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Electronics Manufacturing Insights from ACI Technologies, Inc.

Thermal Interface Materials Testing

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Abstract

There exists a need to efficiently remove heat from power electronics within power systems to enhance performance. Thermal management is a critical function to that operation. Reducing the junction temperature of semiconductor power electronic devices enables them to operate at higher currents. Lowering operating temperatures reduces the thermal stress on electronic devices, which improves efficiency and reduces failures. To improve the heat removal process, the current heat transfer design of a power system has been analyzed and a variety of thermal interface materials (TIMs) and cold plate technologies have been evaluated. This paper will review some of these results.

A thermal test facility was fabricated incorporating a thermally insulated chamber of the same dimensions as an actual power system, a chiller to provide water in the 5°C to 40°C range, and instrumentation to monitor temperature, pressure, and flow rate. By evaluating different thermal interface materials in this setup, the performance of each material can be directly compared in the actual design.

The various TIMs were experimentally tested and the results compared to a Finite Element Analysis (FEA) solid model previously developed to predict thermal management performance. A proven FEA thermal model can help determine the performance of any newer materials that may be available in the future without having to spend excessive resources on expensive laboratory testing.

Key words: TIM, coldplate, thermal grease, PCMA, soft metal film.

Introduction

A series of evaluations were initiated as part of a project to determine the effectiveness of new technologies for high power applications. One of the technologies focused on was heat exchangers.

High performance heat exchangers are used to lower the operating junction temperature of power devices so that their steady state output, as well as their short duration on demand output, is significantly improved. Use of better thermal interface materials, coolants, and high performance cold plate designs and technologies were evaluated using a test vehicle similar to an actual design. While the thermal conductivity of thermal interface materials (TIMs) are always reported by the manufacturer, the value alone is not sufficient to determine which TIM would be better for any particular application. Other parameters may also affect the thermal impedence, thereby influencing the effectiveness of the heat transfer as much, or more than just the thermal conductivity of the TIM. The interface surface roughness, wettability, area, and pressure all affect how well a TIM performs in a particular application. While the manufacturer tests and reports a value of thermal conductivity using optimal conditions for their material, actual use of the material may provide substantially different results. By manufacturing a test vehicle modeled from an actual application, most of the interface parameters are held constant and the cooling effectiveness of different TIMs can be directly compared and contrasted.

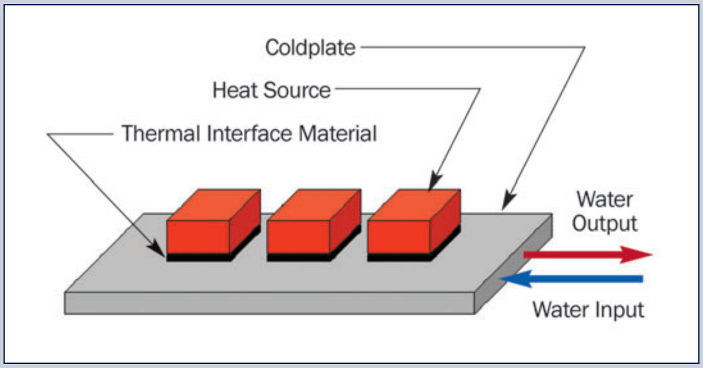

Figure 1: Test vehicle design.

Thermal interface materials, coolants, and coldplate designs were previously analyzed using FEA software to help reduce the number of materials selected for further evaluation. Some of these have been tested in the thermal test facility, including thermal grease, soft metal film, and a phase change metal alloy (PCMA).

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Background

The test vehicle design uses a thermal interface material between the heat source and the coldplate. This model is shown in Figure 1. To simplify the analysis, heat removal due to convection is ignored, since it is negligible in comparison to any heat removal due to conduction.

Fourier's Law states that the flow of heat is proportional to the temperature gradient and the cross sectional area normal to the heat flow direction. For a one dimensional heat flow at steady state, this can be expressed as:

$$Q = (k\,A\,\Delta T) / L$$

where: Q = Heat flow (Watts)
A = Effective area of heat transfer (m^2)
k = Thermal conductivity (W/m °C)
ΔT = Temp difference between heat source (T1) and heat sink (T2) = T1 - T2 (°C)
L = Length of heat transfer path (m)

The thermal conductivity (k) is an intrinsic property of how the bulk material internally conducts heat. It is not dependent on the size or shape of the material and more importantly, does not include any effects from the thermal interface.

Thermal resistance (R) is not an intrinsic material property and should be determined for each configuration according to this equation:

$$R = \Delta T/Q \; (°C/W)$$

Thermal impedance (Z) is the temperature gradient per unit of Heat Flux (Q/A) through the effective area of heat transfer or more simply the thermal resistance times area.

$$Z = \Delta T/ (Q/A) = R\,A \; (°C\text{-}m^2/W)$$

Both the thermal resistance and thermal impedance more accurately predict thermal performance than thermal conductivity since they do not ignore affects at the thermal interface.

When two surfaces are mated under pressure, the contact is not perfect, even for highly polished flat surfaces. As shown in Figure 2, surface irregularities prevent intimate contact of large areas between the mating surfaces. Solid contacts only occur between the high points of the two mating surfaces leaving a large number of voids between the low lying areas. Most of the heat transfer takes place via these solid contact points, but is restricted since the contact areas are very small. Heat transfer also occurs through the air entrapped in the irregular voids, but is extremely low since the thermal conductivity of air is very low compared to the metals that are in direct contact. In order to eliminate the air gaps and improve thermal transfer, a thermally conductive material is used. This material conforms to the surface peaks and valleys and displaces the air, providing more area for heat to flow and reducing the thermal resistance of the interface.

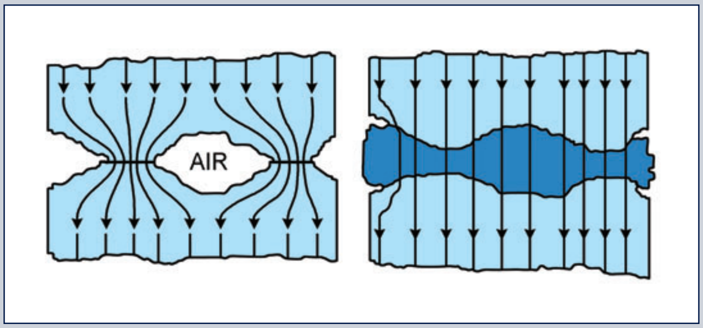

Figure 2: Example of how surface irregularities affect heat transfer. (Courtesy of Parker Thermal Management.)

The thermal resistance at the interface is usually much greater than the overall bulk resistance of the two mating bodies and therefore provides the biggest barrier to increasing the heat transfer rates. This thermal resistance between two heat conducting surfaces depends on several factors such as:

- Geometry/flatness
- Surface finish of mating surfaces
- Hardness
- Modulus of elasticity
- Contact pressure
- Thermal conductivity
- Length of heat conducting path

As can be seen from the earlier heat flow equation, there are four primary parameters that can be changed to enhance the conducted heat flow rate of any system (k, A, ΔT, and L). Once a suitable material with high thermal conductivity is selected, the other three parameters can be improved to enhance the heat removal rate.

To increase the effective area of heat transfer (A), the voids created by the imperfect surfaces, as depicted in Figure 2, must be filled with suitable highly conductive thermal interface materials. Many different approaches have been adopted by the industry to fill in these voids. Thermal greases, soft metal films, soft metal plating, better machining, and surface finishing techniques are some of the commonly adopted approaches.

Heat flow can also be enhanced by increasing the value of ΔT, the temperature difference between the heat source (T1) and the heat sink (T2). Since the temperature of the source is dictated by the junction temperature of the device, the only choice left for designers is to decrease the heat sink temperature.

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Several methods are used in the industry to lower the heat sink temperature. The suitability of any method is dictated by the application's unique requirements. These could be cost, suitability of cooling material, and availability of cooling materials. The coldplate technology's mechanical design, the heat exchange mechanism between coolant and the metal plate, the type of liquid coolants, and how the liquid coolant is applied (either spray or flow mode) are some of the many commonly used approaches to lower the heat sink temperature.

In this study, the heat exchange effectiveness was investigated by using a test vehicle modeled from an actual application and varying the TIM while maintaining the other parameters constant. This paper will focus on how the thermal interface material affects the device temperature.

Experimental Design

Demonstration Test Vehicle

An experimental setup was created based on a coldplate's thermal management performance in cooling a simulated semiconductor device.

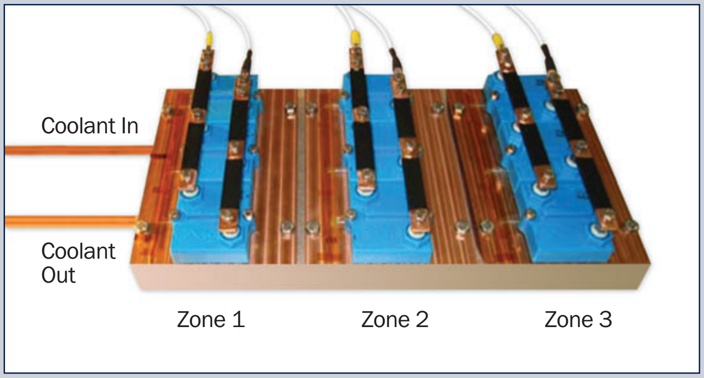

Figure 3: Copper tube coldplate with 3 heating zones.

Instead of using the actual semiconductor device which produces heat during operation, three planar 600 W, 3 Ω resistors were used to simulate the actual power levels predicted (Figure 3). To model a variety of steady state conditions, two power supplies were used to provide different heating to the inner and outer resistors. Attaching the resistors to the cold plate was accomplished using a copper heat spreader designed to accommodate the different mounting requirement of the resistors (Figure 4). The heat spreader also allowed attachment of thermocouples that were placed directly under each resistor and directly above the coldplate using 0.030 inch slots and silver epoxy. These four thermocouples accurately monitor the temperatures at the coldplate surface and at the resistors to detect any anomalies.

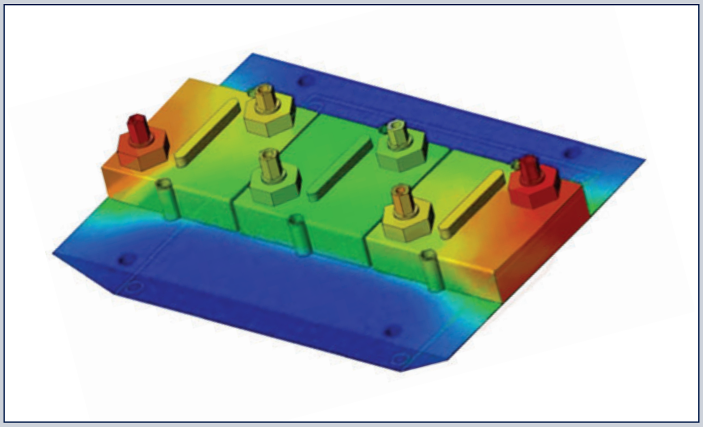

Figure 4: Heat spreader thermal model and drawing.

The three heat spreaders per coldplate provided 12 thermocouple readings (9 under the resistors and 3 above the coldplate) which were fed into a data acquisition system. This continually monitored each experimental run and, together with the water input and output temperature, provided a temperature record of each test. The software output was graphically displayed, showing the temperature readings at each coldplate zone.

Testing Plan

Coldplate technologies and thermal interface materials were tested utilizing this design. Three coldplates using different cooling schemes - copper tube technology, a more advanced pin-fin design, and a new foamed graphite design - were fabricated with identical dimensions. In addition, several thermal interface materials were tested to determine their effectiveness.

The following variables were modified to quantify the thermal management performance of coldplate technologies and TIMs.

Cold Plate Technologies
- Copper Tube
- Foam Graphite
- Pin-Fin Copper

Thermal Interface Materials
- 2 Thermal Greases
- Soft Metal Foil
- Phase Change Metal Alloy (PCMA)
- Thermal Pad
- No TIM

Input Coolant Temperature
- 5°C
- 25°C
- 40°C

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Input Coolant Flow Rate

- 0.5 gallon per minute (gpm)
- 1.5 gpm
- 3.0 gpm

Copper Tube Cold Plate

Copper tubes were embedded into an aluminum plate using a thermal epoxy for attachment (Figure 5).

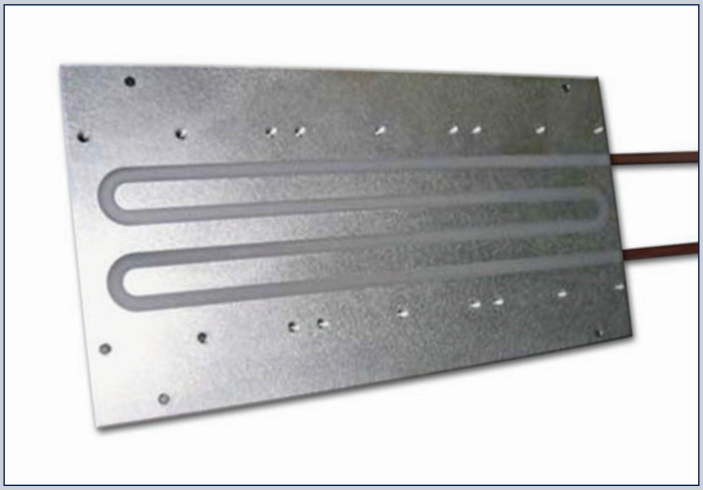

Figure 5: Copper tube in aluminum coldplate.

Pin-Fin Cold Plate

Another cold plate was fabricated to the same mechanical specification using pin-fin technology. The pin-fins were produced through a copper injection molding process. This provided a flat surface on the cold plate top with a unique pattern of heat exchanging pins hanging below, in the coolant path. Also unique to the design, the pin-fins were manufactured into panels the size of the power device, allowing for easy assembly of a cold plate containing any number of devices. To provide uniform flow into each cooling zone, this coldplate was designed with a large copper tubing inlet and outlet for each flow field of pins.

Foamed Graphite Coldplate

The third cold plate design was fabricated using a highly thermally conductive, foamed graphite internal manifold in the coolant flow. By machining the foam into a continuous "S" pattern and bonding to a flat copper surface, a high surface area heat exchanger was produced. The coolant floods the internal channels on the input side and flows through the highly conductive foam section to reach the output.

Thermal Test Facility

The test facility provides thermally controlled coolant between 5°C and 40°C and flow rates from 0.5 gallons per minute (gpm) to 3 gpm into an insulated chamber). The thermal test chamber, shown in Figure 6, is constructed from an aluminum sheet and lined with 1 inch rigid foam. Windows are also provided at each end to allow observation during testing. Another thermocouple attached to the inside top of the chamber provides the internal temperature to the data acquisition software. The inside is lined with aluminum foil and electrically conductive foil tape to provide a completely grounded shield for safety.

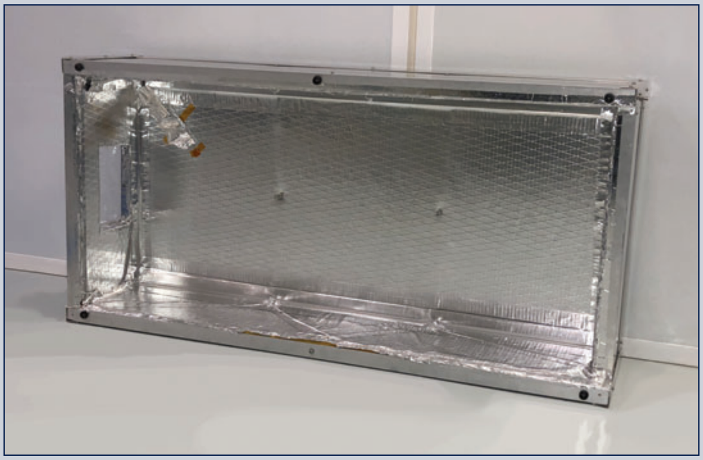

Figure 6: Thermal test chamber.

A chiller provides the controlled temperature coolant into the thermal test area. A bypass valve allows continuous circulation of coolant without passing through the coldplate to maintain coolant temperature and prevent pump damage. A 20 micron filter is directly attached to the chiller output to prevent any foreign particles from entering the coldplate and clogging any channels. The coolant then passes through a flow meter, an external heatable zone, a pressure gauge, and dual thermocouples before entering the coldplate. The heatable zone provides a final adjustment of temperature using the thermocouple measuring the water input in a feedback controller. After exiting the coldplate, the coolant passes through another thermocouple and pressure gauge before returning to the chiller. The heat spreaders were torqued to 16 inch-pounds for all TIMs.

Experimental Results

A series of experiments were performed to quantify the thermal management performance of the cold plate technologies and thermal interface materials identified earlier. The coldplate, thermal interface material, coolant flow rate, power input, and coolant temperature were all changed individually and the effect on steady state temperature recorded in each of three zones. Under the same conditions, the more efficient thermal management system will demonstrate a lower temperature at each zone.

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Figure 7 shows the temperatures obtained when different TIM materials were tested at the same flow rate, input water temp, and power input. Each TIM has a bar triplet that indicates the temperature at the center of zones 1, 2, and 3 (purple, red, and reen, respectively). Under these conditions, the two thermal greases provided similar TIM results, but the testing was sensitive enough to always discriminate one from the other. The soft metal foil TIM was almost as good. This material was developed as a compressible metallic shim for thermal applications under power devices. Rather than being flat, this soft metal foil has an embossed pattern that provides contact with both sides of an interface, even though surface irregularities exist. At the time of these experiments, samples were only available in a 2 inch width, much narrower than the heat spreader. While placed at the hottest portion of the zone, improved results would be expected if the foil covered the full width of the heat spreader. Also shown in this graph, is the higher temperatures obtained when no TIM was used.

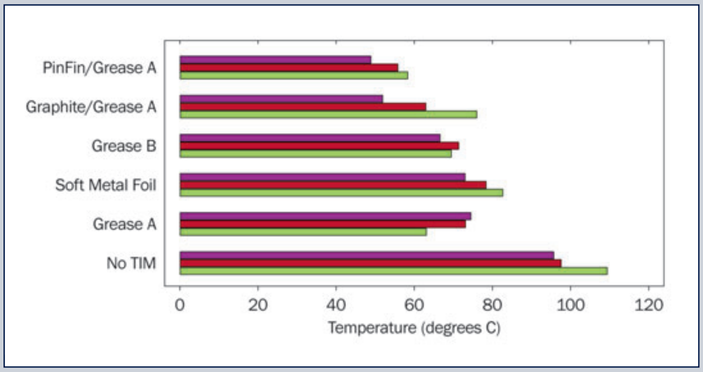

Figure 7: Resulting steady state temperatures (at 3000 W, 1.5 gpm coolant flow, 40°C coolant input) obtained for different TIMs with a copper tube coldplate, and for Thermal Grease A with a pin-fin and graphite coldplate. Temperatures at zones 1, 2, and 3 are indicated by colors purple, red, and green, respectively.

The top two bar groups reflect data obtained when using the pin-fin and graphite coldplates with Thermal Grease A. Both achieved lower temperatures than the copper coil coldplate. While the temperatures in zone 1 (closest to the coolant inlet) were nearly the same, the pin-fin coldplate produced significantly lower temperatures in zones 2 and 3. This was, most likely, not due to just the technology used, but rather the design of the inlet and outlet flow. The foamed graphite coldplate clearly did not provide an equal coolant flow to all three zones, resulting in the temperature increase as the distance from the inlet increased.

Figure 8 shows some of the materials tested at a higher power level, yet by reducing the input coolant temperature, much lower temperatures were obtained, as might be expected. Changes in coolant flow rate, input power level, or coolant temperature did not change the order of performance for each TIM, but simply shifted all the temperatures higher or lower as a group.

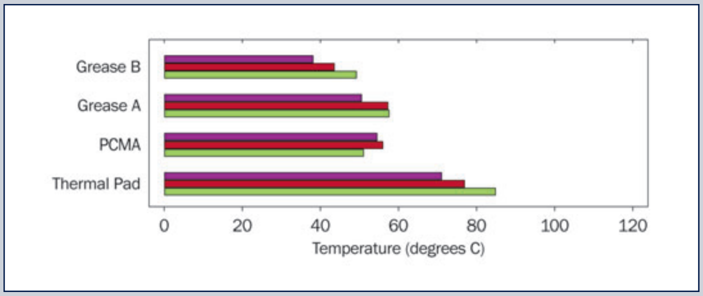

Figure 8: Resulting steady state temperatures (at 3500 W, 1.5 gpm coolant flow, 5°C coolant input) obtained for different TIMs with a copper tube coldplate. Temperatures at zones 1, 2, and 3 are indicated by colors purple, red, and green, respectively.

The phase change metal alloy provided a temperature performance similar to the soft metal foil, however, regions of melting and flow occurred that allowed some of the material to move out of the interface. To properly test this material, the experimental design would need modifications to keep the TIM in place.

The thermal pad material produced the highest temperatures, but was the only TIM that was not maintained at a 0.004 inch bondline. Since it is constructed with three 0.002 inch layers of thermal grease and aluminum, the resulting bondline was greater than the other TIMs. The higher heat transfer path length resulted in a lower heat flow.

Comparison with Previous Modeling

The original modeling work was performed with a slightly different design than the actual experimental design due to changes made in the actual application after the modeling was completed. To achieve a higher power input, three planar resistors were needed instead of two. This required a different heat spreader interface design. However, in order to make theoretical comparisons to the previous modeling, some tests were performed providing the same heating conditions as was modeled.

The FEA case (Figure 9) with 3000 W, 1.5 gallons per minute coolant flow, 40°C input coolant, and thermal grease predicted a coldplate temperature of each zone at 67°C (153°F). This is quite close to the experimental coldplate average of 73°C obtained using the same conditions.

Additional modeling was performed using a different thermal analysis program. Figure 10 shows the solid model representation of the actual test vehicle with similar operating conditions. The thermal profile obtained in this model showed cooler temperatures than the experimental data. By incorporating parameters more reflective of the thermal resistance of the interface (flatness, surface finish, pressure, non-uniform heat input) into this model, a more calibrated simulation was obtained. After verification with experimentally derived data, the

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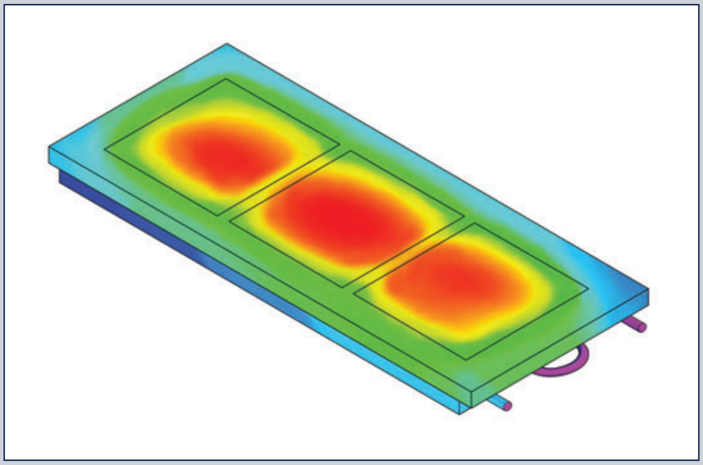

Figure 9: FEA model at 3000 W, 1.5 gallons per minute coolant flow, and 40 °C input temperature.

model can then be easily adjusted to evaluate new material properties and thermal conditions without having to spend excessive resources on expensive laboratory testing.

Conclusions

The ability to accurately model and predict any thermal issues prior to hardware assembly will potentially save a great deal of time and money further down the line. However, while thermal simulation software provides an easy, efficient analysis of thermal conditions, and can quickly trade materials with different properties, it can not be relied on exclusively. Without the experimental data of actual hardware under test (or at least an equivalent model of the hardware), the software results may not be adequate in accurately predicting performance.

Experimental data must be obtained to calibrate the model. With the proper experimental design, conditions that affect the thermal resistance of the interface, such as surface finish, pressure, and flatness, will automatically be included in the results.

Fine differences in performances of thermal interface materials can be experimentally determined if the test vehicle is matched to the actual application. This study indicated that while a standard thermal grease may perform well in a particular application, other TIMs should also be considered. The soft metal foil provided similar thermal control without the careful application processes needed to apply thermal grease. To achieve a uniform coating and repeatable bondline control with thermal grease, an investment in fixturing tools and maintenance is required. The foil offers a more manufacturable, easier to apply, easier to rework, repeatable method for achieving cooling in high power devices.

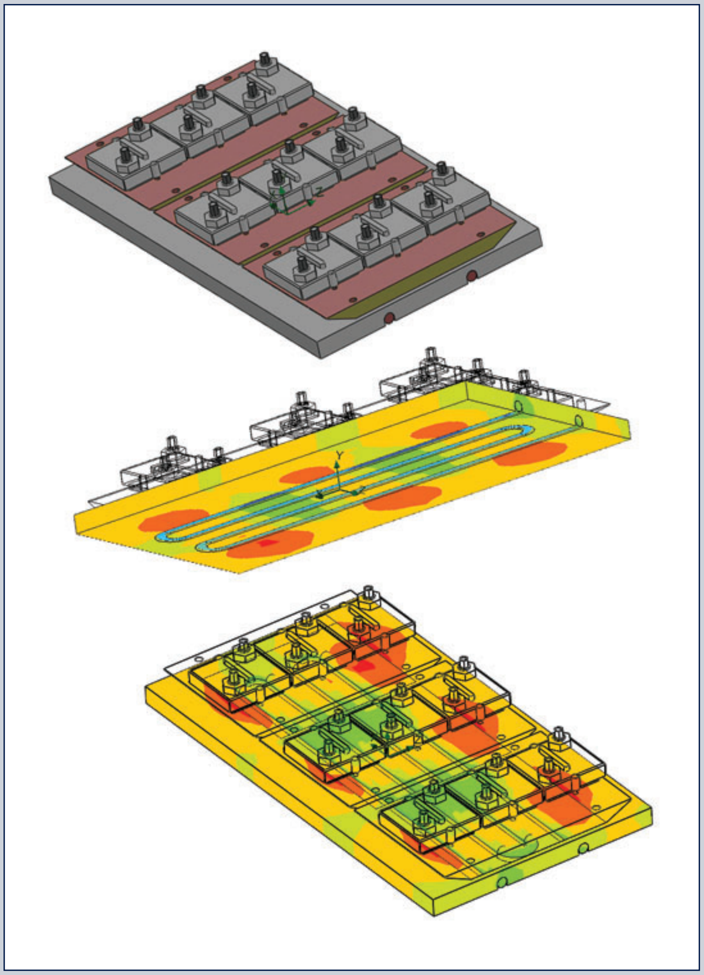

Figure 10: Solid model shown of actual test vehicle with a simulated thermal profile.

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