

Thermal Characterization Methods and Applications



Thermal Application Note

This application note provides a comprehensive set of considerations for the thermal characterization and modeling of power modules. First, it describes fundamental background information and basic thermal modeling theory. Next, it covers thermal characterization methods and metrology. It then discusses the role and usage of the NTCs found in Wolfspeed® power modules. Guidance is then given for cooling solution design. Finally, an example is shown that uses datasheet thermal definitions for a notional system design.

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1. Background Theory – Power Module

To fully synthesize the benefits of Silicon Carbide (SiC) for higher power applications, advanced packaging formats are required, especially as the application power level and complexity scales. Power modules offer a power-dense solution that balance robust electrical performance with effective thermal dissipation. The manufacturing technique in which power modules are assembled results in a layered vertical stack-up. During operation of the power module, heat is generated at the top of the stack by the SiC semiconductors, referred to as the junction in Figure 1.

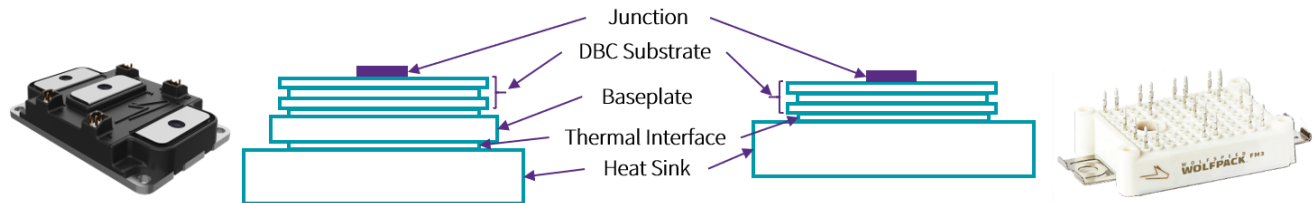


Figure 1: Power module stack-up

In practice, the actual junction is not physically accessible, so properties such as temperature cannot be measured directly. Additionally, there are several die within the module with each having a volume; so specific thermal properties at a particular point in the space cannot be defined. The virtual junction therefore is an implied area representative of an assumed homogenous junction from which conclusions can be drawn. For the purpose of simplicity, in supporting literature the virtual junction temperature is used interchangeably with the actual junction temperature.

Generally, the point at which heat exits the power module is referred to as the case. However, the case in modules can generally be classified into two subtypes: baseplate and baseplate-less. In baseplate modules the ceramic direct-bonded copper (DBC) that provides electrical isolation is typically attached to a copper or aluminum baseplate to aid in heat dissipation. Baseplate-less modules only consist of the DBC substrate, resulting in a smaller package without a compromise in thermal performance. The difference between the two is illustrated in Figure 1.

This distinction is very important to note, as it has implications thermally in the determination of how the module is sinking heat from the junction. The distinction also outlines the way in which we define, measure, and analyze thermal properties, which differ slightly. There are industrial standards that this document discusses, going into further detail to navigate the different form factors of power modules.

Within a power module, there are Thermally Sensitive Electrical Parameters (TSEPs) which are specific properties that respond in a predictable manner to temperature change. TSEPs play a critical role in determining the virtual junction temperature, especially in characterization methods that require on-line based measurements. The module's on-state resistance and body diode forward are common examples of TSEPs used to estimate the virtual junction temperature.

1.1 Thermal Resistance and Impedance

Thermal resistance or R_{THJC} is a system property that describes the steady state resistance of thermal power dissipation from the device’s semiconductor junction to the case with units of K/W (or °C/W). It is an important system characteristic because it is a major factor for determining a module’s ampacity. R_{THJC} is given by the following equation:

$$R_{THJC} = \frac{T_J - T_{CASE}}{P},$$

where T_J , T_{CASE} and P are the device junction temperature, case temperature, and power dissipation in the module respectively.

Power modules consist of multiple layers, attaches, conductors and insulators, each of which contributes to the total thermal resistance. Additionally, each of these layers/materials take time to store or dissipate energy prior to a change in temperature. This quantity of energy required to change the material temperature is called the thermal capacitance (C_{THJC}) of the power module, with reference from the device junction to the power module case. The concepts of these properties are not dissimilar to their electrical counterparts in resistance, capacitance – and by extension, impedance.

Thermal impedance or Z_{THJC} therefore describes the transient thermal properties of the system from junction to case. It is not represented as a constant value, but as a plot of the R_{THJC} over time when a known power dissipation is experienced by the system. On a datasheet, Z_{THJC} is represented by multiple plots at different duty cycles.

Z_{THJC} is the cumulative combination of thermal resistances and R_{THJC} and C_{THJC} and can be represented as a Foster/Cauer model as shown in Figure 2. It is important to know the Z_{THJC} response of the system in order to understand thermal dissipation characteristics under start-up conditions, changing electrical loads, and any transient conditions.

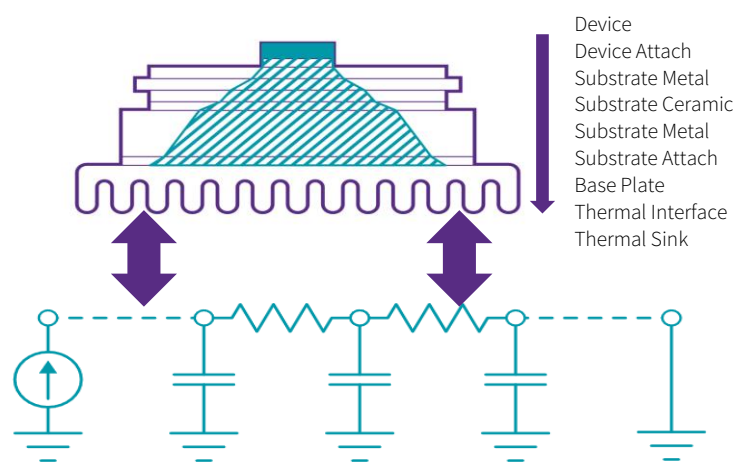


Figure 2: Notational Cauer model of power module thermal network

1.2 Standards – Automotive Qualification Guidelines (AQG)

The European Center for Power Electronics ([ECPE](#)) has prepared the AQG 324 to establish the state of art as it pertains to test conditions for validating the properties of power modules in an effort to align stakeholders by standardizing approaches, definitions, and technical processes.

Wolfspeed® leverages the standards set in AQG 324 to distinguish thermal measurement methods between baseplate and baseplate-less modules. For baseplate modules, AQG 324 references the thermal resistance from the junction to the case (R_{THJC}). The reference temperature at the case T_c is measured using a temperature sensor embedded within a hole of a heatsink with diameter 2.5mm, shown in Figure 3.

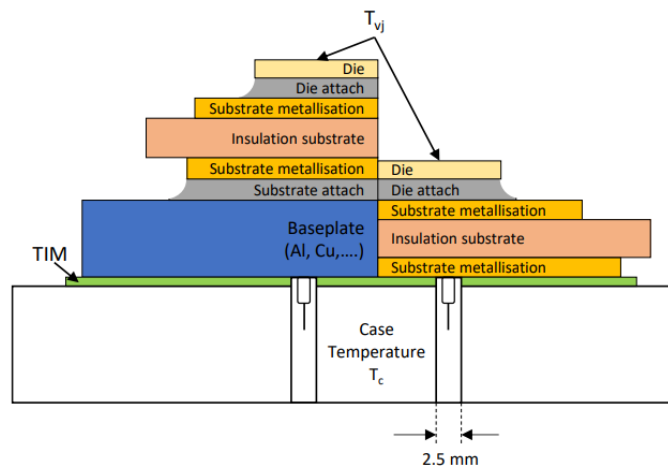


Figure 3: Reference T_c for baseplate modules via [AQG 324 Section 7.2](#)

Wolfspeed reports thermal resistance of baseplate modules using R_{THJC} like AQG 324 specifies. However, R_{THJC} is measured using the Transient Dual Interface Measurement (TDIM) method as defined by the JEDEC standard *JESD 51-14*. A temperature sensor contacting the module's baseplate through the TIM disrupts the heat flux path and underestimates R_{THJC} because it causes the temperature measured by the sensor to be closer to the junction temperature. This method may overstate the device's thermal performance. Using a case sensor makes the reported R_{THJC} highly sensitive to its location relative to the active semiconductor devices, making the measurements less universally useful and less consistent. The TDIM method provides a more useful and repeatable measurement. The methodology behind this technique is expanded upon in Section 3.4.

The thermal resistance convention for baseplate-less modules states that the heatsink temperature T_s becomes the reference from the junction (R_{THJS}). T_s can be measured by making a blind hole inside of the heatsink directly below the module. The hole must have a diameter of 2.5 mm and end 2 mm below the heatsink surface, considering end shape of hole and sensor shape.

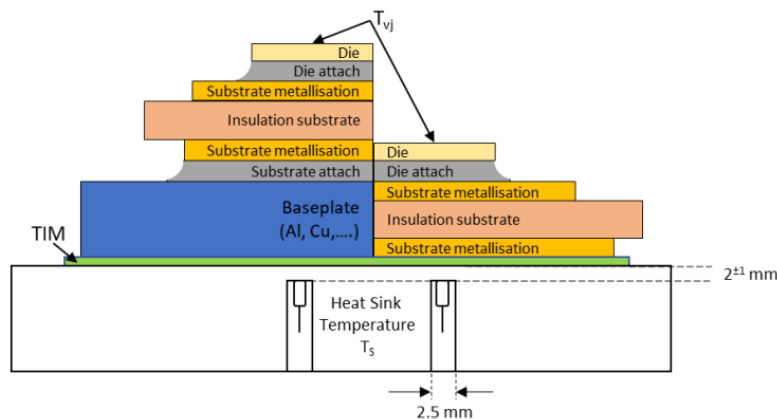


Figure 4: Reference T_s for baseplate-less modules via [AQG 324 Section 7.2](#)

Power modules that are package-sintered to the heatsink or that directly interface with the cooling fluid have their steady-state thermal properties characterized junction-to-fluid (R_{THJF}), sometimes referred to as junction-to-ambient (R_{THJA}). Here, the average of the inlet and outlet fluid temperatures are used as the reference point as shown in Figure 5. Fluid composition, flow rate, and pressure drop are recorded as these parameters will impact thermal performance.

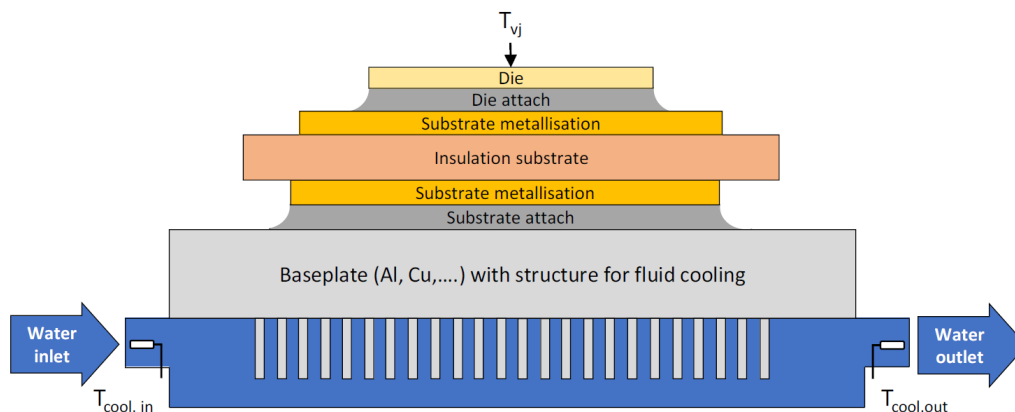


Figure 5: Reference $T_{cool,in}$ and $T_{cool,out}$ for direct-cooled modules via [AQG 324 Section 7.2](#)

All thermal parameters given on any module datasheet are measured with strict accordance to the methodology presented in AQG 324 and JESD 51-14 (R_{THJC}). This includes monitoring the thermal transients of the cooling curve, as opposed to monitoring the thermal response of the heating curve. The cooling curve is used because the diode forward voltage is used to monitor the virtual junction temperature, and this value cannot be monitored under channel conduction. The cooling curve is acknowledged as a reciprocal response to the heating curve, justifying its usage for thermal characterization. Datasheet results are based on the highest R_{TH} device per switch position within a module as that device will be the limiting factor of thermal performance for the unit.

1.3 Background Theory – Thermal Interface Material (TIM)

When the power module is placed upon a thermal sink, the mated metal surfaces seem flat and perfectly in contact. However, metals have microscopic voids and irregularities that prevent perfect joining of the two surfaces. These imperfections result in small pockets of air being trapped at the thermal interface. The trapped air, in comparison to the metal, is a poor conductor of heat. Therefore, there is a need for a Thermal Interface Material (TIM) to fill in the microscopic air gaps between the module baseplate and heat exchanger as shown in Figure 6.

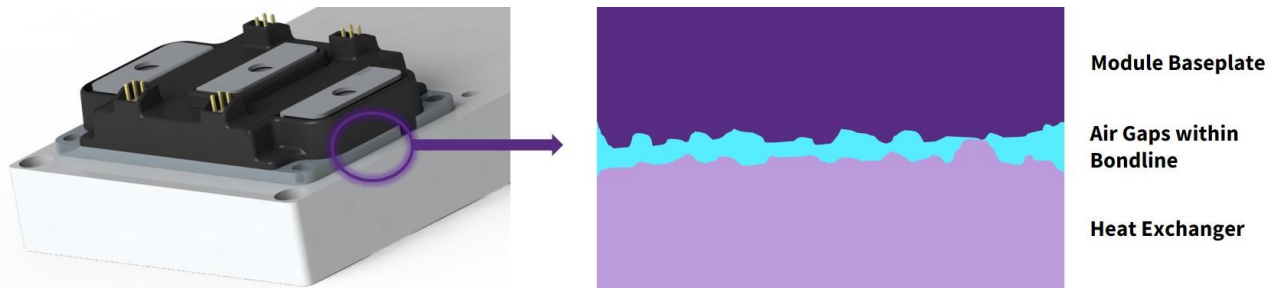


Figure 6: Representation of the microscopic voiding between module baseplate/substrate metallization and heat exchanger

Selecting a suitable TIM for your application is crucial in determining the maximum thermal threshold. By looking at the thermal stack from junction to sink, Figure 7 shows how the thermal resistance of TIM accounts for more than half of the bulk thermal resistance of the system.

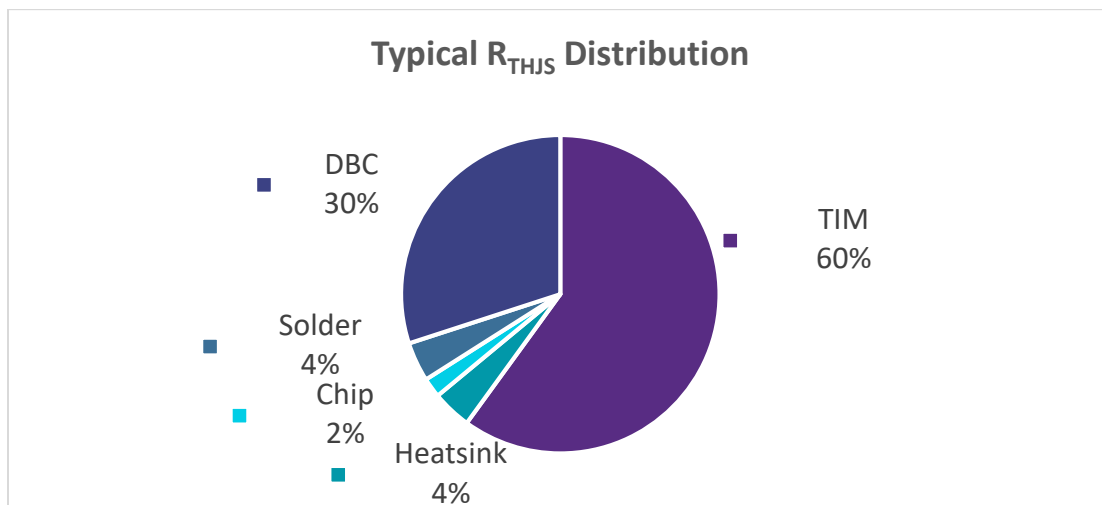


Figure 7: Typical R_{THJS} distribution observed in system application

1.3.1 TIM Selection

TIMs are typically comprised of a carrier material mixed with high thermal conductivity filler particles. The carrier materials provide the viscosity needed for the TIM to distribute itself upon the surface between the module and the thermal sink. The effective thermal resistance R_{THeff} of the TIM can be defined as:

$$R_{\text{THeff}} = \frac{\text{BLT}}{k_{\text{TIM}}A} + \sum_{i=1}^n R_{\text{THci}}$$

Where BLT is the TIM bond line thickness, k_{TIM} is the thermal conductivity, A is the material surface area and the last term being the sum of the contact resistances R_{THci} at the boundary of the contacting surfaces.

There is no golden rule that linearly governs the relationship between mixing the carrier and filler concentration to synthesize high thermal conductivity. The physical boundary resistance between the two materials is intricate and highly irregular, and the bulk thermal conductivity is often largely dependent on the size of the filler particle itself. Contrarily, having larger filler particles can increase the size of the BLT.

Having a viscous carrier in the TIM helps to reduce the BLT, but can add complexity when it's applied and cause "pump out," a phenomenon where thermal cycling and CTE mismatch cause TIM to be squeezed out of the contact area leaving air pockets. A less viscous carrier may make the application process of the TIM itself much more tedious and complex to guarantee consistency and specific layer thickness.

Additional factors to consider for appropriate TIM include:

- Long-term reliability
- Outgassing
- Storage stability
- Electrical conductivity

Therefore, selecting a TIM with the correct balance of these factors and its correct application is essential in system thermal management considerations. For more information regarding TIM, its types and general application methods, please refer to this [link](#).

2. WolfPACK™ Power Modules

When compared to discrete devices, power modules remove the need to design additional insulation by mounting the devices to a suitable ceramic with copper planes (generally referred to as direct-bonded copper or DBC). The traditional stack-up used in power module design is to then attach this DBC to a metal (or composite) baseplate, which includes mounting points for bolting the module onto a heatsink or cold-plate. Wolfspeed WolfPACK™ modules eliminate the baseplate and facilitate direct cooling of the DBC substrate. This enables increased heat transfer from the die, reducing the junction temperature of the chip for a given power level.

There are two main factors required for good thermal transfer between interfaces: thermal resistance, which has been discussed, and the coefficient of thermal expansion (CTE).

The CTE of a SiC die ($4.0 \cdot 10^{-6}/\text{K}$) is normally matched to the CTE of the ceramic substrate, which is made of aluminum nitride ($4.5 \cdot 10^{-6}/\text{K}$) or aluminum oxide ($8.2 \cdot 10^{-6}/\text{K}$). However, the baseplate is generally made of either copper ($16.5 \cdot 10^{-6}/\text{K}$) or an Al-SiC composite ($8.4 \cdot 10^{-6}/\text{K}$) for mechanical motives. This mismatch, coupled with the rigid bond layer between the DBC and ceramic, causes material stresses at joints of these materials. These thermomechanical stresses acting on the large interface between the DBC and baseplate can cause solder fatigue and fractures. Delamination of the solder joint (which greatly increases thermal resistance) can occur from thermal cycling and can even fracture the brittle ceramic DBC, leading to module failures.

The baseplate-less design of the Wolfspeed WolfPACK™ eliminates this mechanical failure point by eliminating the inflexible connection to the mismatched material. The baseplate mounting bolts are swapped for metal tabs that pull on the plastic housing, evenly distributing the force across the substrate. As the interface between DBC and heatsink is flexible grease (rather than inflexible solder), it can allow differential expansion between materials without inducing substantial stress.

3. Thermal Characterization Methods

Quantifying and determining thermal resistances are important steps in the considering the tangential thermal performance within an application scope for designers. The following sections cover a comprehensive list of methods and standards best used to accomplish this. All experimental results shown are based on actual data.

3.1 Test Setup and Guidelines

There are some key considerations that must be made when setting up a power module for thermal characterization. TIM application, baseplate/terminal mounting torque, power/measurement configurations, bussing/strain relief, and cold plate selection can all impact RTH/ZTH measurement results. Because of this, it is advised to replicate all possible parameters from the intended application and follow available application notes for that module's platform.

TIM application is paramount for generating quality thermal measurements, especially for junction-to-sink and junction-to-fluid measurements. Since TIM is part of the measured thermal path of these measurements, it is recommended that the TIM is applied using a stencil. The TIM application should follow procedures outlined in the corresponding application note. Wolfspeed stencil patterns are available upon request.

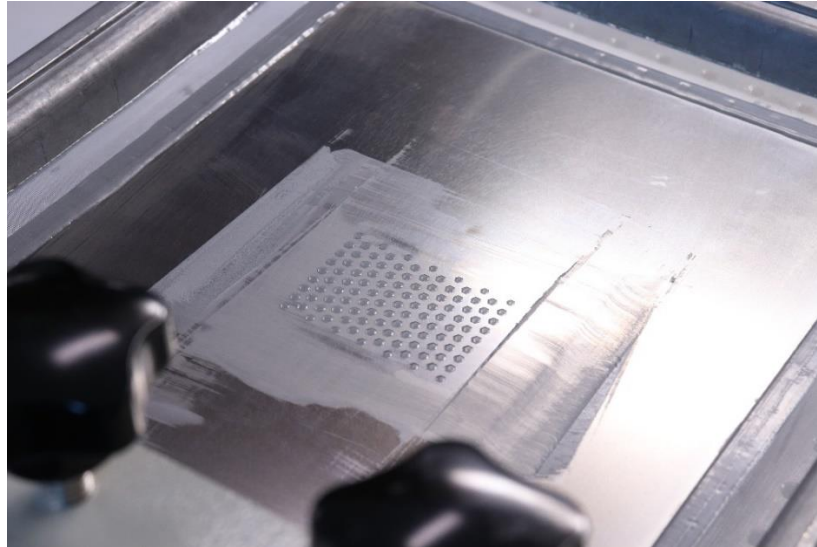


Figure 8: GM module with stencil-applied thermal grease

Proper mounting torque and mounting patterns will ensure better thermal measurements are generated. Inadequate mounting torque will result in the module having poor metal-to-metal contact with the heatsink, altering thermal flux patterns and reducing thermal performance. Having a balanced torque pattern will also enable balanced mounting pressure between mounting locations. Inadequate torque of the power terminals leads to a higher and less consistent contact resistance, which will negatively affect both hotspots at the terminals and produce inaccurate voltage measurements. Excessive torque or excessively long screws could potentially damage the heatsink or power lead frames of the module. It is recommended that mounting torques, patterns, and procedures be referenced from the appropriate datasheet and application notes.

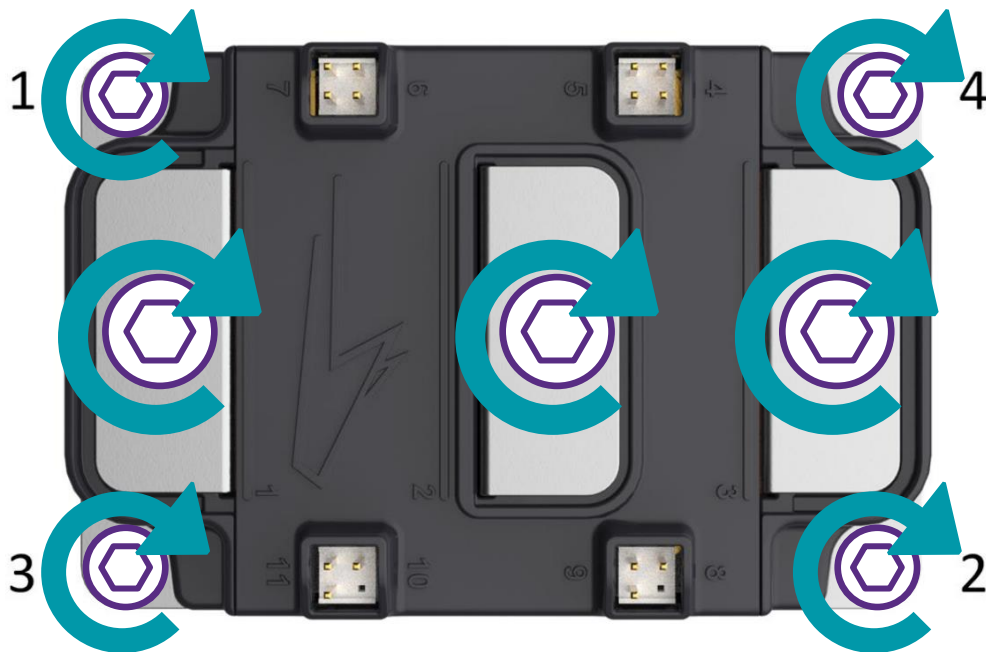


Figure 9: XM module platform mounting diagram

Where and how the module’s connections are made for high current, gate-biasing, measurement current and voltage monitoring will impact thermal characterization results. Z_{TH} is fundamentally calculated from measured temperature and power, so electrical connections should be made to ensure those values are accurate. An example connection diagram is shown in Figure 10.

- Power connections should be made at the module’s designated power terminals.
- V_{GS} should be applied across the gate and source-kelvin pins.
- Measurement current should connect at the same location as the power connections.
- Voltage measurements should be connected to kelvin measurement locations when available. This largely removes the current path from the measurement path, leading to more accurate TSEP and power monitoring.

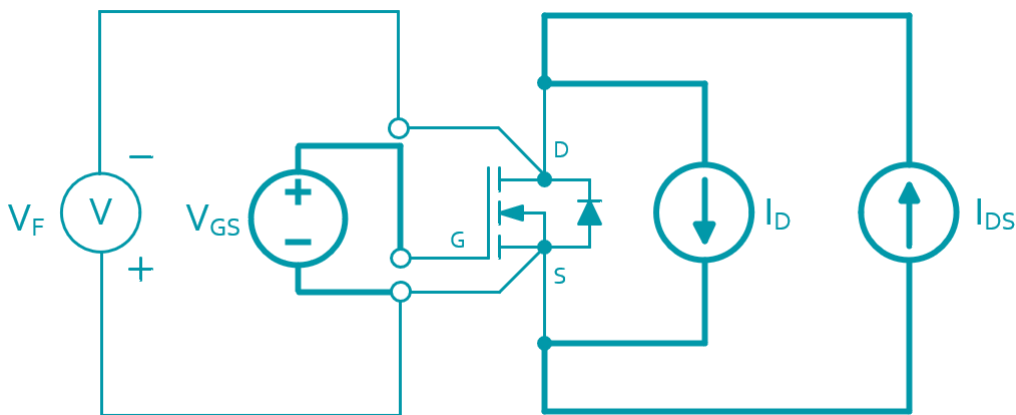


Figure 10: Test electrical connections diagram

3.2 TSEP Calibration – Diode Forward Voltage

A key component of thermally characterizing a device is monitoring the T_J . One of the ways to do this is by calibrating a device’s Thermo-Sensitive Electrical Parameters (TSEP). The forward voltage across the body diode of a MOSFET or a Schottky diode correlates almost linearly with temperature, making it an ideal TSEP candidate to represent a device’s virtual junction temperature (T_{vj}). Below is the equation representing the current flowing in a diode:

$$I_D = I_S \left(e^{\frac{q(V_F - R_S I_D)}{\eta k T}} - 1 \right)$$

where I_D is the diode current, I_S the saturation current, q is the electronic charge, V_F is the diode forward voltage, R_S is the series resistance, η is the ideality factor and k is the Boltzmann constant. Assuming $q(V_F - R_S I_D) \gg \eta k T$, the above equation can be simplified and solved for V_{BD} , resulting in a linear relationship with temperature.

$$V_F \approx \frac{kT}{q} \eta \ln \left(\frac{I_D}{I_S} \right) + R_S I_D$$

For accurate thermal characterization measurements, each device needs its TSEP calibrated. This is done by placing the device in a temperature-controlled environment (e.g. mounted to a liquid cold plate, thermal forcing system, scientific oven, etc.), and monitoring its diode forward voltage excited by a known diode current. For best results, ensure the temperature ripple of the system is $\pm 0.5^{\circ}\text{C}$ or less. Better quality current sources and measurement instrumentation will also help yield more accurate TSEP measurements. The diode current selected will correlate with ampacity of the setup, typically ranging between 50 mA-1 A, though it can be as much as 2 A for high ampacity systems. Higher measurement current results in a better signal-to-noise ratio, but can cause non-negligible junction temperature rise, so it's a tradeoff. If testing a MOSFET, the gate should be reversed biased using the maximum datasheet recommended V_{GS} . The TSEP connection schematic is illustrated in Figure 11.

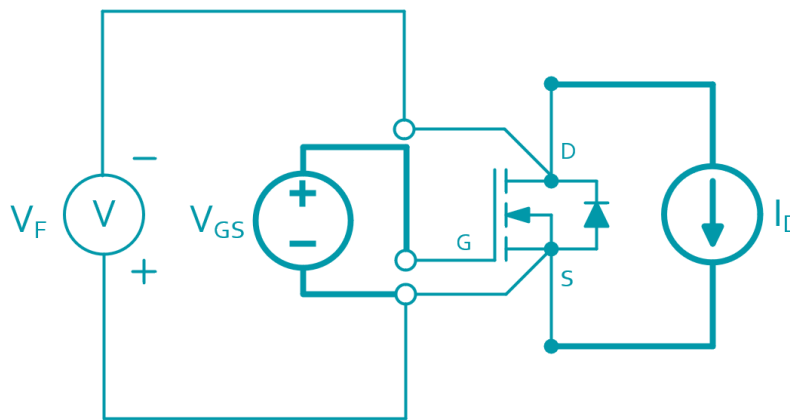


Figure 11: TSEP calibration diagram

During TSEP calibration, the device is passively heated by the temperature-controlled system. The V_F is measured at temperature intervals (typically every 10°C) after the system temperature has stabilized for a certain time period. This stabilization period is 20 minutes for conduction systems and 40 minutes for convection systems. The purpose for this stabilization window is to ensure the device junction's temperature is as close to the system's reference measurement point temperature as possible, and that the temperature ripple is within expectation. Ideally the device will be calibrated fully within its range of operation, though the maximum temperature measurement point will be limited by the capabilities of the temperature-controlled system.

Once the calibration is complete, a V_F vs. T_J plot is generated that is used as a decoder when taking device temperature measurements. A quadratic curve fit should be used for interpolation and extrapolation, as it will mostly account for the nonlinearity of the TSEP curve. Internal testing has shown that a TSEP curve quadratic extrapolation of 50°C is typically accurate within 1°C as seen by the TSEP plot in Figure 12, versus the linear extrapolation shown in Figure 13, which can be off by 6°C or more.

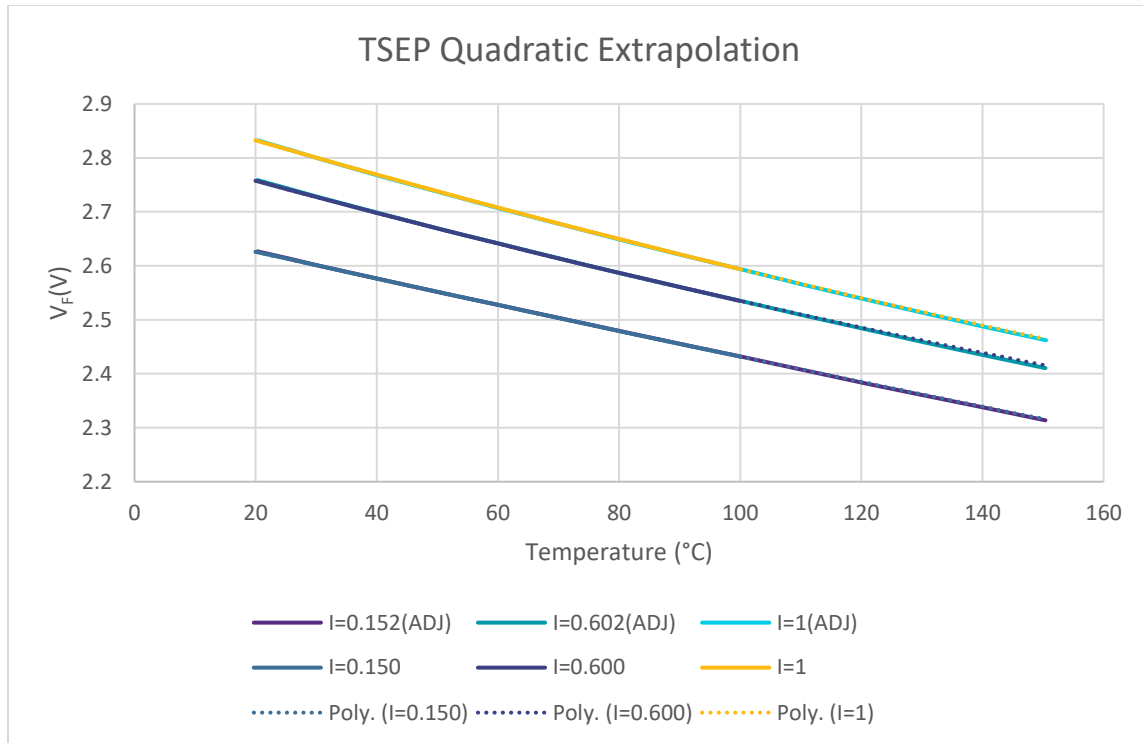


Figure 12: Quadratic TSEP curve fit

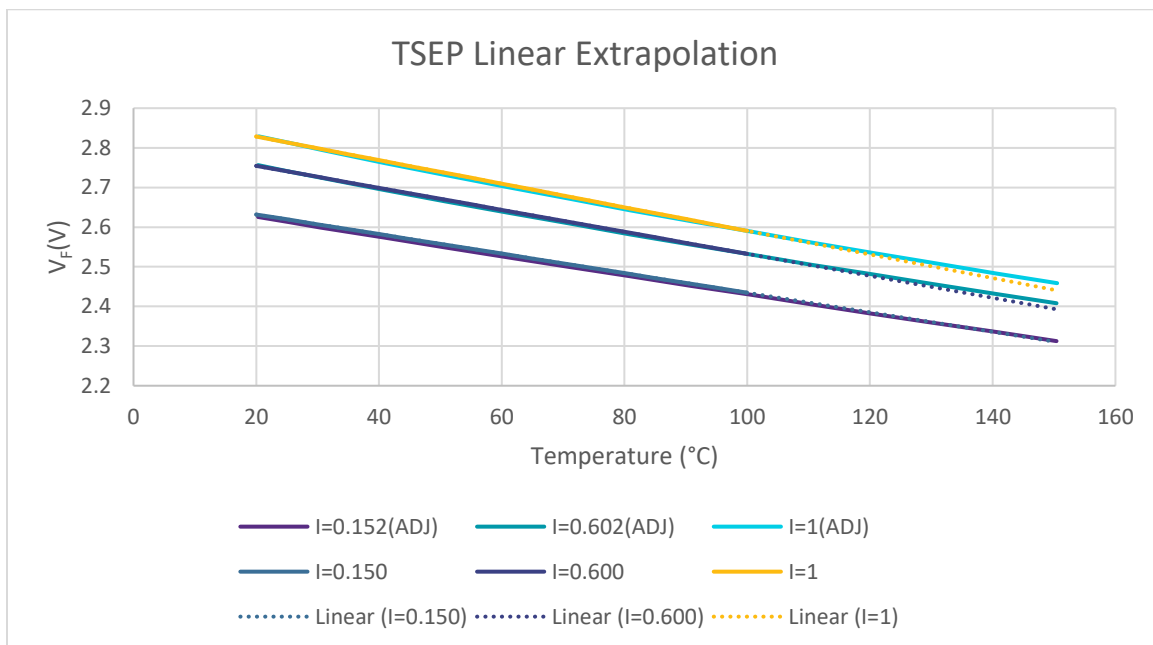


Figure 13: Linear TSEP curve fit

3.3 TSEP Calibration – On-State Resistance (Virtual Junction Method)

The on-state resistance $R_{\text{DS(on)}}$ can be leveraged as another TSEP to aid in the thermal resistance determination. The resistance of the module when turned on at a defined gate-source voltage V_{GS} is profiled based on varying temperature supplied by a coolant loop. A DC current is used to heat the module, from which the case temperature is recorded along with $R_{\text{DS(on)}}$. The thermal resistance can then be determined as based on the equation in Section 1.2. This characterization method is referred to as the **Virtual Junction Static Test**.

The Virtual Junction Static Test proves itself as a convenient method in that the positive temperature coefficient across the parallel die provides a good average indication of R_{THJC} measurements for power modules. However, self-heating from the applied current causes measurement errors in the resistance during testing. The resistance is also extremely non-linear across a wide temperature range, making prediction difficult. Like all TSEP related test methods, precise calibration is a necessity for overall accuracy.

Using the $R_{\text{DS(on)}}$ as TSEP can be extremely useful to thermally characterize modules in scenarios where there is an additional Schottky diode in parallel with the switching device. Because the body diode is intrinsic to the device, the temperature response of the forward voltage corresponds to the junction temperature. However, a Schottky diode is non-intrinsic as a physically separate device from the MOSFET and as such, its forward voltage does not directly represent the temperature of the MOSFET die.

3.4 Transient Dual Interface Method

Let's consider an ideal homogeneous cylinder, comprised of seven layers (1-7) with heat applied to layer 1 into an ideal thermal sink. Cumulatively, the impedance can be plotted as what is called a structure function; an R_{TH} vs C_{TH} (generic thermal resistance and capacitance) comparison through the layers of the cylinder. When the heat reaches the ideal thermal sink in the structure function, a singularity is achieved since the sink ideally has no thermal impedance, allowing all heat to be sunk. The sum of the resistance to the location of the singularity provides the cylinder's total thermal resistance.

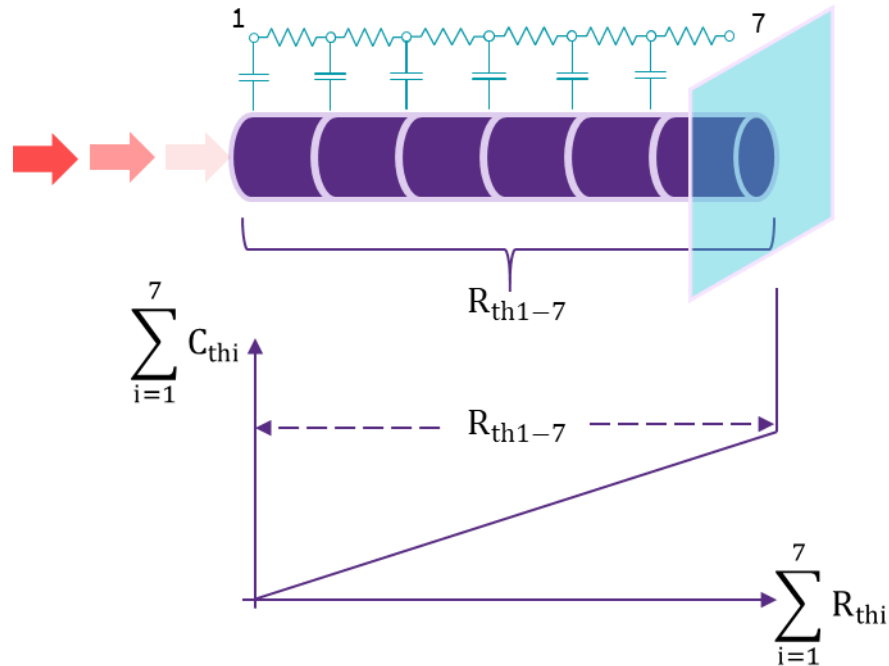


Figure 14: Cumulative structure function of homogeneous cylinder

Modifying the thermal stack in Figure 14 such that it consists of a dissimilar material with different properties produces the following changes in the corresponding structure function shown in Figure 15. The different thermal properties in different sections of the stack changes the slope of the structure function. With this, the partial thermal resistance and thermal capacitance can be extracted.

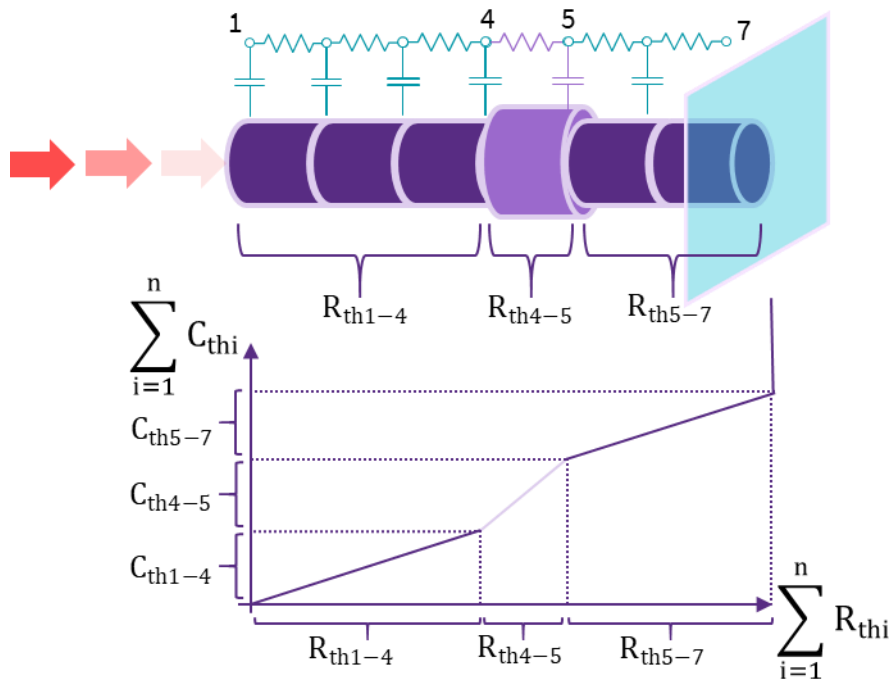


Figure 15: Cumulative structure function of non-homogenous cylinder

The Transient Dual Interface Method (TDIM) leverages the power of structure functions to thermally characterize devices. TDIM is a [JEDEC-51-14-0](#) standardized method to determine the Z_{THJC} , based on the comparison of the deconvolution of the thermal network model of the Z_{THJC} . Each layer of the cylinders in Figure 14 and Figure 15 corresponds to a layer within the power module. Therefore, by assessing the cumulative structure function of two step response measurements with different thermal stacks (module with TIM referred to as ‘wet’ and module without TIM referred to as ‘dry’), the point of divergence determines the steady state $Z_{THJC}(t)$ which corresponds to R_{THJC} .

Within a power module, there are Thermally Sensitive Electrical Parameters (TSEPs) that are properties that respond in a predictable manner to temperature change. TSEPs play a critical role in the TDIM process to determine T_J and must be carefully established. The TSEP used within TDIM is selected as the diode forward voltage. Through the ideal diode equation, the voltage drop across the diode is approximately proportional in relationship to the temperature at low current:

$$\ln\left(\frac{I_D}{I_S} + 1\right) \cdot \frac{\eta k T}{q} \approx V_{SD}$$

Where I_D is the diode current, I_S is the reverse saturation current, η the emission coefficient, k is the Boltzmann constant, T is the absolute temperature and q is the elementary charge.

A small current is injected into a switch on the module from source to drain through the body diode. Therefore, by measuring V_{SD} while the module is on a cold plate with a variable temperature coolant loop, the resultant measurements can be used to generate a polynomial function to correlate the TSEP to the junction temperature as shown in Figure 16.

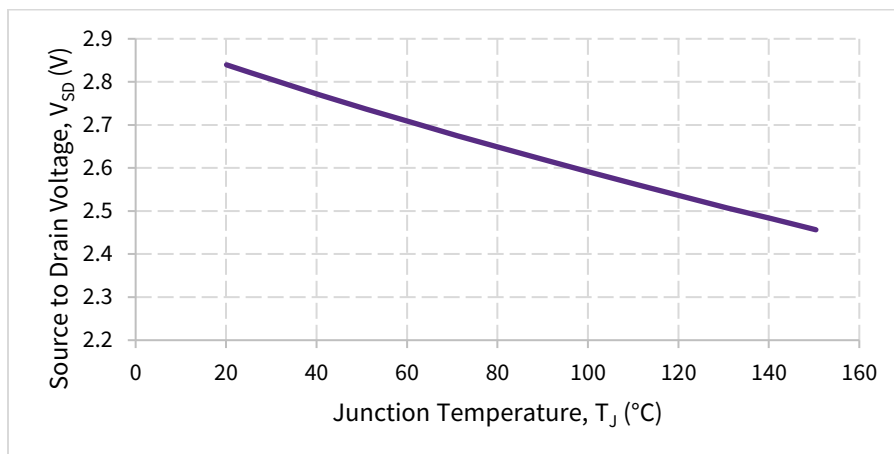


Figure 16: Diode forward voltage response V_{SD} across temperature

It is recommended that the heating current is $\frac{1}{2}$ to $\frac{3}{4}$ the current rating of the module to provide sufficient temperature bandwidth without compromising the module. It is applied to the module until a steady state temperature is achieved. The unit impulse moment for TDIM is taken as the instant the current is shut off. The resulting cooling curve of the temperature difference between T_J and T_{CASE} is then measured over time by V_{SD} . This now becomes the reference response function from which the analysis is made as shown in Figure 17.

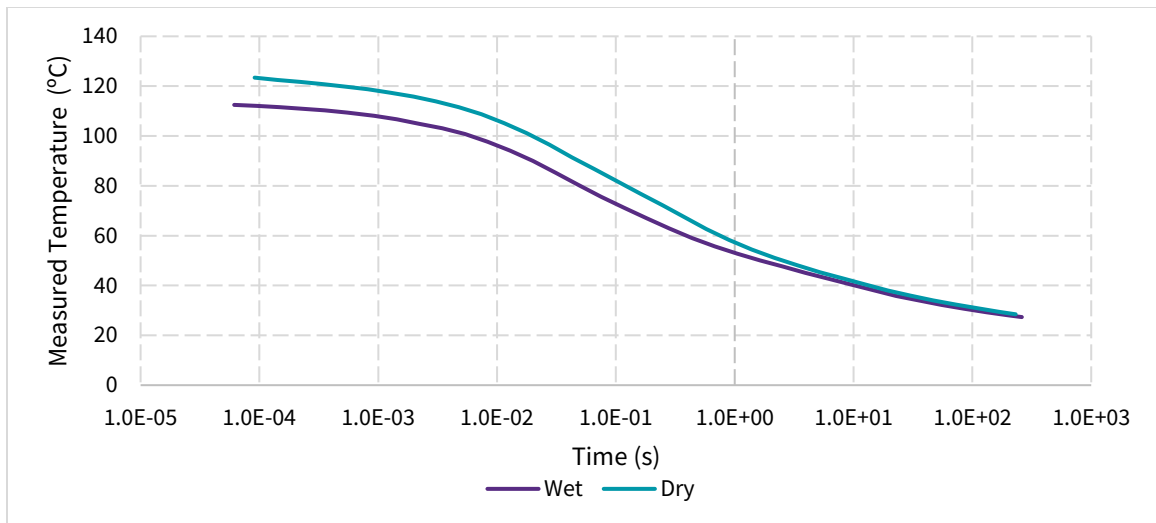


Figure 17: Temperature response of power module across pulsed moment

The structure functions for both wet and dry application of the TIM $f(R_{THJC}) = C_{THJC}$ is computed. The value of R_{THJC} for which C_{THJC} starts to clearly rise as per JESD51-14 is the steady state thermal resistance. This determination point is extracted through an empirical intersection of the differential structure function and a function ϵ , derived from finite element simulation. [Reference 1](#) provides a detailed analysis of the TDIM and computation of the structure functions. Figure 18 shows that at 0.109 K/W, the structure functions start to clearly separate as given by ϵ and is therefore the value of R_{THJC} .

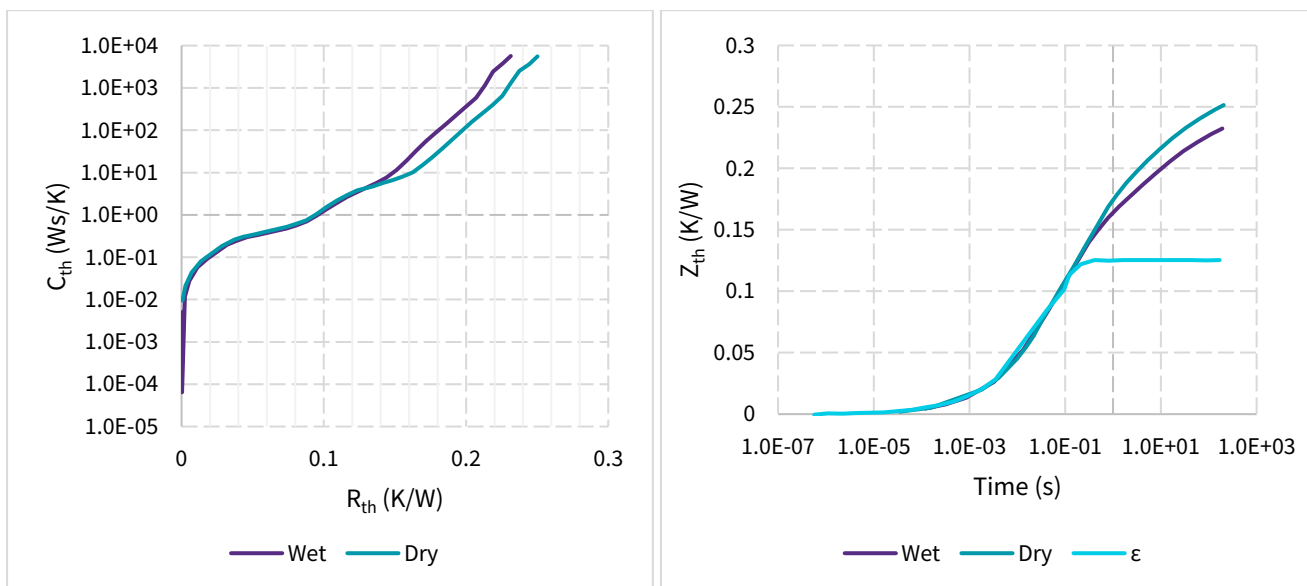


Figure 18: Structure function and derived thermal resistance

The TDIM provides not only the steady state R_{THJC} , but also provides the transient Z_{THJC} which is important in determining the thermal response of the module under start-up conditions, changing electrical loads, and under time-related power events. The resultant differential structure functions also reveal the thermal impedance layer-to-layer from die to baseplate. The method also proves to be non-destructive, in that a non-

modified power module can be used to carry out this test. However, the computation required is significant and can be severely skewed by inconsistent calibration of the TSEP.

This entire characterization process can be performed in an all-in-one hardware and software combination to streamline the process, such as the Siemens® T3ster™ – Thermal Transient Tester which is used at Wolfspeed®. A chiller such as the Julabo® SC10000W provides a stable coolant loop for calibrating the TSEP for the devices under test.



Figure 19: Thermal transient test equipment

3.5 Infrared Optical Test

While other characterization methods rely on the ability to be in contact with the module to extract temperature related data, infrared cameras offer a non-contact solution for thermal characterization. Infrared cameras produce thermal images by capturing the infrared energy of objects. This heat signature can then be converted to an image with corresponding temperatures of the object in focus.

To use infrared cameras to thermally characterize power modules, the power module internal surface must be revealed so that the junction can be visible. The highly polished surface of the die and wire bonds presents a challenge for thermal cameras to detect true surface temperature because of their low emissivity. Figure 20 shows the thermal capture difficulty of heated black-striped aluminum bars when this is the case.

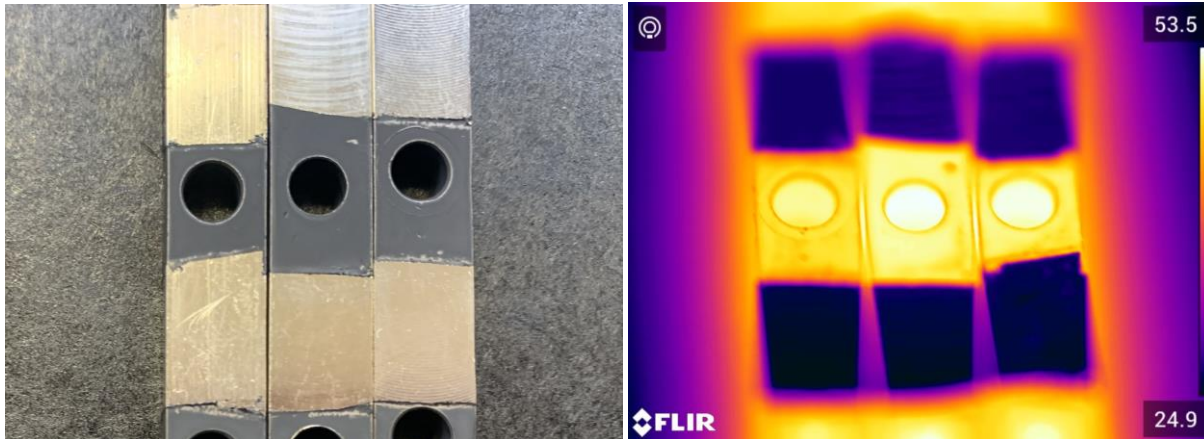


Figure 20: Emissivity effect on thermal image capture



Figure 21: Emissivity coating application method

Mitigation of this phenomenon is achieved through coating the internally exposed module with a high emissivity (0.9-0.95) nonmetallic paint. A flat paint with sufficient thickness is recommended in two layers of application. Figure 21 illustrates the recommended application of the high-emissivity coating to the bare module. For safety during the testing method, a high temperature ($>> 250^{\circ}\text{C}$) withstand paint is suggested to prevent testing failures and melting.

3.6 Finite Element Analysis Simulation

Simulations can be used to supplement experimental analysis, offering additional insight into thermal results and a much easier method for studying changes to the system. A numerical approach called finite element analysis (FEA) is used to solve partial differential equations (PDEs) for problems in engineering and physics. FEA is a powerful tool for simulating the behavior of complex structures and systems. Multiphysics software such as COMSOL[®] employ FEA to simulate a wide range of physical phenomena, including thermal analysis. The governing equations for heat transmission, such as heat equation or the Navier-Stokes equations with thermal components, are solved at each node of the mesh in a COMSOL[®] thermal simulation, for instance. These equations describe how heat is transferred within a system, such as through conduction, convection, and radiation, demonstrated in Figure 22.

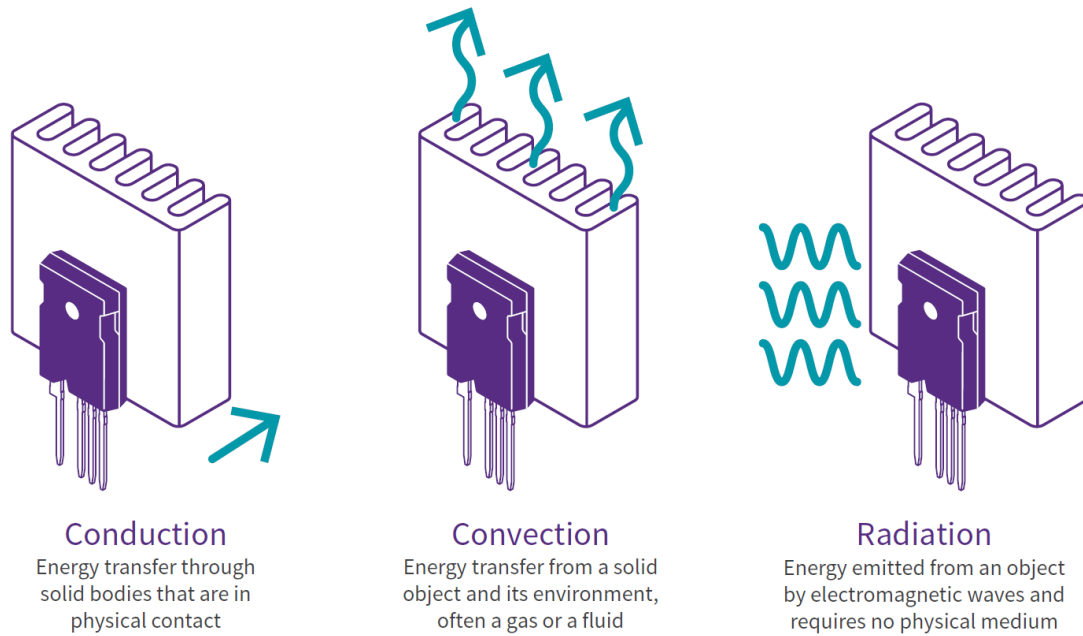


Figure 22: Primary modes of heat transfer

To simulate the thermal behavior of a power module using COMSOL®, the first step is to build a 3D model of the device in the software. Relevant geometry information such as the dimensions and shapes of the power components and any thermal sinks or thermal interfaces must be included. For the sake of simplicity, all unnecessary components of the model utilized in this simulation such as the wire-bonds and other terminals that have negligible or no effect on how heat is distributed throughout the power module have been removed.

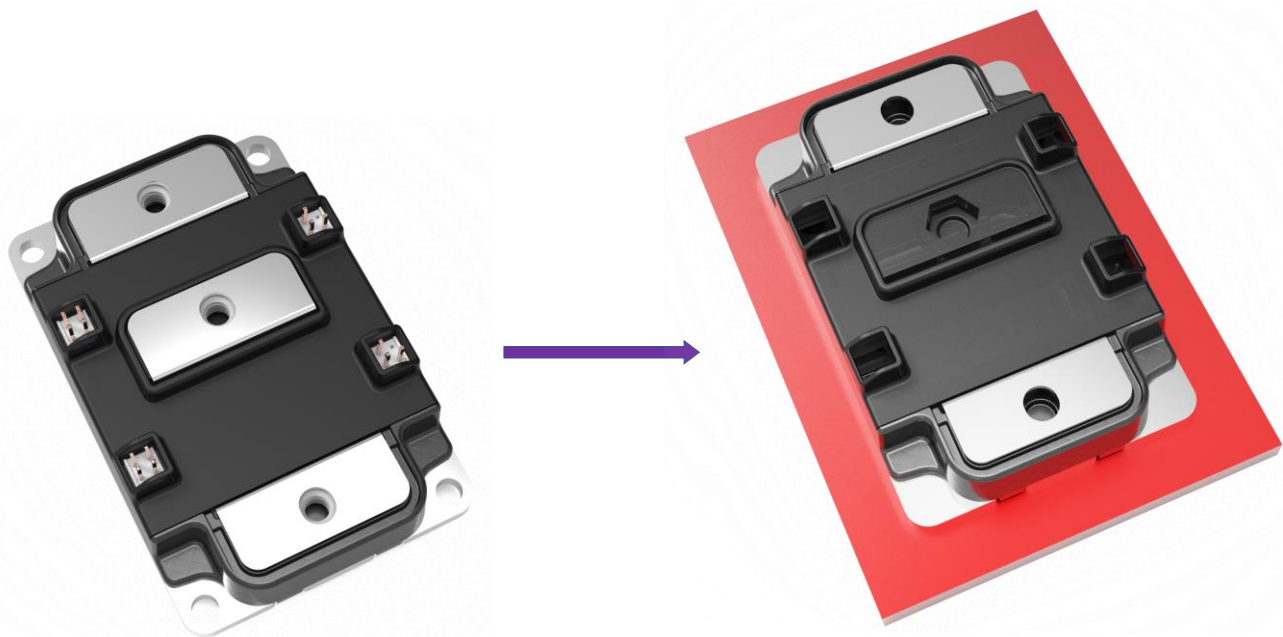


Figure 23: Finalized COMSOL® CAD geometry

Once the 3D model is completed as shown in Figure 23, the next step is to assign material properties such as thermal conductivity and specific heat capacity to the different materials present in the module. These properties are critical because they determine how heat is transferred throughout the system. The next step in the simulation process is to define the boundary conditions. This includes specifying the temperature and heat flux at the various surfaces of the power module, as well as other external conditions that may affect the system such as ambient temperature, heat transfer coefficient (HTC), and external air flow.

A critical component of the model is the simplifications made of the external cooling system. On one extreme, the simplest method is to set the bottom of the module to a fixed case temperature, but this ignores hot spots and will overpredict module ampacity. For maximum complexity, a Multiphysics simulation could be conducted on a cold plate with fluid solutions used to predict heat transfer, but this involves both significant simulation time and detailed knowledge of the end system. An appropriate compromise is to create a simplified “cold plate,” which is a few mm of copper (or aluminum) with a fixed HTC on the bottom side. HTC is defined by:

$$h = \frac{q}{\Delta T}$$

where q is the heat flux and ΔT is the temperature difference. The HTC can be set using datasheet specifications for the cold plate that will be used in the real system. Values for conventional liquid cooling systems can range from 100 to 30,000, as HTC is determined by surface geometry, fluid type, flow rate, etc.

Another important step in the simulation process is “meshing,” which is the discretization of the continuous domain into a finite number of small, interconnected elements or cells. At these discrete points, where each cell represents as a small section of the domain, the properties of the thermal problem are evaluated. Meshing aids in the determination of a system’s internal temperature and heat flow distribution during thermal simulations. The accuracy of the simulation depends on the quality of mesh. The use of a coarse mesh can lead to inaccurate results, while using finer mesh can lead to excessively long simulation times. Consequently, it is crucial to use a meshing technique that guarantees accurate and effective thermal modeling. Figure 24 shows the results of employing some of the meshing techniques available in the literature. In general, the choice of meshing method depends on the geometry’s complexity, the required level of precision, and the available computer power.

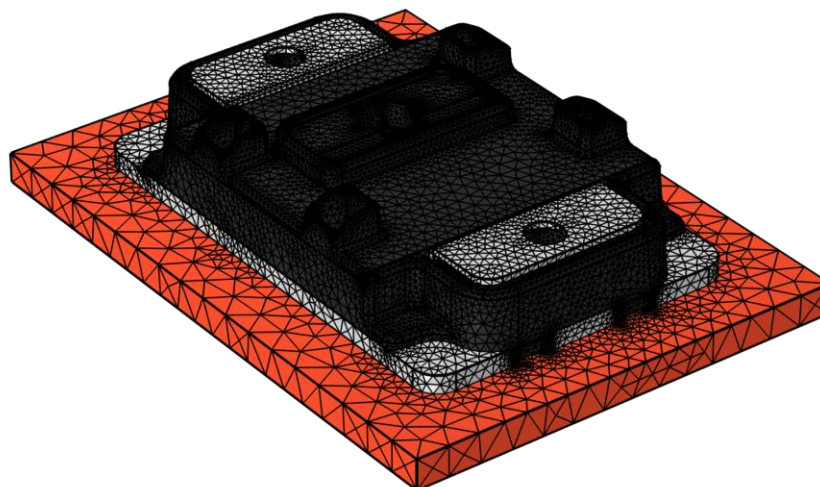


Figure 24: Finalized COMSOL mesh model

Prior to running the simulation model, it is required to define the input power boundary condition. The low-side and high-side dies are powered at the same time as shown in the enclosed region marked yellow of Figure 25.

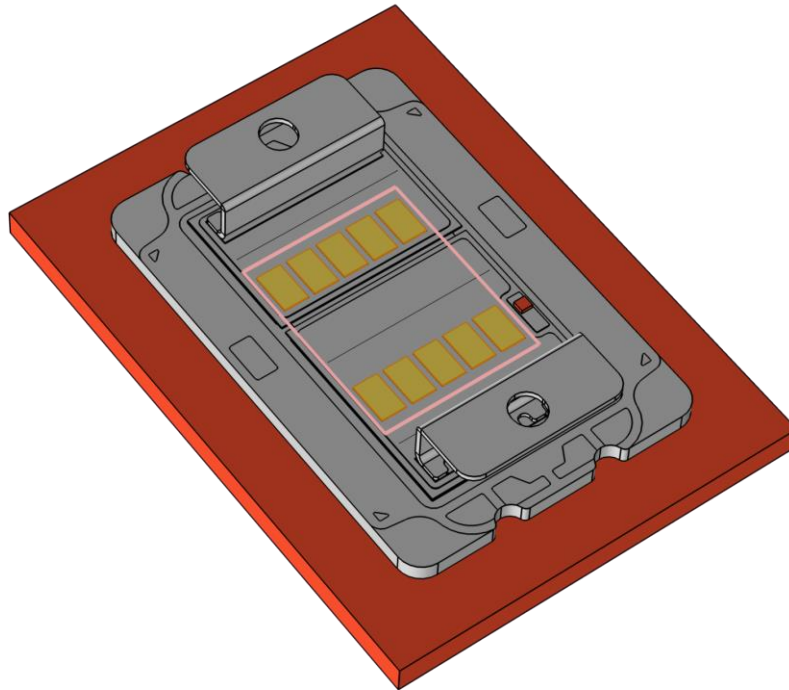


Figure 25: Module internal simulation view

In order to measure the case and junction temperatures that are required in calculating the thermal resistance (R_{THJC}) in the simulation model, temperature sensors need to be defined. Temperature sensors in COMSOL® are typically represented as point probes or surface probes. The surface probes are configured for this simulation so that they return the average of the entire die surface being considered as a single value junction temperature output. Similarly, the probe is positioned so that it monitors the average temperature throughout the region beneath the die at the bottom of the case in order to measure the case temperature. To achieve this, the baseplate of the power module is enhanced with die shadows that symbolize the region being considered and correspond to the area covered by the die. In COMSOL® thermal simulations, parameter sweeps are a useful tool since they help us improve system performance, comprehend how sensitive the outcomes are to the various parameters, and check and test the simulation model. The material sweep, the heat transfer coefficient (HTC), the coolant temperature, and the power input to the die are just a few of the parameters that can be adjusted for this simulation. The power input parameter to the die is configured to be swept from 100 W to about 800 W in order to observe its impact on the thermal resistance, which is how the performance of the power module is measured.

The final step in the process is to run the simulation using the built-in COMSOL® solvers after the model, materials, boundary conditions, and meshing have been appropriately defined and employed. The result of the simulation is the detailed map of the temperature distribution within the system, as well as other thermal properties such as heat flux and thermal stress. Another key output of the thermal simulation is the thermal

resistance of the power module from junction to case, R_{THJC} . The thermal resistance results obtained from the simulation can provide valuable insights into the performance of the module under different operating conditions and can be used to optimize the design of the system to improve its thermal performance.

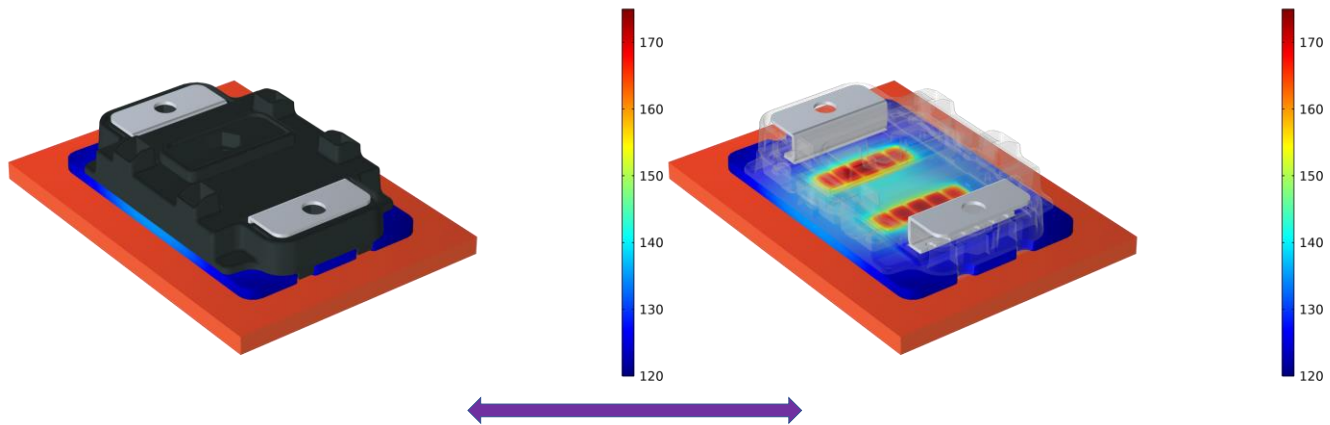


Figure 26: Temperature ($^{\circ}\text{C}$) distribution of the CAB450M12XM3 model (Top view)

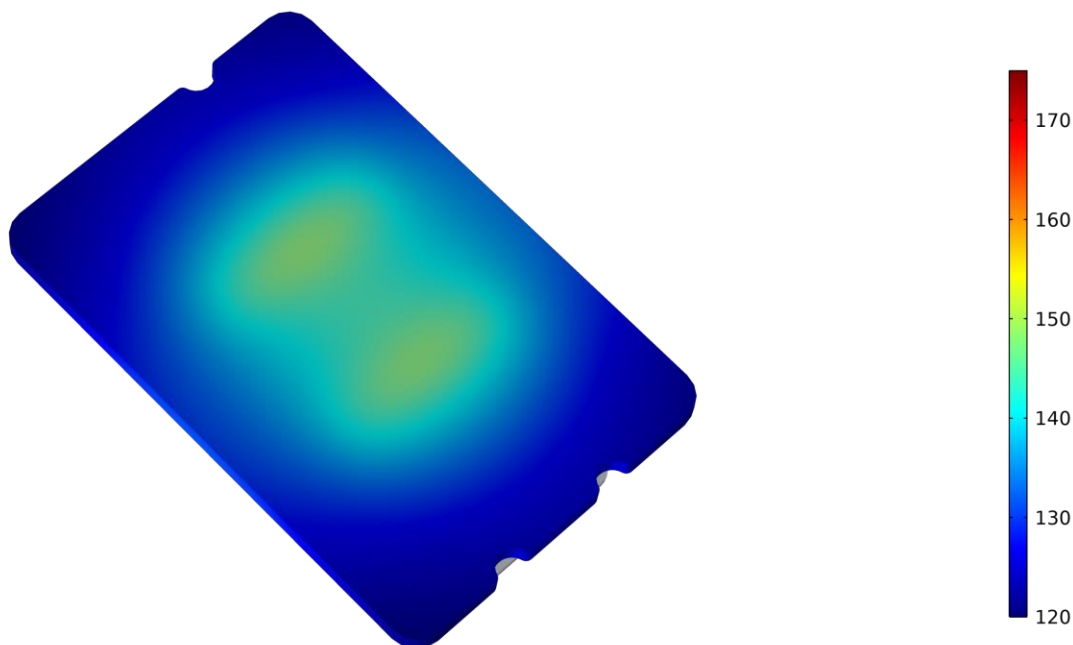


Figure 27: Temperature ($^{\circ}\text{C}$) distribution of the CAB450M12XM3 model (Bottom view)

Figure 26 and Figure 27 show the temperature distribution of the power module. As shown in Figure 26, thermal coupling is observed between the top and bottom die. This leads to a more uniform temperature distribution across the power module. Localized hotspots are prevented by this thermal coupling leading to overall improvement in the thermal management of the power module. Power dissipation of the module is also increased as a result of the transfer of heat generated by one die being transferred to the other die. No coupling is observed between the Negative Temperature Coefficient (NTC) thermistor and the die as shown in the callout

image of Figure 26. This is because the NTC is loosely coupled to the junction and more strongly coupled to the case. Therefore, the NTC gives a better measure of the temperature of the case and not the junction.

3.7 Characterization Method Comparison

The following table provides a comparison between the characterization methods and the main considerations between them. Complexity refers to the computational effort required to characterize the module from start to finish. Accuracy is interpreted as the variation of the measured value in comparison to the simulated value taken as the mean. Destructivity is the determination of module usability after the test. Repeatability is quantified as the value at which the difference between repeated measurements under identical test conditions fall within a 95% probability across 10 modules.

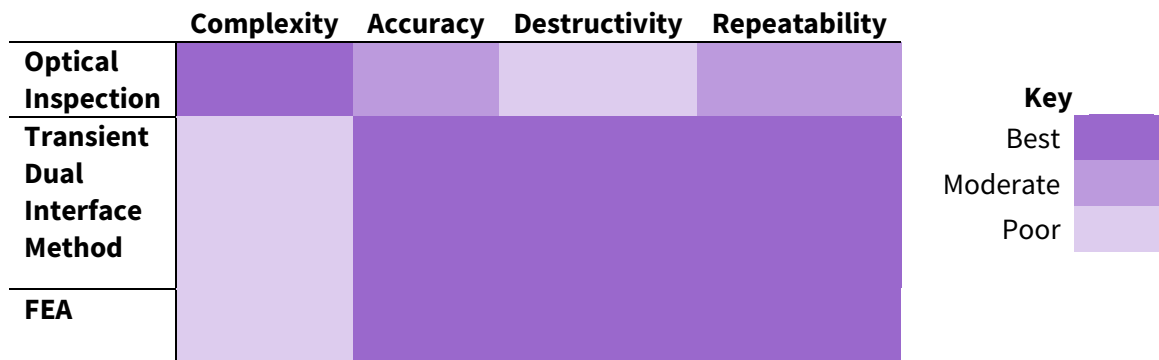


Figure 28: Thermal Characterization method comparison illustration

The TDIM is used as the standardized method for thermal characterization, in that the steady state and transient thermal properties are described. The thermal information provided on a given datasheet for Wolfspeed® devices are taken by using this method. The table below compares the characterization from the other methods.

Table 1: Characterization Method Results

Characterization Method	R_{thjc} High Side (°C/W)	R_{thjc} Low Side (°C/W)
Optical Inspection	0.111	0.144
Transient Dual Interface Method	0.1083	0.1169
FEA	0.1140	0.1124

4. In-Situ Measurements With NTC

NTC (Negative Temperature Coefficient) thermistors have been used in power semiconductor modules for many years to provide thermal protection and temperature sensing. The exact time when NTCs were first introduced to power semiconductor modules is not clear, as their use may have evolved gradually over time as their benefits became more apparent.

However, it is known that NTCs were widely used in electronic circuits by the 1960s and 1970s. By the 1980s, NTCs were being used in power semiconductor modules to protect against over-temperature conditions, particularly in applications such as motor drives and power supplies.

Since then, the use of NTC thermistors in power semiconductor modules has become widespread due to their many benefits, such as their low cost, high sensitivity, and ease of integration into electronic circuits. Today, NTCs are commonly used in power semiconductor modules to provide temperature sensing and thermal protection in a wide range of applications, including electric vehicles, renewable energy systems, and industrial automation.

The NTC is a type of thermistor or resistance thermometer, typically comprised of metallic oxides encapsulated within glass or epoxy. The NTC resistance has an inversely proportional relationship to temperature as seen in Figure 29 for a generic component.

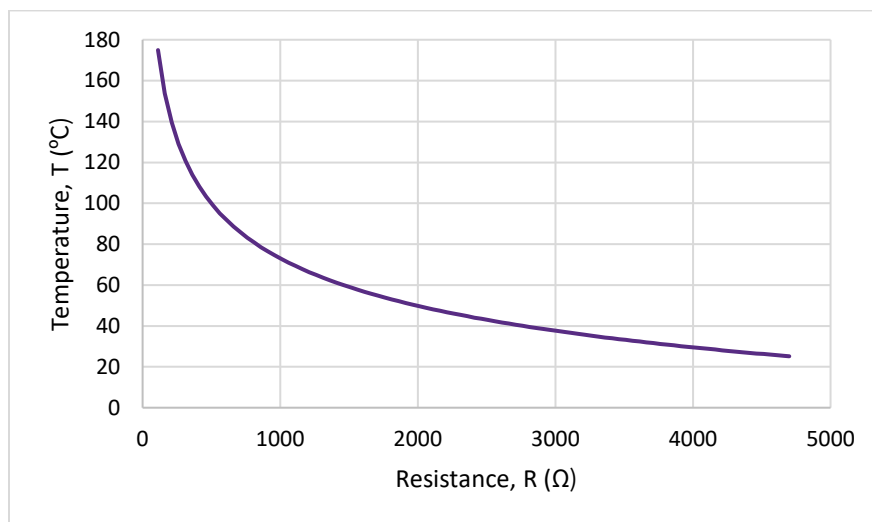


Figure 29: Typical resistance vs temperature relationship for NTCs

Mathematically, the NTC's relationship between temperature and resistance is described as a varying exponential curve known as the Steinhart-Hart equation. The form used for the equation for Wolfspeed power modules for observed values of resistance R at temperature T is given as:

$$\frac{1}{T} = A + B \ln\left(\frac{R}{R_{25}}\right) + C \left(\ln\left(\frac{R}{R_{25}}\right)\right)^2 + D \left(\ln\left(\frac{R}{R_{25}}\right)\right)^3$$

where A, B, C, D are experimentally derived curve fitting coefficients, and R_{25} is the defined resistance at 25°C. The NTC is generally located on the same ceramic substrate as the bare die. However, they do not share the same top-side substrate metal so that the NTC remains electrically insulated from the high voltage and switching operation of the device.

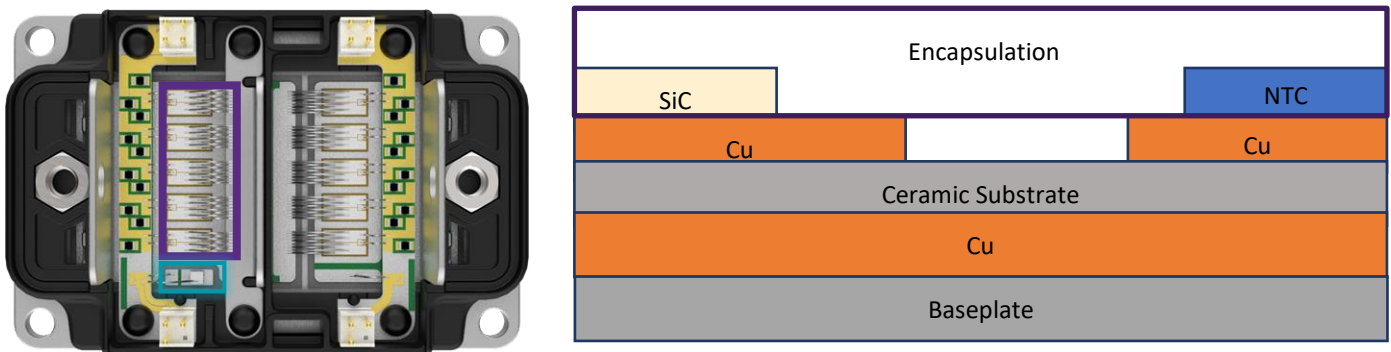


Figure 30: NTC Location (blue) within power module next to bare die (yellow)

Despite its convenient availability within the power module, it is important to determine the suitability of the NTC for certain measurements, and to also know the factors that affect the interpretation of the NTC’s inferred temperature.

4.1 Thermal Time Constant

Each thermal event or dissipation of power has a time duration attributed to it. The length of this duration determines how far through the thermal stack the heat travels. This is called the thermal penetration depth. For some thermal events, the duration may be long enough such that the heat makes it through the entire stack into the thermal sink. Short impulse moments such as short-circuit faults dissipate large losses that have a chance of staying within the substrate.

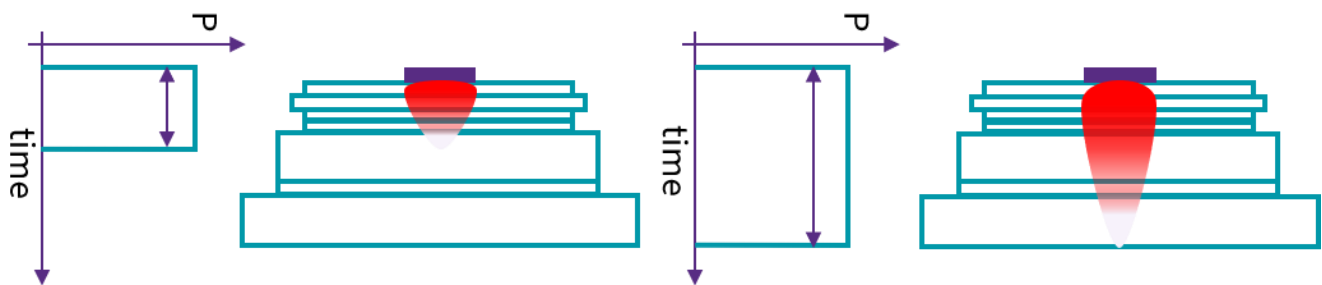


Figure 31: Thermal penetration for different power dissipation durations

The time taken for the heat to travel from the device junction to the case depends entirely on its thermal impedance. The responsiveness of the case to changes in junction temperature is given as the thermal time constant τ_{THJC} . It is defined as the time required for the case to receive 63.2% of the total heat dissipated from a given step change. After approximately $5 \cdot \tau_{THJC}$, 99.3% of the total step change in heat is expected to get to the case.

T_{THJC} can be derived by the product of the cumulative thermal resistance and capacitance as defined from the junction to the case. Using the structure function derived via TDIM, this value can be calculated.

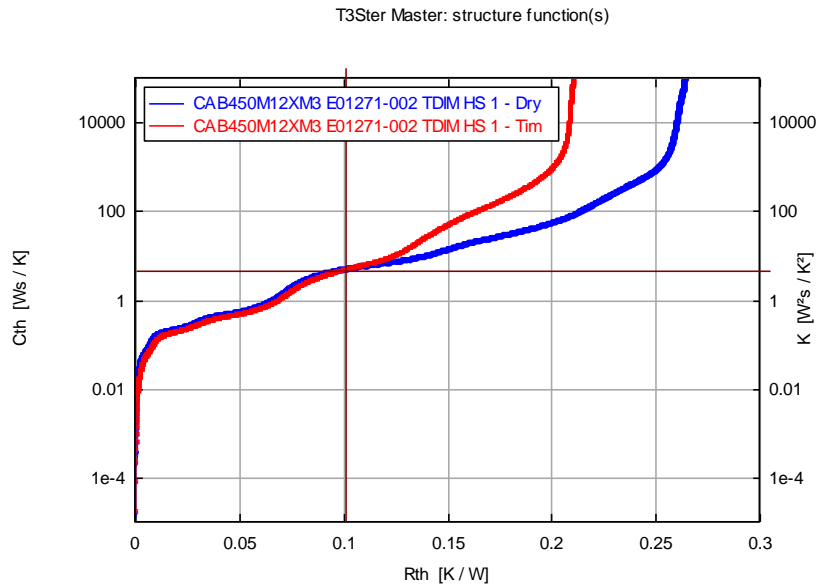


Figure 32: Deriving τ_{THJC} from structure function

Interpreting this value of τ_{THJC} allows designers to determine how much heat from a given thermal event can be extracted from the system. For a given thermal event of duration t , this percentage value of removable heat from the case can be calculated as:

$$Q_{removable} = 100\% \left[1 - e^{-\frac{t}{\tau_{THJC}}} \right]$$

4.2 NTC Response Time

In the previous section, the time taken for the heat to travel from die to case was characterized and empirically derived. However, in real-time monitoring of the module temperature, the time taken to detect this response using the NTC is different.

By design, the NTC is not coupled well thermally to the various die junctions. Applying a constant load to a module, Figure 33 shows the difference in steady state temperature between the die and the NTC on a cold plate varying the coolant flow rate at a constant 60°C.

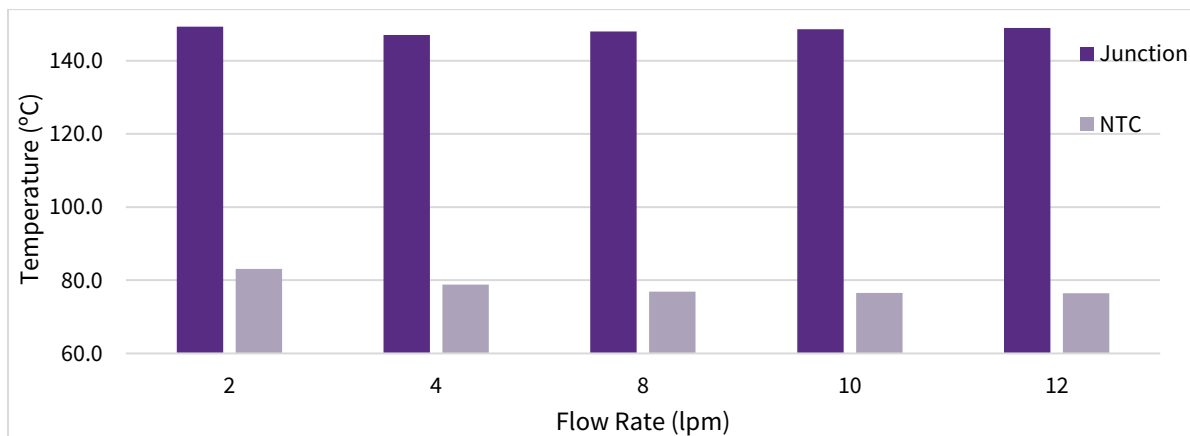


Figure 33: Temperature comparison between junction and NTC

The average temperature difference between the die and the NTC is 70°C whereas the average temperature difference between the die and the coolant at the baseplate is 18°C; **therefore the NTC should not be used to estimate junction temperature as it is much closer thermally coupled to the case.**

Conversely, it is strongly coupled with the case. This can be seen by looking at the time constant response of the NTC and comparing it to measurements taken from the junction and case via embedded thermocouples.

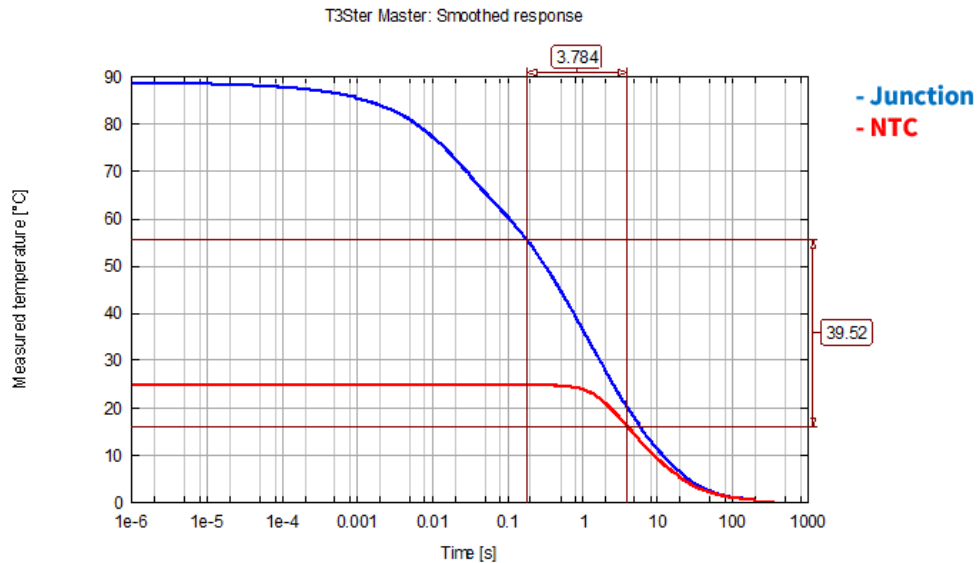


Figure 34: Time constant comparison between junction-case and NTC

With a thermal time constant τ_{THJNTC} of ≈ 4 s compared to the τ_{THJC} of 0.18 s, dynamic events along the order of the power module’s switching periods are too quick considering the response time of the NTC. For this reason, **we recommend using the NTC in conjunction with system losses within applications for steady state thermal observations.**

Because of the strong thermal coupling between the case and the NTC, there are some factors that affect the obtained value and response time of the NTC. The cold plate coolant flow rate primarily affects the response time, while poor TIM application can have adverse effects on its reading.

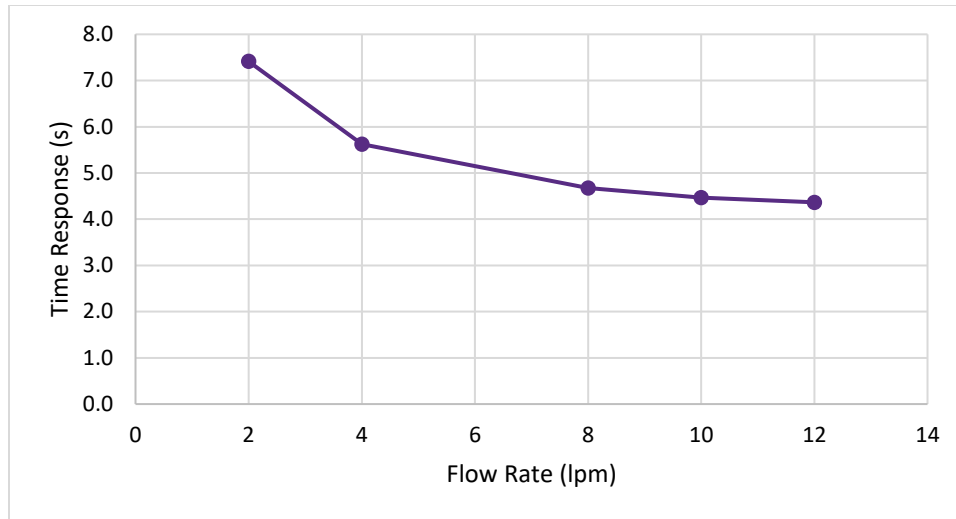


Figure 35: NTC response vs flow rate

The NTC ratings given on Wolfspeed® datasheets are specified based on our TIM Application and Stencil guide, at a predetermined coolant flow rate. For application accuracy, it is highly suggested that the NTC be characterized within the parameters of the specific application setup.

4.3 How to use the on-Module NTC

The NTC resistance can be used within a comparator circuit to implement an analog-to-digital conversion of the signal. This digital signal representing the NTC temperature can then be converted to a variable frequency over a differential pair and sent to a controller. The accompanying CGD12HBXMP gate driver connects directly to the NTC pins on the module and contains the circuitry to do the Temperature to Output Frequency conversion. The [CGD12HBXMP Technical Datasheet](#) provides more insight into the circuitry and implementation of this. For this specific gate driver, Figure 36 shows the relationship between the NTC Temperature, resistance and the output frequency of the differential signal.

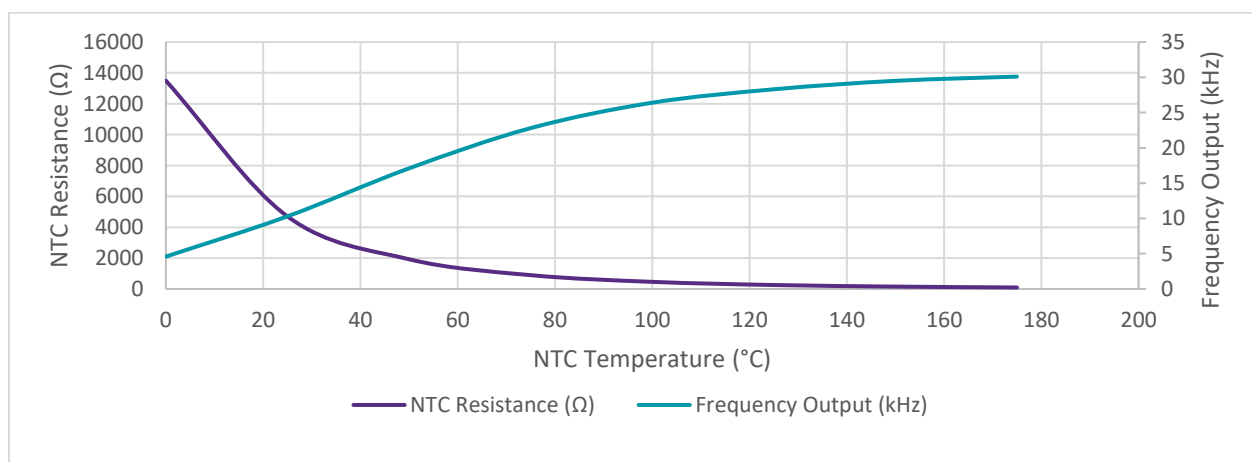


Figure 36: Temperature to output frequency

5. Cooling Solutions

To conclude the thermal evaluation of a system, we must additionally consider the thermal sink. The thermal sink completes the thermal stack and is responsible for the absorption and dissipation of all generated heat into an appropriate medium, whether it be the ambient air or a liquid. There are many types of thermal sinks, but they mainly can be categorized into styles of cooling: liquid cooling and air cooling.

5.1 Air Cooling

Air-cooled thermal sinks, commonly known as heatsinks, consist of a finned array of metal attached or extruded from a contact base as shown in Figure 37. Heat is conducted through the contact area and is removed via convection from air passing over the fins. Depending on the geometry, the fins can add significant surface area to the heat exchange area, which allows for improved heat transfer from the device to the ambient air. The convective heat transfer can be accelerated by increasing the speed of the air through the fins by using fans.

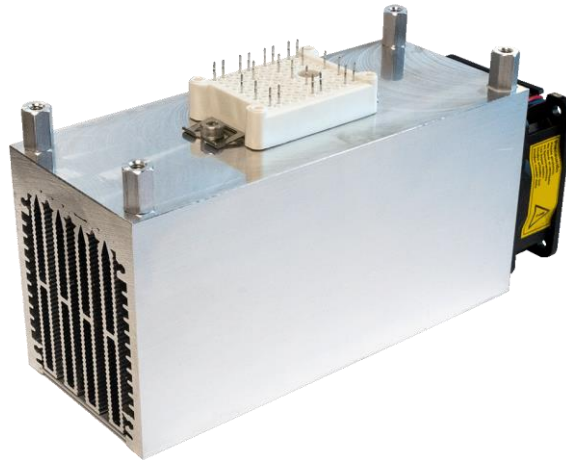


Figure 37: Heatsink example

Heatsinks are generally simpler in construction and offer a balance between cost and thermal performance. However, there are specific thermal drawbacks. The air enclosed within the volume of the system has a poor specific thermal capacity, so the system is not able to absorb much thermal energy. Increasing the heatsink's capacity to absorb heat can be mitigated, however the absorption energy is directly proportional to its size and mass, which may not be ideal in applications where space is limited.

5.2 Liquid Cooling

Liquid cooling methods generally consist of a cold plate such as aluminum embedded with pipes or channels to move the heat away from the system. While air cooling methods are reliant on convection to remove heat, liquid cooling often relies on the conduction of heat from the devices to the working fluid. By doing this, large amounts of thermal energy can be sunk from the system because the specific heat capacity of the fluids such as water or 50/50 water-glycol far exceed that of air. This reduces the total area needed for heat exchange leading to a more power dense overall application.



Figure 38: Example of direct-cooled XM modules mounted on a CP4012 cold plate

Cold plates can also feature complex internal geometries and features to enhance heat exchange at the baseplate. Modification of the cold plate internal channels to facilitate jet impingement significantly enhances the heat transfer coefficient of the coolant. The channel dimensions can also determine the flow characteristic of the coolant; whether laminar flow or turbulent flow is desired to enhance heat transfer.

Thermal solutions featuring cold plates are often suited for high thermal performance applications where having the most power density is critical. However, cold plates do add an additional layer of complexity when considering the total thermal solution for systems. The heat extracted from the system into the coolant must still be dissipated to the ambient environment via a heat exchanger.

6. Using Datasheet Thermal Attributes – Application Example

The above sections provide a good outline of how to interpret the thermal datasheet figures on every device. To make practical use of the information, an application example is given to demonstrate the means by which a designer can make useful the method of designing a converter and how to aid assessment of performance.

Consider a CAB450M12XM3-based boost converter for a constant power industrial application. The converter is rated at 30kW and is expected to operate at this power level for long durations. There is an available 25°C building coolant loop that can be tapped for the converter; however, the pumping requirements depends on the required flow rate to cool the system. The specifications and conditions for the converter are listed in Table 1.

Table 1: Converter Parameters

Parameter	Value
Power, P	30 kW
Overload Power, P_{ov}	50 kW, 0.1 s
Switching Frequency,	20 kHz
Duty Cycle, D	0.5
Coolant Temperature, T_{coolant}	25 °C
Allowed Temperature Change, ΔT	85 °C

6.1 Moving from Zth(t) to RC

Thermal design considerations for the converter are made using a worst-case operating scenario. This “situation” occurs when the converter is operating at maximum power and is experiencing the most losses. By designing at this point, the converter’s integrity is guaranteed for all other operating conditions.

Using the Wolfspeed® [SpeedFit 2.0 Design Simulator™](#) simulation tool, it can be seen that 30 kW produces a total loss of 295.55 W.

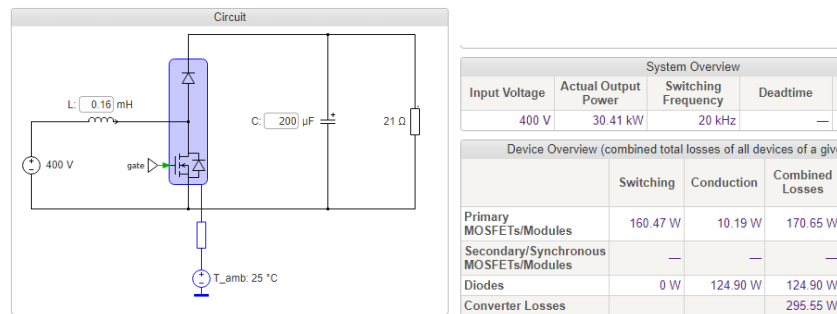


Figure 31: Wolfspeed SpeedFit™ simulation tool

The Z_{THJC} provided on Figure 17 of the CAB450M12XM3 Technical Datasheet is a cumulative representation of a thermal Foster RC model given as:

$$Z_{THJC}(t) = \sum_{i=1}^n R_i \left[1 - e^{-\frac{t}{R_i C_i}} \right]$$

where R_i and C_i are the thermal resistances and capacitances that compose the thermal model given from the Transient Dual Interface Method. These values can be found through rearranging the given equation by sweeping the single-pulse R_i for which the single-pulse Z_{THJC} is defined. Additionally, Wolfspeed® provides the direct Cauer RC model in LTspice® and PLECS® [here](#).

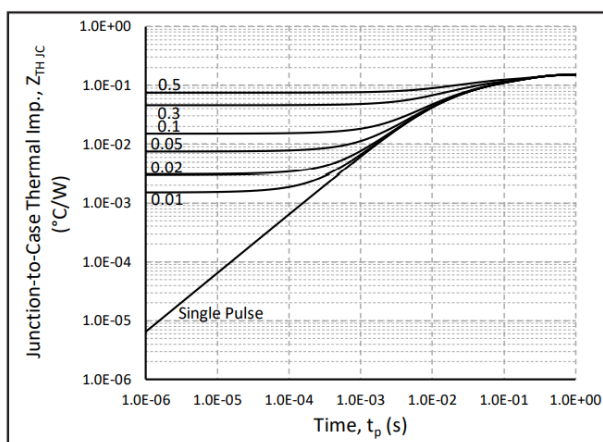


Figure 17. MOSFET Junction to Case Transient Thermal Impedance, Z_{thJC} (°C/W)

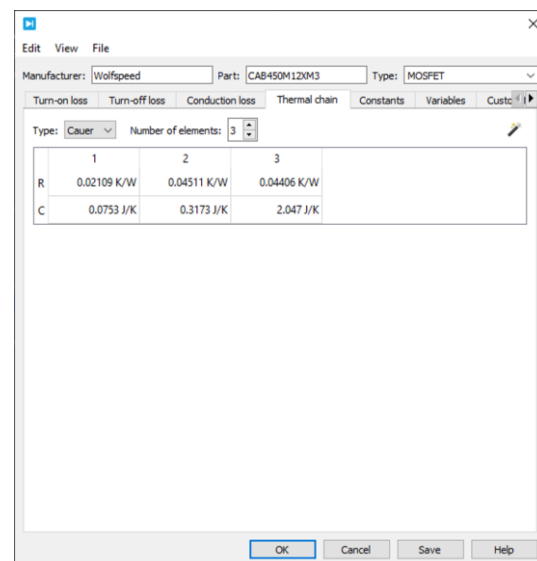


Figure 32: Datasheet Z_{THJC} and provided RC values

Therefore, the thermal representation of the module can be modeled as:

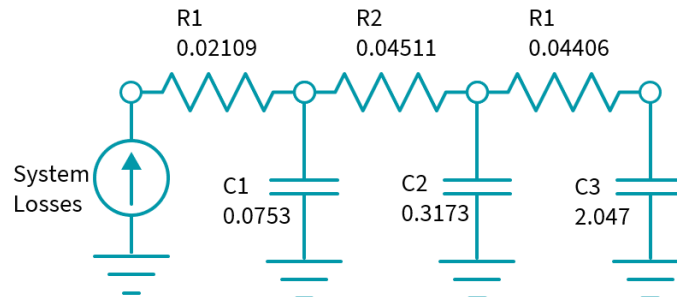


Figure 33: Thermal representation of power module

It is important to note that Wolfspeed® determines Z_{THJC} for a given device. However, within a system, the junction temperature will be a result of the total junction-ambient thermal impedance Z_{THJA} . For this system, a cold plate represents the ambient conditions of the system. Therefore, it is important to include the total thermal representation of the system, including the thermal interface layer and the cold plate characteristics.

Assuming the cold plate is able to dissipate all the heat being transferred to it ($C_{CP} = \infty$) and $R_{THTIM} = 0.1$ °C/W, the system can be modeled as shown below.

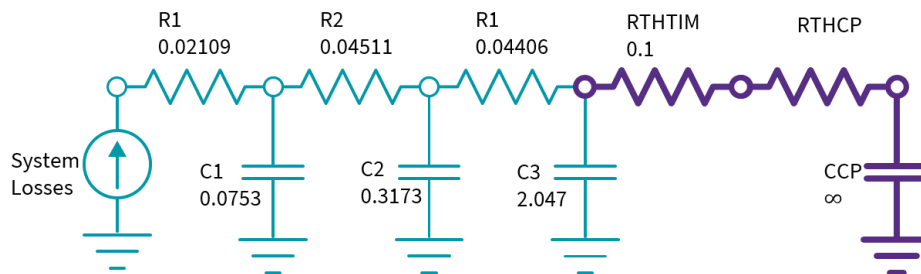


Figure 34: Total system thermal representation

6.2 Selecting Appropriate Thermal Sink

The cold plate thermal resistance is inversely proportional to the flow rate of the medium flowing through it. Therefore, to meet junction temperature thresholds, the appropriate flow rate should be selected. The Wieland 4000 Series suite of cold plates accompany the XM3 footprint and its thermal characterization is provided in Figure 35.

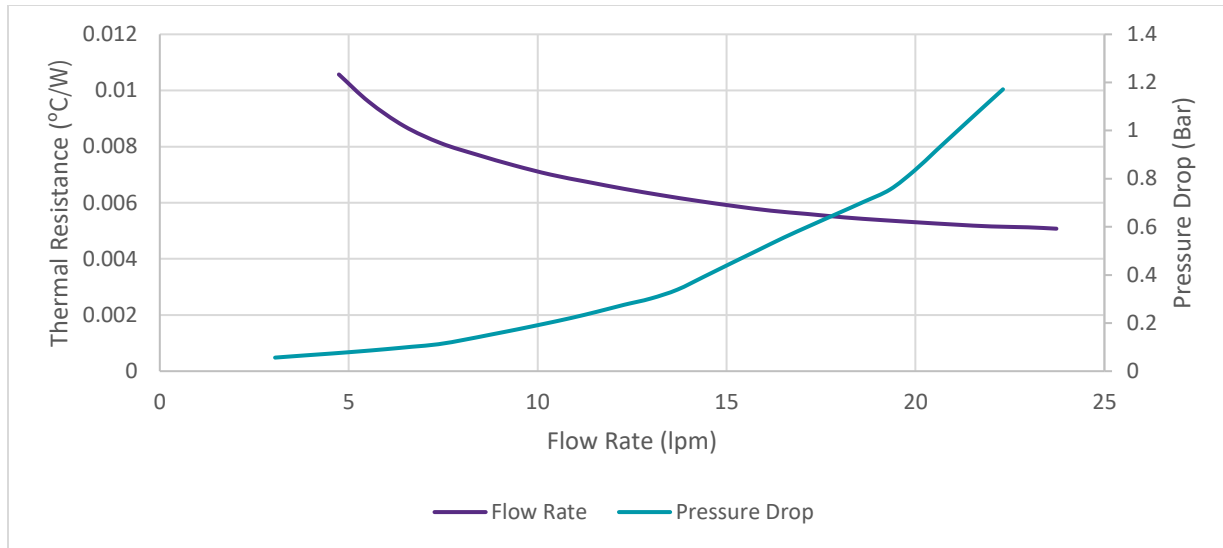


Figure 35: Wieland 4000 series cold plate thermal characteristics

The flow rate is proportional to the pumping pressure requirement to drive the fluid. This pressure drop normally translates to increased overall system costs for more/larger pumps.

For the ΔT specification given in Table 1, a cold plate thermal resistance of 0.008 °C/W is required, which correlates to a flow rate of 7.5 lpm. Modeling this in Figure 35 and simulating the system with its losses produces a maximum junction temperature of 107.69 °C including the overload condition induced at 1s, satisfying all specifications listed.

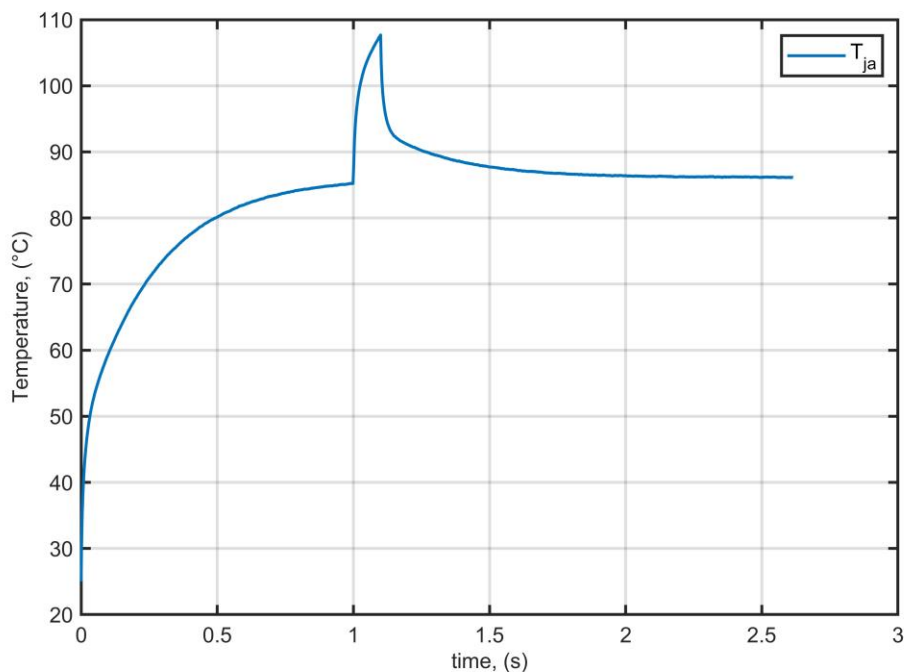


Figure 35: Junction temperature of power module through system range of operation

7. Summary

There are numerous methods to characterize the thermal resistance for silicon carbide power modules. The different characterization approaches presented in this document allow the designer to select the most appropriate method depending on the application scope. Further insight into the role of the NTC and how to use it additionally provides application thermal monitoring guidance. Wolfspeed® recommends that designers who desire higher performance systems consider the thermal characterization approaches and considerations highlighted in this application note.

8. Revision History

Date	Revision	Changes
January 2024	1	Initial Release

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- [1] "Department of Defense Interface Standard: Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment MIL-STD-461G," [Online]. Available: http://everyspec.com/MIL-STD/MIL-STD-0300-0499/MIL-STD-461G_53571. [Accessed 10 May 2023].
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