

# Liquid-Dispense Gap Fillers versus Thermal Pads: A Case Study on Thermal Performance

WHITE PAPER

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## ABSTRACT

A key to the advancement of high energy-density, lithium-ion, battery packs is effective management of heat generated during charge and discharge cycles. Heat is often managed by connecting battery cells and/or modules to a heat sink via a thermal interface material (TIM). The TIM promotes heat conduction by displacing any air that resides within the large gaps and microscopic rough surfaces that exist between the substrates to be bridged. In practice, battery manufacturers typically use one of two types of TIM products, i.e., a cure-in-place, liquid-dispense gap filler or a pre-cured thermal pad (also called gap pad), each of which has their pros and cons. The purpose of this study was to compare the thermal impedance of LORD CoolTherm™ gap fillers versus commercially available thermal pads having equivalent bulk thermal conductivities. Data from this and future studies on battery packs will better enable designers to develop more efficient and cost effective battery packs.

## INTRODUCTION

Currently there is a strong trend toward the electrification of vehicles in the transportation industry. In order for electric vehicles (EVs) to gain more acceptance in the market, the trend has been to increase the range and performance to be similar to current internal combustion engine vehicles. This puts a lot of pressure on the battery pack engineers to increase energy density. The increased density means more heat is being created in smaller volumes making thermal management a key issue for battery pack performance and design.

Figure 1 shows the three ways a battery pack can release or absorb heat, i.e., radiation, convection, and conduction. Conduction between battery packs and a cooling plate is the most widely utilized means of heating and/or cooling EV battery packs. The limiting factor for heat transfer by conduction is the

interface between components such as the battery module and the cold plate. These surfaces, although appearing smooth and flat to naked eye, are rough on the microscopic scale as depicted in Figure 2(a).

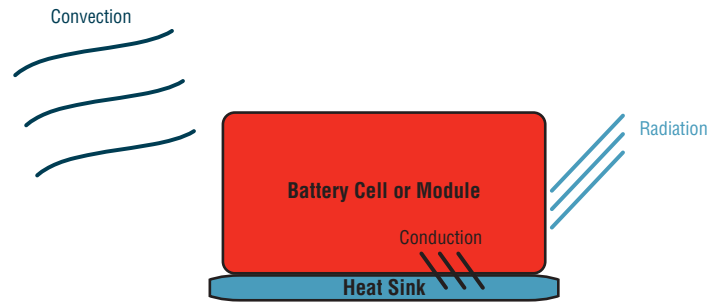


Figure 1: Methods of heat transfer within a battery cell or module

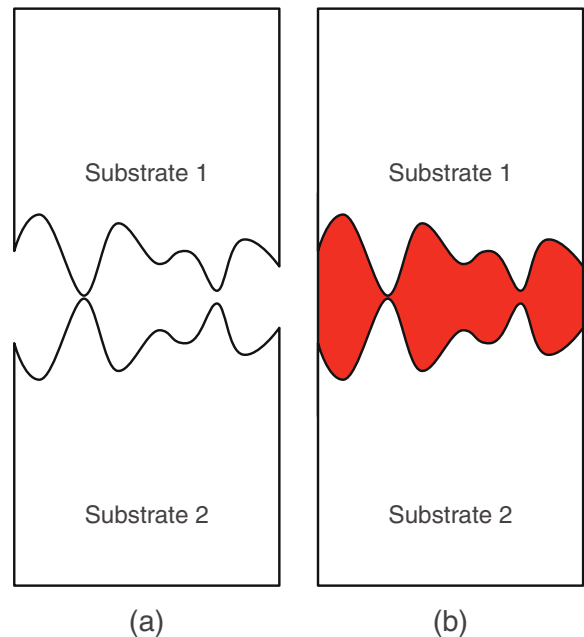


Figure 2: Microscopic depiction of interface formed between two solid surfaces containing (a) air and (b) a well-conforming TIM

The surface roughness leads to only a small fraction of the apparent surfaces coming in direct contact with one another, thereby entrapping air. To overcome this issue, TIMs are used to bridge the interfaces thereby displacing air and conforming to the microscopic surface roughness of the substrates as shown in Figure 2(b). It is also important to note that TIMs are designed to provide additional electrical insulation to further safeguard against any high voltage breakdown occurring between the energized battery and the often metallic heat sink.

In practice, battery manufacturers typically use one of two types of TIMs, i.e., a cure-in-place, liquid-dispense gap filler or a pre-cured thermal pad. Gap fillers are often applied by meter-mixing a 2-part system, dispensing on one of the two substrates, and pressing to the two substrates together to reach a specified thickness. The material is then allowed to cure to form a solid, but compliant interface. Thermal pads, on the other hand, are pre-cut to a desired shape, applied to one substrate, compressed down to a set thickness, and fixed in place. The applied compressive load forces the solid, yet compliant, pad to make intimate contact with the rough surfaces. The amount of pressure applied to the pad can have a large impact on its thermal resistance.

Given the inherent application and physical differences of cure-in-place, liquid-dispense gap fillers versus solid, pre-cured thermal pads, it was of interest to compare the steady state heat transfer characteristics of the two materials when mated against two solid substrates. Specifically, the thermal impedance of metal-TIM-metal sandwiches measured on two LORD CoolTherm gap fillers as compared to thermal impedances obtained on commercial solid thermal pads having equivalent bulk thermal conductivities. The data from this fundamental study and future application investigations on battery packs will better enable designers to develop more efficient and cost effective battery packs.

## HEAT TRANSFER TERMINOLOGY AND DEFINITIONS

A brief description of common heat transfer terminology and definitions for TIM materials is warranted before discussing the experimental methodology and results for this study. The ability for heat to transfer from a hot substrate to a cooler one will be governed by the thermal resistance of the bridging TIM. This resistance can be defined by the following equation:

$$R = \frac{\Delta T}{Q}$$

where  $R$  is the resistance of the TIM in degrees Celsius per watt ( $^{\circ}\text{C}/\text{W}$ ),  $\Delta T$  is the temperature difference in degrees Celsius ( $^{\circ}\text{C}$ ) between the hot and cold substrates, and  $Q$  is the heat flow in watts (W). (Note the temperature can also be expressed in Kelvin, K.) It is more common to use the definition of thermal impedance

of the interface which is very similar to above thermal resistance equation but takes into account the heat flux, i.e.,

$$\theta = \frac{\Delta T}{Q/A}$$

where  $A$  is the cross-sectional area in square meters ( $\text{m}^2$ ) of the interface.

The thermal impedance of the TIM is a reflection of two properties, the ability (or inability) of the TIM to transfer heat across the discrete interfaces of the substrates and the bulk thermal resistance of the TIM material; this can be represented mathematically as,

$$\theta = \theta_i + \frac{t}{k}$$

where  $\theta$  is the thermal impedance of the TIM bondline,  $\theta_i$  is the interfacial impedance of both the top and bottom interfaces of the bondline,  $t$  is the bondline thickness of the TIM, and  $k$  is the thermal conductivity of the TIM. In practice, the thermal impedance of the TIM is determined by measuring the  $\Delta T$  for a given steady state heat flux. The conductivity and interfacial impedance can be determined by measuring the thermal impedance over a series of TIM bondline thicknesses as illustrated in Figure 3. As previously mentioned, these individual parameters are especially important in assessing how well the heat is transferred both across the discrete interfaces and through the bulk of the TIM material itself. For example, a TIM material may have a high thermal impedance despite having a high thermal conductivity and thin bondline; this is often the result of the material's poor physical contact with one or both substrates and in-turn a high interfacial impedance,  $\theta_i$ . It is for reasons like these that demand the comparison of thermal impedance properties for gap fillers versus that of thermal pads.



**Figure 3: Determination of bulk thermal conductivity,  $k$ , (inverse slope) and thermal interfacial impedance,  $\theta_i$ , (y-intercept) from thermal impedance versus thickness measurements**

## EXPERIMENTAL

Table 1 lists the gap filler and thermal pad TIM materials along with key properties used in this study. The thermal pads were selected to have comparable thermal conductivity and hardness values to that of LORD CoolTherm SC-1200 and SC-1500 cure-in-place liquid gap fillers. A series of pads, of varying thickness, were acquired to span the typical bondline values encountered in between battery modules/packs and heat sinks.

**Table 1: List of gap filler and thermal pad TIM materials used in thermal impedance study**

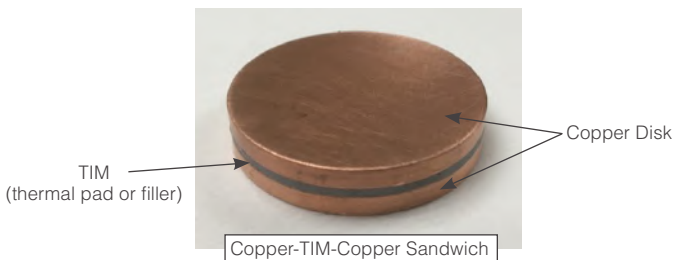
Product	Product Form	Supplier	Reported Conductivity (W/m·K)	Nominal Thickness (mm)	Shore Hardness
SC-1200	Gap Filler	LORD	2.0 <sup>(a)</sup>	NA	OO-85
SC-1500	Gap Filler	LORD	3.8 <sup>(a)</sup>	NA	OO-75
Thermal Pad 1	Thermal pad	Company 1	2.0 <sup>(b)</sup>	1, 2, 3	OO-45
Thermal Pad 2	Thermal pad	Company 1	4.0 <sup>(b)</sup>	1, 2, 3	OO-75

(a) Measured via ISO 22007 Hot Disk method

(b) Value reported on technical data sheet determined via ASTM D5470

Thermal impedance was measured according to ASTM D5470 using a 1400 TIM Tester from Analysis Tech. Copper was chosen to mimic the metallic surface of the heat sink while having very little thermal resistance contribution to the metal-TIM-metal measurements. The contribution of copper to the thermal impedance measurements was removed from the below reported values.

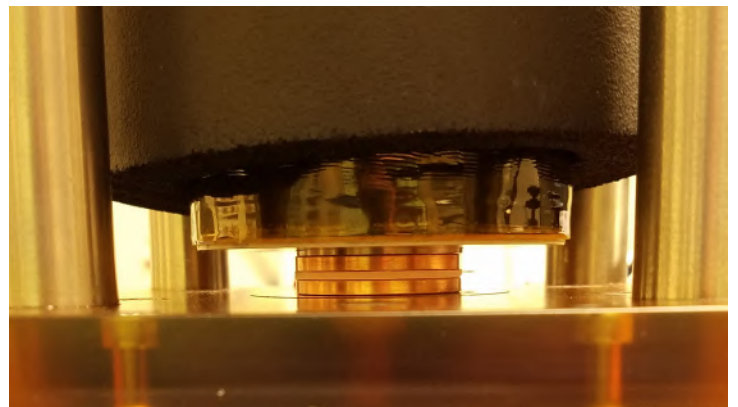
Copper-Gap Filler-Copper sandwiches were prepared by dispensing LORD CoolTherm SC-1200 and SC-1500 gap filler on top of flat copper disks measuring 3 mm in thickness and 33 mm in diameter. Samples were compressed to varying thicknesses and cured at room temperature before conducting thermal analysis. Copper-Thermal Pad-Copper sandwiches were prepared by cutting 33 mm disks from the supplied thermal pads and sandwiching them between the copper disks. The thickness of the pad along with the applied pressure determined the thickness of the bondline. Figure 4 shows a picture a Copper-TIM-Copper sandwich.



**Figure 4: Photo of Copper-TIM-Copper sandwich sample geometry used for thermal impedance testing**

Before measuring the thermal impedance of the TIM, the resistance of the copper substrates and the interfaces of the TIM tester platens at various pressures was determined. The bulk resistance of the copper was calculated from its thickness and reported conductivity of 398 W/m·K. The interfacial resistance of the platen interfaces was determined by measuring the thermal impedance of one copper disk that was wetted out on top and bottom with a drop of 200 cSt silicone fluid. This experiment was repeated at various pressures. The bulk resistance of the copper disk and the measured platen interfacial impedance were then subtracted out of Copper-TIM-Copper samples to get the impedance of just the TIM material.

The thermal impedance for gap fillers were measured at the lowest allowable pressure of 50 kPa on the TIM tester. In the case of the thermal pads, impedance measurements were tested over a series of pressures ranging from 50 to 650 kPa. This pressure range was used to capture a broad range of loads that could be applied to achieve good contact and given final bondline thickness. Figure 5 shows a picture of the Copper-TIM-Copper sandwich inside the TIM tester. A small amount of silicone oil was placed onto the interfaces between the copper sandwich and the TIM tester to ensure air was excluded from the test stack up.



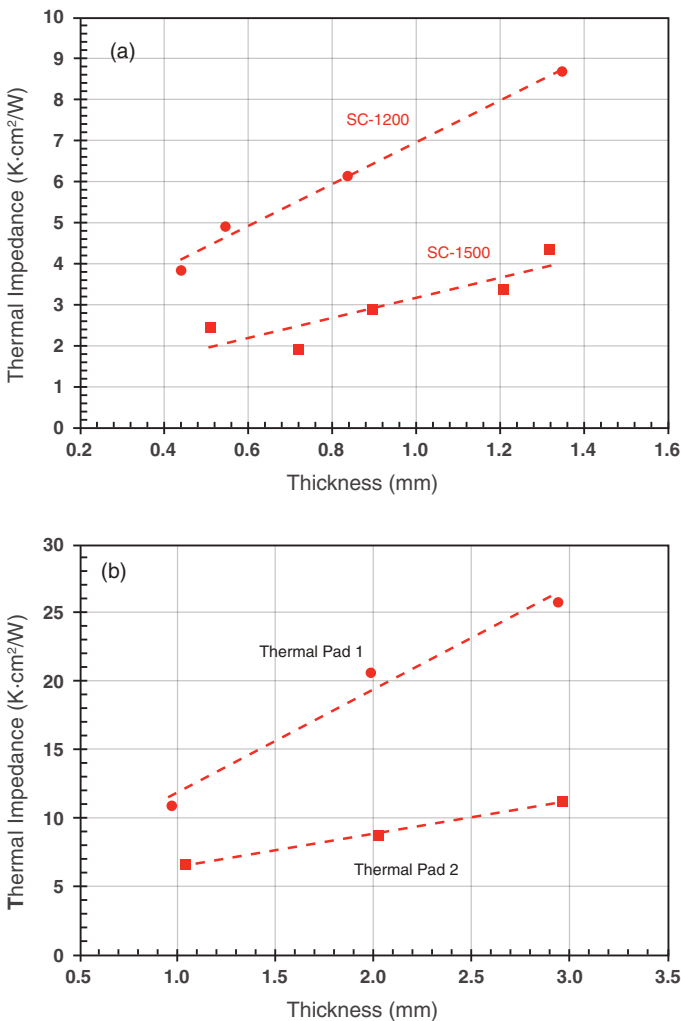
**Figure 5: Picture of Copper-TIM-Copper sandwich between the platens of the ASTM D5470 certified TIM tester**

## RESULTS AND DISCUSSION

The first step was to compare the measured conductivity of the four materials using the TIM tester to their reported values (see Table 1). Thermal impedance measurements were made at 50 kPa at multiple thicknesses. The resulting impedance values were plotted as a function of thickness with the inverse of the slope being the thermal conductivity (see Figure 6 and Table 2). The values measured for the gap fillers fall closely to that of values reported by LORD using the ISO 22007 Hot Disk method. For the thermal pads, Thermal Pad 2 is in close agreement to that of technical data sheet (TDS) of Company 1; however, Thermal Pad 1 measured about 0.7 W/m·K lower than its reported value.

It is unclear as to why the reported value from Company 1 is significantly higher than measured here. It is possible that conductivity reported on the TDS was measured by Company 1 at a pressure higher than 50 kPa. Unfortunately, the specific test details were not provided on the TDS.

It is also worth noting the differences in interfacial impedance obtained on the pads versus the gap fillers, which is reflected in the y-intercepts of the lines in Figure 6 and their values shown in Table 2. Thermal Pad 1 exhibited 2.3 fold higher interfacial impedance than that of the CoolTherm SC-1200 gap filler, while the interfacial impedance for Thermal Pad 2 is nearly 5.5 fold higher than that of CoolTherm SC-1500 gap filler. The significantly lower values for the liquid gap fillers are likely due to the liquid gap filler being able to displace the air, thus providing better contact and lower interfacial impedance.

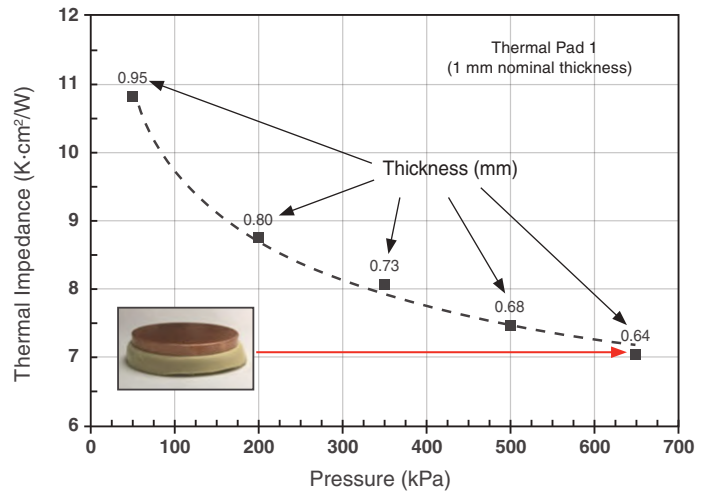


**Figure 6: Thermal impedance of (a) LORD gap fillers and (b) commercial thermal pads as a function of thickness at P = 50 kPa**

**Table 2: Thermal conductivity and interfacial impedance values measured on LORD gap fillers and commercial thermal pads**

Product	Measured Thermal Conductivity - Inverse of Slope (W/m·K)	Measured Interfacial Impedance - y-Intercept (K·cm²/W)
SC-1200	2.0	1.86
SC-1500	4.1	0.75
Thermal Pad 1	1.3	4.31
Thermal Pad 2	4.2	4.10

It was also of interest to determine the effect of pressure on the thickness and impedance of thermal pads as shown in Figure 7 for Thermal Pad 1. As expected, thermal impedance and thickness decrease with increasing pressure. However, the pressures needed to obtain these low impedance values are impractical. Specifically, Thermal Pad 1 had to be compressed from 1 mm to 0.64 mm using 650 kPa of pressure to have a comparable thermal impedance as CoolTherm SC-1200 gap filler at 1 mm at 50 kPa. Such high pressures risk damage to the battery module or heat sink during assembly.

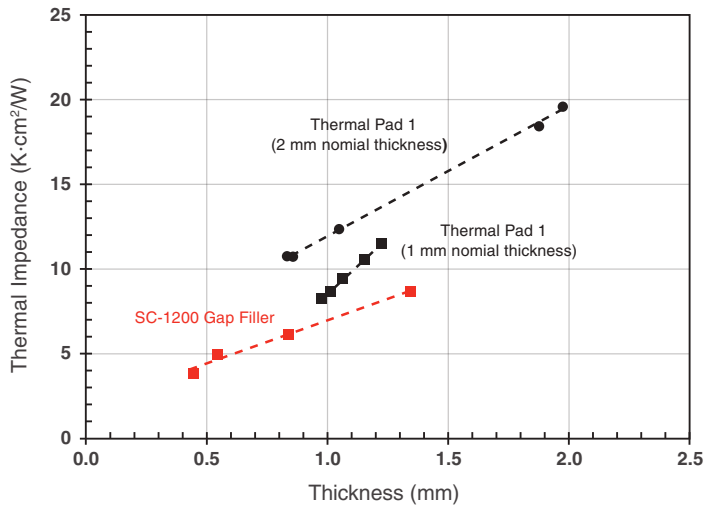


**Figure 7: The effect of pressure on the thermal impedance of Thermal Pad 1. The inset photo was taken of the sample following the measurement at 650 kPa.**

Figure 8 compares the thermal impedance of Thermal Pad 1 versus CoolTherm SC-1200 gap filler as a function of thickness. Note, the thermal pads were compressed to different thicknesses, whereas the gap fillers were cured at different thicknesses and analyzed at a fixed pressure of 50 kPa; this comparison was made to best mimic a real world scenario. Interestingly, thermal impedance values for the thermal pad are significantly higher than the gap filler for equal thicknesses. This difference is largely a reflection of the material's significantly higher interfacial impedance as previously reported in Table 2; however, some of the difference can be attributed to



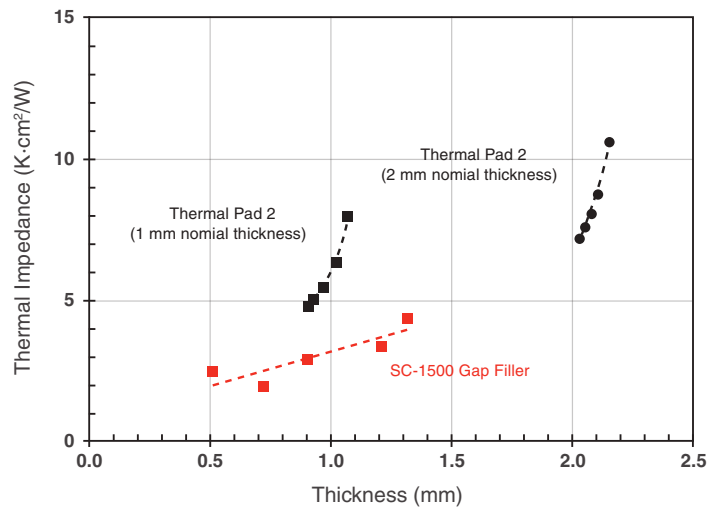
the lower thermal conductivity of the thermal pad. In addition, the thickness dependency for pads is much more pronounced especially for the thermal pad having a nominal starting thickness of 1 mm. For example, the thermal impedance of the 1 mm Thermal Pad 1 at 1.2 mm is over 3  $\text{K}\cdot\text{cm}^2/\text{W}$  higher than the value obtained at the highly compressed 0.95 mm thickness.



**Figure 8: The effect of thickness on thermal impedance of Thermal Pad 1 and CoolTherm SC-1200 gap filler**

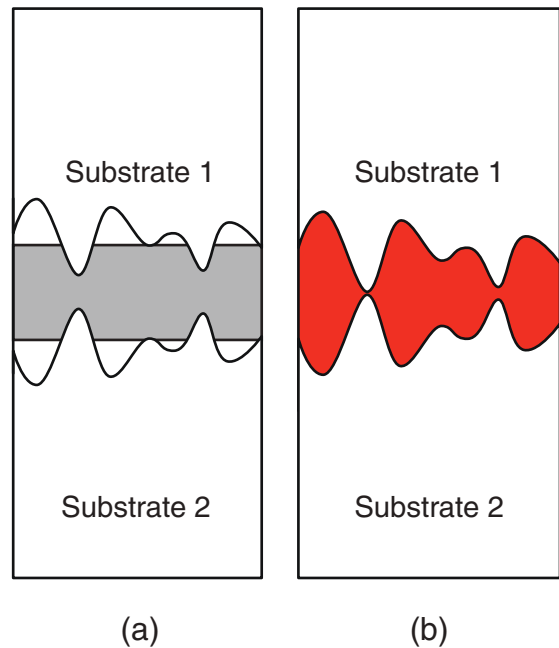
It is important to note that the y-intercepts for Thermal Pad 1 in Figure 8 are not the interfacial impedance values. Interfacial impedance has to be determined at a fixed pressure at multiple TIM thickness. In this study, higher pressures were applied to compress the pad to smaller bondline thicknesses. This will also cause the interfacial impedance to change. In addition, the thermal conductivity may also change with increasing pressure. A downside of going to high pressures, as previously stated, is one risks exceeding the allowable compressive forces on the device or part that needs to be cooled.

Similar conclusions can be drawn in the comparison of Thermal Pad 2 with CoolTherm SC-1500 gap filler when plotting thermal impedance versus thickness (see Figure 9). The thermal pads have significantly higher impedance values as compared to the gap filler. Moreover, the thickness dependency is even more pronounced. For example, the impedance increases  $\sim 3.2 \text{ K}\cdot\text{cm}^2/\text{W}$  over just 0.17 mm for the pad with a starting thickness of nominally 1 mm. This very high slope is attributed to the material's higher modulus as compared to the more compliant Thermal Pad 1. Also, the pad is only capable of bridging a small range of gaps. The overall higher impedance is once again a reflection of the significantly higher interfacial impedance of the pad as compared to the gap filler. Interestingly, the Thermal Pad 2 impedance values are near that of CoolTherm SC-1200 gap filler at equivalent thickness despite the pad being  $\sim 2\text{X}$  the bulk conductivity of the gap filler.



**Figure 9: The effect of thickness on thermal impedance of Thermal Pad 2 and CoolTherm SC-1500 gap filler**

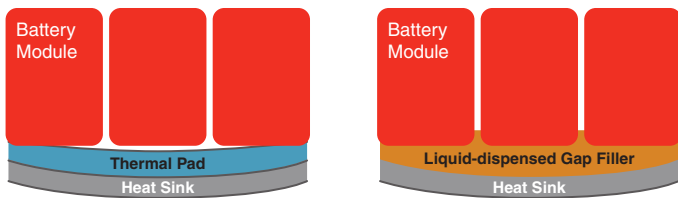
The large aforementioned differences in thermal performance of gap fillers versus thermal pads can be explained by the ability of the TIM material to conform to microscopically rough surfaces. Unlike solid thermal pads, liquid-dispense gap fillers can readily flow into the small valleys, thereby creating more intimate contact with the surface and in turn allowing more efficient transfer of heat between the upper and lower substrates. Figure 10 illustrates the differences in conformability between the two product forms.



**Figure 10: Illustration of the lack of microscopic conformability of (a) solid thermal pads relative to (b) liquid-dispense gap fillers**

In addition to microscopic conformability, liquid-dispense gap fillers can much better accommodate macroscopic variations in thickness across the length of a bondline. It is not uncommon for bondlines to vary by several millimeters across the length of a

battery pack due to tolerances in substrate planarity and battery module heights. Thermal pads are limited in this regard as their height is fixed and force must be applied to the pad in order for it to conform to varying heights. In addition, the forces along the bondline will vary significantly, lead to large differences in local thermal impedance and, in turn, produce local hot spots. Liquid-dispense gap fillers, however, can bridge large gaps without the need to apply large forces that add stress to the design, maintain a more consistent interfacial impedance, and, in turn, minimize hot spots. Figure 11 illustrates the conformability of thermal pads versus liquid-dispense gap fillers when dealing with large differences in bondline thickness as encountered in EV battery packs.



**Figure 11: The effect of variable bondline thickness on the conformability of thermal pads (left) versus liquid-dispense gap fillers (right)**

In addition to the thermal differences, there are also manufacturing considerations. Thermal pads are made in large sheets that then need to be cut into the desired shape. This results in waste because the remnants are not the correct size or shape to be

used in the pack. Another consideration is that the thermal pads tend to be made of low Tg (glass transition temperature) polymers to allow them to flow into the microscopic valleys as much as possible. This leads to sticky surfaces that will require a release liner on both sides of the pad. The large dimensions of the thermal pads used in EV battery packs also pose difficulty with automated manufacturing processes. Liquid-dispense gap fillers are well suited for high volume production and are easily automated using meter mix dispense (MMD) systems. Another advantage of liquid-dispense gap fillers is that it can easily accommodate design changes by reprogramming the MMD dispense pattern. Table 3 summarizes the advantages of liquid-dispense gap fillers over gap pads.

## CONCLUSIONS

Steady state thermal analyses show that LORD liquid-dispense gap fillers provide lower thermal impedance than thermal pads having comparable bulk thermal conductivity and thickness. This result is largely due to the ability of the gap filler to readily conform to microscopically rough surfaces of the adjoining substrates which consequently greatly lowers the interfacial impedance. This conformability effect was found to be quite pronounced in that the thermal impedance of CoolTherm SC-1200 gap filler at 1mm is comparable to Thermal Pad 2 despite the gap filler being 2X lower in conductivity, i.e., 2 versus 4 W/m·K, respectively. Better thermal performance coupled with ease of assembly, low applied forces, ability to span large, variable bond lines, and lower cost make gap fillers a logical choice as a TIM material.

**Table 3: Comparison of key attributes for thermal pads versus liquid-dispense gap fillers**

Comparison	Thermal Pad	Liquid-Dispense Gap Filler	Detail
Relative Cost	High	Low	Manufacturing process for pads leads to costly scrap, i.e. die cut waste.
Heat Dissipation	Good	Best	Gap fillers can flow into the microscopic surface roughness due to their liquid nature. Better flow leads to lower thermal interfacial impedance at each surface.  Gap fillers also cure to form a cross-linked network, thereby eliminating any issues with bleed and pump-out of the TIM from the bondline.
Air Entrapment	Frequent	Negligible	
Design Freedom	Fixed	Highly Flexible	Hardness and working time of gap fillers can be adjusted using mix ratio of the gap filler's two parts.  The dispense pattern of gap fillers can be manipulated to use as little material as possible and to allow heat flow in a given location.  Unlike liquid-dispense gap fillers, the thermal conductivity of a thermal pad can be sensitive to local differences in applied pressure due to uneven surfaces across the bondline thickness.
Rework	Possible	Possible	Both types of thermal materials can be reworked. Thermal pads tend to be easier to remove than liquid-dispense gap fillers since thermal pads are less conforming to microscopic crevices.  Clean up is more involved for liquid-dispense gap fillers after cure. Thermal pads come off as one piece.
Manufacturing	Difficult	Good	Large form-factor thermal pads can be difficult to apply without trapping air.  Automation is difficult for thermal pads.  Liquid-dispense gap fillers require MMD equipment, but are easily automated.

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