Basic Thermal Interface Parameters
and Review of Materials for Complete Thermal Management

Slide	Notes
TecKonnect International **Basic Thermal Interface Parameters and Review of Materials for Complete Thermal Management** *Mike Firmstone* *TecKonnect International* *Strategy –Marketing - Technology*	Hello and welcome to this presentation which deals with some of the more pragmatic aspects of thermal management.
TecKonnect International **Thermal Management** Introduction Examples Fundamentals Materials options Properties, performance and reliability Selection criteria Selector Guide	First we will review some examples of heat generating devices and constructions (fairly quickly since I am sure these are also presented elsewhere). More importantly we will look at some of the fundamentals of heat flow, thermal interface materials options – what are they? what's in them? – and how to choose the most appropriate material for the application. If you think of the heat transfer process as first harvesting the energy, then transporting it and finally dumping it, then it is obvious that there will be thermal interfaces between the various elements in that chain. Minimising the thermal impedance of these is of key importance to the overall efficiency of the thermal management process.
TecKonnect International **Introduction 1** Microprocessor speeds have reached 3 GHz + representing power dissipation levels of approximately 250 watts + The current industry road map predicts a 1 billion transistor CPU by 2007/2008 A 1 billion transistor CPU represents power dissipation levels of approximately 600 watts! *Excess temperature limits performance, reliability and device lifetime*	So let's take a look at some of the factors that are making thermal management more and more necessary. As microprocessor speeds increase so does the power dissipation and the need to remove the heat generated
TecKonnect International **Votre petit dejeuner (oeuf et “chips”) est pret a manger, mais votre CPU est mort** 	[As microprocessor speeds increase so does the power dissipation and the need to remove the heat generated]

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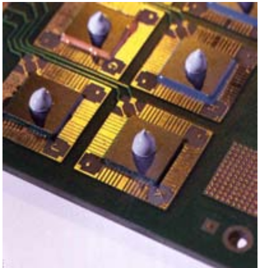
Slide	Notes
TecKonnect International **Introduction 2** Smaller package sizes restrict the free surface area available for attaching heat sinks Multi-chip modules and system on chip schemes are growing Increased packing density causes devices to heat each other and restricts convection cooling	Miniaturisation is another factor. More and more functionality in smaller packaging inevitably generates excess heat problems.
TecKonnect International **Introduction 3** Temperature control can be achieved via heat sinks, heat spreaders, etc. Heat transfer between the device and the heat sink is optimised with thermally conductive interface materials (TIMs) Thermally conductive encapsulants are required in applications such as AC/DC and DC/DC converters Thermally conductive adhesives are used to attach high power die, LEDs, etc.	So there is a need to limit temperature rise which can be achieved with heat spreaders and heat sinks. Transfer between the heat generator and the heat-sink is achieved via thermal interface materials.
TecKonnect International **Some heat- generating devices** High-power, high brightness LEDs AC/DC & DC/DC converters RF transmission devices Solid state power switching, IGBTs High speed logic devices. PV arrays (from sun concentrators)	Here is a list of just some of the types of devices which generate heat. Note that in the case of photovoltaic arrays the heat is from the sun and not from the devices themselves. Nevertheless the problem is the same in that both efficiency and reliability are compromised if the temperature is not limited.
TecKonnect International **Examples 1** Between the silicon die and device lid, case or lead frame Note: Thermal Management materials for use internal to devices MUST be manufactured under clean room conditions 	Here are some further examples of devices and constructions. I’m sure these are pretty familiar, so there’s no need to dwell on them, just to comment that they are more and more commonplace.

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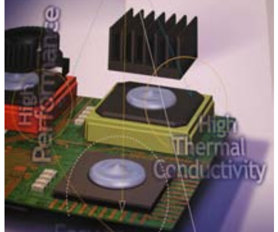
Examples 2

- Between microprocessor and heat sink
- Between Chip On Board or MCM and heat sink
- Between BGA and heat sink
- Encapsulation of the complete circuit board!



[Here are some further examples of devices and constructions. I'm sure these are pretty familiar, so there's no need to dwell on them, just to comment that they are more and more commonplace.]

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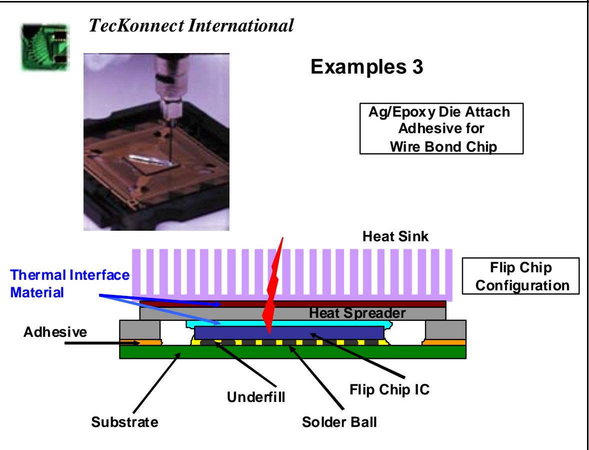
Examples 3



[Here are some further examples of devices and constructions. I'm sure these are pretty familiar, so there's no need to dwell on them, just to comment that they are more and more commonplace.]

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Examples 4

- Power supply modules
- DC/DC Converters
- Optical devices
- Laser Applications
- Aerospace and automotive applications

[Here are some further examples of devices and constructions. I'm sure these are pretty familiar, so there's no need to dwell on them, just to comment that they are more and more commonplace.]

Next we will have a look at some of the fundamentals involved in thermal management and heat transfer…

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Fundamentals

Basic Parameters of Thermal Management Materials

- Bulk thermal conductivity
- Thermal resistance
- Thermal impedance
- Bond-line thickness
- Factors affecting thermal impedance
- Wetting characteristics

Thermal modeling is a complex task but some of the fundamental parameters are easy to understand and some simple arithmetic will yield at least a ballpark figure which can facilitate the selection of thermal interface materials.

We will go on to gain an understanding of bulk thermal conductivity, thermal impedance and resistance, the influence of bond-line thickness and some material properties affecting performance.

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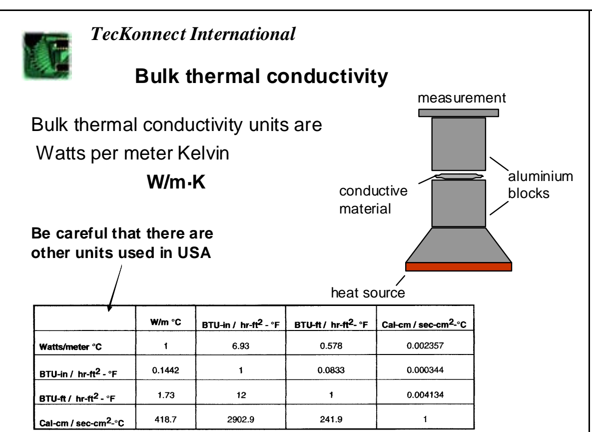

	W/m °C	BTU-in / hr-ft^2 - °F	BTU-ft / hr-ft^2- °F	Cal-cm / sec-cm^2-°C
Watts/meter °C	1	6.93	0.578	0.002357
BTU-in / hr-ft^2 - °F	0.1442	1	0.0833	0.000344
BTU-ft / hr-ft^2 - °F	1.73	12	1	0.004134
Cal-cm / sec-cm^2-°C	418.7	2902.9	241.9	1

Bulk thermal conductivity is the most commonly quoted property and the units are W/m·K. However, there are a number of other units used, especially by our American buddies, and so here is a conversion table.

Note also that this property is derived using a cast block of material usually about ¼ inch thick. Obviously then thermal conductivity does not tell the whole story when the interface material is used in systems between the heat generator and the heat-sink.

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Thermal Performance of the SYSTEM

Bulk thermal conductivity does not include bond-line thickness, interfacial effects, voiding, shrinkage, pressure, wetting ability, etc.

System thermal performance is more accurately characterised as:

Thermal impedance (°C·cm²/W)
or (°C·inch²/W in USA)

This is the thermal resistance (ºC/W) normalised per square centimetre of contact surface which is the **power density (W/cm²)**

This can be extrapolated to any application area

The thermal performance of the system depends also on bond line thickness, interfacial effects, voiding, shrinkage, wetting, and other factors. Also, in the case of materials which stay liquid, pressure is an important factor in maximizing performance.

Performance is thus more accurately described by the thermal impedance of the material which takes these factors into account. The units are °C-cm^2/W.

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Thermal resistance

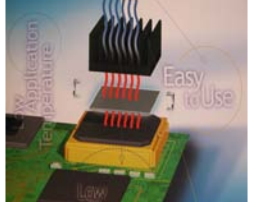
$$R = \frac{T_{interface\ 1} - T_{interface\ 2}}{q}$$

R = Thermal resistance

T = Temperature

q = Steady state heat flow (W)

BUT, for this to be of use, we need the area of the heat flow



Thermal resistance can be calculated from a knowledge of the respective temperatures either side of the interface material and the heat flow. However this does not fully characterize the performance unless the area is also defined. In other words, the power density is clearly important.

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Thermal impedance

$$R = \frac{T_{interface\ 1} - T_{interface\ 2}}{(q/A)}$$

R = Thermal impedance

A = Area in in^2 or cm^2

q = Heat Flow (W)

These next two slides illustrate the difference between thermal resistance and thermal impedance.

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Example

Application with power density 30W/0.15in^2
(= 200W/in^2)
TIM has k = 2.3 w/m.K and thermal impedance 0.06 **°C.in^2/W**
@ 0.0015 inch bond-line thickness

$$Q = \frac{k \times \Delta T \times A}{t}$$

2.3 W/m·K = 0.584 W/in·K

$$Q = \frac{0.0584 \times 0.15 \times \Delta T}{0.0015}$$

From which ΔT, the temperature differential across the interface, is 5.14°C

T.I. = (ΔT x A)/Q

ΔT = T.I. x Q/A

ΔT = 0.06 x 200

The temperature differential across the interface is 12°C

Because thermal impedance includes interfacials

Here is a simple calculation which illustrates the point that bulk material property can be misleading compared to measured thermal impedance.

Note that the calculation using thermal impedance predicts worse performance, since this figure takes into account the effects of interfacial resistance caused by imperfect wetting, voiding, and all those other factors.

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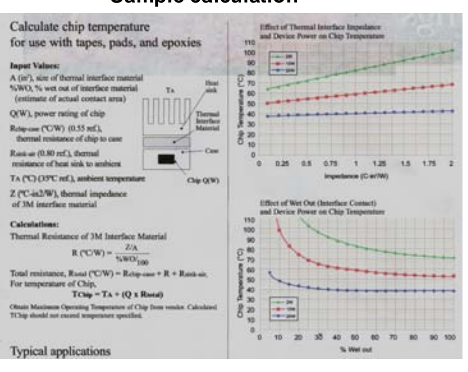
Sample calculation



A more sophisticated calculation shows the influence of material “wet-out” on the overall efficiency of the heat transfer process. Wet-out is important to materials which cure to gels or adhesives, as well as those like greases and gels which remain liquid.

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Factors affecting thermal impedance

Thermal impedance is the combination of the bulk material and the two interfaces i.e. the total pathway between the device and the heat sink

Low bond-line thickness** and good interfacial resistance is essential for maximum heat transfer

Thermal interface material should have good wetting characteristics, minimal air voiding and low cure shrinkage or cracking in the case of adhesives.

Pressure of mechanical fasteners or during cure affects the interfacial resistance

** Note that there is a trade-off as very thin bond lines are not good in thermal shock/cycling when using higher modulus adhesives

The heat flow performance then is dependent on both the bulk thermal conductivity and the two interfaces with the heat source and the heat sink. Minimising bond-line thickness, voiding, cracking and cure shrinkage is critical to optimization of thermal interface materials. As before, “wet-out” and pressure are also critical factors.

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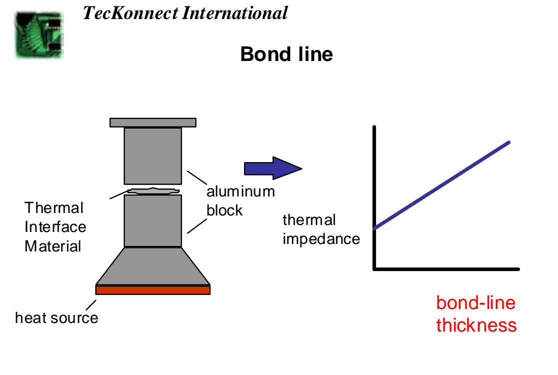
Bond line



[As before, “wet-out” and pressure are also critical factors.]

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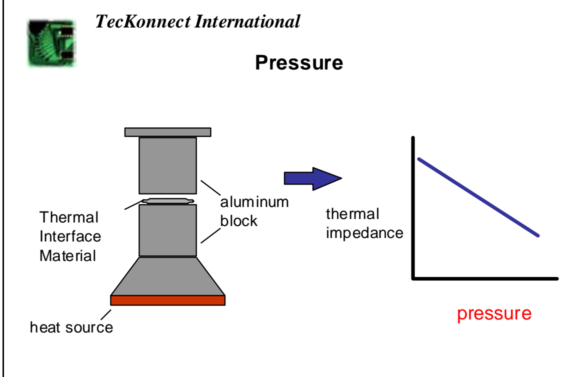
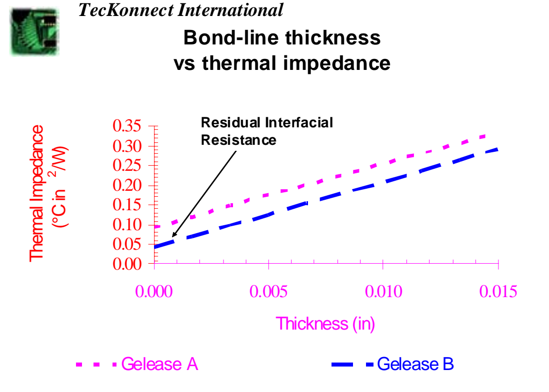


[As before, “wet-out” and pressure are also critical factors.]



A plot of bond-line thickness against thermal impedance clearly shows the relationship, but note that the plot does not go through the origin due to residual interfacial resistance. Minimising this then is the task for the formulator, and it can be seen that Gelease B is an improvement on Gelease A.

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Materials options

Thermal management options

Paste adhesives *

Film adhesives

Thermoplastic materials

Greases *

Gels *

Thermally conductive encapsulants

* *Addressed in detail in following sections*

Now we come to the main focus of this presentation which is the materials themselves. These separate out into true adhesives which have structural integrity and grease, gels, tapes, etc, which need mechanical support.

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Liquid/Paste Thermal Interface Materials

Gels

Low thermal resistance of a grease with the integrity of a gel when cured, minimizes bleed, separation, and pump-out. Exhibit excellent flow properties.

Thermal greases

Microelectronics-grade, high temperature resistant greases, offering very high thermal conductivity and easy dispensability.

Thermal adhesives

Offering high thermal conductivity and superior adhesion/strength.

We will examine the paste adhesives, greases and gels in detail here. There is a lot of data in the properties tables which I will not talk over in detail, but will just highlight some of the more noteworthy properties.

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1: Thermal Grease

Composition fundamentals

- Typically silicone grease but glycol and fluoropolymers are known
- Silicone has high temperature performance: 200°C continuous rating
- Silicone is "slippy" allowing high filler loading without viscosity becoming unworkable
- Fillers are typically ZnO, AlN, BN, Al_2O_3, Al etc; with tri-modal PSD to maximise volume fraction
- ** metal filled have poor dielectric strength

Advantages to using a grease

- Easy to apply
- Can conform to any package design and shape; provides good surface contact
- Compensates for surface irregularities and non-planarity
- Can minimise bond line thickness
- Lowest stress interface
- Easy to rework

Starting with greases, let's look at some of the fundamentals. Typically, silicones are used as they have excellent high-temperature properties and high filler loadings can be achieved.

Fillers are normally ceramic powders or even aluminium metal. The ceramic fillers are chosen for their thermal conductivity, which is then set aginst dielectric strength and cost in final formulations. Advantages include ease of application, low stress and easy rework.

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Typical physical properties of thermal grease

Property	Value
Carrier type	Silicone
Viscosity @ 1 rpm @ 10 rpm	600,000 cps 165,000 cps
Pseudoplastic Index	5.0
Specific Gravity	2.92 g/cc
Colour	Grey
Cont. operating temperature	200°C
Shelf life @ 5°C	6 months

Here we can see some typical properties. Note particularly the high operating temperature, high thermal conductivity… [and the non-linearity of the thermal resistance versus bond line thickness.]

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Typical thermal properties of thermal grease

Property	Value
Thermal conductivity	2.90 W/m·K
$Theta_{jc}$ (on flip chip die)	0.50 °C/W
Thermal resistance @ 25 microns BLT	0.20 °C/W
Thermal resistance @ 250 microns BLT	0.63 °C/W

… and non-linearity of the thermal resistance versus bond-line thickness.

In this case we can guess from the grey colour that the filler is probably aluminium powder. The high thermal conductivity will therefore be offset against poor dielectric strength and high dielectric constant. In many cases of course this is not an issue..

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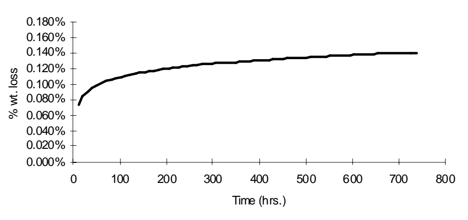
Reliability 1

Plot of 30 day at 100°C weight loss for thermal grease



Another aspect of silicone greases is long term reliability.

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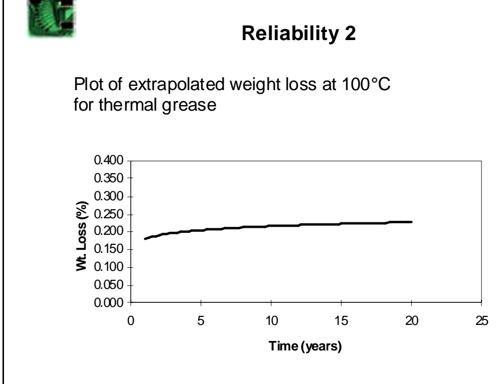

Silicone chemistry is resistant to oxidization and thermal degradation which makes the grease an ideal carrier for the thermally conductive fillers.

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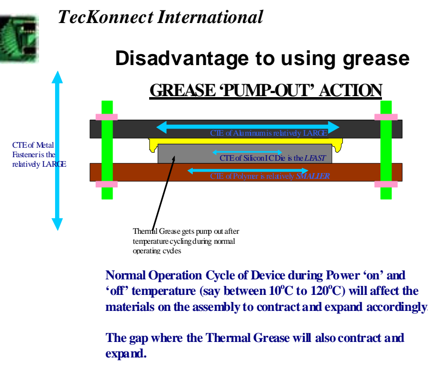
Reliability 3

Test results for thermal grease

Test	Condition	Results
power cycle	5000 cycles @ 25-100°C	Passed
temperature cycle	1000 cycles @ -55 to +150°C	Passed
humidity	500 hours of 85°C/85 RH	Passed
aging	500 hours @ 135°C	Passed

Thus the resultant TIM has excellent long-term reliability, as these slides show.



These actions will pump out the grease.

Thermal greases are very efficient and exhibit good wetting properties, but can suffer from "pump-out", which means that the grease itself may be displaced due to expansion/contraction of the components and/or the fillers in the grease may bleed out. A diagrammatic representation of this can be seen in the slide.

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2: Gels

Composition fundamentals

- Typically addition-cured Pt-catalysed poly-dimethyl-siloxane
- Fillers are typically aluminium metal, but metal oxides also used
- Consists of polymer, catalyst, inhibitor and filler
- Components are adjusted to control degree of cross-linking, working life and cure schedule

Advantages to using a gel

- Has the thermal performance of a grease with the integrity of a gel
- Easy to apply in the uncured state and has excellent wetting and surface conformity
- Minimises bleed and "pumpout"
- Reworkable and low stress interface

Disadvantages: needs heat;
ultimate conductivity and reliability inferior to grease

The answer to those problems is the use of materials which are applied as greases, but which become gels when cured, thus totally locked in place.

Cross-linkable silicone resins for this application are normally Pt-catalysed poly-dimethyl-siloxane but there are many variations on that theme. These gels (often referred to as geleases) have the thermal advantages of silicone grease but the integrity of a gel.

In the ultimate, however, the grease formulations will always have the superior thermal conductivity.

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Typical physical properties of thermal gel

Property	Value
Glass Transition Temp Tg	-121°C
Viscosity @ 10 rpm @ 20 rpm	81,000 cps 60,500 cps
Pseudoplastic Index	3.6
Storage Modulus	20 kPa
Working life @ 25°C Cure schedule	8 hrs 2 hrs @ 100°C, 1 hr @ 125°C, 30 mins @ 150°C
Cont. operating temperature	200°C
Shelf life @ 5°C @ -30°C	3 months 6 months

In the properties tables, note the low Tg and modulus, which indicate a very soft low stress polymer.

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Typical thermal and electrical properties thermal gel

Property	Value
Thermal conductivity	2.30 W/m·K
Thermal impedance	0.06 °C.in^2/W
Volume resistivity	8 x 10E13 O.cm
bond-line thickness	50 ~ 60 microns

The volume resistivity figure is surprisingly good considering that the filler is aluminium powder.

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Technology improvement

Thermal Conductivity of 2.34 W/m·K

Low Modulus –15 Kpa

Excellent Temperature Cycle Performance

Thermal Impedance of **0.02°C·in^2/W**

Low Viscosity = 76,000 cps @ 10 rpm

Shelf Life of 3 mo. @ -30°C and 1 mo. @ -5°C

Originally developed for Intel but now generally available

Note also that an improved version has similar bulk thermal conductivity but only one-third of the thermal impedance.

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Reliability 1 - Test results for thermal gels

Test	Condition	Results
power cycle	2000 cycles @ 25 to 100°C	Passed
temperature cycle	500 cycles @ -55 to +150°C	Passed
humidity	500 hours of 85°C/85 RH	Passed
aging	500 hours @ 125°C	Passed

Next we have some general reliability data for these types of materials, where it can be seen that continuous development … [has improved the temperature/humidity withstand by a factor of 3.]

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Reliability 2 - HAST * Performance

Gel A - ≥ 48 hours

Gel B - ≥ 48 hours

Gel C - > 96 hours

Gel D - > 96 hours

Gel E - > 150 hours

* 110 °C/85% RH

… has improved the temperature/humidity withstand by a factor of 3.

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3: Adhesives

Fundamentals of composition

Both epoxies and silicones are used

Both 2 part and 1 part systems are available

Fillers can be alumina, AlN, BN, aluminium, silver depending on application

These combinations yield materials from highly electrically conductive to completely insulating.

Thermal conductivities ranging from < 1 to > 10W/m.K

Advantages for adhesive

Provides structural integrity / strength required when mechanical fastening is impossible

Provides ultimate thermal conductivity if required (13W/m·K is achievable)

Provides outstanding electrical conductivity if needed (90µO.cm is achievable)

Also provides outstanding electrical insulation (10E16 O.cm achievable)

Disadvantages: 155°C max operating temp typical for epoxies; high modulus; rework not normally possible

For structural integrity combined with thermal conductivity the most widespread materials are filled epoxies. An unfilled epoxy has a thermal conductivity of about 0.2 W/m·K. Filled with silver, this can rise to as much as 20 W/m·K, whereas simple alumina additions will be in the region of 1.0 to 1.5.

Silicones and silicone/epoxy hybrids are also used in order to take advantage of their respective properties. Silicones induce very low stress compared to epoxies, but epoxies are very much stronger. Balancing these properties opposite the thermal requirements is the job of the formulator and specifier alike.

Fillers are the usual suspects, as can be seen from the slide. Electrical properties can also be manipulated by choice of filler ranging from highly insulating to highly conductive.

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Properties – Review 1

Property	A	B	C	D
polymer	epoxy	epoxy	Si/epoxy hybrid	epoxy
filler	alumina	ZnO and Al	ZnO and Al	silver
thermal conductivity	1.35 W/mK	2.35 W/mK	4.20W/mK	7.30W/mK
thermal impedance	NA	NA	NA	0.020 °C.in²/watt
BLT achievable	100µm	100µm	100µm	100µm
volume resistivity	10E16 ohm.cm	2×10E13 ohm.cm	1×10E7 ohm.cm	0.00043 ohm.cm
some applications	metal/metal bonding with high heat flow and strength package attach with RT curing	power die and LED attach metal/metal bonding with rapid in line curing	low stress bond lines e.g. Si to Si bonding where high CTE mismatch occurs	die attach and thermal interface for power devices and processors heat sink to flip chip bonding

Next is a review of adhesive properties. I won't read out every figure on the slides but there are some noteworthy points to make.

Note the change in electrical resistivity and conductivity opposite fillers going from alumina to aluminum to silver. Also in the applications area, the epoxy/silicone hybrid polymer is particularly aimed at low-stress bond line for delicate components and substrates such as silicon.

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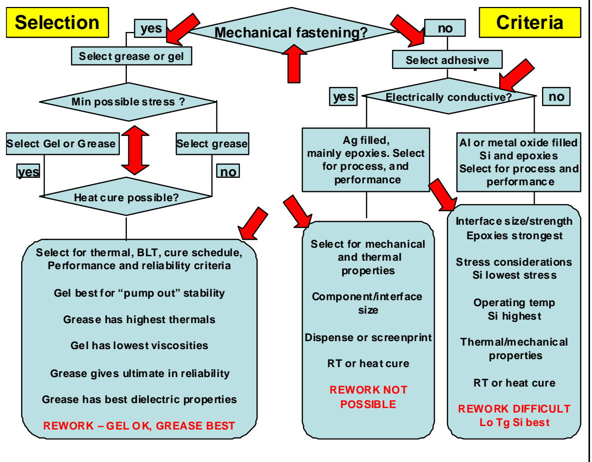
Properties – Review 2

Property	A	B	C	D
lap shear strength Al/Al	26.2 MPa	20.1 MPa	4.5 MPa	6.2 MPa
storage modulus	4.0 GPa	7.0GPa	0.156GPa	3.2 GPa
Tg °C	+126°C	+123°C	- 90°C	+75°C
CTE ppm/°C alpha 1 / alpha 2	22 / NA	31 / 73	25 / 82	52 / 148
hardness Shore	D 91	D 86	A 95	NA
max. operating temp °C	155°C	155°C	200°C	155°C
viscosity	250kcps	95~115 kcps	72kcps	85 kcps
work life	2~3 hrs @ 25°C	2 weeks @ 25°C	1 week @ 25°C	24 hrs @ 25°C
cure schedule	24 hrs @ 25°C	8 mins @ 150°C, 30 mins @ 125°C	10mins @ 150°C	30 mins @ 150°C

Note also the decrease in lap shear strength opposite filler type and filler loading. A simple view is that, the higher the loading, the better the thermal conductivity, but less resin usually means less adhesion.

The effect on modulus and hardness can also be seen, the silicone hybrid polymer, being extremely low compared to epoxy. The silver is in the form of flakes which improves particle to particle contact and thus both thermal and electrical conductivity.

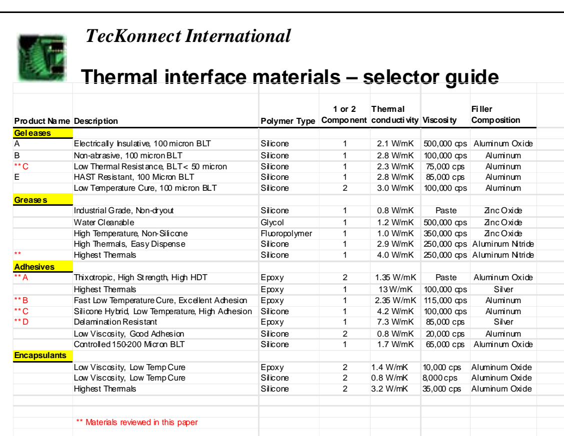


Clearly there are many parameters to take into account when selecting a thermal interface material. So far we have considered the materials themselves, but what about your processing? For instance can you heat cure? What maximum temperature? Is rework an option, etc. This flow chart should help with those decisions, although, in the ultimate, a detailed discussion with the supplier will (hopefully) refine the choice.

Let's start with the first question. Does your design include mechanical fastening? If yes, then you probably want to go down the grease or gel route. If no, then an adhesive will be more suitable.

Continuing down the adhesive route the next decision is on electrical conductivity, and down the grease/gel route, stress and cure schedule.

Having decided the broad issues, then the chart highlights aspects of process and performance for consideration. This in turn will lead to a data sheet comparison of the hundreds, no thousands, of products available. Fortunately most suppliers are very applications-smart these days so, once the design engineer has narrowed the field, final selection should involve no more than two or three candidate materials.



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Thermal interface materials – selector guide

Product Name	Description	Polymer Type	1 or 2 Component	Thermal conductivity	Viscosity	Filler Composition
Geleases						
A	Electrically Insulative, 100 micron BLT	Silicone	1	2.1 W/mK	500,000 cps	Aluminum Oxide
B	Non-abrasive, 100 micron BLT	Silicone	1	2.8 W/mK	100,000 cps	Aluminum
** C	Low Thermal Resistance, BLT < 50 micron	Silicone	1	2.3 W/mK	75,000 cps	Aluminum
E	HAST Resistant, 100 Micron BLT	Silicone	1	2.8 W/mK	85,000 cps	Aluminum
	Low Temperature Cure, 100 micron BLT	Silicone	2	3.0 W/mK	100,000 cps	Aluminum
Greases						
	Industrial Grade, Non-dryout	Silicone	1	0.8 W/mK	Paste	Zinc Oxide
	Water Cleanable	Glycol	1	1.2 W/mK	500,000 cps	Zinc Oxide
	High Temperature, Non-Silicone	Fluoropolymer	1	1.0 W/mK	350,000 cps	Zinc Oxide
	High Thermals, Easy Dispense	Silicone	1	2.9 W/mK	250,000 cps	Aluminum Nitride
**	Highest Thermals	Silicone	1	4.0 W/mK	250,000 cps	Aluminum Nitride
Adhesives						
** A	Thixotropic, High Strength, High HDT	Epoxy	2	1.35 W/mK	Paste	Aluminum Oxide
	Highest Thermals	Epoxy	1	13 W/mK	100,000 cps	Silver
** B	Fast Low Temperature Cure, Excellent Adhesion	Epoxy	1	2.35 W/mK	115,000 cps	Aluminum
** C	Silicone Hybrid, Low Temperature, High Adhesion	Silicone	1	4.2 W/mK	100,000 cps	Aluminum
** D	Delamination Resistant	Epoxy	1	7.3 W/mK	85,000 cps	Silver
	Low Viscosity, Good Adhesion	Silicone	2	0.8 W/mK	20,000 cps	Aluminum
	Controlled 150-200 Micron BLT	Silicone	1	1.7 W/mK	65,000 cps	Aluminum Oxide
Encapsulants						
	Low Viscosity, Low Temp Cure	Epoxy	2	1.4 W/mK	10,000 cps	Aluminum Oxide
	Low Viscosity, Low Temp Cure	Silicone	2	0.8 W/mK	8,000 cps	Aluminum Oxide
	Highest Thermals	Silicone	2	3.2 W/mK	35,000 cps	Aluminum Oxide

** Materials reviewed in this paper

Here now is a selector guide which highlights the main parameters of a variety of materials.

Note the letters at the left hand side with two stars. They correspond with the property charts shown previously.

Of course this is only a small selection of the available product,s but it covers a broad range of applications and performance. Also I have included some encapsulants which are the thermal interface materials between components and the outside world in the case of "potted" electronic modules.

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Slide	Notes
TecKonnect International Many thanks to LORD CORPORATION for material properties information, data points and graphics **LORD Tech Service** paul_hough@lord.com **+49 (0) 2131 / 5 12 27-0** **+49 (0) 172 919 97 88**	I hope this presentation has given some insight into the materials issues of thermal management, and that it will be of some practical use in the day-to-day decision-making. Finally I must thank the Lord Corporation, Thermoset products for much of the data presented here and, not to get too commercial, I can thoroughly recommend Mr Paul Hough as an expert in the field. Thank you for your attention and … HAPPY INTERFACING!

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