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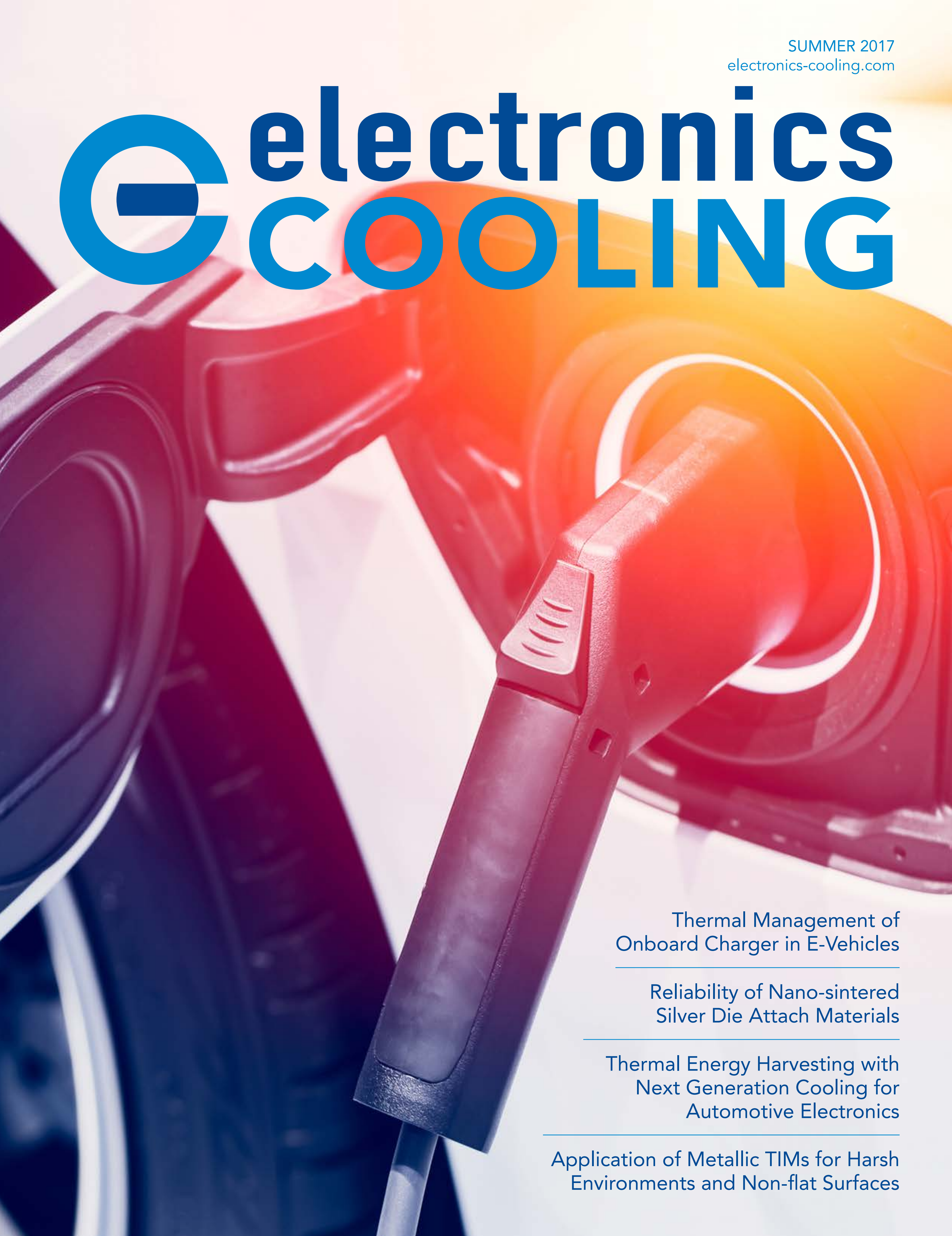

Thermal Management of Onboard Charger in E-Vehicles

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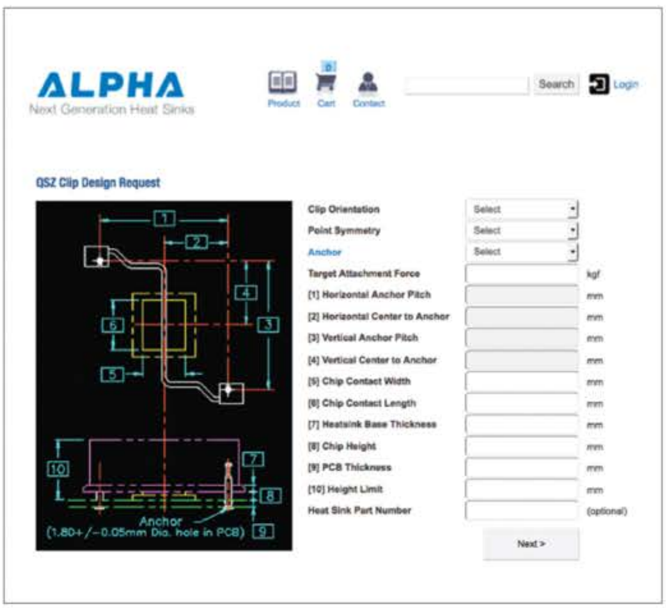

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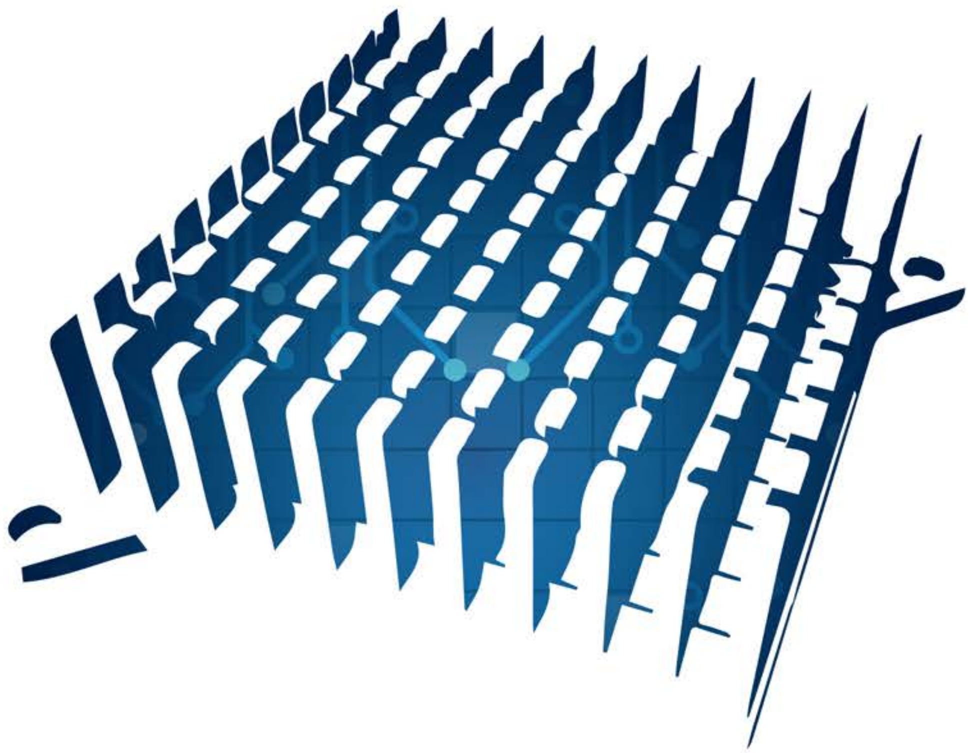

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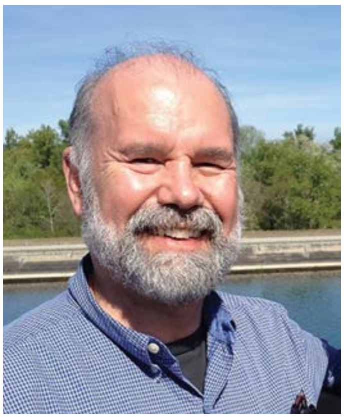

Dear Reader,

We members of the Editorial Board of ElectronicsCooling® have been working closely with our publisher, ITEM Media, to bring to you issues that have a tighter technical focus than we did in years past. This particular issue concentrates on cooling technologies for automotive and for power devices.

As we are well aware, there are many efforts around the world directed at reducing our dependence on fossil fuels in our power sources and migrating to more sustainable forms of power generation. This is occurring with large-scale power generation and at a smaller scale in transportation, with the increased use of electric cars and trucks.

The path to greater use of electric vehicles relies not only on improved battery technology and a more widely distributed recharging infrastructure, it also depends on greater energy efficiencies within the vehicle itself, both during the charging process and while on the road. We have two articles in this issue that deal with two key challenges: "Thermal management of Onboard Chargers in E-Vehicles," and "Thermal Energy Harvesting with Next Generation Cooling for Automotive Electronics."

An important factor in determining the successful deployment of power devices in electric vehicles as well as in many other fields is the choice of an appropriate thermal interface material (TIM) that will meet the thermal performance and reliability requirements of a particular application. The following two articles deal with some of the latest developments in TIM characterization and development: "Reliability of Nano-sintered Silver Die Attach Materials," and "Application of Metallic TIMs for Harsh Environments and Non-flat Surfaces."

To round out the issue, we offer you a Tech Brief devoted to the ever-growing area of wearable electronics: "Thermal Management and Safety Regulation of Smart Watches." Finally we have a very informative installment of Thermal Facts and Fairy Tales, to help you separate fact from fiction in applying a popular rule of thumb: "Does a 10°C increase in temperature really reduce the life of electronics by half?"

We hope you enjoy the issue and look forward to getting your feedback.

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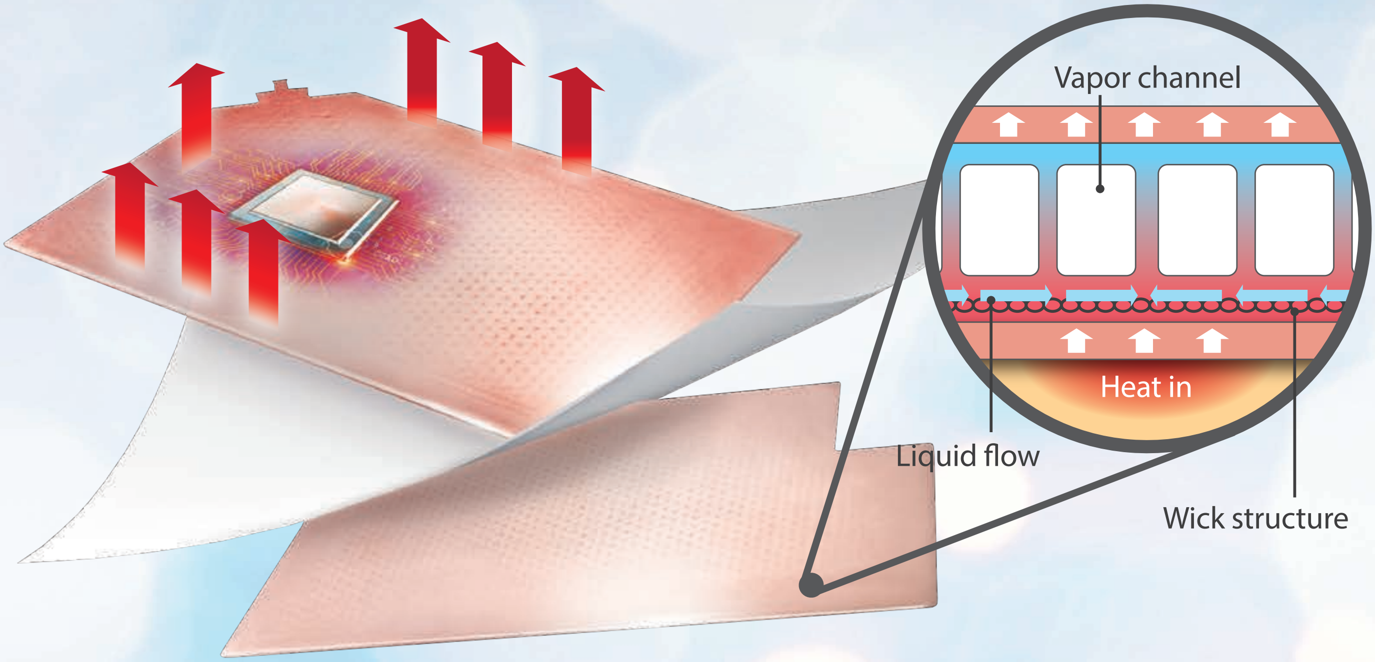

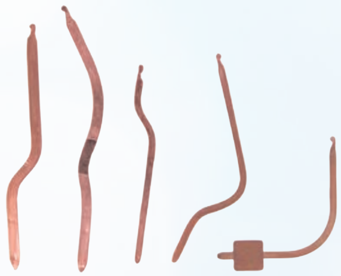

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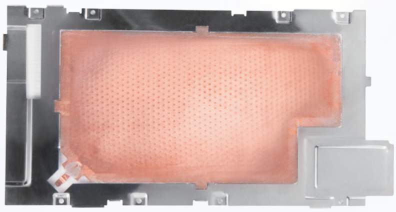

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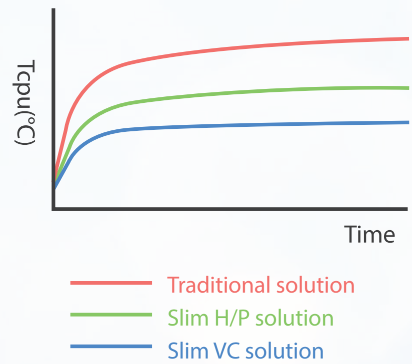

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http://www.battery-expo.com/index.php?lang=en

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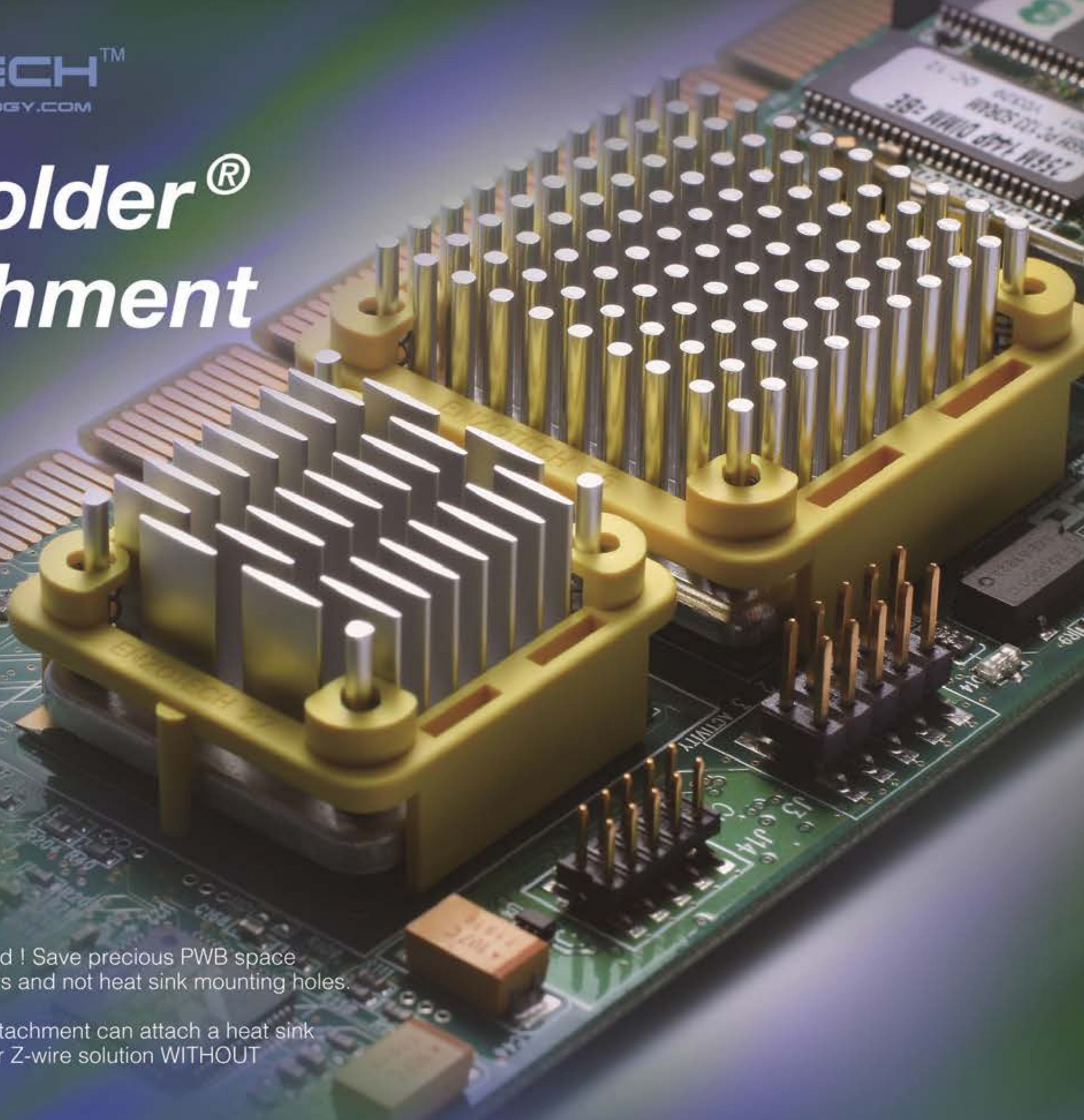

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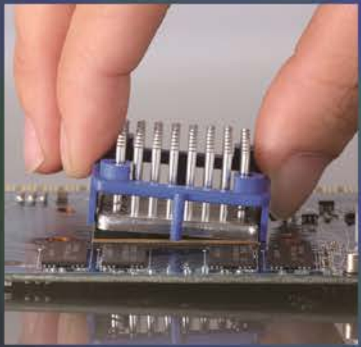

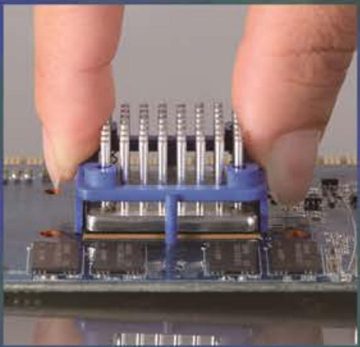

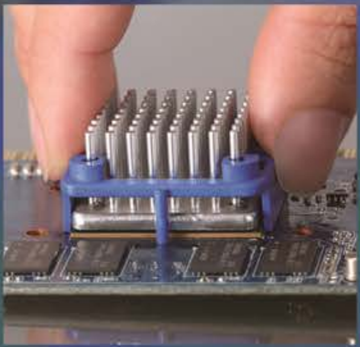

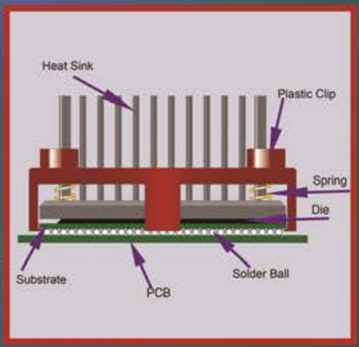

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Does a 10°C Increase in Temperature Really Reduce the Life of Electronics by Half?

Ross Wilcoxon
Principal Mechanical Engineer
Rockwell Collins Advanced Technology Center

This may seem like a silly question to ask in a magazine entitled "Electronics Cooling", but why do we really care what temperature of electronics really is, anyway? The simple answer to that question is that it is universally recognized that electronics reliability when devices are too hot for too long of a time. The difficult answers to the question are in defining exactly what 'too hot' and 'too long' are. Since the objective of the field of electronics cooling is ultimately to ensure that electronics are reliable, it is worth thinking about the relationship between temperature and reliability.

If one were to ask people in the electronics industry how device temperature and reliability are related, it is likely that the most common response would be something along the lines of "the rule of thumb is that every 10°C increase in temperature reduces component life by half". Using a common search engine, the search term "electronics reliability 10 degrees" yielded six references out of the first ten that mention that rule of thumb. Four of those references described how the rule is used while two described why it is incorrect.

The "10°C increase = half life" rule is based on applying the Arrhenius equation, which relates the rate of chemical reactions, R, to temperature, to failure mechanisms that occur in electronics. In applying the Arrhenius equation to electronics, it is assumed that the rate of chemical reaction corresponds to the damage to devices over time and the equation can then be used to compare the damage accumulated over time for different operating temperatures. The Arrhenius equation can be written as:

$$R = \frac{damage}{time} = A\exp\left(\frac{-E_A}{kT}\right) \quad (1)$$

where A is a constant related to reaction, E_A is the activation energy associated with the reaction, k is the Boltzmann constant (8.617×10−5 eV/K) and T is the absolute temperature.

Equation {1} can be rearranged to develop an acceleration factor (AF) that relates the life of a component when it is operated at its use temperature, Tuse to a test time at temperature T_{test}.

$$AF = \frac{time_{use}}{time_{test}} = \exp\left(\frac{E_A}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{test}}\right)\right) \quad (2)$$

The activation energies for many different failure mechanisms in electronics have been reported in documents such as Ref.[1]. Many mechanisms have reported activation energies in the range of ~0.6-1eV/K. If T_{test} is set to 10K above T_{use}, *Equation {2}* can be used to estimate the acceleration factor as a function of T_{use} for different activation energies. For an activation energy of 0.8 eV/K over the temperature range of ~75-125°C, the resulting AF is ~2 – which leads to the "10°C increase = half life" rule of thumb.

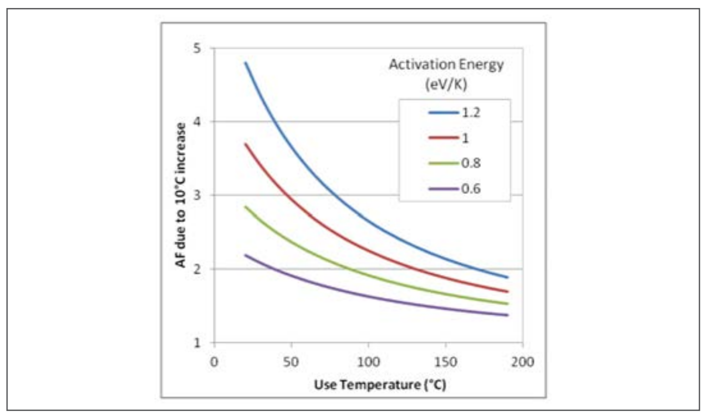

Figure 1. Acceleration Factor for a 10°C Temperature Increase

This approach for using elevated temperature testing to estimate life time of electronics was popularized by MIL-HDBK-217, which was first published in 1965. The earliest reference that I have personally seen to a rule of thumb that relates a higher operating temperature to reducing operating life by half was in a proposal prepared by Collins Radio in 1968 [2]. Two interesting aspects of the information in that proposal were that a) 'new' results from MIL-HDBK-217 show that a 15°C increase in temperature reduces life by half and b) thermal cycling between minimum and maximum environmental temperatures decreased life by a factor of 8x. This suggest that from its birth it was recognized that the '10C=1/2' rule of thumb was a rough approximation and factors other than operating temperature could very much affect electronics reliability.

The use of the Arrhenius equation in general, and the '10C=1/2' rule in particular, has been criticized for the fact that it ignores significant failure modes that are not due simply to the maximum operating temperature [3, 4, 5]. Others have recognized the need to account for the multiple failure modes and have suggested statistical methods to define effective activation energies [6, 7]. The reliability of an electronics device is such a complicated issue that, even if the '10C=1/2' rule is correct for a specific failure mechanism, it may be irrelevant for another. As an example, testing on a commercial resistive switching random access memory device found that it had an activation energy of 1.13 eV/K. With this activation energy, *Equation {2}* tells that the effect of increasing operating temperature from 45°C to 55°C would give an acceleration factor of more than 2; it would actually be ~3.8. However, using the researchers' conclusion that the device could operate for 10 years at 85°C, this increase in temperature from 45 to 55°C would alter the predicted life from ~3800 years to ~1000 years. Presumably, other failure mechanisms would likely become relevant long before the maximum operating temperature would become of concern. In this case, to paraphrase Obi-Wan Kenobi, "These aren't the failure mechanisms you're looking for".

In general, the Arrhenius model is likely appropriate for certain failure mechanisms including corrosion, electromigration and certain manufacturing defects [1], but is not suitable for other significant failure modes, such as the formation of conductive filaments, contact interface stress relaxation, and fatigue of package-to-board level interconnect [5]. Ref [9] reviews electronics failure modes that are influenced by temperature and discusses which of them can be modeled with the Arrhenius equation.

While it would be comforting to have a simple equation that can be used to quickly determine 'how hot is too hot?' in electronics, we live in a world that is a bit more complicated than that. Failing to recognize the severe constraints of the '10C=1/2' rule of thumb can lead to problems. For example, many years ago a study showed that a heat pipe degraded over time, with the degradation following the Arrhenius equation. The author of that study then assumed that this result meant that the heat pipe followed the '10C=1/2' rule and provided a reliability prediction guideline that propagated through a few publications. The original data provided sufficient data to estimate the activation energy and acceleration factors that significantly differed from the assumed rule of thumb [10].

While the Arrhenius-based reliability approach certainly has its limitations, when it is used correctly and its assumptions are understood it can provide reasonable predictions. An interesting, albeit dated, conference publication described how the reliability of avionics systems used in the F-15D aircraft changed when the F-15E, which provided 15°C cooler air to the electronics, was introduced. The mean time between failure (MTBF) for that fielded equipment improved with the lower temperatures by amounts equal to, or better than, the improvements predicted using MIL-HDBK-217 [10].

As many others before me have explained in detail, complex issues like predicting component reliability require complex approaches such as Physics of Failure to account for the combined effects. An overview of that analysis approach is beyond the scope of this article; the goal here was simply to point out that that the '10C=1/2' rule, is really only valid for a failure mechanism with a specific combination of activation energy / operating temperature and only if that is the mechanism that leads to failure in a component.

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Thermal Management of Onboard Charger in E-Vehicles

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Electric vehicles are poised for a rapid growth phase with the combined effect of longer range, lower battery cost and faster charging rate. In particular, sales of plug-in electric vehicles (PEV) have tripled since 2013 and continue to grow at over 40% a year. It is expected that at these growth rates, 8 out of 10 new cars sold globally in 2030 will be a PEV. In some countries like Norway, nearly a third of new cars sold currently are electric.

With the rapid adoption of PEVs comes some unique thermal challenges. The PEV has different types of heat loads than internal combustion vehicles, particularly in the batteries and on-board electronics for power conversion and management that include the on-board charger, DC to DC converter and inverter. While battery thermal management deals with bulk heat removal, the power electronics requires heat removal from tightly-packed, concentrated heat loads. Since battery thermal management is an important topic by itself and has already been addressed in several publications [1], the main focus of this article is on thermal management of the power electronics components.

One of the key challenges in PEVs is the time required for charging the batteries and the availability of power outlets. Charging of PEVs is classified into *Levels 1, 2 and 3* by the Society of Automotive Engineers.

- Level 1 – Slow charging at 120/240V AC and 15 amps using the standard available household power outlets up to 3.3kW. The AC to DC power conversion is done on board.
- Level 2 – Medium rate charging using 240V AC and 60 amps up to 14.4 kilowatts from power outlets specifically made for PEV charging. The AC to DC power conversion is done on board.
- Level 3 – Fast charging used specially for PEV charging rated over 14.4 kilowatts. In this case, the AC to DC power conversion is usually done off-board.

On-board chargers, used primarily for AC to DC power conversion, contain several types of power electronic devices like MOSFETs, diodes and magnetics. The advantage of having an on-board charger (compared to off-board) is that the vehicle can be charged from AC power outlets. However, it also requires the vehicle to carry the extra weight of the power electronics and heat sinks. Newer designs have integrated multiple functionalities into the charger to include bi-directional power conversion [4] as well as DC to DC conversion. This makes the overall design more compact. *Figure 1* illustrates the multiple functionalities that can be included in the on board charger along with the different levels of charging [3].

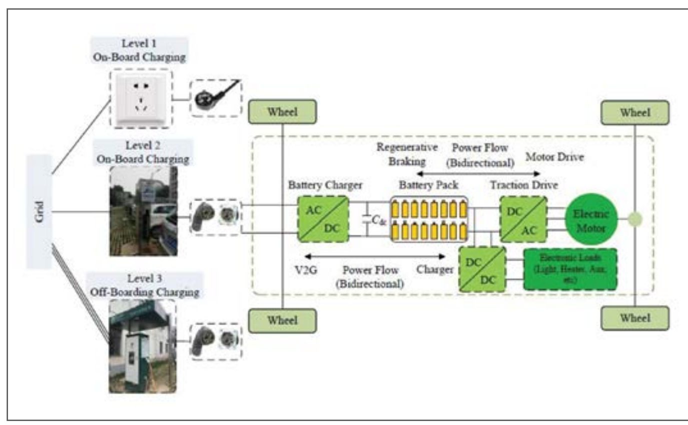

Figure 1: Multi-functional roles of an on board PEV charger. Source: Energies, 2016, 9, 493 [3]

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Dr. Avijit Goswami is the Director of the India Design Center at Aavid Thermalloy. He has over 15 years' experience in the field of thermal management in a wide variety of domains including power, networking, aerospace and electric vehicles. Dr. Goswami holds a Ph.D. in Aeronautical Engineering from Stanford University and a B.Tech. from the Indian Institute of Technology, Mumbai. In addition to thermal management, he has keen interest in the area of of clean energy and electric transportation.

The first step in properly defining the thermal problem is to estimate the power dissipation from the electronic components in the charger. The overall power conversion efficiency (AC to DC) is usually in the range of 93-94% which means that a 3.3kW charger (Level 1 charging at 220V, 15 Amps) will dissipate around 250W. Integrated, multi-functional chargers will have additional power loads due to DC-DC conversion. However, since the AC-DC load (charging mode) and DC-DC load (drive mode) do not occur at the same time, the loads do not add up. This makes the thermal management of a multi-functional charger easier in being able to share a common heat sink which reduces overall size, weight and cost. The package type for the MOSFETs is usually TO-247 or similar and the power densities at the device level can be in the range of 10-30 W/cm^2 (*Level 1*). The maximum allowable junction temperature for these devices is 150 ^{o}C (Tj-max) with an R-jc (junction-to-case thermal resistance) of around 1 C/W.

The charger electronics need to be packaged inside an enclosure which has to be sealed to prevent environmental contamination. This requires that the heat loads be thermally connected to the enclosure walls in order to efficiently dissipate the heat. The enclosure wall, therefore, need to function as a heat sink in order to dissipate the heat to the outside air (or liquid). To ensure that the heat loads are thermally connected to the enclosure wall, a suitable thermal interface material which provides not only good thermal conduction but also the required electrical insulation between the device and the enclosure must be selected. The outside ambient air temperature can be as high as 50C (worst case scenario lik).

At *Level 1* charging, the required R-sa (sink-to-ambient thermal resistance) for the heat sink should be less than 0.24 ^{o}C/W for a 3.3kW charger based on the above thermal parameters. *Figure 2* shows the thermal resistance network for multiple power devices mounted to a common heat sink which was used to calculate the required R-sa.

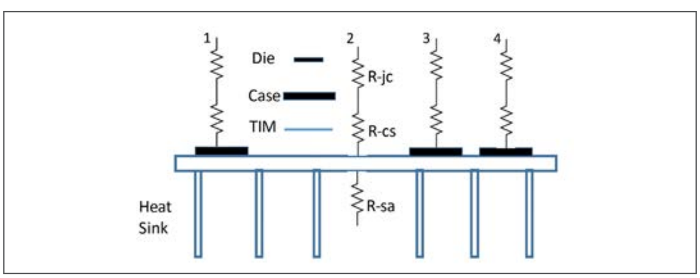

Figure 2: Thermal resistance network for multiple power devices (with powers P1 to P4) mounted to a common heat sink

For this relatively low power case, the heat load can be easily removed by forced air convection from the outside of the enclosure walls using a fan. Considering that the charging load occurs when the vehicle is stationary, there is no additional airflow benefit due to vehicle movement. Since there is no need to use the vehicle liquid cooling systems at *Level 1*, the systems integrator has greater flexibility on how to position the charger inside the vehicle. The weight of the charger can be significantly reduced by adding heat pipes to the heat sink base to spread the heat from the concentrated heat loads. The weight (& space) savings can be a double bonus in terms of increased vehicle range and lesser space requirement. Heat pipes can also be used to extend the feasibility of air cooling to higher power densities. *Figure 3* shows an example of a heat pipe heat sink assembly for power electronics applications.

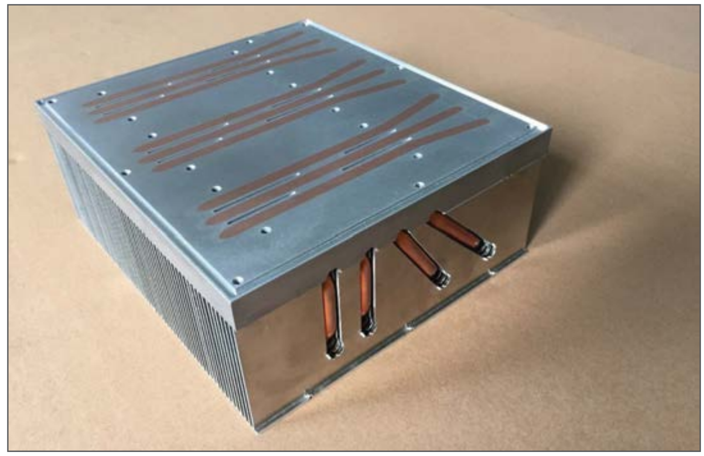

Figure 3: Example of heat pipe assembly for power electronics. Courtesy: Aavid

It includes multiple heat pipes embedded into the aluminum base for better heat spreading from concentrated heat loads. Heat pipes are also used to transport heat into the aluminum fins for better fin efficiency.

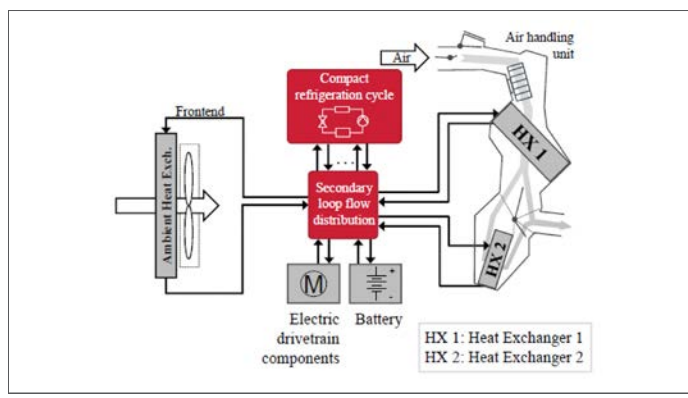

Figure 4: Example of a system level cooling architecture for electric vehicle. Source: Weustenfeld et al, Audi AG, Germany [5]

As the vehicle size and range increase, the battery size and consequently the charger power requirement also increase. This is compounded by the trend towards faster charging (*Level 2* and *Level 3*). As a result, the charger power dissipation increases and the R-sa requirement for the heat sink becomes more stringent making it necessary to rely on the vehicle liquid cooling systems to provide chilled liquid. The thermal solution for the charger, therefore, needs to take into account the system level cooling constraints such as available liquid flow rate/pressure drop and inlet liquid temperature before considering the component level cooling. *Figure 4* shows a typical system level cooling architecture for a PEV [5].

The system consists of a central refrigeration system that is cooled by a radiator and provides chilled liquid to multiple sub systems – like HVAC, batteries, chargers and other electronic components. These sub systems have their own heat exchangers, pumps and controllers to provide the required cooling capacity for their respective heat loads. At the component level, a suitable liquid cold plate (LCP) is required to cool the heat loads in the charger. *Figure 5* shows some of the commonly available LCP design options that can be used to extract the component heat loads.

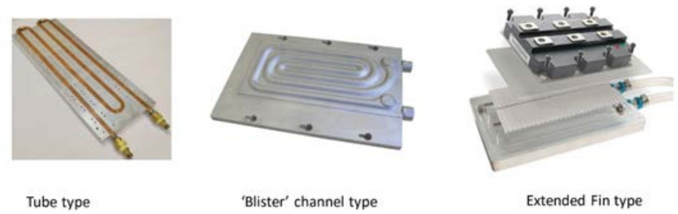

Figure 5: Examples of common types of liquid cold plates for cooling power devices. Courtesy: Aavid

While the tube and channel types can be used for lower power densities, the extended fin type is more suitable for higher power densities. The final selection of the LCP type depends on a variety of factors and the LCP design typically must be customized to address the layout of heat loads, power density, pressure drop constraints and material compatibility with the rest of the cooling system. It also need to be mechanically integrated into the charger enclosure (see *Figure 6*) to ensure that the electronic components are sealed.

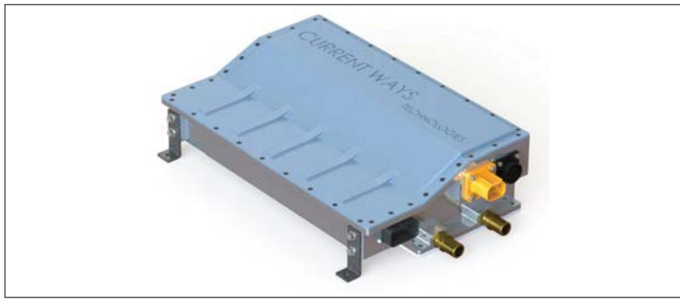

Figure 6: Example of a 6.6 kW EV charger with integrated liquid cold plate. Source: Current Ways Technologies

If current trends continue, it is expected that the requirement of fast charging (*Level 3*) will continue to accelerate. At very high power levels, it is likely that the AC-DC power conversion will be carried out off-board to avoid the additional space and weight required in the vehicle. For example, the Tesla Supercharger can provide 120 kW of DC power from the charging station and charge the Model S up to 50% in 30 minutes. However, until these Supercharging DC stations become as ubiquitous as gas stations, it is likely that PEVs will continue to carry an on-board charger to provide the flexibility for charging from more commonly available AC power outlets [2]. The future thermal management of on board chargers will likely evolve to use high-end LCPs integrated into the charger enclosure along with intelligent interfaces with the vehicle liquid cooling system. Also, the thermal engineer will have to engage very early in the vehicle design cycle to be able to dissipate all the heat loads efficiently including charger, inverter and batteries.

ACKNOWLEDGEMENTS

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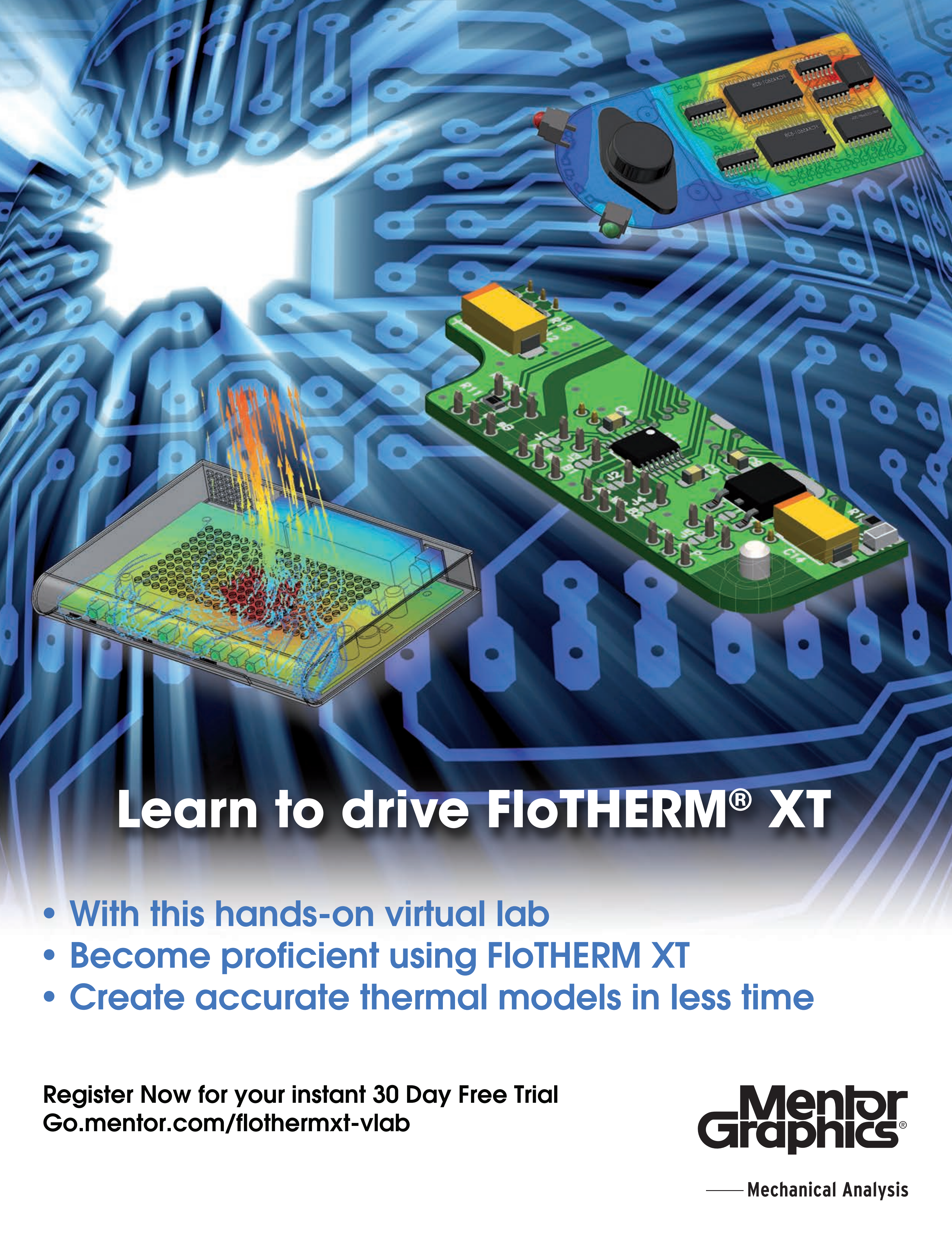
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Reliability of Nano-sintered Silver Die Attach Materials

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INTRODUCTION

Die attach can play a significant role in the package level thermal resistance of wire bonded devices. Die with moderate heat flux can often be attached to the carrier substrate with organic, Silver Filled Die Attach (SFDA) materials that require relatively benign processing requirements and temperatures. However, the higher power densities seen in components such as power inverters drive designers to use materials that require higher processing temperatures, such as soldering, which can impose significant residual stresses.

Over the past decade, there has been growing use of Nano-Sintered Silver (NSS) materials that can improve thermal performance without the need for extreme processing temperatures. Studies have also shown that NSS die attach maintained lower thermal impedance[1] and higher strength[2] than soldered attach materials during thermal cycling. However, other studies have shown that the strength of NSS materials decreased by ~50% after thermal cycling[3].

This article discusses an evaluation of how thermal shock conditioning affected the thermal performance of a conventional SFDA and two commercial NSS die attach materials. The goal was to assess NSS die attach materials for use in high power electronics used in harsh environments.

TEST VEHICLE AND PROCEDURES

The test vehicle (*Figure 1*) consisted of a 25.4mm square, 0.635mm thick FR4 printed wiring board (PWB) that had a 5mm x 6mm rectangular hole milled into it. A 6mm x 10mm x 0.66mm etched copper (Cu) substrate, with electroless gold/nickel plating, was attached to the bottom of the PWB under the rectangular hole.

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A 2.54mm square test die[4], which included resistive heaters and temperature sensitive diodes for monitoring temperature, was attached to the Cu substrate in the cavity formed by the hole in the PWB and the Cu substrate. Three different die attach materials were used to attach this die to the copper plate: a conventional SFDA (200°C)1 and two NSS materials, NAA1 (250°C) and NSS2 (175°C). The die was then wire bonded to the PWB and encapsulated. In all, 60 test vehicles were produced: 20 for each die attach materials included in the study.

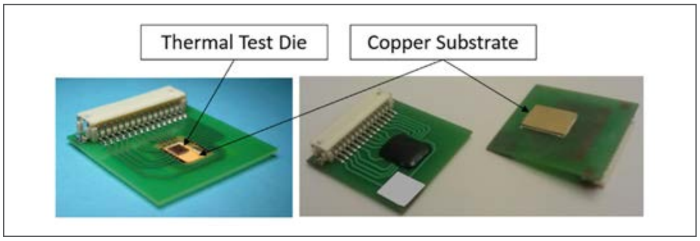

Figure 1. Thermal test vehicle, prior to encapsulation (left image) and after encapsulation (right images – top and bottom views.

The test vehicle thermal resistance was measured using the test fixture shown in *Figure 2*. This test fixture consisted of an aluminum plate with alignment posts mounted to it. A commercial thermal grease was applied to the bottom of the test vehicle copper plate prior to its being placed onto the top surface of the aluminum plate. A plastic retaining bracket with clearance holes for the alignment posts was then placed over the test vehicle A cavity on the bottom of the bracket ensured that it only contacted the perimeter of the test vehicle PWB. A 1 kg brass block, also with alignment holes, rested on the brass block to provide a retention force for the test vehicle when it was under test.

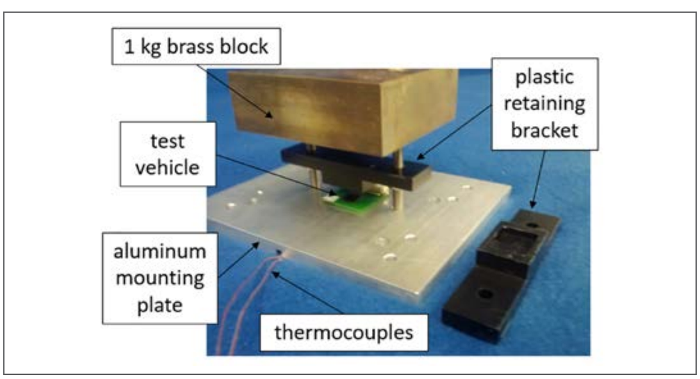

Figure 2. Thermal test fixture that pressed the test vehicle against the aluminum plate with the 1 kg block.

The aluminum plate was mounted to a commercial thermoelectric chiller[5]. The temperature sensitive diodes on the test die were calibrated by placing the test vehicles on the test fixture and monitoring the diode electrical resistance (with no power dissipated from the test die) over a range of baseplate temperatures. Once the diodes were calibrated, the test vehicles were powered with nominal levels of 6.8 and 15W while the aluminum baseplate was maintained at a set point temperature of 25°C. Diode resistance, voltage and current were recorded and the thermal resistance, $R_{thermal}$, was calculated using $R^{thermal} = (T_{diode} - T_{tc})/(V*I)$, where Tdiode is the diode temperature determined using the resistance measurement and diode calibration parameters, Ttc is the average temperature of two thermocouples placed under the test vehicle and routed through a slot on the bottom of the aluminum plate, and V and I are the voltage and current supplied to the test vehicle.

Once the initial thermal resistance of all 60 test vehicles was measured, they were then subjected to thermal shock testing. This was conducted in a dual chamber thermal shock system in which samples are transferred between two temperature chambers with forced air convection. The airflow rates in each chamber were 400 SCFM (11.3 m3/min) and the chamber temperatures were set to -55°C and +125°C. The transition time between chambers was approximately 1 minute and samples were held at each temperature extreme for 15 minutes. Due to their small size, the test samples equilibrated to the chamber temperature within the first 5 minutes of the dwell. Samples accumulated approximately 40 thermal shocks per day.

Test vehicles were assigned to one of three groups that included 6 or 7 samples for each die attach. These groups of samples were periodically removed from the chamber and their thermal resistance was measured. One group was removed from the chamber 4 times during the testing while another group was removed 10 times. This was done, in part, to determine whether the thermal resistance testing process affected the results. Further details on the assembly processes, test die calibration sample test groups, testing methods, and test results are provided in Ref[6].

TEST RESULTS

Figure 3 shows the averaged package-level thermal resistance data for all components with each die attach material as a function of the number of cumulative thermal cycles. Error bars correspond to one standard deviation. These data show a relatively monotonic increase in the thermal resistance with continued thermal cycling for all of the die attach materials. The NSS 1 material did show an increase in thermal resistance at 500 cycles that appears to be due to two outlier data points in a small population.

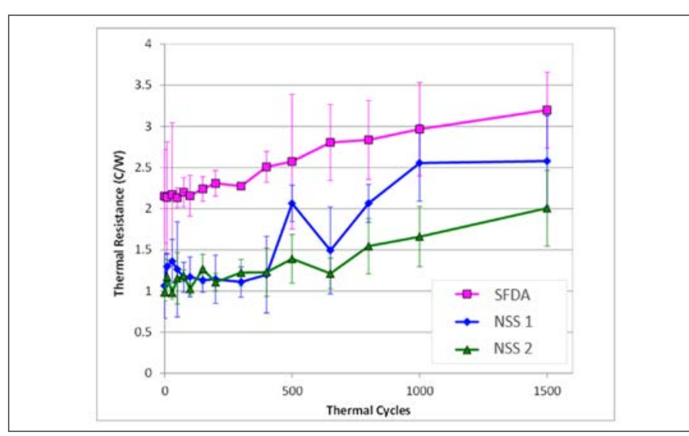

Figure 3. Increasing thermal resistance of test vehicles with accumulated thermal shocks.

In addition, a comparison of the results for the different test groups showed that there were no significant differences in the thermal resistance of samples subjected to more thermal resistance measurements.

During the course of testing, a number of the copper substrates separated from the PWB, leaving the die embedded in the encapsulant. None of the copper substrates that lost adhesion showed any residual black encapsulant, which indicates that the encapsulant delaminated from the copper plate due to poor adhesion between the two materials. Since this failure was due to poor adhesion between the copper substrate and encapsulant, it was assumed to be unrelated to the conductive die attach materials and these failed components were not included in calculating the averaged thermal resistance results.

Figure 4 shows the cumulative copper/encapsulant adhesive failure rates for the three die attach materials. This shows that the test vehicles with the NSS 1 sintered silver die attach materials had significantly more adhesion failures than those with the SFDA die attach. The NSS 2 test vehicles were also more likely to experience adhesion failures than the SFDA, but the difference was not significant until last round of thermal shocks.

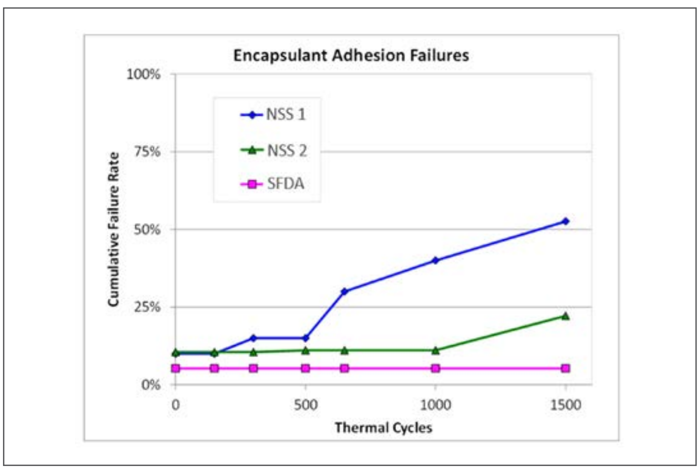

Figure 4. Test vehicles with NSS die attach materials exhibited significantly more adhesive failures between the copper substrate and encapsulant material.

FINITE ELEMENT MODEL

The goal of the study was to evaluate how thermal shocks affected the thermal resistance effects of the die attach material. However, the testing measured the overall package thermal resistance, which included the effects of conduction through the test die, thermal spreading in the copper substrate, interface resistance between the copper substrate and the aluminum mounting plate, and spreading within the aluminum plate. To isolate the effects of the die attach, a finite element model (FEM) was created (*Figure 5*)[7]. This relatively simple model, with ~17,000 elements, included the test die, die attach, a copper plate, thermal grease and the aluminum plate of the test fixture. The test vehicle substrate and encapsulant were not included in the model since they played a minimal role in the thermal path for the package.

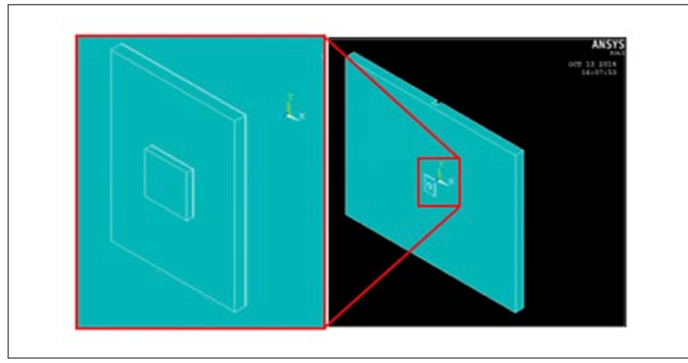

Figure 5. Finite element model of the test vehicle used to estimate the effective die attach thermal conductivity.

The thermal conductivity of the die attach in the FEM was varied from 2-250 W/mK while a 1W heat load was applied to the silicon. The resulting temperature drop through the package was used to determine the thermal resistance over a range of die attach thermal conductivities (*Figure 6*).

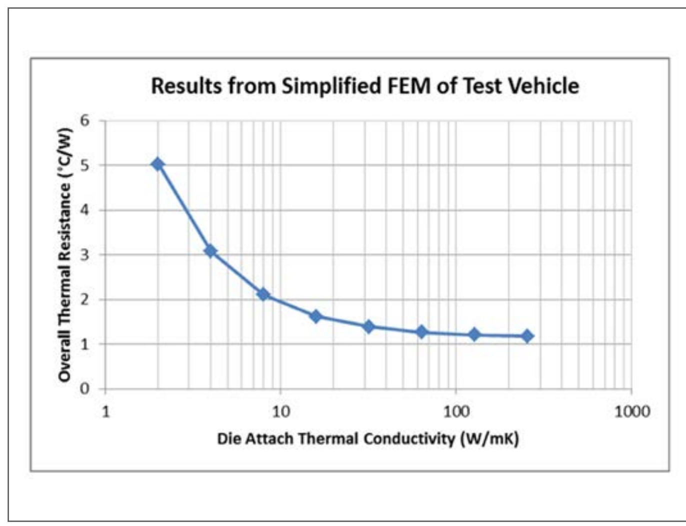

Figure 6. FEM results for package-level thermal resistance as a function of die attach thermal conductivity.

The average thermal resistance measured on the test samples with each die attach was compared to the overall thermal resistance predicted with the FEM for different die attach thermal conductivity values. This was then used to estimate the before/after effective thermal conductivity values for each die attach shown in *Table 1*.

Table 1. Die attach effective thermal conductivity values as estimated from finite element model results.

Material	Effective Thermal Conductivity (W/mK)	
	As Built	After 1500 Thermal Shocks
SFDA	3	3.5
NSS 1	20	7
NSS 2	80	10

DISCUSSION

The two nano-sintered silver die attach materials reduced the package-level thermal resistance compared to the baseline silver filled die attach material by approximately half. After thermal shock conditioning, the thermal resistance of all test vehicles increased, with the NSS samples continuing to show lower thermal resistance than the SFDA samples.

A simple finite element model indicated that the NSS materials initially exhibited much higher initial thermal conductivities, up to > 10x higher than the SFDA. However, based on this same model, the NSS materials degraded more significantly than the SFDA material; while the effective thermal conductivity of the SFDA material fell by over 40%, the NSS material thermal conductivities fell by nearly 90%.

Despite the more significant impact on the NSS materials, the test vehicles still exhibited lower thermal resistance after thermal shock conditioning than the SFDA test vehicles had prior to that testing. It should be noted that the degradation of the die attach thermal interface is likely much more extreme than what would occur in an actual component package, such as a Quad Flatpack No lead (QFN) device that uses a much thinner (and therefore more compliant) copper substrate.

The test vehicles with NSS die attach did experience adhesive failures between the copper substrates and encapsulant material. The root cause of these failures was not identified as part of this study. It is possible that the NSS paste may have out gassed a volatile compound that inhibited adhesion between the copper and the encapsulation that was subsequently applied to it. Further study is needed to determine if additional cleaning prior to encapsulation is required to eliminate any residual materials from the NSS.

CONCLUSIONS

This testing showed that commercially available nano-sintered silver die attach materials could substantially improve package-level thermal resistance compared to silver filled die attach. This improvement was consistent over extended thermal shock conditioning. While both commercial NSS materials in this study exhibited superior thermal performance relative to the SFDA material, one material clearly performed better than the other. In addition, test vehicles with both NSS materials were more likely to experience loss of adhesion between the copper substrate and the encapsulant than those packaged with the SFDA materials. The testing demonstrates that NSS die attach materials can reduce package-level thermal resistance as compared to conventional SFDA, but testing should be conducted to verify that the materials and the assembly processes used with them lead to components with adequate reliability for their application.

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Thermal Energy Harvesting with Next Generation Cooling for Automotive Electronics

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INTRODUCTION

In 2012, vehicle fuel-efficiency standards were announced that require all US cars and light trucks to reach 54.5 miles per gallon on average by model year 2025. As a result, automobile manufacturers are working to improve fuel efficiency in order to meet current and future fuel economy requirements plus emissions regulations. Vehicle fuel efficiency is logically related to the efficiency of the internal combustion engine. It has been estimated that the thermal efficiency of a modern internal combustion (IC) engine is limited to 20-40%, while approximately 60-70% of fuel energy is wasted in the form of heat.

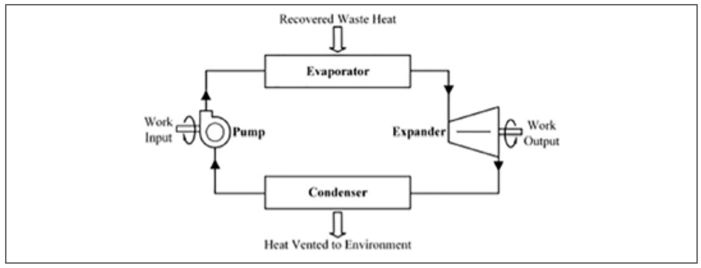

Figure 1: Schematic of a general Rankine Cycle (RC) system layout including four main components: evaporator, expander, condenser and pump [1].

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Several technologies have been investigated for waste heat recovery including thermoelectric generators (TEG), turbochargers, six-stroke cycle internal combustion engines, and the Rankine Cycle (RC), etc. The RC system has been identified as a promising solution to harvesting part of this waste energy from vehicles as regenerated mechanical or electrical power [2]. A RC system includes four main components: 1) an evaporator, 2) an expander, 3) a condenser, and 4) a pump; refer to the flow loop of a typical RC system in *Figure 1*. The pump drives the working fluid to circulate through the loop, and the evaporator utilizes a waste heat source to vaporize the working fluid. The fluid vapor expands in the expander and converts thermal energy into mechanical power output. Then, the expanded vapor flows through a condenser to turn back into liquid phase, thus completing the cycle. The application of RC to passenger vehicles is very challenging due to space limitations. In this article, a new concept and case study into the future application of Rankine Cycle to vehicle waste heat recovery combined with next generation power electronics (PE) cooling is provided.

RC FOR AUTOMOTIVE APPLICATION

For automotive applications, the RC system is usually installed downstream of the catalyst to avoid negative influence on emission control by extending the time for the catalyst to reach light-off temperature at cold start and to utilize the extra energy produced by pollutant conversion within the catalyst. Heat sources on vehicles are different from other typical industrial heat sources, which are stable and have fewer space limitations for system implementation. The most common and simple RC system structure is shown in *Figure 2*, which utilizes the exhaust gas as the heat source to evaporate the working fluid.

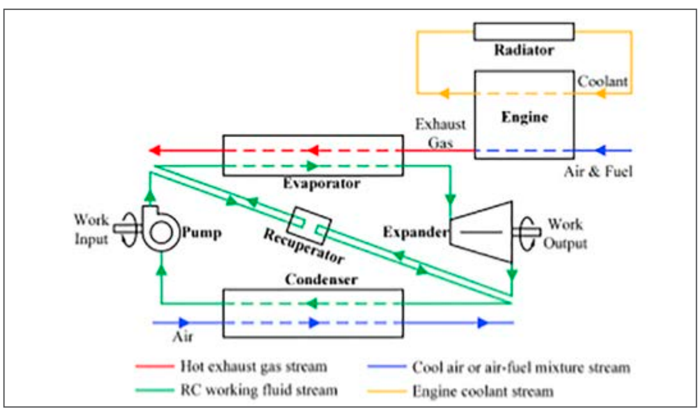

Figure 2: Structure of a typical RC system for automotive application [1].

The pump drives the working fluid to circulate through the loop, and the evaporator utilizes the waste heat source to vaporize the working fluid. The fluid vapor expands in the expander and converts thermal energy into mechanical power output. Then, the expanded vapor flows through a condenser to turn back into liquid phase, thus completing the cycle. A recuperator could be added before the evaporator using the steam from the expander to preheat the working fluid. The working fluid of the RC cycle could be wet fluid, e.g. water and ammonia, dry fluid, e.g. R113, R245fa, etc. or isentropic fluid, e.g. R11, R134a, etc. The reader is referred to Zhou et. al [1] for details about different RC structures for automotive application and the criteria for working fluid selection.

Given the structure of a typical RC system, a question then arises regarding what is the best platform, e.g. vehicle type, for RC application. This is linked to another question of how to utilize the RC expander power output. Generally, there are two ways to use this recovered energy: 1) outputting the mechanical energy directly to the crank shaft or 2) combining the RC system with electrical generators to convert the mechanical energy into electricity. In the former method, a speed reduction gearbox might be required if the expander has a speed mismatch with the engine. For long-haul diesel trucks, there is more room in the engine compartment and the exhaust gas condition is more stable making these vehicles good candidates for the first RC power utilization method. For small passenger vehicles, the driving profile is not as stable leading to a fluctuating exhaust gas temperature. In this case, the second energy recovery method seems to be a more reasonable option, which requires an energy storage system to store the generated electricity. A hybrid vehicle (HV), which recovers some braking energy to increase the overall fuel efficiency, provides an ideal platform for transforming thermal energy to electricity, storing the electricity in batteries, and feeding this electricity back to the vehicle. By integrating a RC system into a HV to recover a portion of the waste energy, a hybrid vehicle will break the energy efficiency limit of the internal combustion engine to further boost fuel economy. Another advantage of applying a RC system to a HV is the relatively constant load conditions for the engine in a HV.

Regarding the integration of a RC system to a HV, the approach taken in minimizing the system complexity, weight, cost, and negative effects on existing components is balanced with maximizing the RC power output. Currently, as an add-on system to an existing vehicle, RC system integration might lead to important interactions and consequences, such as increased vehicle weight, increased engine back pressure, increased cooling demand of the vehicles, etc. Therefore, minimizing the interactions with existing vehicle components, and minimizing added RC components, is a main target for RC automotive application. Then, we must determine the best way to integrate the RC system into a HV for waste energy harvesting. Before answering this question, let's switch gears to another topic: two-phase liquid cooling for power electronics.

TWO-PHASE POWER ELECTRONICS COOLING

A transition away from silicon toward wide band-gap (WBG) semiconductor materials for power devices is expected in the next decade. For future electrified vehicles, the use of WBG devices, e.g. silicon carbide (SiC), gallium nitride (GaN), or diamond, in power electronics enables higher operational frequencies, lower switching losses, and high temperature, >200 °C, operation. However, the increasing demand of higher performance combined with smaller PE module size results in a continuously growing heat dissipation requirement, which challenges the limit of single-phase liquid cooling and makes two-phase (2j) liquid cooling [3, 4] attractive due to enhanced thermal performance.

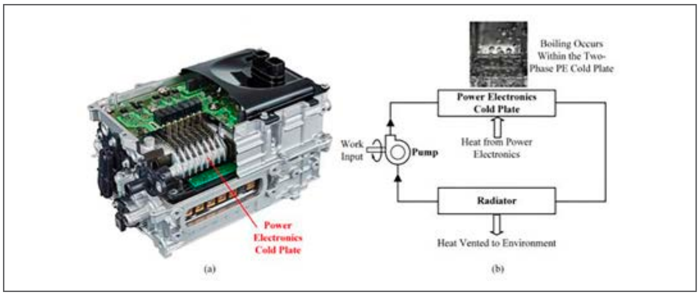

Figure 3: (a) Representative single-phase liquid cooled PCU; adapted with permission from [5]; (b) Structure of 2j power electronics cooling loop with three main components: a PE cold plate, a radiator and a pump [1].

A 2j cooling loop has three main components: 1) a two-phase cold plate, 2) a radiator/condenser, and 3) a pump; refer to *Figure 3 (a)* for a representative single-phase liquid cooled power control unit (PCU) and (b) for the structure of a 2j power electronics cooling loop. A refrigerant, such as R245fa, HFE7100, or HFC 134a is typically used as the working fluid in a 2j power electronics cooling loop. Different fluids may be selected depending on the type of power device utilized and its maximum operational temperature. In the current study, R245fa was selected as the working fluid for demonstration purpose. Comparing the RC structure shown in *Figure 1* and the 2j cooling loop in *Figure 3 (b)*, it is evident that both of the systems have a pump, a heat exchanger to dissipate the heat from coolant to environment, and a heat exchanger to absorb heat from the heat source. Furthermore, the same working fluid, e.g. R245fa, may be used for the two different systems. Therefore, if a RC system is integrated with a 2j cooling loop, not only more waste heat may be utilized to generate power, but under-hood space may be conserved since only an extra evaporator and expander are required.

SYSTEM CONCEPT & ANALYSIS

Figure 4 shows the concept of combining the RC system with the PE 2j cooling loop. Here, the pump, cold plate and HV radiator are three main components for the 2j cooling loop. To realize waste heat recovery, an evaporator and an expander are added to the system. A recuperator is also included in the current system, which is not necessary depending on the available space and capacity of the HV radiator. The waste heat from the engine coolant is not utilized in this system, but a liquid-to-liquid heat exchanger may be added to recover part of the coolant heat, considering the low boiling point of the refrigerant.

A thermodynamic model of the RC-2j system is developed on a commercial numerical modeling platform [6] to analyze the impact of the PE cold plate to the whole energy recovery system; a detailed sketch of the model is available in [1]. The model has six sub-models: 1) pump, 2) power electronics, 3) evaporator, 4) expander, 5) HV radiator, and 6) recuperator. The system working fluid and working conditions including assumed component efficiencies are summarized in [1]. The overall system coefficient of performance (COP) is evaluated as $COP = W_{expander}/W_{pump}$, in which $W_{expander}$ is the work output of the expander and W_{pump} is the work consumed by the pump system.

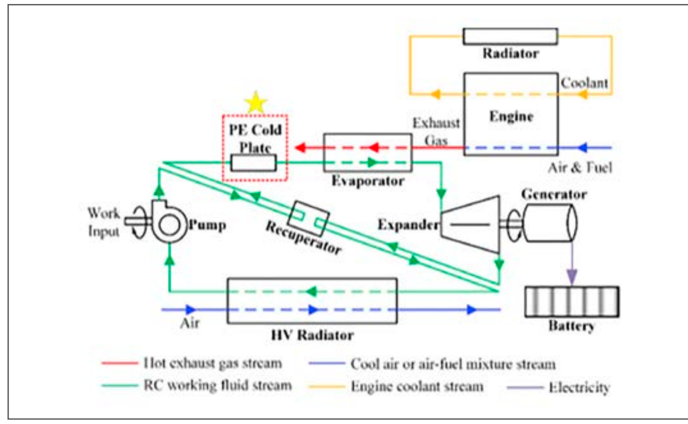

Figure 4: Integrated RC-2j cooling and waste heat recovery system for HV application which has dual functions of PE cooling and waste energy harvesting [1].

Figure 5 shows the expander power output, COP and evaporator inlet vapor quality as a function of expander pressure ratio for the RC system with recuperator (structure shown in *Figure 2*) at different R245fa mass flow rates, 0.05, 0.06, 0.07 and 0.08 kg/s. Observe that as the pressure ratio increases the expander can generate more power, however the system COP increases first and then decreases gradually. As for the R245fa vapor quality at the evaporator inlet, it decreases as the pressure ratio increases. High expander pressure ratio leads to higher system pressure within the intercooler and evaporator which can suppress boiling. For different R245fa mass flow rates, the expander power output varies between 1.2 kW and 1.5 kW and decreases as the mass flow rate increases. The COP also decreases as the mass flow rate increases due to higher power consumption by the pump. The vapor quality decreases as the refrigerant mass flow rate increases.

The results for the proposed RC-2j integrated system with recuperator are shown in *Figure 6*. For the current system with two-phase power electronics cooling, the vapor quality at the cold plate outlet (i.e. evaporator inlet) is an important parameter that requires dedicated control. If the flow rate is excessively low, all of the refrigerant flowing through the cold plate vaporizes, which might result in dryout of the heat exchange surface within the cold plate. The flow rate also cannot be excessively high otherwise the flow through the cold plate becomes single-phase, which lowers cooling performance.

The power electronics is an additional heat source in the cycle, so higher refrigerant flow rates are necessary to avoid dryout. Therefore, for the current system structure, the studied flow rates include 0.08, 0.09, 0.10 and 0.11 kg/s. The variation of the expander power output, COP and cold plate outlet vapor quality follow the same trends shown in *Figure 5*. However, at the same flow rate (e.g. 0.08 kg/s), the power electronics module boosts the expander power output ~58% to 1.9 kW from 1.2 kW for the system without power electronics. The COP also increases ~20% from 20 to 24 since additional heat is recovered by the system. The impact of heat input from the power electronics to the waste heat recovery system is well demonstrated.

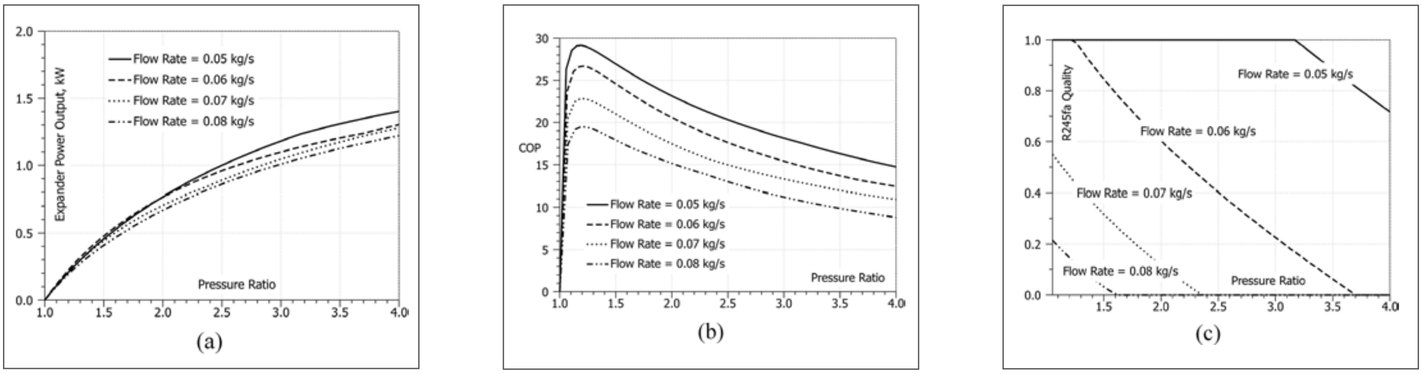

Figure 5: Expander power output, COP and evaporator inlet vapor quality as a function of expander pressure ratio for traditional RC system without PE cooling (structure as shown in Figure 2) [1].

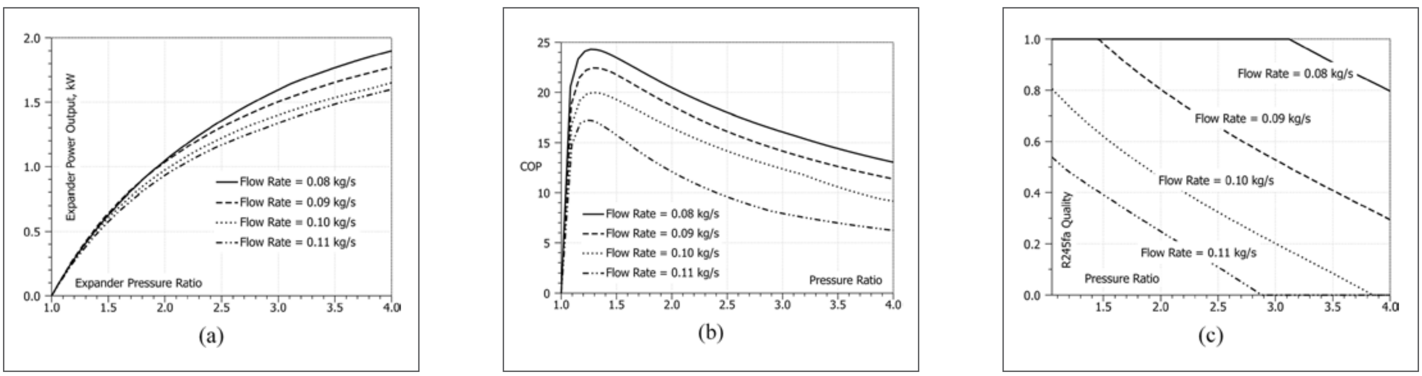

Figure 6: Expander power output, COP and cold plate outlet vapor quality as a function of expander pressure ratio for the proposed RC-2j integrated system with recuperator as illustrated in Figure 4 [1].

CONCLUSIONS

Applying a RC system to a HV platform has great potential to further boost fuel economy to meet future emission requirements with system integration as one of the biggest hurdles. Nonetheless, a novel aspect of the RC-2j integrated system concept presented herein is that it not only keeps the HV power electronics cool at high efficiency, but also recovers more heat from the PE module for higher total system power output. It is found that the RC-2j integrated system boosted the expander power output ~58% from 1.2 kW to 1.9 kW under the same working conditions. The COP is also increased by 20% since an extra heat source is added to the system without consuming additional pumping power. Co-designing the RC system and HV power train in combination with other technologies, such as turbocharging or in-wheel motors, may drive the fuel efficiency of such vehicles to a higher level.

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Application of Metallic TIMs for Harsh Environments and Non-flat Surfaces

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INTRODUCTION

Electronic systems, implemented in such diverse industries as aerospace, vehicle, geothermal exploration, and mobile devices with a range of more challenging application conditions, create new challenges for component and material reliability. Non-flat mounting conditions, increases in ambient and operating temperatures, effects of moisture, corrosive gases, dust, and vibration can all affect product reliability, leading to development of increasingly specialized in categories such as thermal interface materials (TIMs).

FUNCTION

Not all thermal interface materials are alike or designed to perform under the same conditions. A single criterion, such as bulk thermal conductivity, is insufficient to assess overall performance and reliability. Attention to improving selection and application of TIMs has gained in importance to improve overall assembly thermal resistance. An ideal interface (with perfectly polished and flat mating surfaces) would require no material between the two components; however, at a prohibitive cost. A TIM acts as an intermediate medium that eliminates the insulating layer of air that would otherwise be present in the interface. Maximizing thermal performance is a primary goal for the selection of a TIM; other factors include attributes that meet specific application needs, such as relative thixotropicity, ease of rework, ability to fill a stated gap, and durability.

An important factor for reducing thermal resistance of a TIM is minimization of the thickness of applied material, i.e. "bond line thickness". Ideally, materials are as thin as possible, have no voids and are compressible under clamping that is used to ensure a thin bond line Many TIM contain a paste- or gel-like carrier and thermally conductive fillers. Paste or gel carriers improve the material's contact

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Dave has thirty-nine years of business development and technical marketing experience with advanced packaging and thermal materials, components, and two-phase liquid cooling systems. He has chaired or given technical conference presentations in eight countries on thermal management topics. Dave is general chair for the IMAPS ATW on Thermal Management (eighteen years), has participated with the IMAPS France thermal and packaging workshop organizing committee (fourteen years), and served as general chair for Semitherm in 2006. Dave founded and has operated a full-time consulting business for fourteen years to assist in applying new materials and technologies for applications as diverse as handheld devices and HEV powertrain inverters. He has made hundreds of visits to OEM engineering groups globally.

Tim Jensen

Tim Jensen is the Product Manager for Indium Corporation's Engineered Solder Materials, the company's most diverse product group. His product group encompasses solder preforms, wire, ribbon, and foil, and thermal interface materials, including gold-tin and tin-lead solder preforms, Solder Fortification® preforms, Heat-Spring® thermal interface materials, and indium-containing preforms. He is responsible for ensuring the product line is poised for future growth and best meets the needs of existing and potential customers.

for minute surface imperfections, i.e. "surface wetting", but also can lead to separation or outgassing of the carrier under temperature. Reliability testing includes power and thermal cycling, humidity, extreme temperatures, dynamic loading, etc. Characteristics related to assembly processes for the material, such as working life, bond line thickness (post-assembly), dispensing process, rework, and environmental characteristics must be considered.

MECHANICAL CLAMPING AND THERMAL RESISTANCE

The ideal solution is application of the thinnest layer of TIM that is practical, with a high clamping force to ensure metal-to-metal contact in the high point areas and to force movement of the TIM to fill low points and microscopic surface imperfections, such as machining marks. The combination of applied force and the thinnest of materials are desirable, given the low bulk thermal conductivity of TIM organic compounds such as gels, thermal greases, and phase-change forms. The specific clamping force on an organic, thixotropic TIM, rather than its bulk thermal conductivity, primarily determines thermal resistance of the interface. Clamping force is also important for graphitic and metallic TIMs and is achieved with mechanical fasteners applied to the thermal solution. (No mechanical fasteners are required if a simple adhesive is sufficient.)

Figure 1 shows an example of how applied force affects thermal resistance of a TIM. Even though these solid materials do not include a surface-wetting carrier, clamping force plays a critical role and should not be ignored.

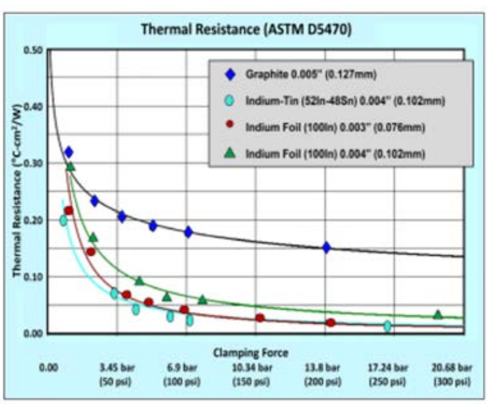

Figure 1. Thermal resistance for selected thermal interface materials versus applied clamping force.

Testing of TIM materials for thermal resistance per unit area may be accomplished per an industry standard methodology, ASTM D 5470-12 [1]. The primary value of ASTM D 5470-12 as an accepted standard methodology is to allow direct comparison between data sheet values. Application-specific test vehicles and thermal test die may also be used [2, 3].

NON-FLAT CONDITIONS

Mounting surfaces need to be designed to be as close to parallel as possible, post-assembly. Increasing clamping force minimizes TIM thickness and improves thermal performance, and additional characteristics such as flatness, roughness, and co-planarity must be considered. Surface roughness and flatness criteria are typically called out in the manufacturing specification for a heat sink or cold plate mounting surface, and may be designated milled surfaces only in specified areas on a cold plate surface, to avoid milling an entire surface, to reduce cost.

The sum of the maximum out-of-flat specification for the module baseplate external surface and the maximum out-of-flat specification for the liquid cold plate can exceed 250 µm, in worst cases. For example, the largest IGBT modules (190mm) may have a total gap of 50-270 µm while smaller modules, such as the Infineon EconoDUAL™, may exhibit a total gap value of approximately 50 µm at locations, such as the center of the module [4].

TIM materials also need to address "non-flat" conditions that may be due to die warpage in ICs or purposeful design approaches such as engineered domes, found in the largest IGBT power semiconductor modules that utilize AlSiC (aluminum-silicon-carbide metal matrix cast composites) baseplates. A specific patterning of TIM application is called out in manufacturer specifications and torqueing sequences are identified to properly apply the necessary clamping load [5].

IGBT module assembly operations, such as soldering or sintering may create physical stresses within the baseplate of an IGBT module that can potentially lead to warpage; modules can dissipate significant power (kilowatt range) with heat fluxes that can be detrimental to ceramic substrates and other materials, due to thermal expansion coefficient mismatches. Operation of a large IGBT module with rapid switching, in applications such as traction and wind turbine converters, creates acute conditions for a TIM that can induce "pump-out" of greases and other organic compounds. Rigid materials, such as graphite and metallic TIMs, may degrade due to tearing if relatively brittle forms are selected.

Surface warpage may be present if the heat source contact surface is a silicon (or GaN or other) die in a non-lidded package configuration.

Semiconductor test and burn-in commonly have non-flat conditions by design. Test heads often have gimbaled mounts to allow slight rotation for devices with different footprints. Semiconductor burn-in (temperature cycles to 145-185°C) may require thousands of contacts with a single TIM. These factors, combined, severely limit options for TIM selection.

HARSH ENVIRONMENTAL CONDITIONS

Increasingly specialized TIM development is also driven by increasingly harsh environmental conditions, and may be combined with non-flat conditions. Monitoring tools for geothermal/oil/gas exploration, as an example, include temperatures (and shock, vibration, and corrosive gases) well above typical automotive underhood values, generally beginning at 225°C. *Table 2* provides examples in selected industry market segments [6, 7, 8].

Market Segment	Typical Condition
Geothermal/Oil/Gas Exploration GaN Power Modules*	200°C/1 year Mechanical shock 500g, 100,000 shocks under temperature Vibration
Space Applications GaN Power Modules+	150°C/15 years Thermal cycles, 500 cycles -55°C to +100°C
Semiconductor Burn-in	A. 80°C/8 hours/cycle B. 110°C/8 hours/cycle C. 125°C/8 hours/cycle
Aerospace 150kW Motor Drive SiC Power Module#	Tj 200°C Continuous

*Notes: * Schlumberger (Partner in MEMPHIS Project)*
+ Astrium (Airbus, partner in MEMPHIS Project)
 # Thales Microelectronics SAS

Table 2. Examples of Harsh Environment Industry Segments

Metal and graphite sheet TIMs provide the high durability and thermal conductivity desirable for high clamping forces and non-flat surface conditions. They also provide the critical benefit of meeting residue- and outgassing-free application requirements. Higher cost of metallic TIMs can be offset with reclamation programs. Absence of a silicone oil carrier is critical in systems with optical, optoelectronic, and diode laser components in which outgassed silicone may redeposit on lens elements and electrical contacts. While the avoidance of silicone redeposition is not typically considered under the umbrella of harsh environment requirements, this is a specification that is increasingly found in individual system OEM requirement statements.

RECENT TIM DEVELOPMENTS FOR NON-FLAT CONDITIONS

A very wide range of TIM relative bulk thermal conductivities can be found; *Table 3* shows values for common as well as more recently developed materials. Note that certain materials shown have properties that are important differentiators between conventional TIM and heat spreader materials, a different material category with different requirements.

Recent TIM development programs include graphite sheet materials, primarily used for in-plane heat spreading with relatively little through-plane heat transfer. These materials are inaccurately referred as TIMs, largely because the materials are generally somewhat similar to TIMs and vendors are commonly TIM manufacturers [10, 11, 12].

Related recent TIM developments use vertically-aligned graphite fiber and carbon nanotubes; several commercialization efforts are vertically-aligned CNTs (“VA-CNT”) in polymeric carriers [13]. Vertically-aligned carbon fibers (“VA-CNF”) with polymeric carriers have been commercialized; one form of VA-CNF has been developed with a single-sided construction for the semiconductor test and burn-in market requirements [14, 15].

TIM Classes	Λ (W/mK), Typical
Silicone-Filled Compounds	0.3 – 7.0
Phase-Change Compounds	0.3 – 7.0
Liquid Metal Alloy (LMA)	20
Indium, indium alloys	66 - 86
Aluminum (for reference)	205+
Pyrolytic Graphite (PG)*	300 (X-Y); 3.5 (Z)
Copper (for reference)	385+
Highly-oriented PG (HOPG)*	1200 (X-Y); 4-12 (Z)

*Notes: * Heat spreader materials, for reference*
+ Values shown as measured at 25°C; aluminum and copper are used as carriers for some TIMs.

Table 3. Bulk Thermal Conductivity, High-Performance TIM2 Material Classes [9]

RECENT METALLIC TIM DEVELOPMENTS FOR NON-FLAT AND HARSH ENVIRONMENT CONDITIONS

Metallic TIMs have been used in die-cut preforms for decades in telecommunications, radar, and other flange-mount RF semiconductor markets. Additionally, reflowed indium solders in “TIM1” (between the backside of the die and the underside of a lid, in a lidded IC package) have been a standard for major processor manufacturers since 2003.

Indium metal and related alloys are easily die-cut as a soft, compliant TIM with die-cut through-holes and other features. Patterning creates metallic TIMs that are expanded in different heights with different pattern formats for extreme gaps. Further developments in this area include the use of tin and other metals as well as aluminum cladding on one surface [16]. These are used for the largest-footprint IGBT modules, semiconductor test, enterprise server processor modules, and GaN RF devices [17]. These materials are

particularly advantageous with large (190mm) IGBT modules in which a relatively large gap may exist; due to long-term reliability requirements, the mechanical pump-out, outgassing, or dry-out that can occur with silicone oil carriers must be avoided. Electrical conductivity of the TIM for GaN RF devices can be critical in applications such as phased-array radar [18, 19].

Another development in metallic TIMs is the application of silicone-free thermal compounds applied to one surface of an aluminum foil, targeted for semiconductor testing requirements where durability for thousands of contact cycles is needed. The surface without compound faces the Device under Test (DUT) to provide a durable contact without marking or residue [20]. For large gaps, two-layer aluminum foil coated with a non-silicone compound has been developed with total TIM thickness up to 250μm (0.0098”). Evaluation in electrical drives has been completed, including reliability testing in vertical orientations at elevated temperatures and high clamping force applied (1 to 15 bar).

Reliability testing of these expanded metallic TIMs has included power cycling to compare their performance to conventional TIMs, as shown in *Figure 2*.

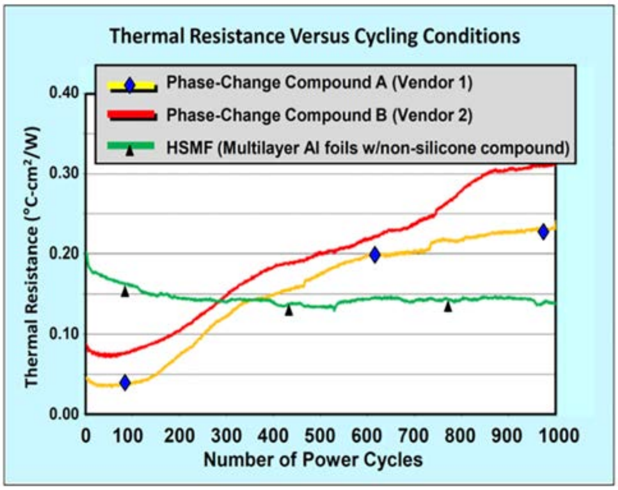

Figure 2. Comparative thermal resistance values from time zero through 1,000 power cycles for two commercial phase-change compounds and a two-layer aluminum foil coated with a non-silicone, non-electrically conductive thermal compound. [Power cycling (modified) in this test was conducted with thermal test vehicles (TTVs) with bare die contact at one surface. Cycling: Peak heat flux over a 0-50 W/cm² range, cycle duration of three minutes on/two minutes off). Peak temperatures during the cycle are a function of thermal resistance, to a maximum 80°C.]

Thermal resistance test data for two forms of specialized metallic TIMs is shown in *Figure 3*. The "OS" material is coated with a compound on one side only; a 100In preform (100% indium) with a specific patterning format and two common silicone greases.

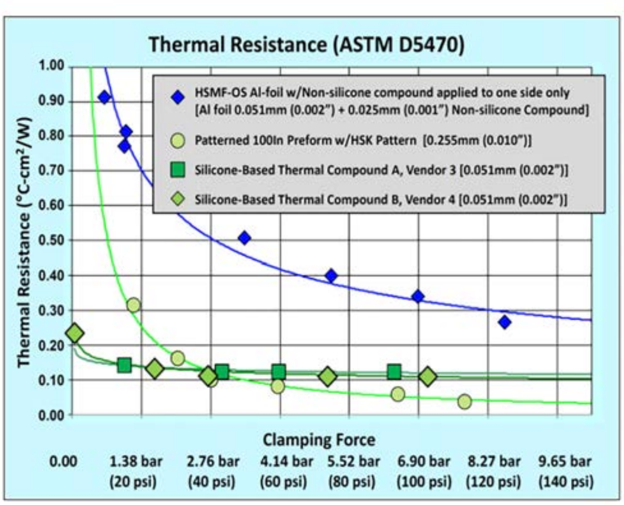

Figure 3. Thermal resistance versus clamping force applied for metallic and non-metallic TIMs.

Exceptionally high operating temperatures, such as those shown in *Table 2*, can limit options for TIM selection. Specialized metal TIMs manufactured with tin, lead, and copper have been developed for operating temperatures for higher temperature ranges [21].

SUMMARY

Specialized application requirements drive development of equally-specialized TIMs, including large area surfaces with large gaps, manufactured with different compositions and formats and now available for evaluation, particularly for use in environments not suitable for conventional TIMs.

ACKNOWLEDGMENTS

Contributions made to these development programs with dozens of thermal resistance, thermal cycling, and power cycling tests by Bob Jarrett, with support from Carol Gowans, Seth Homer, and Ron Hunadi, of Indium Corporation.

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Thermal Management and Safety Regulation of Smart Watches

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ABSTRACT

A smart watch is one of the most popular wearable devices now. Along with battery life and security, thermal safety is the most common concern. We show how to meet the ergonomic standards for users and predict thermal performance in typical scenarios. Thermal simulation software applied at the design stage can provide guidance on the use of heat spreading materials and other thermal solutions to meet the design requirements.

INTRODUCTION

According to the International Data Corporation (IDC) Worldwide Quarterly Wearable Device Tracker [1], by 2019, worldwide shipments of wearables will reach 173.4 million units, resulting in a five-year compound annual growth rate (CAGR) of 22.9%.

Since the smart watch market is relatively young, many concepts of how to integrate electronics are still very new and in the prototyping phase. However, designs are moving in the same direction as mobile phones: engineers must balance performance and high power consumption within very limited space. Customers wear smart watches much longer than they hold smart phones. With greater direct contact with the skin for longer times, thermal comfort is a very important factor in determining the quality of the user experience.

LOW TEMPERATURE BURN AND THERMAL STANDARD

We know that high temperature burns can be very painful and destructive. While burns occurring at low temperature seem to initially be mild and not too painful, they can also cause damage while the victims are less aware that the burn has occurred [2].

In this paper, we suggest values on the lower end of the burn threshold spreads shown in *Figure 1* from the IEC guide 117 for temperature limits of smart watch-based burn risk during operation.

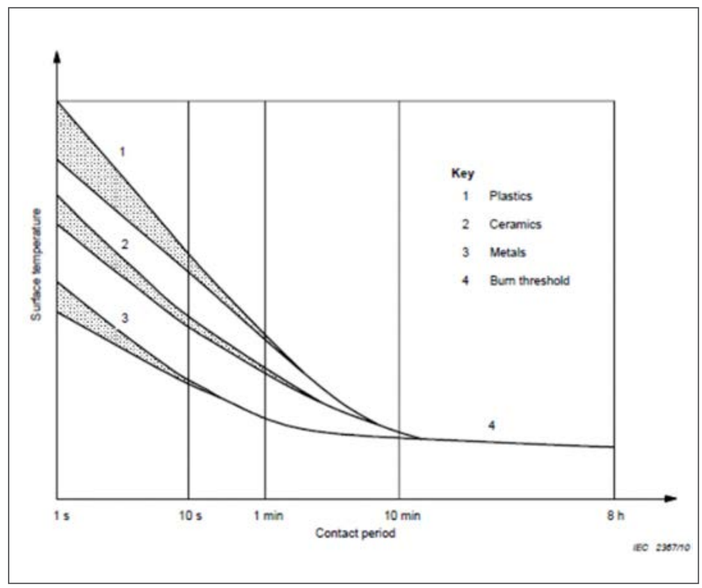
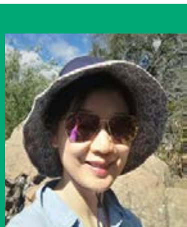


Figure 1. Material temperature and contact period [3]

Temperature limits are different for different time durations. For younger children, short-time maximum temperature limits are lower and stricter. To be more conservative when possible, a smart watch as a heat source that increases skin temperature, which is typically at 32°C, by 3-4 K for days and months will lead to reactions from the body/skin. This local heating will at least



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feel uncomfortable to the user. The goal is then to maintain the temperatures rise to within 1K for stand-by conditions.

THERMAL MODEL AND TYPICAL SCENARIOS

The smart watch's thermal performance can be simulated with thermal analysis software. The 3D CAD model can be imported to the thermal simulation tool in which boundary conditions can be applied and detailed thermal profile will be obtained.

Material properties of all the components in the model need to be assigned. It is popular to place heat spreaders between high power density chips and the enclosures to reduce the hot spot. Graphite has an anisotropic crystal structure that results in different properties in different directions. This anisotropy can be used advantageously to both spread the heat and to eliminate a hot spot by shielding a surface adjacent to the heat source, as mentioned before. In many cases, metal films made of copper or aluminum can serve as heat spreader in the device.

Scenario 1 is the low power consumption application and the *Scenario 2* is the extremely high power consumption application. When the smart watch must process specific functions, the different working cycle and duty cycle value will determine the power consumption, battery usage and thermal profile.

Table 1. Typical scenarios of smart watches

Scenario	Scenario Description	Working Period	Duty Cycle
Scenario 1	CPU Wake Up	25	120
	Display on	25	
	Accelerometer and sensor running	25	
	Motor vibrator	10	
	GPS search and tracking	25	
Scenario 2	CPU Wake Up	45	120
	GPS search and tracking	45	
	Motor vibrator	20	
	Display on	45	
	Accelerometer and sensor running	45	

TEST RESULTS

The two power level scenarios were studied on a watch prototype. In *Scenario 1*, the watch case temperature was less than 3°C higher than room temperature, as shown in *Figure 2*. For the same working period, the longer the duty cycle, the lower the watch case temperature.

Typical scenarios are closely related to particular design function of a smart watch. *Table 1* lists typical product function scenarios.

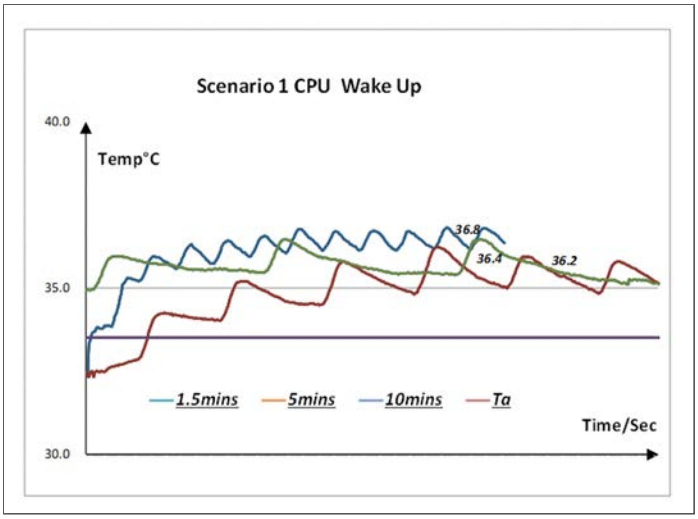

Figure 2. Test result of scenario 1. Test device: Huawei watch prototype, working period 25s, rest period set for 1.5mins/5mins/10mins.

It is not surprising that the temperature rises in the higher power *Scenario 2* were larger than in the low power cases. *Figure 3* shows that the maximum case temperature was about 5°C above the ambient air temperature. *Figure 2* and *Figure 3* both show that the resulting temperature is a function of working period and duty cycle.

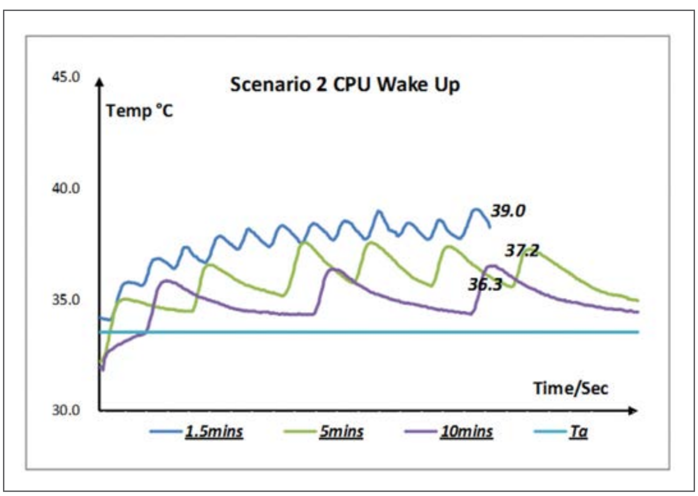

Figure 3. Test result of scenario 2. Test device: Huawei watch prototype, working time as in the table, rest time 1.5mins/5mins/10mins.

The simulation show relatively good agreement with experiment results, the error is below 7% [5].

CONCLUSION

In summary, working period and duty cycle play significant roles in the temperature rise of smart watches. This in turn is a key factor to adjust the power consumption. Thermal solutions, including heat spreading material as graphite and copper film can be applied to reduce the hotspots [5, 6]. Miniature heat pipes [7, 8], are also one of the options for hot spot mitigation. Phase change materials show potential to improving user experience in high power scenarios [9], which can regulate temperature during sprinting [10].

Ergonomic considerations and the device performance need to be well balanced to achieve the best user experience. In smart watch design, maximum inner case temperature is a primary design goal, and perceived performance is more critical than actual performance.

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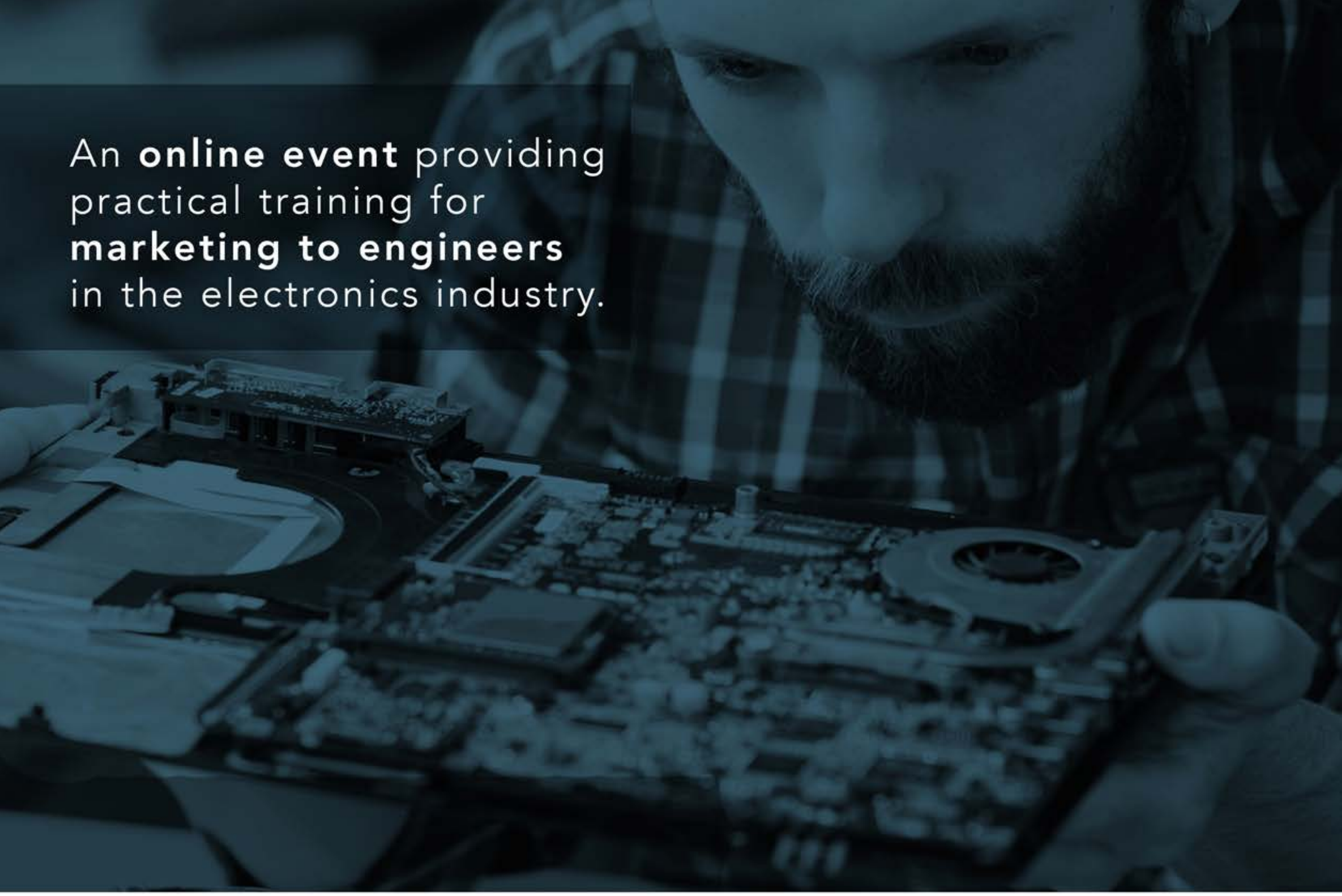

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