incoming resin or (most important) predicting performance of the prepreg in lamination. DSC data on epoxy is more likely to be useful to the user than that on polyimide.

The degree of polymerization, or "advancement" of the B-stage is critical to its flow characteristics and performance and will affect the final quality of laminate produced from it. DSC will not indicate the degree of polymerization or the distribution of molecular weight of the B-staged system. Additional methodology -- HPLC (High Pressure Liquid Chromatography) or GPC (Gel Permeation Chromatography) -- determines the distribution of molecular weight.

Most laminators do not routinely do HPLC or GPC testing of B-stage, and it would not be considered an effective tool for "real time" process control because of the time required to perform it and evaluate results.

What is the significance of DSC Testing?

DSC, Differential Scanning Calorimetry, measures changes in heat flow in a material as we heat it from room temperature (or below) to some predetermined maximum temperature or as we cool it from that maximum temperature back to a low temperature (below the Tg). It is known as "differential" because there is always an aluminum reference measured at the same time as the sample (making the actual measurement the "difference" between the reference and the sample itself).

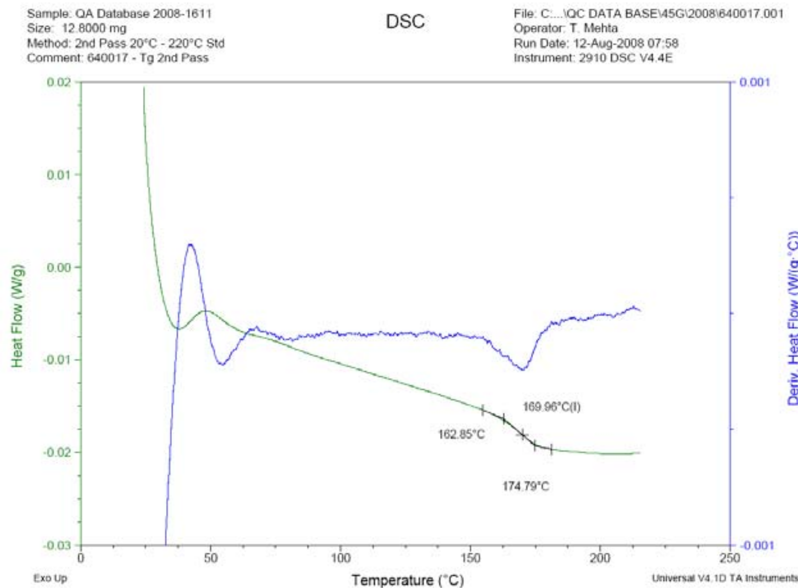
Chemical reactions and many physical changes (such as melting) result in the absorption or release of heat energy as they occur. Heat given off during a reaction is called an exotherm. The absorption of heat by a material is called an endotherm. By measuring the occurrence of these exotherms and endotherms, the DSC takes a "motion picture" of the chemical and physical state changes that are occurring in the sample.

DSC can tell us a good deal about the resin systems we are using when compared to those of known good material. In addition, we can learn some or all of the following things from the DSC:

- What is the melt point? (Usually associated with a sharp melt endotherm.)

- At what temperature does cure begin to take place, and what is its duration? (Cure exotherm)
- Has the prepreg aged excessively? (Reduced "Heat of Reaction")
- Is there a difference in cure between C-stage and B-stage layers in a multilayer board? (Dual Tg values)
- Is the laminate fully cured? (Normally this is tested by running two passes on the sample, and if the second pass shows significantly higher Tg than the first pass, it is likely that the sample was undercured.)

DSC also can give a measure of the Tg of epoxy systems based on identifying energy changes associated with a change in the relationship between crystalline and amorphous segments in the polymer. Polyimides do not exhibit this transition as sharply and hence the Tg occurs over a wider range than epoxy, making Tg detection more difficult by DSC than TMA. The chart below is a typical DSC curve on Arlon's 45N, Tg~175°C.



What is TMA?

TMA, Thermo-Mechanical Analysis, measures dimensional changes in a material as it is heated from room temperature (or below) to a preset final temperature. The change in length (width, or height) with change in temperature is the Coefficient of Thermal Expansion. A rapid rate of change in thermal expansion takes place as the test temperature passes through the Tg due to an increase in the free molecular volume. This is seen in a change in the slope of the graph of Z-direction expansion vs. temperature. The point of inflection is taken to be the Tg.

We use TMA to measure CTE in our products. Because the CTE changes at the glass transition temperature, we can determine Tg by TMA.

Principal uses for TMA include:

- Determining X, Y and Z CTE's for various laminate materials systems.
- Determining total Z-direction expansion from room temperature to 260°C.
- Measuring the Tg of finished laminates and multilayer boards to determine whether a full and satisfactory cure has been achieved.
- Simulation of solder float stability, such as with T260, T288 or T300 tests in which product is ramped to the test temperature and held isothermally until failure, or a predetermined minimum time. The test determines microcracking or micro-delamination in the resin structure long before the appearance of visual measling or blisters would be seen visually.

What is the difference between TMA and DSC for Tg measurement? Why is epoxy different from polyimide?

DSC measures changes in the heat flow in a material. It can detect "exotherms" when heat is given off, such as during cure, or "endotherms" when heat is absorbed such as during melting of a prepreg or during a physical change of state such as amorphous to crystalline ratios. That transition is the so-called Tg measured by DSC.

Most epoxies have distinct and detectable crystalline transitions that are easily measured by DSC. Heat flow in polyimides is not easily detectable compared to the standard aluminum reference, making finding a transition difficult.

TMA measures the actual change in physical thickness of sample as it is heated. The rate of change, expressed conventionally as ppm/°C is what we call the CTE (Coefficient of Thermal Expansion). In many materials there is a fairly distinct change in CTE that occurs at or around a certain temperature, and it is that change we can readily see on a graph and call Tg. Because the two methods are measuring different properties, they will not necessarily give the same Tg's.

NOTE: when materials are mixed or blended, or when there is not a sharp transition temperature, it may be hard to pinpoint a Tg. The Tg of blended and mixed polymers occurs over a range of temperature (it is not a sharp fixed temperature such as a melting point) due to the so-called molecular weight distribution.

TROUBLESHOOTING TIP: Do not take the Tg and CTE values as calculated by some computer program as being gospel. Look at the curves and make educated judgments. All kinds of "bugs" -- from operator technique to equipment malfunctions -- can result in odd or ambiguous Tg's. Laminate stress relief which may occur near the Tg temperature can confound

results when measuring X-Y CTE values. When in doubt, recalibrate, check the sample size or preparation and then repeat the test.

What is TGA?

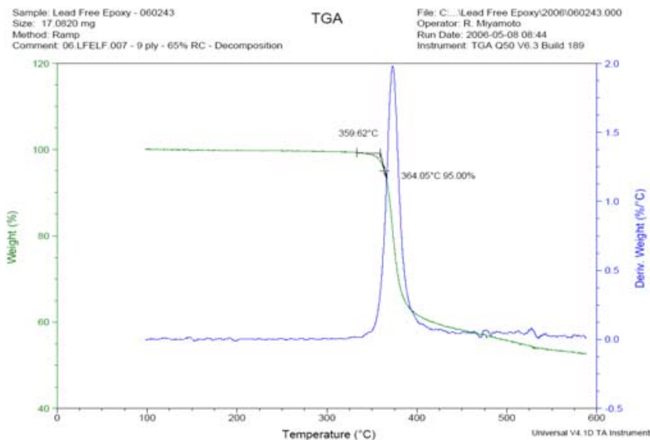
TGA, Thermo-Gravimetric Analysis, measures weight loss as a function of temperature as a material is heated (either in an isothermal mode or a controlled heat up ramp). The TGA unit is a sensitive microbalance with a precision controlled furnace. As a material increases in temperature, various changes in weight occur, which we measure and record, either as a function of time or temperature.

Some of the things that can be learned from TGA are:

- Amount of moisture contained in the sample, which will be driven off at 100°C.
- Total volatiles in the sample (up to some preset temperature).
- Thermal Decomposition Temperature (Td)
- Rate of thermal decomposition.
- Ash residue after everything else has been burned off.
- Arrhenius plots to predict long-term thermal stability.
- Elucidation of structure through the type of gasses given off by looking at weight loss at specific temperatures

UL has attempted to correlate TGA to long term thermal stability in an effort to see whether or not it could be used as an alternative method of assigning temperature ratings to materials. To date, they have not shifted to any form of thermal indexing that is not related to specific electrical or mechanical properties, such as loss of breakdown resistance or flexural strength, which is their current means of indexing printed circuit materials. My own view is that the very high temperature reached by TGA is affecting the decomposition of the material in a totally different environment than the normal four temperature aging method whose principal mechanism is resin oxidation.

The graph (below) is a typical TGA curve to determine the Td of Arlon 51N lead-free low flow epoxy system. You can observe the onset of decomposition at 359°C and the 5% decomposition level at about 364°C.



What is IR?

IR, Infrared Spectrophotometry, takes the "chemical fingerprint" of a material in terms of the characteristic absorption and transmission of infrared frequencies. It's simpler than it sounds. Infrared radiation is broken up into narrow wavelength bands by a refraction grating and the various wavelengths pass through the sample of material. Based on the sample's molecular structure it either transmits or absorbs IR at every frequency. When a bond absorbs IR radiation, the energy gives rise to – or "excites" -- a specific molecular motion such as "stretching," "bending," "rotation" or "scissoring" and the like, that can be detected by the instrument and is plotted as a change in absorption/transmission as a function of the specific frequencies at which those molecular motions are "excited."

The IR curve is a plot of absorption and transmission over the entire spectrum of frequency measured from about $3000/cm^{-1}$ to $600/cm^{-1}$.

Each organic compound has a characteristic "fingerprint" of IR absorption, and this is a means of identification of the types of molecular structures contained in the sample. Caution: IR is mostly used as a qualitative technique, as it is better at identifying what is present than how much is there, although experiments can be designed to use IR quantitatively using controls of known composition, etc. when there are well defined absorption peaks that change predictably with concentration.

IR is relatively insensitive to small (or even large) amounts of materials unless they have strong absorption bands. UL (Underwriters Laboratories) uses IR as one principal way of determining whether a material is chemically the same as was originally submitted for evaluation.

What is Rheology?

Rheology is the science that studies the flow of materials under heat and pressure. In layman's terms it allows us to characterize the viscosity (which relates to flow) of a material as a function of temperature, rate of heat rise, applied shear, and so forth, permitting us to provide data relevant to press lamination.

The classical model for characterizing the rheology of a material consists of two parallel plates with the material to be characterized in between them. In the model one plate moves relative to the other and the resistance to the movement defines the viscosity of the material between the plates. It is not hard to see that a laminating press in which there are parallel plates with a viscous material flowing under conditions of heat and pressure has a close similarity to the classical model. As a result, measurement of the rheological properties of resins used in MLB manufacture can provide useful data in helping define appropriate press cycles.

What kinds of flow testing are available and what information do they provide?

The real question as we see it is how to define "flow" in such a way that the test used to measure it gives us the most information pertinent to its intended end use. It is apparent that the current tests, including the IPC-TM-650 4-ply and scaled flow methods, deal only with the "state" of the prepreg after the test vs. the "state" of the prepreg before the test and do not address suitably the issue of what happens in between.

We think that an understanding of the changes in chemistry and rheology of the resin during melt, flow and gelation are critical to this issue. There are several approaches to the testing of prepreg, none of which have yet emerged as "The Test."

1.) Dynamic Mechanical Spectroscopic methods are under investigation as ways of characterizing prepreg. Use of an oscillating disc rheometer (ODR) capable of measuring loss and storage modulus of materials can give us much information about the change in viscosity of a resin as it melts and flows. When testing is done in the presence of fabric reinforcement, the fabric itself becomes a more significant part of the system as the resin cures, obscuring the resin dynamics. Use of an ODR on neat resin removed from prepreg may partially overcome this deficiency, although to be objective, the product is used with the resin and glass both in place.

2.) Dielectric Spectroscopy, measuring the change in dielectric properties as the resin melts, flows and cures has also been investigated as a means of controlling lamination conditions. It has not been well established how precise the correlation is between this measurement and the rheology of the resin itself. The approach may also be skewed by ionic conductivity or impurities on a batch-to-batch basis. As with DMS, the equipment is relatively costly and the test methods are too lengthy to be compatible with real-time testing during prepreg manufacture. A variation of dielectric spectroscopy has sometimes been used during actual lamination to "pick the moment" for application of pressure in stepped pressure cycles.

3.) Dynamic Scaled Flow (aka Parallel Plate Rheometry), an attachment to the standard TA Thermal Analyzer, -- distinctly separate from the Oscillating Disc Rheometer (ODR) -- is a source of potentially useful information on the rheology of a resin in a prepreg. This method (like the ODR) involves placing a pressed pellet of resin (removed from the glass reinforcement) between parallel plates under low pressure and heating it at a fixed rate. Measurements of the rate at which the plates close when the resin melts provides information about melt point, relative viscosity and gel or cure time. Because theoretical modeling of viscosity often involve parallel plates, calculation of a complex viscosity value is theoretically possible from these tests. The test apparatus is costly if you do not already have it, and the method is unrealistically to use as a real-time process control test.

4.) Oscillating Disc Rheometry (ODR), now in common use in the industry as a developmental tool, is becoming accepted as the most accurate and scientific way to characterize resin flows. Like the dynamic scaled flow (parallel plate) method, it normally looks at the resin separate from the fabric, and thereby is not fooled by fabric geometry factors.

What does rheological characterization mean to you?

1.) You can compare the flow characteristics of the resin system you are using with standard materials with which you are already familiar.

2.) You can look at the effect of rate of rise of temperature on fluidity of your selected resin system. Sometimes you can make major improvements in MLB lamination by achieving slightly more flow.

3.) You can determine the "open time" available to you in your standard press cycle by modeling the cycle on the rheometer.

4.) Determination of the minimum melt viscosity for different rates of temperature rise gives insight into the optimization of press cycles for lamination of particular resin systems.

What is Parallel Plate or Oscillating Disc Rheometer?

The parallel plate rheometer or ODR consists of a set of parallel plate tools, ground to exacting tolerances. The tools are contained within a programmable oven to provide either an isothermal (steady state) or programmed heat ramp. The operator programs the heating profile into the instrument as well as the shear stress -- inputted as a test strain and frequency.

The oscillating disk parallel plate rheometer (ODR) permits the resin development chemist to characterize the melt viscosity of various resin systems dynamically. We can look at the changes in viscosity as a function of heat up rate as well as time at temperature. By programming the heatup rate, the thermal profile of a press cycle can be duplicated on the rheometer and the manner in which that resin melts and flows can be characterized.

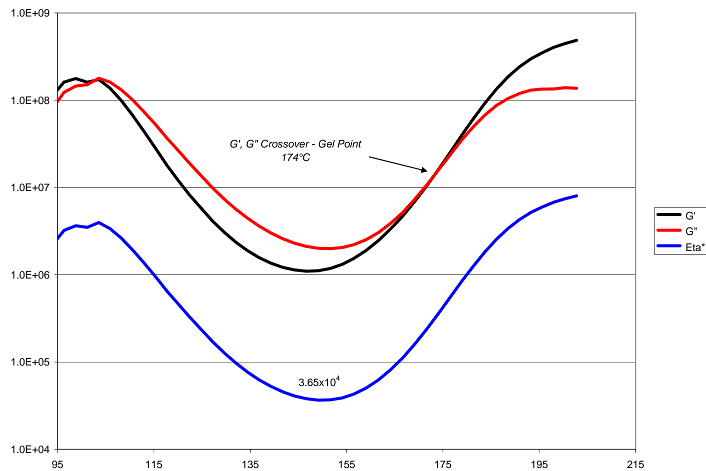
The prepreg is "crinkled" to extract the resin from the glass fabric, because within the parallel plates, glass fabric does strange, unrepeatable things to the inputted strains. The test sample is cold-molded from the debrided resin, and the molded specimen is placed between the two plates. The bottom plate oscillates to the programmed strain (measured as an angular displacement) and frequency (cycles per unit time). The angular displacement creates a strain which results in a stress (force) being applied to the visco-elastic material between the plates.

The term “visco-elastic” refers to the mixture of properties of the material being tested. All materials have some proportion of elastic behavior (the ultimate “elastic” material is steel, which in the test would largely transmit the energy created by the shear force directly through to the sensor -- a transducer -- on the top plate of the test apparatus) and viscous behavior (a typical viscous material would be oil, which flows readily and hence a relatively small part of the energy from the shear would be transmitted through the material to the transducer). The test apparatus is able to measure values of both the solid-like character of the sample (referred to as G’ or Shear Storage Modulus, whose units are dynes/cm^2), and its liquid-like character (referred to as G” or Shear Loss Modulus, whose units are dynes/cm^2). From these values and the geometry of the test apparatus, a value is derived using Hook’s Law (relating shear stress, shear strain and the

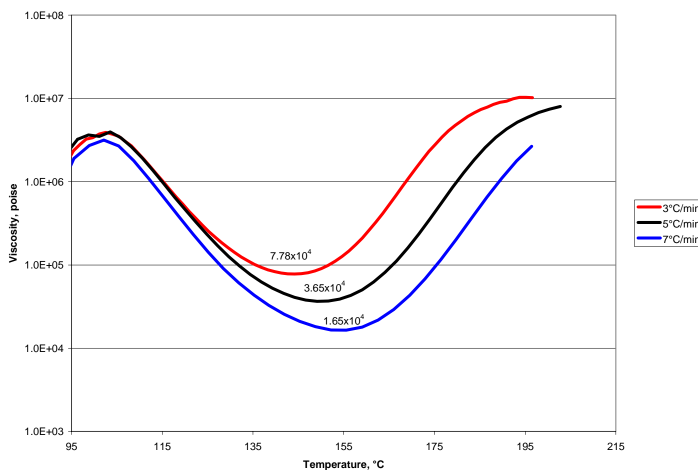
complex modulus of the material being tested) which we call the complex viscosity (the inverse is fluidity) of the sample, designated Eta* and expressed in units of poise.

How does the Parallel Plate Rheometer provide this data?

Arlon's ARES Rheometer (supplied by TA Instruments) is used to determine the softening point of the resin, show how its melt viscosity varies with temperature, indicates the point of "minimum viscosity" and then shows how quickly it thickens as it approaches the gel point. Several different "curves" are generated simultaneously as the sample is heated from room temperature through melt and as it begins to cure. As the resin is heated it will melt and a minimum melt viscosity (MMV) is reached before the resin begins to cure and a gel point is reached. The "gel point" is defined to be when the G' and G" curves cross one another. Both minimum viscosity and gel points are illustrated in the following figure.



The next figure shows the effect of varying the heatup rate on the minimum viscosity of a resin system (in this case Arlon's 37N Low Flow polyimide). Note that increasing the heatup decreases the minimum viscosity, so that a higher heat rate will result in more flow as the resin goes through its melt and minimum viscosity.



The "integrated flow" is an expression of the total area under the flow curve (remember that flow is proportional to the inverse of viscosity, or 1/Eta*) over time and gives an idea of the total flow achievable by a system. Integrated flow allows a convenient comparison of prepregs in terms of total flow.

The instrument can also be programmed mimic the actual gradual, slowing heat rise of a press cycle, to provide rheological characterization under realistic cure conditions.

In practical terms several important pieces of information can be derived from RDA scans:

- Information concerning the melting range of materials. This is important in defining the point at which pressure should go from low to high during the lamination cycle.
- Information concerning the effect of heatup rate on fluidity of resins. Faster heatup rates result in more fluidity when a resin melts. Selecting the "right" heatup rate is part of defining a robust lamination cycle.
- Information concerning the "open time" available during lamination. This also is heating rate dependent, and the laminator has to have a balance between fluidity and "open time".
- The RDA can be used to monitor prepreg ageing or “build-up” in prepreg over time by comparing MMV at different time intervals.
- With the proper fixture, the instrument can also be used as a dynamic analyzer and measure the Tg of a laminate by Dynamic Mechanical Analysis (DMA) in which the change in flexural strength of the material is used as the defining point for Tg.

What is Cone & Plate Rheometry?

A cone and plate rheometer (example, the Visco-Plot) is a constant temperature and shear instrument that is suitable for real time evaluation of prepregs by the coater operators as they are being manufactured. The unit typically has a 2 degree cone and oscillates at a steady rate of 39/sec. The test is performed isothermally, with epoxies typically tested at 140°C, while polyimides are tested at higher temperatures. Since flow values can vary by Rheology and by resin content, cone and plate Rheology helps to provide an added dimension and degree of consistency in prepreg over simple flow and gel testing.

How do we test Thermal Conductivity?

Although there are several methods (standardized and otherwise) for measurement of thermal conductivity of materials, Arlon employs the ASTM E-4161-01 method using a Laser Micro-Flash instrument. The sample material is irradiated with a single laser beam pulse and the temperature rise on the other side of the sample is measured using an infrared detector. This rise

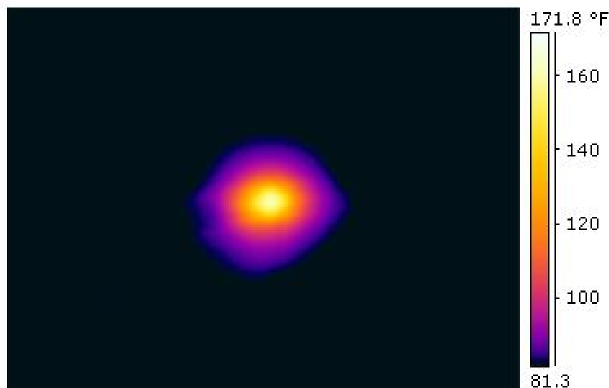
in temperature is plotted as a function of time. The thermal conductivity is then derived from the thermal diffusivity, specific heat and bulk density of the material using the formula:

K = (a)(p)(Cp) where

K is the thermal conductivity (W/m-K)
a (alpha) is the thermal diffusivity (a function of how quickly heat moves through the sample)
p (rho) is the bulk density of the sample (g/cc)
Cp is the Specific Heat of the material (cal/g)

The diffusivity value is derived from one of several standard mathematical models from the data generated.

The effects of thermal conductivity on an actual PWB can also be measured using thermography, in which an infrared camera measures the temperature at various places on a sample and generates a "thermogram" that shows by varying colors how the heat spreads out from a hot spot, or how heat is distributed across a sample at steady-state operating conditions. This typical thermogram shows the maximum temperature (72°C) reached on a PWB made from Arlon's TC-600 thermally conductive laminate in a steady-state test using a single resistor on the board at a controlled power input. By comparing this material to others under the same test conditions, the benefit of thermally conductive materials in reducing the overall temperature at the surface of a PWB can be illustrated graphically. More information on Arlon's Thermally Conductive Materials can be found at our website, www.arlon-med.com.



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