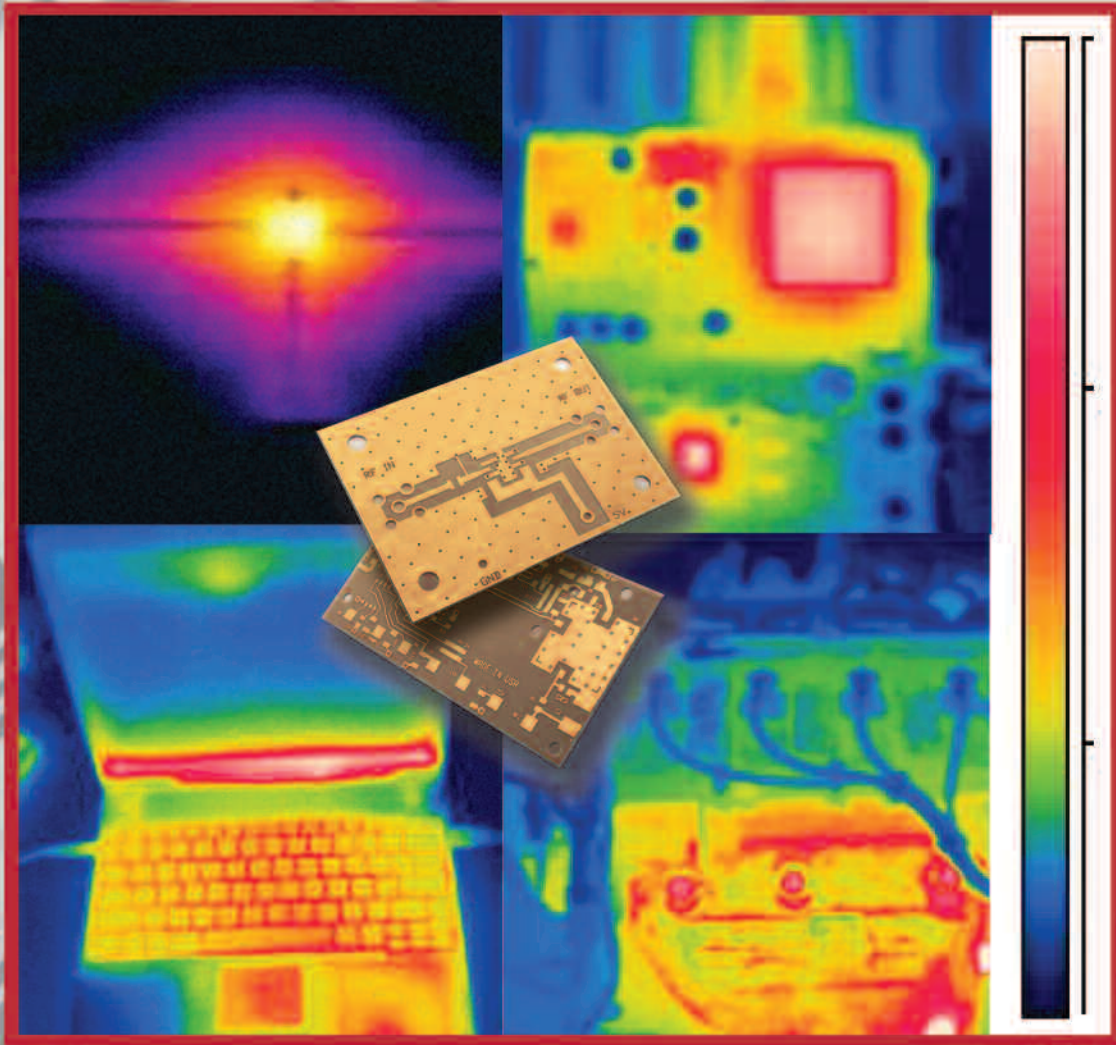
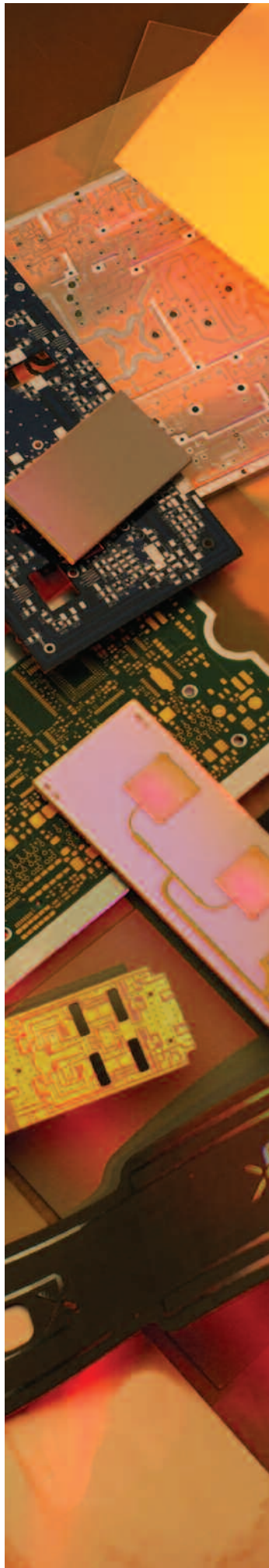


ARLON

TECHNOLOGY ENABLING INNOVATION



**Thermal Management
Solutions for Electronics**



INTRODUCTION

Whether in consumer electronics or high-end aerospace technology, printed wiring board assemblies for today's increasingly complex electronics present design engineers with an ever growing need for improved, cost-effective thermal management. Many industry trends, such as cost reduction pressures, reduced footprints, and reduced weight, are counterbalanced by the need for higher circuit density to provide increased functionality to support more user "features." The end result is an increase in heat generated—an a growing need for improved, cost-effective thermal management.

Typical applications include:

- Defense & Aerospace
- High brightness LED's
- Automotive Electronics
- Power Converters
- Chemical & Process Industry instrumentation
- Telecommunications Infrastructure
- Cell phones & feature-rich consumer electronics
- High power RF combiner/splitters & power amplifiers
- Semiconductor chip packaging
- Server backplanes

To meet the design challenges of these diverse applications, material options have evolved to provide engineers with a broader and more versatile tool kit to optimize device cost, performance and reliability. Arlon's electronic materials have been engineered to enhance thermal management to ultimately improve device reliability. Arlon's broad product-line of PWB materials offers design engineers access to multiple and enhanced thermal management strategies to meet the end-use requirements, from overall cost reduction to mission critical performance.

THESE DESIGN STRATEGIES INCLUDE:

Removing the Heat – Many designs today continually push limits for heattransfer, resulting in high device operating temperatures. Newer Arlon PCB materials offer increased thermal conductivity to reduce peak operating temperatures and improve component life.

Beating the Heat – For over 30 years, high temperature applications have used Polyimide laminate & prepreg systems to provide device reliability in operating environments exceeding 200°C. Arlon's new EP2 enhanced polyimide system and newer lead-free compatible thermally conductive epoxy systems offer designers new approaches to maximizing reliability in tough operating environments.

Surviving the Environment – How materials respond to cyclic thermal exposure remains a critical contributing factor in determining device reliability. Designing PWB's on materials that reduce or control thermal expansion will improve PTH reliability and reduce stress and fatigue on solder joints to SMT components.

Reducing the Heat – Low loss materials for microwave & High Frequency applications minimize heat generated by transmission line loss.

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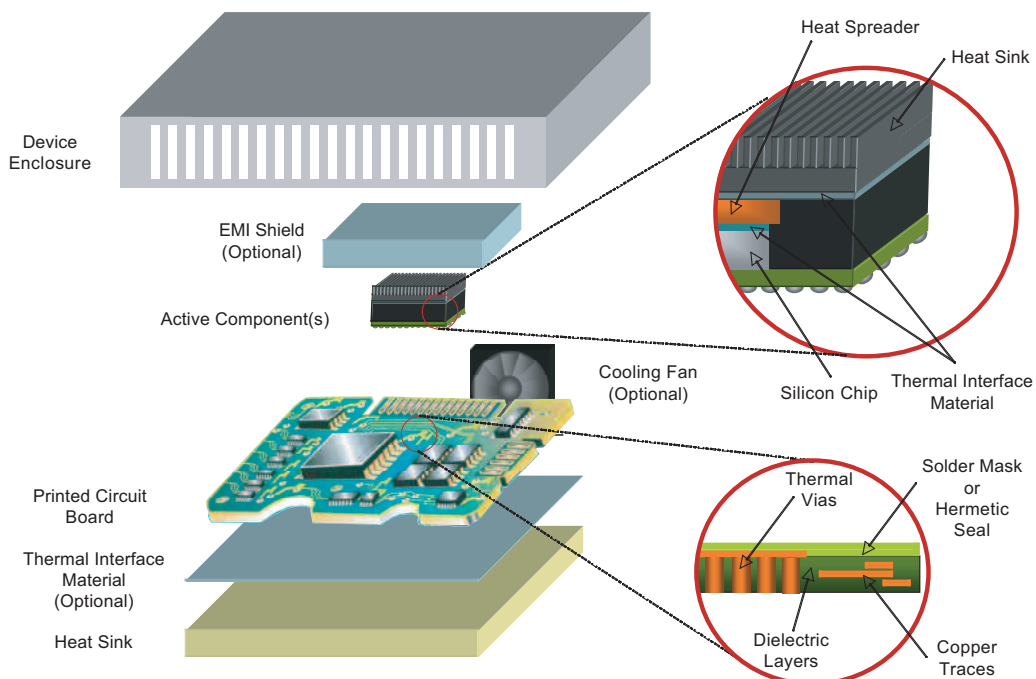
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Thermal Management: Designing for Reliability

Device reliability is a complex function of the heat generated by the operation of an electronic device, the tools used to dissipate or manage the heat, the thermal stability of the materials used and the environment in which the device is required to operate. Because of diversity of applications and the increasing demand for electronics, diverse thermal management tools have evolved to help mitigate reliability issues. These tools include gap fillers, active cooling systems, heat pipes and heat sinks. While many of these tools overlap in terms of potential benefits, the selection of which tools to apply depends on the ultimate constraints of the device in terms of cost, power requirements, weight, size and reliability. Arlon's Electronic Materials product line has long been a part of this solution set, including low-loss materials for high frequency applications, polyimide materials used in high temperature electronics, and silicone thermal interface materials. Recently, Arlon has expanded the technology options through the development of engineered thermally conductive laminate & prepreg systems for multilayer printed circuit board applications. The breakdown of a typical electronic device demonstrates the various tools used to facilitate heat dissipation when designing for reliability. **Diagram 1** below shows a generic device with an active component mounted on a typical circuit board. Complementing these active components may be heat sinks, thermal interface materials, thermal vias and active cooling systems. Many of these approaches are implemented to compensate for the fact that most traditional electronic components and dielectric materials are thermal insulators, necessitating secondary cooling systems, such as heat sinks and cooling fans. Thermal interface materials are used to minimize gaps or variation between materials that can occur in assembly, which can retard heat transfer.

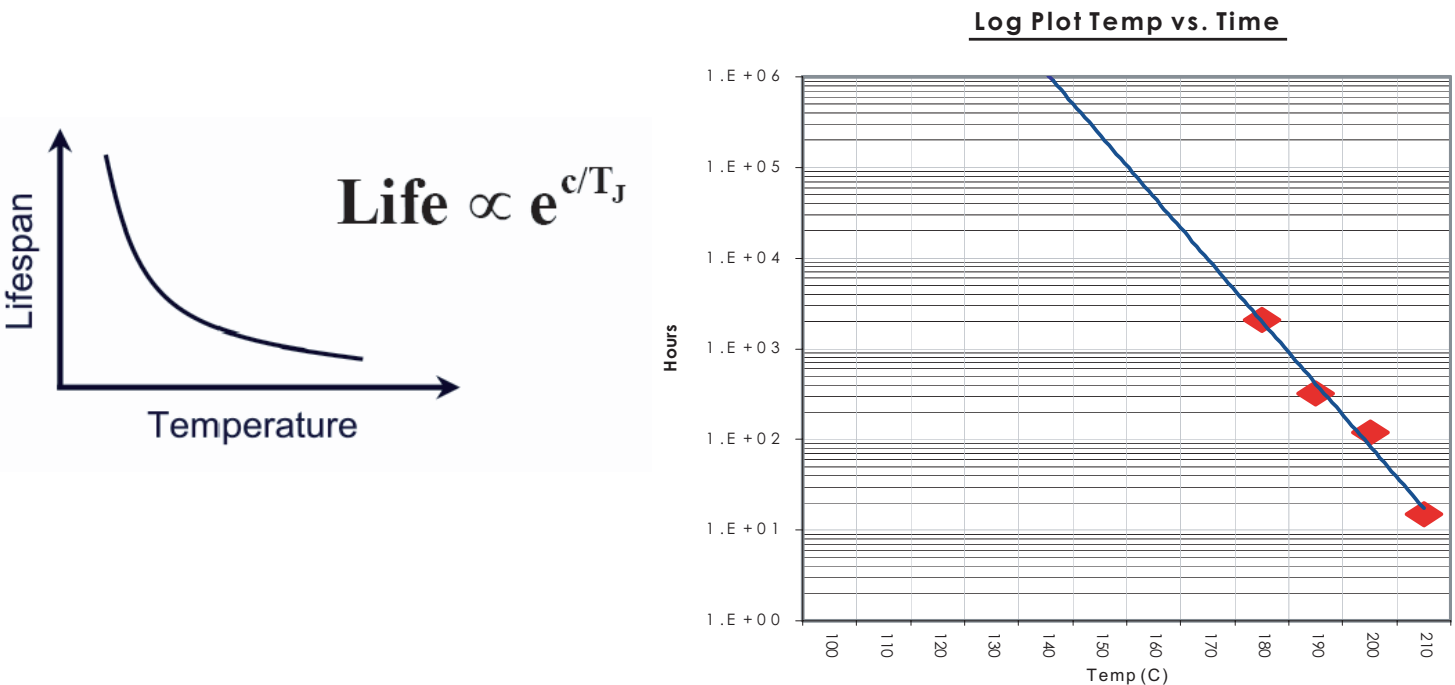
Diagram 1: Typical Device Breakdown



Thermal Management — Continued

Selection and optimization of thermal management tools are often based on a combination of experience, knowledge and device testing to understand failure mechanisms. Device failure is a function of the reliability of the components, materials, time and operating environment (humidity, temperature, thermal cycling, etc.). In most cases failures can be grouped into one of several categories, such as component failure, connector/solder joint failure, or board failure, to facilitate further root cause analysis. Ultimate causes of these failures may include chemical or electrical degradation of base materials, connection failures caused by thermal expansion mismatches, air gaps causing a reduction in heat transfer, oxidation caused by high temperature or mechanical failures. One cause of temperature related failures of boards or components relates to change or degradation at the molecular level. This type of failure is best modeled as a first order kinetic reaction, typically described as an Arrhenius Equation, which is proportional to the inverse log of the temperature. A simplified Arrhenius equation and a resulting reliability plot against operating temperature are displayed in **Diagram 2**. Since failure rates, often described as a mean-time-to-failure (MTTF), increase exponentially with temperature, a 10°C increase in temperature can double the failure rate. In an operating device where reliability is critical to success, even 1°C can matter. The key to improving reliability is to reduce device temperature by increasing the rate at which heat is removed from the device and from the working area of the PWB immediately adjacent to the device. Understanding heat transfer then becomes the next step.

Diagram 2: Arrhenius Equation & Reliability Chart





Understanding Heat Transfer

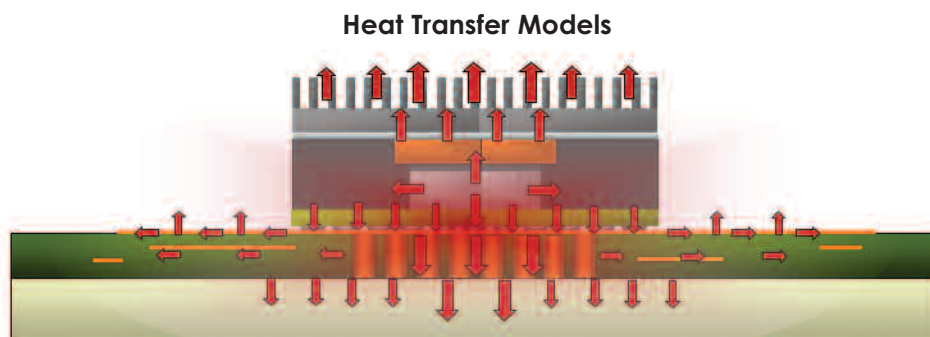
Heat is generated every time an active device is in operation. Device operating temperature is a result of the balance between heat generation and heat dissipation. Heat itself does not become a problem until there is enough heat to result in an increase in temperature above a critical point, in many cases about 105 to 120°F. Since many designs are set based on function, the heat generation side of the equation is already determined by the time it comes to managing heat dissipation. As such, it is important to understand the basics of heat transfer to determine possible strategies for reducing device temperature. In simple terms, the whole business of managing heat in a PWB assembly is about preventing the junction temperature from getting high enough to “fry” the active devices.

Heat is moved from a “hot” body to a cooler body by one of three basic modes: **conduction**, **convection** or **radiation**. In a PWB assembly, all three are in play to one degree or another.

Conduction can be the most effective for heat transfer, where the cooler body is in direct (and preferably intimate) contact with the warmer one and the heat moves from hot to cold materials in an attempt to reach equilibrium. The rate at which heat is carried from one to the other depends on the thermal (temperature) gradient, the coefficient of heat transfer of materials involved (thermal conductivity), the amount of material involved in the thermal path (thickness), the quality of the interface and to a lesser extent, the heat capacity of the “cool body” that is absorbing the heat. The combined effects of thermal conductivity, the material thickness in the thermal path and the interface effects on heat flow is often characterized in terms of the thermal impedance.

Convection is the transfer of heat from a hot body to a cooler fluid which carries it away through molecular motion. This can happen naturally in a fluid based on resulting density gradients caused by temperature variation. Convection may be aided by forcing the cooling fluid to flow past the warm body, thus carrying away the heat faster. Conversely, convection heat transfer can be significantly impeded by device enclosures that restrict air flow, resulting in higher device temperatures.

Radiation is the removal of heat from a body by the emission of energy in the form of electromagnetic radiation, which may be in the infrared (heat) or even visible (light) parts of the spectrum depending on the temperature of the radiating body. RF signals, such as those generated by an antenna, are also a type of radiation that dissipates energy.



Thermal Management Design Options

The number of approaches and possible solutions to reduce temperature through heat removal from active devices is almost endless. This remains an active area for development across all application areas and the tools available to designers will continue to evolve. While Arlon does not participate in all of these areas, this section covers some basic approaches, highlighting some common tools with a brief summary of their advantages & disadvantages.

Tools for increasing Convection

- Active Cooling – Forced Air, Conditioned Air
- Water Cooled, Vapor Cooled, direct, indirect

While active systems, such as cooling fans, may be extremely effective in heat removal, they add additional design & power requirements, increase costs, and add to device size & weight. They also add to potential reliability concerns as failures of these systems typically result in device failures.

Tools for increasing Conduction

- Heat Sinks, Heat Spreaders, Heat Risers & Heavy Metal Backplates
- Thermal Vias (PTH used to leverage thermal conductivity of copper)
- Thermal Coins (Inserts of metal conductors in PCB cut-outs under active components to improve heat transfer)
- Thermal Interface Materials, Thermally Conductive Adhesives, Gap Fillers, Grease, etc.
- Thermally Conductive Printed Circuit Board Materials

Each of these tools brings its own advantages & disadvantages. Heat-sinks and backplates add cost and weight to a system. Design & optimization of these systems requires a consideration of the metallurgy (usually copper, brass or aluminum) to balance heat transfer requirements with material thermal conductivity, heat capacity, density, machinability, processing requirements and costs. Thermal vias can be extremely cost effective, but there are practical limits in the area covered. Heat transfer in thermal vias is limited to thru-plane heat transfer and can cause reliability concerns if the PTH's fail due to stresses from thermal expansion. Thermal coins are potentially more cost-effective than a large heat-sink and potentially more reliable than thermal vias, but they add to assembly complexity and costs.

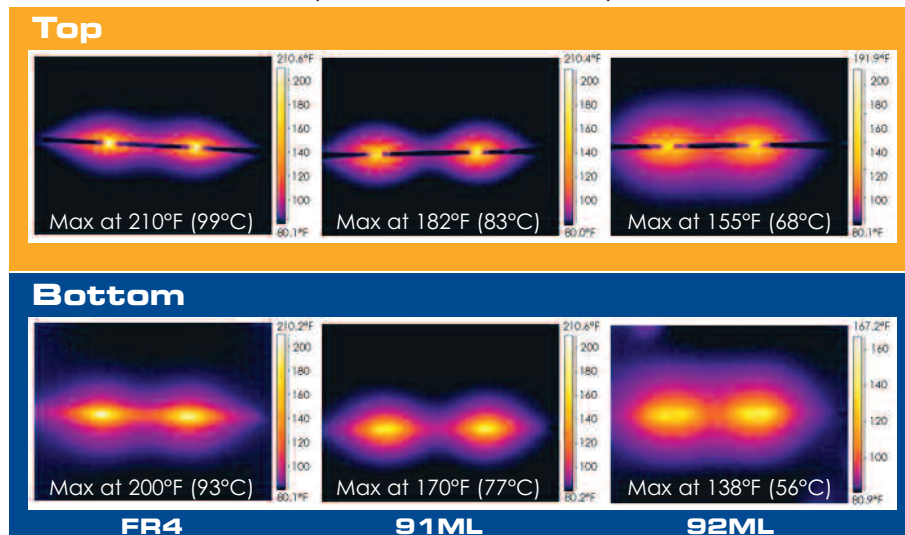
Thermal interface materials can be either electrically conductive or electrically insulating and cover a wide variety of materials, such as thermal pastes, greases, phase change materials, tapes, bonding plies, and prepregs. Their primary advantage is that they can displace air gaps & reduce impedance to heat flow at interfaces. Some types of materials can also offer thermal-mechanical de-coupling to minimize stresses from thermal expansion, and to reduce vibration related failures or joint failures and improve reliability through thermal cycling.

Circuit board thermal conductivity is often neglected as a potential area to improve heat transfer since this has historically not been a controllable design option. The primary purpose of these materials are to provide electrical isolation of the various components and traces. This has yielded materials that are also good thermal insulators which trap heat within the active components of the board. By

Design Options — Continued

modifying the base properties of these materials, Arlon created materials that provide not only the electrical insulation required for typical circuit boards, but also improve heat transfer rates relative to traditional materials. This benefit is demonstrated in the following tests, comparing a traditional FR-4 materials with laminates of increasing thermal conductivity in the same circuit design with a 0.5 Watt heat source. As thermal conductivity is increased, so is the heat transfer rate, resulting in a lower peak temperature by over 50°F (30°C).

Practical Application — 0.5 W Heat Source (0.3, 1.0 & 2.0 W/m-K)



Heat spreading associated with 92ML is related to higher TC_{xy} vs TC_z (2X)

Optimization

Design optimization usually begins with thermal modeling tools to identify hot spots or other issues. There are several good software packages on the market today that can help designers understand the effects and trade-offs of the various thermal management tools. This can be time consuming and requires a good understanding of the model limitations to fully translate the results into practice. Unfortunately most modeling software assumes isotropy which may result in over or underestimation of the heat removal. In most PCB materials, the heat transfer coefficient in the perpendicular direction (down through the PWB) is different from that in the plane of the board. The models also rarely account for potential issues, complications or variation in materials, fabrication or assembly. Interfaces interfere with the heat transfer mechanism, through imperfections in conduction. This often results in reduced efficiency in heat transfer and results in excessive temperatures. Addressing these potential issues is generally where actual thermal testing of sub-assemblies & devices can help. Such testing can be as simple as power cycling or single point thermocouple measurements, all the way to sophisticated thermal imaging equipment. Testing can help designers further optimize their designs by identifying potential problems or lower cost substitutions, such as trade-offs in materials choice (aluminum vs copper, cast vs machined heat sinks, etc.).

Surviving the Environment

The first step towards ensuring long term survivability of a device in a thermally stressing environment is to select materials that can meet the thermal excursions in the PWB manufacturing & assembly process. IPC specifications for “Lead-Free” & “High Reliability” materials include such factors as Tg (glass transition temperature), Td (thermal decomposition temperature), total thermal expansion perpendicular to the plane of the board (Z-axis) and short term stress tests such as T260, T288 and T300. The key to success is to avoid latent defects such as hidden cracks in PTH copper that can later propagate and cause resistance change or opens when the board is at operating temperature.

Arguably, Tg is usually the first consideration in material selection as it relates to the survivability of PTH's during thermal cycling. A high Tg material will exhibit lower overall Z-expansion from room temperature to the operating temperature, and will normally retain its adhesion to copper up to and even somewhat beyond the Tg. Z-Axis thermal expansion from 60-260°C is also a key metric in comparing materials for potential PTH reliability.

Decomposition Temperature (Td) is a determinant in assessing long term survivability of materials at elevated temperatures, and while the temperature of a PWB rarely reaches anything approaching its Td, it is reasonable to say that a material with a high Td is likely more survivable at any long term temperature exposure than a material with a lower Td.

T260, T288 and T300 tests are good measures of the likelihood of a PWB substrate surviving short-term exposure at the extreme thermal limits. These tests are measured by ramping samples to the specified temperature and holding them isothermally until irreversible change occurs, usually in the form of delamination.

Other factors such as water absorption (hence the impact of the relative humidity), resistance to various process and environmental chemistries, ozone resistance, etc. may have additional roles to play, although few of them have been analyzed in depth in terms of long term operation of a PWB.

LAMINATE PERFORMANCE FACTOR	PERFORMANCE IMPACT
Glass Transition Temperature (Tg)	<ul style="list-style-type: none"> • Strongest factor in determining total z-axis expansion • Higher Tg related to greater PTH reliability
z-axis Expansion (CTE _z)	<ul style="list-style-type: none"> • Lower (CTE_z) related to PTH reliability, but total z-axis expansion more important
Decomposition Temperature (Td)	<ul style="list-style-type: none"> • Primarily affects catastrophic laminate failure during assembly or rework • Not necessarily related to performance over time on sustained exposure to high temperature in actual use
Time at Temperature (T260/T288/T300)	<ul style="list-style-type: none"> • Measure of time to delaminate at a specific temperature (260, 288 or 300°C) • Related to performance over time on sustained exposure to high temperature in actual use



Surviving the Environment — Continued

Other factors such as water absorption (hence the impact of the relative humidity), resistance to various process and environmental chemistries, ozone resistance, etc. may have additional roles to play, although few of them have been analyzed in depth in terms of long term operation of a PWB.

The following table of properties of Arlon's PWB materials will give a sense of the range of the key thermal mechanical and chemical properties available to the designer. Note particularly the thermal conductivity of standard vs. thermally conductive materials.

		Preliminary IPC Pb-Free Spec (/124)	33N	35N	85N	EP2	45N	91ML	92ML
Product Type			Polyimide UL-94 VO	Polyimide UL-94 V1	Polyimide UL-94 HB	Enhanced Polyimide	DiCy Epoxy	TC Epoxy	TC Epoxy
Glass Transition (Tg)	°C	>155	250	250	260	250	175	170	170
T260	min	>30	>60	>60	>60	>60	8	>60	>60
T288	min	>15	23	>60	>60	15	0	>30	>15
T300	min	>2	8	11	>60	10	0	>10	>5
Td (initial)	°C		353	363	387	363	299	354	340
Td (5%)	°C	>330	389	407	407	424	311	368	400
CTE _z (<Tg)	ppm/°C	<60	53	51	55	25	50	36	22
CTE _z (>Tg)	ppm/°C	<300	164	158	149	150	185	192	175
CTE _z (50-260C)	%	3.5	1.2	1.2	1.2	0.65	2.6	2.6	1.8
Thermal Conductivity	W/m-K		0.25	0.25	0.25	0.45	0.25	1.00	2.00

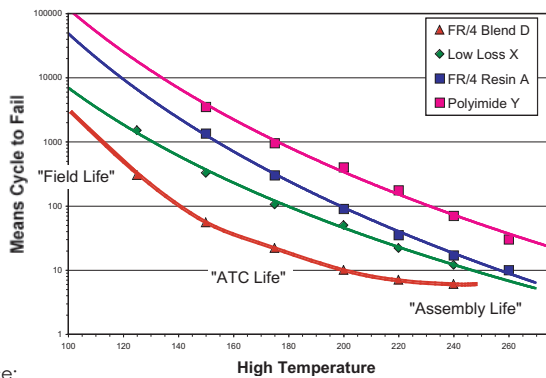
Beyond temperatures observed during PWB fabrication and assembly, the working environment of the finished PWB -- the thermal environment in which it will actually live and work, so to speak -- will throw new challenges at the devices and substrates employed in making the board. Any active device on a PWB will generate its own heat as the junctions on its silicon chip flip on and off billions of times per second. When a piece of electronic gear is turned on and off over time, the temperature inside the enclosure will cycle up and down. Beyond these temperatures, electronics today often encounter elevated service times and temperatures in certain difficult environments such as down-hole drilling, under-hood automotive electronics and some space applications. The combination of the environment with the heat generated from device itself result in a widely varying thermal operating zone that requires special design consideration to insure device reliability.

High Temperature Electronics

High temperature electronics are devices that are designed to operate in severe conditions, such as engine mounted sensors, jet-engine control systems, and chemical process & oil-drilling instrumentation. Operating temperatures for these devices can exceed 250°C. These temperatures can start to chemically degrade polymers and lead to device failure. Selecting a thermally robust system that is design to handle high temperatures for long periods are critical for success. Arlon's polyimide prepreg & laminate materials, such as 33N, 35N and 85N have long been a preferred material in these applications for their ability to survive severe conditions.

Surviving the Environment — Continued

PTH Reliability — Mean Cycles to Fail



Source:
Proof is in the PTH —
Assuring Via Reliability from Chip Carriers to Thick Printed Wiring Boards
 Kevin T. Knadle and Virendra R. Jadhav,
 Endicott Interconnect Technologies, Inc
 Paper presented at the 2005 Electronic Components and Technology Conference

Thermal Cycling & Reliability

Thermal cycling can be caused by device on/off cycles or from the operating environment, such as day/night temperatures, seasonal temperature changes, or satellite orbits, etc. These temperature cycles can cause additional thermal stresses on a PCB, particularly on the plated through holes (PTH). Temperature cycles can range as much as 150°C and cause significant failures. High ambient temperature during peak cycles also reduce heat transfer and can result in higher device temperatures without additional design consideration.

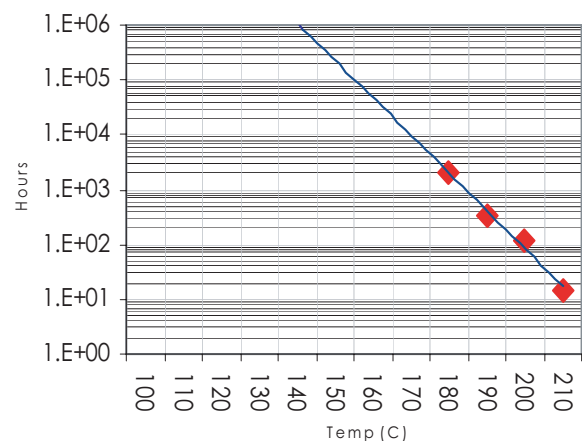
In terms of PTH reliability, materials with low thermal expansion rates can minimize copper fatigue and reduce failure rates. The greater the severity in the thermal cycle, the greater the influence of the material on reliability. Polyimide materials and filled epoxy systems with low Z-axis expansion rates are often used in these applications to extend PTH life.

Heat transfer influences the peak operating temperature of a device, which in turn influences the peak operating temperature during thermal cycling. Thermally conductive substrates such as 91ML (1.0 W/m-K) or 92ML (2.0 W/m-K) help remove heat from hot spots and active devices, but also spread the heat out over a wider area so that the temperature within the device is noticeably reduced. Reductions in temperature through the use of thermally conductive substrates will not only greatly increase the survivability of operating devices (which double in service life for every 10°C of temperature reduction at the junction), but will slow surface oxidation of the resin system which also degrades its performance in a similar manner.

Additional Material Considerations

There are several factors which will determine the degree of survivability of a PWB and the components mounted on it, given the temperature extremes & the heat cycling it undergoes. The inherent properties of the substrate material such as decomposition temperature, glass transition temperature, resistance to thermal oxidation (and this is one that can be a subtle killer, since oxidation resistance is not included in any specifications for PWB materials), MOT (as determined by UL multipoint ageing tests and extrapolated out to 100,000 hours), retention of copper peel strength at elevated temperatures, etc. are the baseline for surviving use temperatures.

UL Long-Term Thermal Aging
 Log Plot Temp vs. Time





Surviving the Environment — Continued

While the UL Relative Thermal Index may not identify the ultimate use temperature of a material, it is a good starting point reference as it measures the decline in electrical or mechanical strength at elevated temperature. Use above that temperature can result in increasingly rapid failure (the rate of any chemical reaction roughly doubles for every 10°C as previously discussed). The UL plot is logarithmic and can provide a relative impact on reliability with an increase (or decrease) in temperatures.

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 of the material, 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, such as epoxies with fairly labile bromine and the like will deteriorate substantially at temperatures which are relatively harmless to polyimide. Oxidation rates can be further reduced through the use of conformal coatings that can protect copper & dielectric materials to improve reliability at higher higher temperatures or elevated humidity.

Board-specific stress testing such as IST (Interconnect Stress Testing), HATS (Highly Accelerated Thermal Shock) and HAST (Highly Accelerated Temperature and Humidity Stress Testing) are used to give an estimate of the long term survivability of both material and manufacturing process, and are often used in critical programs to qualify new materials. Any accelerated stress test by definition is going to exceed the actual long term survivability conditions of the material being tested in order to achieve a reasonable test duration, and therefore, like the UL MOT test, can only be used as general guidelines for extended life performance.

The HATS test (IPC TM-650 2.6.7.2B) measures the resistance of PWBs to thermal shock (sudden changes in temperature), while the IST test (IPC TM-650 2.2.26) tests the reliability of PTH's by measuring the change in resistance during thermal cycling due to internal heating of the board by applying current to a test pattern. HAST testing looks at both temperature and humidity, but does not currently have a standard IPC test method.

Beyond the inherent resistance to temperature of higher Tg materials is the issue of the management of heat to prevent temperatures on the PWB from reaching unacceptably high levels. Here we begin to see the benefit of “secondary” material properties such as coefficient of heat transfer which manage the heat instead of simply coping with the temperature, and design issues such as the use of heat sinks, thermal vias, thermal pastes and gels to conduct heat away from hot spots, and even thermo-mechanical schemes such as forced convective cooling to move heat away from the PWB. Some of the old massively parallel supercomputers actually cooled stacks of PWB's with liquid nitrogen, and even a brief failure of the cooling system could cause a system meltdown.

Microwave & RF Systems

Traditional RF Cooling

While the traditional approaches towards heat removal apply, high frequency devices add additional complexity in terms of cooling due to the potential concerns with signal interference. The need for EMI shielding in some devices also reduce heat transfer as it limits the opportunity for convection. Primary options include: thermal vias, heavy metal laminated backplanes, embedded coins, heat sinks, and various types of active and passive cooling. These techniques are very effective, but, have cost and mechanical implications. With additional heat constraints, today's RF & microwave designers are forced to find more cost effective and higher reliability methods to provide heat management at the microwave PCB level with minimal impact on signal integrity.

With the advancement of today's RF and Microwave circuit designs, greater constraints are placed on the printed circuit boards because:

- Power density (Watts/square inch of circuit board area) continues to increase
- Packaging is getting smaller & hotter (inherently increasing watt density still more)
- EMI shielding limits convection heat transfer
- Tower mounted & outdoor electronics increase environmental exposure while requiring higher reliability, usually limited active cooling systems
- Complex waveforms decrease amplifier efficiency, resulting in more energy lost to heat
- Higher temperatures reduce component reliability
- Dielectric constant of many materials varies significantly with temperature

With the constraints of RF devices, the importance of base laminates is critical to performance. While this has been traditionally focused on dielectric constant (D_k or E_r) and loss tangent (D_f), secondary material properties, such as thermal conductivity (T_c), thermal expansion (CTE) and thermal coefficient of the dielectric (TCER) becomes equally critical in device optimization. By selecting low-loss materials that offer increased thermal conductivity, designers can significantly improve the performance and reliability of their devices, which can be used to reduce warranty or service costs. Key areas for device optimization include:

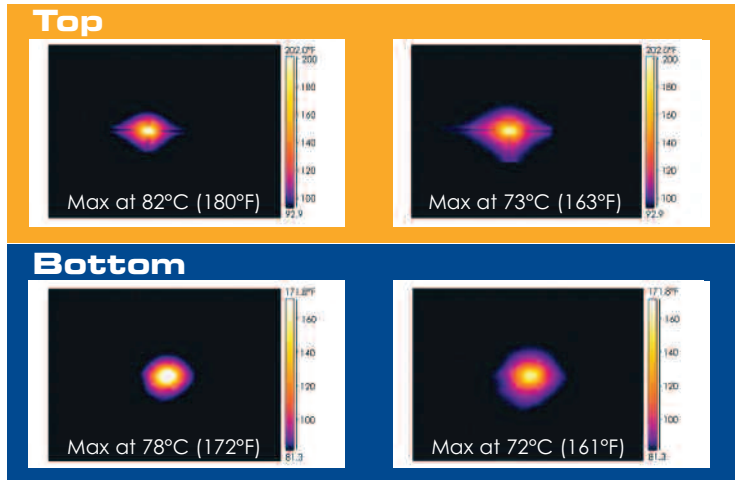
- Component and Solder Joint Reliability is improved due to reduction in temperature in critical areas. Lower temperatures and lower thermal expansion rates complement each other, reducing thermal stresses & work hardening of plated thru holes and solder joints.
- At constant heat rise, the improvement in heat transfer can be used to increase power handling 5-10%
- Lower loss tangent materials are more effective dielectrics. Less signal power is converted to heat, further reducing operating temperatures.
- Low Thermal Stability of Dielectric Constant (TCER) reduces "Dead Bandwidth", increases phase stability over temperature and reduces design limits & complexity
- Compliments or improves all other alternative sources of heat transfer. There is no trade-off, provided the material is priced competitively with other materials.
- Potentially simplifies, reduces dependency on, or lowers costs of other thermal solutions (using cast vs. more expensive machined heat sinks, reduction in copper plate thickness from 3mm to 1mm, etc).

Microwave & RF Systems – Continued

Benefits of Higher Thermal Conductivity

Increases in base laminate thermal conductivity can be readily observed in the following comparison. As measured using an infrared camera and depicted in the pictures on the right, an existing design changed materials to increase thermal conductivity from 0.46 W/m-K to 1.1 W/m-K. Resulting peak operating temperatures decreased nearly 10°C.

Alternative ($T_c(z) = 0.46$) **TC600** ($T_c(z) = 1.1$)



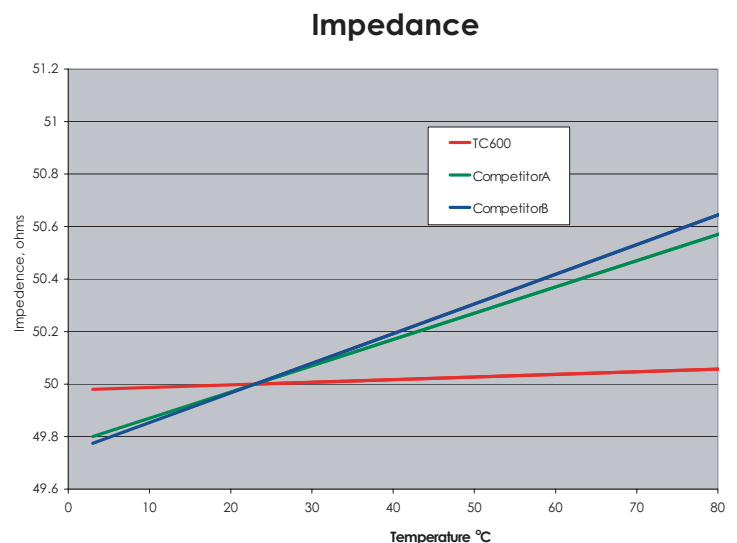
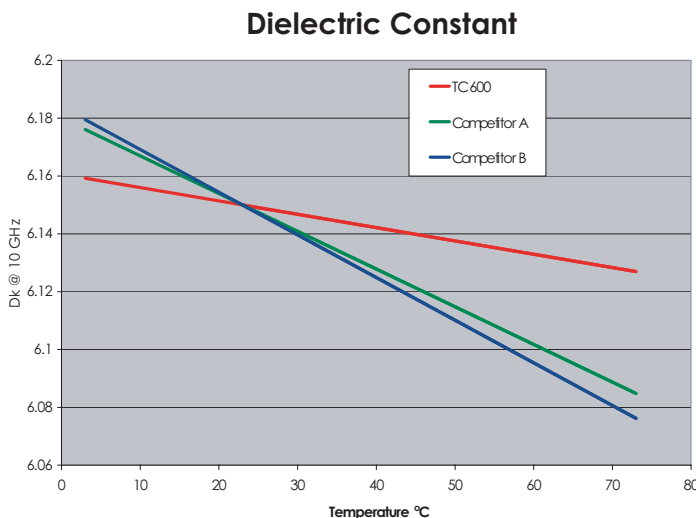
Phase Stability Across Temperature

The impact of dielectric sensitivity to temperature can be observed in the following comparison of materials in the chart below. Dielectric materials that are less sensitive to temperature have lower resulting impedance shifts created by hot spots. This translates into a more stable signal within any range of temperature fluctuation, minimizing reflections and increasing device efficiency.

More specifically:

- Temperature insensitive materials help amplifier and antenna designers minimize dead bandwidth which is lost to dielectric constant drift as operating temperature changes;
- For antenna designs, a significant shift in resonance frequency and bandwidth roll off at specific frequencies, results in lower gain performance; and
- Thermal stability is critical to phase sensitive devices such as impedance network transformers utilized for matching networks of power amplifiers.

Dielectric Constant & Temperature Affects of Three Competitive Materials



Arlon Thermal Interface Materials

A thermal interface material (TIM) is placed in the physical junction between two materials of differing temperatures through which heat must travel to move from the warmer material to the cooler material. TIMs work by ensuring intimate contact between surfaces within the assembly to eliminate and prevent formation of air gaps that can create localized areas of high thermal resistance. The interface is a critical element in the thermal path since the interface can be the “weak link” for heat transfer. Most materials are not perfectly flat, and two materials that are placed together face-to-face tend to be in contact only at “high spots” on the two surfaces. As a result, most of what is between them is air, which reduces the effectiveness of the heat-transfer. This is why a variety of compliant materials are available to use as thermal interfaces, ranging from thermally conductive rubbers, conformal gels and pastes and thermally conductive prepregs. These materials melt and/or flow into the irregularities of the mating surfaces, resulting in improved heat-transfer.

The basic equation for heat flow is:

$$dQ/dt \sim T_c \cdot (A/T_k) \cdot \Delta T$$

Where:

- dQ/dt is the rate of heat flow
- T_c is the coefficient of heat transfer (W/m-K)
- A is the surface area between the hot and cool materials
- T_k is the thickness of the interface material
- ΔT (delta T) is the temperature difference between the two materials

In simple terms this means that the amount of heat that can be removed from a warm material to a cooler material through a thermal interface is proportional to the temperature differential, the coefficient of heat transfer and the amount of total area in contact. It is inversely proportional to thickness, which means in the most general sense that thinner is better, given that there is enough thickness of material to conform to the irregularities in the mating surfaces. Because the interface is so critical, some suppliers of materials prefer to define a thermal resistance for interface materials which is roughly proportional to the inverse of the thermal conductivity (1/T_c). A TIM’s thermal resistance is dictated by the material’s bulk thermal conductivity and thickness – high thermal conductivity and low thickness are desirable for minimal thermal resistance and maximum performance.

Issues critical to TIM effectiveness include, but are not limited to the following:

- Interfacial contact resistance – Each interface in the assembly presents thermal resistance in addition to the thermal resistance of the material. The sum of material thermal resistance and all interfacial contact resistances is the thermal impedance. To minimize thermal impedance and maximize performance, choose TIMs with intimate bonding to assembly substrates.
- Operating temperature range – Exceeding TIM capabilities can cause phase transitions such as glass transition, changing TIM properties dramatically, and potentially causing system failure.



Arlon Thermal Interface Materials—Continued

- Thermal stress – Rigidly attaching materials with different coefficients of thermal expansion (CTEs) creates significant stress on assemblies. This can lead to assembly detachment, creating air gaps and areas of localized high thermal resistance. The use of compliant materials that compensate for these differential movements can minimize this risk.
- Thermal cycling – Besides stresses from CTE mismatch, thermal cycling can also lead to pump-out of some kinds of TIMs, causing disruption to the contact between assembly surfaces. The use of chemically crosslinked (“Cured”) materials in the interface eliminates the issue of pump-out.
- Vibration – In high vibration environments, reliable material attachment is critical. Rigid attachment materials can stress fracture over time, leading to detachment.
- Assembly testing needs – Testing populated PCBs prior to heat sink attachment ensures that each component performs as required. However, the process conditions required for many TIMs are too harsh for electronic components, so the TIM must be applied before the board is populated.

Arlon manufactures a range of products to serve this market in its Thermabond® silicone rubber products and its family of low-flow and thermally conductive prepreg product lines. Arlon’s Thermabond silicone thermal interface adhesives are the gold standard TIM for ultimate system reliability. Thermabond adhesives are thermoset polymer film adhesives that offer significant reliability advantages.

- Thermal conductivity to 3 W/mK
- Exceptional adhesion strength to a wide variety of surfaces
- Temperature service range -100 to 200°C
- Low modulus, with compliance retained over service temperature range
- Consistent film thickness, typically .008”, but available as thin as .004”
- Low temperature cure cycle (120°C recommended, with as low as 100°C possible)
- Low pressure cure cycle (vacuum bag pressure is sufficient for most variants)

Arlon’s thermoset prepreps are available in a range of thicknesses based on the fiberglass reinforcement, and in several ranges of thermal conductivity ranging from 0.25 W/m-K to 2.0 W/m-K. For applications that are moderate in their heat transfer needs, standard products such as 47N low flow epoxy prepreg or 51N lead-free low flow prepreg are suitable with typical values of Tc of 0.25 to 0.3 W/m-K. For more critical applications we have developed thermally conductive products that can be used either as thermal interface materials, with Tc values of 1.0 W/m-K (91ML) and 2.0 W/m-K (92ML), to bond PWB’s to heat sinks, or to build full thermally conductive PWB’s that will dissipate heat within the plane of the board (heat spreading) as well as increase heat transfer perpendicularly from the board to the heat sink. In addition to their thermal properties, 91ML (1.0 W/mK) and 92ML (2.0 W/mK) are halogen-free for use in commercial electronics where regulatory and marketplace needs dictate use of such materials.

Arlon’s EP2 enhanced polyimide represents a breakthrough in the chemistry of polyimide technology, offering a cost-effective product with higher Tc (0.45 W/mK), lower CTE (~0.65% 50 to 260°C), improved internal cohesive strength and higher copper peel strength (8 lb/in for 1 oz. ED) for pad attach durability under shock and vibration.

Abbreviations and Reference Formulas

Tc	Thermal Conductivity W/m-K
PTH	Plated Through Hole
Tg	Glass Transition Temperature
Td	Decomposition Temperature
T260/T288/T300	IPC Delamination Test at Time of Temperature
Thermal Impedence	Sum of Thermal Resistance and Interfacial Resistance
Thermal Resistance	Thickness/Tc
$dQ/dt \sim Tc \cdot (A/Tk) \cdot \Delta\Delta T$	
dQ/dt	Rate of Heat Flow
Tc	Thermal Conductivity
A	Area
Tk	Thickness
$\Delta\Delta T$	Temperature Gradient

Arlon Thermal Management Material Options & Selection

Thermally Conductive Laminate & Prepreg Circuit Board Materials

Product	Description	Tc (W/m-K)	Tg (°C)	Td (Onset)	Td (5%)	T260	T288	T300	Peel (1 oz)	CTE(XY)	CTE(Z)	Flammability
99ML	Thermally Conductive Epoxy	1	175	291	303	5	0	0	5	14	44	UL94-V0
91ML	Low Cost Halogen Free TC Epoxy	1	170	354	368	>60	>30	>10	5	23	36	UL94-V0
92ML	High Performance Halogen Free TC Epoxy	2	170	340	400	>60	>15	>5	5	19-20	175	UL94-V0

High Reliability & High Temperature Materials

Product	Description	Tc (W/m-K)	Tg (°C)	Td (Onset)	Td (5%)	T260	T288	T300	Peel (1 oz)	CTE(XY)	CTE(Z)	Flammability
33N	Polyimide UL94 V0	0.25	250	353	389	>60	>60	11	6.3	16-17	55	UL94-V0
35N	Fast-Cure Polyimide	0.25	250	363	407	>60	23	8	6.3	16	51	UL94-V1
85N	Polyimide	0.25	260	387	407	>60	>60	>60	7.1	16	55	UL94-HB
EP2	Enhanced Polyimide (Release mid-2009)	0.45	260	363	424	>60	15	10	8	13-14	25	UL94-V0

Microwave Materials for Improved Thermal Management

Product	Description	Tc (W/m-K)	Dk(10 GHz)	Df(1 GHz)	TC _{Er}	CTE(X Y)	CTE(Z)	Water Abs. (%)	Peel (1 oz)	Flammability
CLTE-AT	Commercial Ceramic PTFE	0.64	3	0.0013	-10	8	20	0.03	6.5	UL 94-V0
CLTE-XT	High Precision Ceramic PTFE	0.56	2.94	0.0012	-9	8	20	0.02	7.2	UL 94-V0
TC600	Thermally Conductive Ceramic PTFE	1.1	6.15	0.0020	-75	9	35	0.02	8.0	UL 94-V0
TC350	Thermally Conductive Ceramic PTFE	1.0	3.5	0.0020	-10	8	24	0.05	7.0	UL 94-V0
AD1000	High Dielectric Ceramic PTFE	0.81	10.2	0.0023	-380	8-10	20	0.03	>12	UL 94-V0
25N	Low-Cost Ceramic Hydrocarbon	0.45	3.38	0.0025	-87	15.0	20	0.09	5.0	N/A
25FR	Low-Cost Ceramic Hydrocarbon	0.45	3.58	0.0035	50	17.0	59	0.09	5.0	UL 94-V0

Low-Flow Thermoset Prepregs

Product	Description	Tc (W/m-K)	Tg (°C)	Td (Onset)	Td (5%)	T260	T288	T300	Peel (1 oz)	CTE(X Y)	CTE(Z)	Flammability
47N	Quick Cure Epoxy Low-Flow	0.25	130	290	314	18	0	0	9	15-17	85	UL94-V0
49N	Standard Epoxy Low-Flow	0.25	170	291	302	10	0	0	9	14-16	87	UL94-V0
51N	Lead-Free Compatible Epoxy Low-Flow	0.25	175	354	368	>60	>30	15	6.7	14	44	UL94-V0
37N	Polyimide Low-Flow	0.25	210	322	340	>60	5	2	6.8	16	76	
38N	High Performance Polyimide Low-Flow	0.25	220	311	330	50	5	3	8.5	17	54	

Silicone Thermal Interface Materials

Product	Description	Tc (W/m-K) @ 100C	Thermal resistance (m ² * K/W)	Shear Modulus (psi)	Shear Modulus (psi)	Lap Shear Strength (psi)	Bonds Without Primer?	Pressure Required	Electrical Properties	Thickness Range Available	Fiberglass Reinforcements
99A90X008	A9 Thermabond	3.0	6.0E-05	265	140	500	Yes	Platen Press	Insulative	.004" and up	No
99A50X008	A5 Thermabond	1.4	9.6E-05	145	290	710	Yes	Vacuum or platen	Insulative	.004" and up	No
99A30N008	A3 Thermabond	1.0	2.1E-04	30	495	475	Yes	Vacuum or platen	Insulative	.004" and up	No
48991A010	Support Thermabond	0.4	7.1E-04	50	475	185	Yes	Platen Press	Insulative	.004" and up	Yes
99950N008	Primerless E35 Thermabond	2.5	8.4E-05	54	475	1000	Yes	Vacuum or platen	Conductive	.004" and up	No
99730N008	E35 Thermabond	2.5	8.4E-05	43	475	600	No	Vacuum or platen	Conductive	.004" and up	No
99000W008	Low Outgassing Thermabond	1.5	4.2E-04	65	185	600	No	Platen Press	Insulative	.004" and up	No
99990A008	Primerless Thermabond	0.4	5.2E-04	75	1000	600	Yes	Vacuum or platen	Insulative	.004" and up	No
99510N008	Original Thermabond	0.4	5.7E-04	100	600	600	No	Vacuum or platen	Insulative	.004" and up	No

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