DEVELOPING *TECHNOLOGY* TO *TRANSFORM* THE EVERYDAY TOGETHER

WhitePaper – Thermal conductivity isn't everything

Empowering partnership | Siemens and Henkel

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THERMAL *CONDUCTIVITY* ISN'T EVERYTHING

Understanding the factors that determine thermal management material selection for industrial automation applications.

When designing a new device or system, what are the most important criteria for selecting a thermal management material for the application? If you answered thermal conductivity – also known as lambda value – you're not alone. And you'd be a little bit right ... but not completely. Thermal conductivity is an essential factor, but it's not everything when it comes to the final result. Other considerations include processability, curing mechanisms, adhesion characteristics, thermal impedance/interfacial resistance, base chemistry, bond line thickness, and so on.

Throughout today's automated smart factories powered by Industry 4.0 digital oversight, power supplies, drives, and controllers are the engines that keep production moving. And, in many cases, they work all day, every day to maximize output. With many of these devices integrating advanced, high power density components and expected to provide continual operation, thermal management has become a vital consideration for the modern digital factory. **Though a key part of the manufacturing systems landscape for decades, thermal interface materials (TIMs) are now increasingly considered key enablers of data-controlled production facilities.** TIMs are abundant in AC/DC power supplies, programmable logic controllers (PLCs), and motor drives – all found throughout most manufacturing ecosystems. But, how are the best TIMs for the job decided? This article will explain the role of TIMs, what variables to consider, and provide information on selecting a material that's fit for purpose.

Thermal Interface Materials (TIMs) Basics: Function and Form

If not adequately addressed, the heat generated by an electronic component can affect system reliability and performance. To safeguard against this possibility, electronic designers and system engineers use TIMs to effectively transfer heat by connecting the heat-generating device with a heat sink. The efficiency of this heat transfer determines the effect on the life span of the component or system. The component and the heat sink have surface structures and roughness characteristics that present microscopic deviations and uneven planes on each side. *(Figure 1)*

> **Minimizing the voids or air pockets by filling them with thermally conductive material lowers thermal resistance and allows for more efficient heat dissipation.**

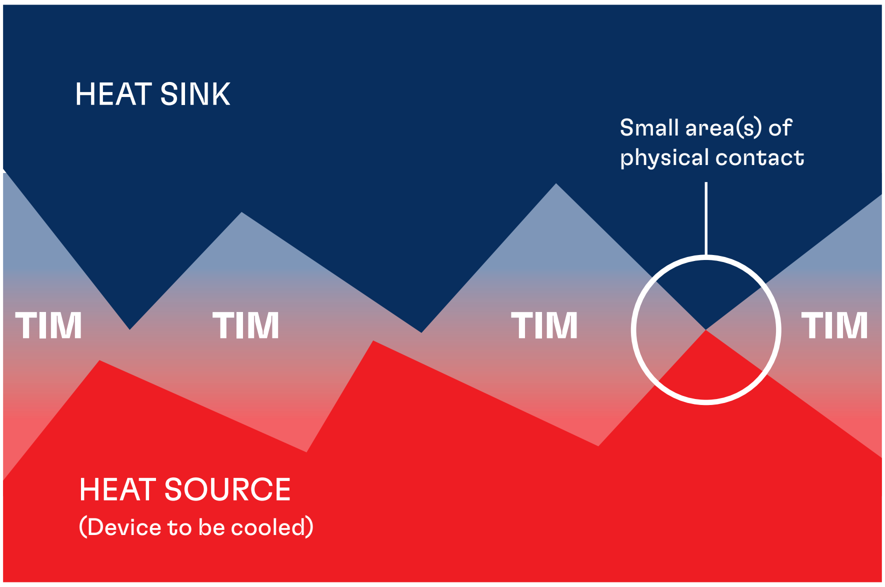


Figure 1:

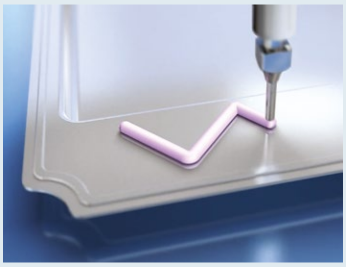
TIMs transfer heat from the source to the heat sink. Filling the microscopic deviations on both sides as thoroughly as possible allows maximum transfer efficiency.

Thermal management goals can be realized with various TIMs of different formats, including pads, films, adhesives, greases, and gels. *(Figure 2)* For each specific application, the tolerances between the two surfaces should be considered to select the material that best compensates for those tolerances. Two relatively flat surfaces, for example, a printed circuit board (PCB) and a power module housing, may have a surface tolerance of ±0.1 mm, so a thin TIM pad would be an appropriate choice. On the other hand, a larger tolerance of between 0.1 mm and 3.0 mm, for instance, is quite a dramatic variation and would likely require a liquid TIM to manage this difference adequately.

Figure 2:

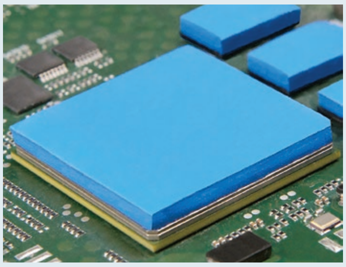
Thermal Interface Materials (TIMs)
TIMs (Henkel's materials shown here) are available in various formats to accommodate application and production requirements.

THERMAL GAP FILLERS

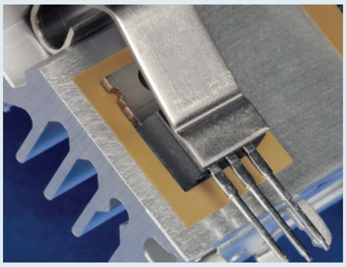


THERMAL GEL
(PRE-CURED AND CURABLE)

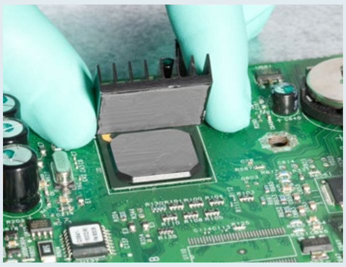
THERMAL GAP PAD®
MATERIALS



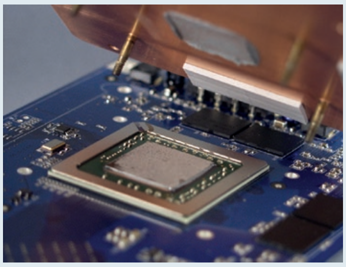
THERMAL SIL PAD®
MATERIALS



PHASE CHANGE
MATERIALS (FILM AND PASTE)

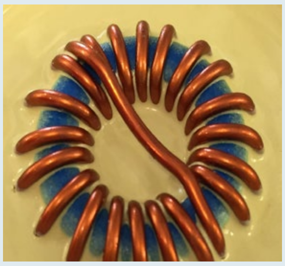


THERMALLY CONDUCTIVE
GREASE



THERMALLY CONDUCTIVE
ADHESIVES (FILM AND LIQUIDS)

THERMALLY CONDUCTIVE
POTTING



Selecting the Right Material for the Job

Diving deep into the application requirements is the basis for thermal management material selection, and numerous TIM variables must be considered, including:

- **Base resin technology:** Silicone, Polyurethane, or Epoxy
- **Format:** One-part (1k) paste, pad, gel, phase change material, two-part (2k) liquid Gap Filler, or 1k or 2k adhesive
- **Cure kinetics:** Moisture, thermal, or UV
- **Dielectric isolation:** Is this a high-voltage application?
- **Thermal conductivity**
- **Processability and application:** Is this a manual or automated process; if automated, material density, dispensability, and flow rate
- **Servicing:** Reworkability
- **Color:** Visual requirement for inspection
- **Cost estimations, expectations, and value assessment**
- **Material handling**
- **Logistics** (label, packing, storage conditions)
- **Certifications and documentation required** (IMDS, PPAP, MSDS, ITAR, etc.)

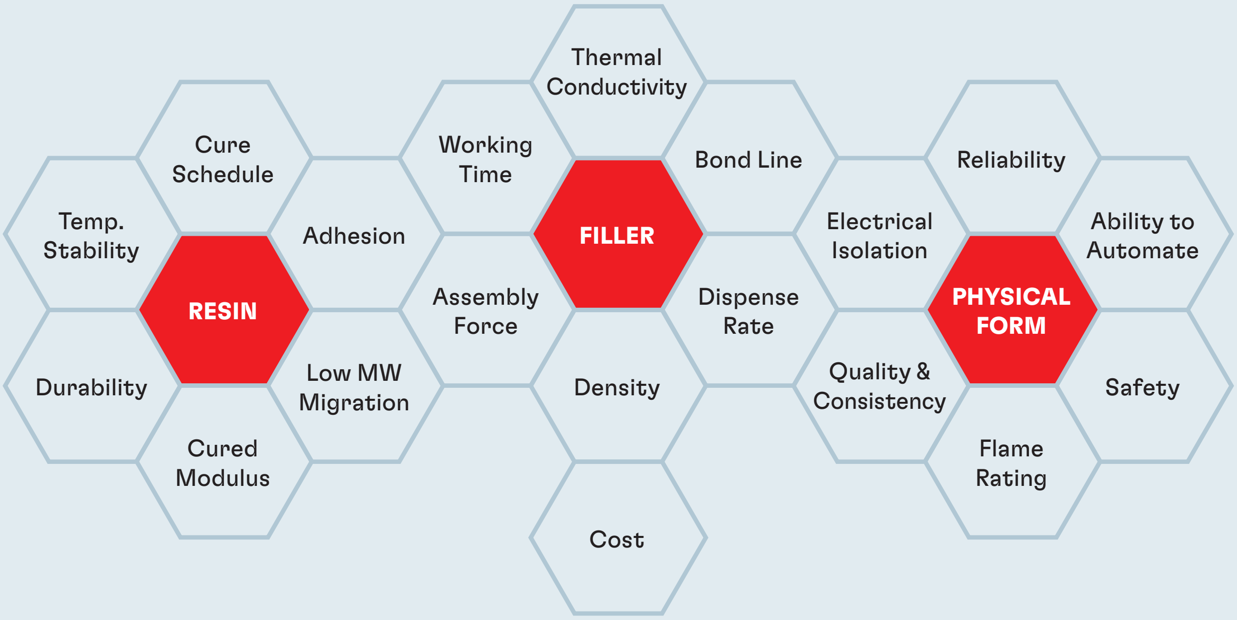
Within this long list of attributes are the **three core TIM characteristics** determined by balancing specific properties. *(Figure 3)* The building blocks of a thermal management material are physical form, resin system, and filler content. Around all these central features are various values such as adhesion, working time, durability, shelf-life, and reworkability, among others. Starting with the core elements and moving out from there will help define the proper material for the job.

Engaging with us in the early design phase allows manufacturers to leverage our expertise, ensuring optimal material selection, compatibility, and cost-effectiveness, ultimately leading to efficient production and optimized product performance.

Figure 3:

BUILDING BLOCKS FOR TIM

The building blocks of TIM selection; application specifics drive the selection process.



Physical Form

When determining which TIM format is most conducive to the job, factors include **material placement method, safety requirements, and the level of automation each medium can accommodate**. These aspects are important because they influence manufacturing efficiency (will the TIM application fit within current production throughput expectations?), dielectric assurance (is there adequate electrical isolation?), and the material's efficiency (will the medium appropriately accommodate for surface tolerances?).

Resin System

The base chemistry – the resin system – of a TIM is critical. One must consider the operating temperature of the application, the flexibility (modulus) required based on the stress that may be induced, resistance to the industrial device's potential exposure to contaminants like dust or moisture, and its adhesion to the intended surface.

Other factors, such as the impact of silicone outgassing on certain systems, are also key criteria. *Table 1* below highlights the characteristics of certain resins used to build thermal interface materials.

Table 1:

BASE RESIN TECHNOLOGY CONSIDERATIONS FOR TIM SELECTION

Characteristic	Epoxy Thermoset	Siloxane-free (PUR, SMP, SIPU)	Silicone
Max Service Temp	High Up to 180°C	Medium 115 – 150°C	Very high 230 – 260°C
Hardness (Shore) Compression Modulus (Mpa)	High shore D (50 – 100)	Shore 00 to D (1 – 30)	Shore 000 to A (0.3 – 3)
Flexibility	Medium	High	Very high
Chemical Resistance	Very high	Medium	Low/medium

Filler Package

The filler technology in a TIM is vital in developing its thermal conductivity. In addition, filler content directly impacts the material's weight, its adaptability to automated processes (in the case of liquid TIMs, dispense rate), and its cost. As with other core features, a decision about filler technology can affect other material considerations. For example, the thickness of the TIM (also determined by the filler package) defines its isolation value (the thicker a TIM, the higher the dielectric isolation) and its thermal resistance. A higher thermally conductive material may be required, so there is a need to balance thermal resistance and dielectric requirements. **When deciding the material balance between thermal resistance versus tolerance, the general rule is: as thin as possible, as thick as necessary.**

Taking all these inputs, one might arrive at an evaluation matrix that looks something like *Table 2* below:

Table 2:

MATERIAL CATEGORY – VALUE PROPOSITION MATRIX

A characteristic matrix can help visualize requirements and material capabilities.

	Thermal Performance	Dielectric Isolation	Bonding	Rework	Reliability
Grease	●	✕	✕	●	○/✕
Adhesive Liquids	●/○	●/○	●	✕	●
Adhesive Films	●/○	●/○	●	✕	●/○
TC Foils/PCM	○/●	●	○/✕	●/○	●
Gap Fillers (Pads)	●/○	●	✕	●	●
1k Gels	●/○	●/○	✕	●/○	●/○
1k CGel	●	●/○	✕	○/✕	●
Gap Fillers (Liquids)	●	●/○	✕	○/✕	●
TC Potting	●/○	●/○	●/○/✕*	✕	●

● = Good **○ = OK** **✕ = Limited/Poor** * Depending on Chemistry

The Role of TIMs in the Factory of the Future: Power Modules for Motor Drives

Thermal interface materials are found throughout today's industrial factories, enabling the performance of numerous electronic systems. Anywhere heat must be controlled for reliable electrical performance, integration of pad, liquid, film, phase change, and/or gel thermal management solutions are necessary. One such critical industrial application is the power module.

These vital systems generally contain multiple power semiconductors and other components to enable switching for servo drives that fuel robotics and material handling applications, mid-power drives for fans and process automation, and high-power drives for exceptionally demanding industrial end uses. All power module variations require reliability in extremely harsh environments.

Practical Example: Power Module for Motor Drive

Across the spectrum of power module types and applications, new semiconductor chips are enabling designs that deliver higher power density in the same or smaller footprint. This design shift dictates the use of thermal interface materials that comply with next-generation structures, accommodating thinner bond lines and low thermal resistance to facilitate maximum heat dissipation to the heat sink. In addition, power modules are expected to have long operational lifetimes – as long as 30 years in some cases – so reliability is a priority. A detailed analysis of requirements and performance expectations is necessary to determine the application's most effective thermal control solution.

To better visualize the evaluation process, TIM selection for a standard motor drive power module is demonstrated using this practical, real-world example.

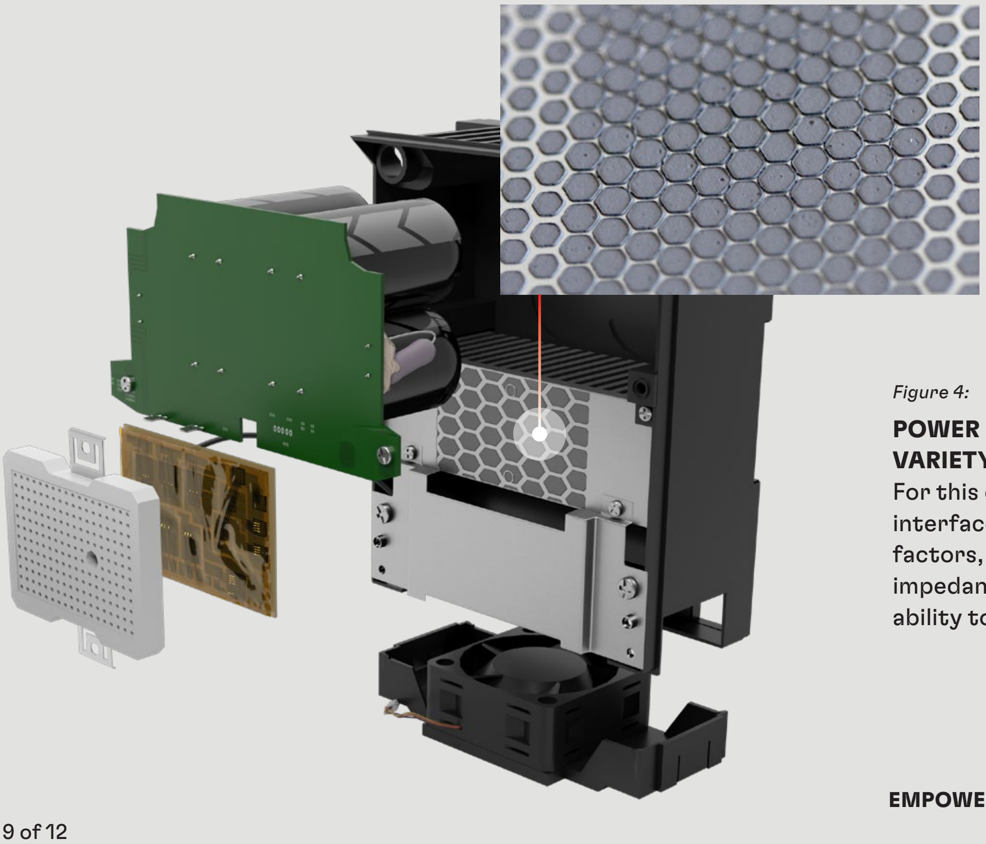


Figure 4:

POWER MODULE STRUCTURES MAY USE A VARIETY OF TIMs.
For this design, a phase change thermal interface material was selected due to several factors, including its thin bond line, low thermal impedance, high thermal cycling reliability, and ability to pre-apply the material at manufacture.

Moving through the list of core building blocks of TIM selection, the material analysis process for the power module example in *Figure 4* included these considerations:

Physical Form
This application required the ability to pre-apply the material in various patterns and thicknesses while achieving a thin bond line. In this case, the customer wanted a phase change material that could be pre-printed and dried on the power module before shipping, allowing simplified handling and end-product integration ease. Therefore, a paste-based printable phase change TIM was selected.

Resin System
Phase change TIMs are solid at room temperature and flow at the transition temperature to fill gaps and dissipate operational heat, extending lifetime performance which can increase field reliability and reduce field returns by 20% to 40%. With high operating temperatures and thermal cycling performance requirements, this phase change material's temperature stability of up to 150°C is vital for this application's reliability.

Filler
Based on thermal conductivity and thermal impedance requirements, LOCTITE TCP 7000 was chosen for this power module application. It has a thermal conductivity of 3.0 W/m-K and low thermal impedance compared to alternative options.

Viscosity / Rheology
As mentioned, the TIM material remains in a solid state until heated to its phase change temperature (45°C), when it flows and wets the interface. The phase change format – as opposed to thermal grease – helps avoid material migration ('pump out') over time. Because of the higher power density of this system, this attribute is beneficial in protecting long-term thermal performance and reliability.

Conclusion

Selection of TIM solutions for various industrial electronic applications is a complex exercise and involves many factors other than establishing a thermal conductivity value alone. Consider everything that plays a role in the thermal management ecosystem – from operating conditions to environmental exposure, reworkability requirements, and of course, thermal conductivity. When all factors are weighed, most electronics engineers ultimately realize that it is not only a TIM's lambda value that's important.

What often begins as a desire for the highest thermal conductivity available (our company has materials that range up to 40 W/m-K) generally results in a material solution with a significantly lower heat transfer rate once all aspects are considered.

As electronic content improvements in design and capability expand, it allows these essential electronic systems to be smaller, higher functioning, more efficient, and increasingly powerful. This, combined with 24/7 operational expectations in the smart factory, make thermal materials a key element of reliable performance.

Their effectiveness may well be determined by how thoughtfully they were selected.

Summary

APPLICATION CHALLENGE	REQUIRED TIM CHARACTERISTICS	PRODUCT SOLUTION
Thick gap between heat sinks and components	Soft, low-stress, high-conformity material, with high thermal conductivity and gap height	**GAP PAD® TIM**
Complex, non-flat architectures, multiple topographies, and high-volume manufacturing requirements	Adaptable with good wetting characteristics, soft, low thermal resistance, dispensable, adaptable volumes and patterns	**Liquid Gap Filler and Thermal Gel**
Thin gaps between component and heat sink, electrical isolation required, high voltage resistant dielectric strength	Thin, low thermal resistance material, clean/non-grease, durable, automatable	**SIL PAD® TIM**
High-power discrete components that require thermal control and bonding, mechanical solutions inefficient	Heat-dissipating material that also provides an alternative to mechanical bonding	**Thermal Adhesives**
High-voltage components that require protection but also effective heat management	Environmental protective benefits of traditional potting, but also heat management and electrical insulation	**Thermally Conductive Potting**
High-performance devices with low and high-power densities that require a good wet-out of both mechanical interfaces	Ultra-thin bond line, low interfacial resistance to maximize thermal management performance and lower thermal impedance to allow for better conductivity within an application	**Thermally Conductive Grease**
High power density, large component bodies with multiple thermal tolerances, emerging lidless multichip devices that require very low thermal resistance between the component and heat sink	Ultra-thin bond line, low pressure/low-stress material with minimal pump out concerns, low thermal impedance, can be applied at point of assembly or heat sink supplier	**Phase Change TIMs in paste or film formats**
Silicone-sensitive components (optics, sensors), gears or processes, silicone volatiles/outgassing or silica dust is a concern	Robust heat dissipation in the reduction/absence of silicone, reduces concerns of contamination exposure and protects sensitive components from residue interference	**Low-volatile silicone and silicon-free TIMs in a range of formats**

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DC-DC Power Converter
Power Module
Programmable Logic Controller (PLC)
AC/DC Power Supply

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