

## Thermal Characterization Process For Open-Frame Board Mounted Power Modules

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### Characteristics of Open-Frame Modules

The traditional method of using module case temperature for assessing thermal performance of potted modules is not applicable to open-frame modules, since the components are not in direct thermal contact with one another. Instead, open-frame modules have unique thermal characteristics that require a different testing and thermal derating process. This application note describes the issues involved in testing open-frame modules, and also provides details of a thermal derating process. Based on Lineage Power's extensive experience, open-frame modules have been observed to have the following characteristics:

- The thermally limiting component in the module varies depending on operating conditions. For example, at low airflow and light load conditions it might be the transformer core, whereas at higher loads the limiting component might be the power MOSFETs in the secondary stage.
- Module orientation with respect to airflow is more critical. Depending on the layout, any one of the four orientations could be the "best" or "worst" orientation for thermal performance.
- Temperature differences among components become larger than in potted modules, and therefore all the important components (those with significant power dissipations and/or sensitivity to higher temperatures) need to be monitored during thermal testing.
- Spacing between test boards and wind tunnel configurations play a larger role in influencing thermal testing results.
- Examining the component power dissipation  $P_{d,comp}$  and component junction-to-case thermal resistance  $R_{jc}$  for each critical component becomes more important in the derating process since they determine the actual junction temperature that limits the module's thermal performance. In typical situations, the junction temperature for a typical power semiconductor is not within 1 or 2°C of the measured component case temperature as widely assumed.

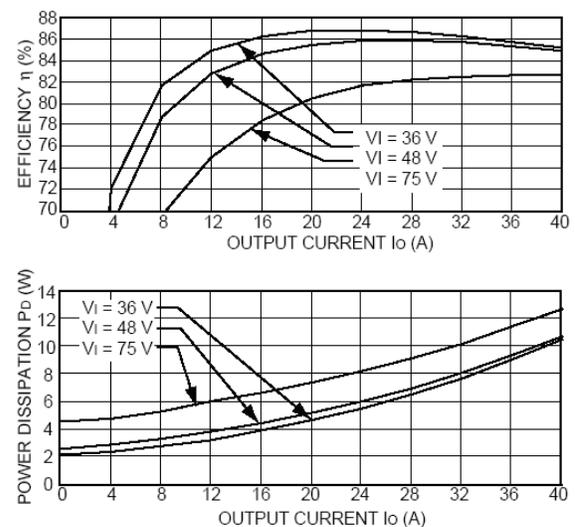
- Linear extrapolation based on tests at room ambient temperature results in huge errors at high ambient temperatures when compared to actual measurements done at the elevated temperatures. Thermal performance is generally more dependant on the location of both velocity and ambient temperature sensors, than with potted modules.

### Preparation for Thermal testing

Prior to the thermal testing, a complete set of efficiency and power dissipation curves of the test module is obtained through electrical testing at various ambient temperatures. Examples for a quarter-brick module at 85°C are shown in Figure 1.

Next, the module layout, an example of which is shown in Figure 2, is used to identify critical components and their locations. The critical components are those that limit the thermal performance of the module, such as power MOSFETs, control ICs, magnetic cores, and opto-coupler ICs. The data required for each critical component are the power dissipations ( $P_{d,comp}$ ) at various output levels, and the junction-to-case (lead) thermal resistance  $R_{jc}$ .

It should be noted that the actual power dissipation of a component is often a function of the module output. The maximum power dissipation capability given in the component-supplier's datasheet is not the actual power dissipation and cannot be used for thermal characterization. Instead, power dissipations at various output current levels are obtained directly from the design engineer, as shown in Table.1. Then, a curve of



**Fig. 1. Examples of module efficiency and power dissipation curves.**

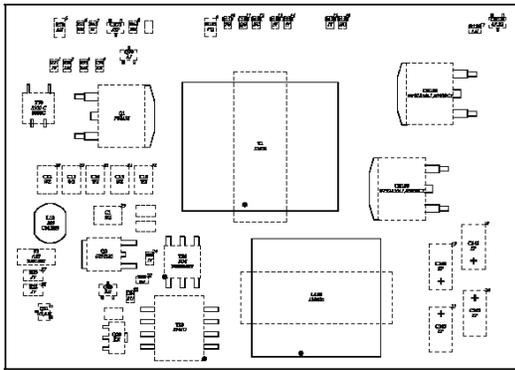


Fig. 2. Example module layout of an open-frame module.

power dissipation vs. module output current can be plotted for each of the key components, as shown in Figure 3.

Typically, the junction-to-case (lead) thermal resistance  $R_{jc}$  of a component given in the supplier's data sheet is tested with a 1"x1" FR4 board with 1-oz or 2-oz copper under natural convection. However,  $R_{jc}$  varies with testing conditions such as the airflow velocity, and the size and material composition of the test board. It is imperative to obtain the specific  $R_{jc}$  based on the actual application, either from the supplier or through testing (such as using a semiconductor thermal analyzer). When using the  $R_{jc}$  directly out of the supplier's datasheet, it is verified that the application of the component matches the supplier's testing conditions. (More details will be discussed in later sections).

Table 1.  
Example of component power dissipation data at various loads

Module load	20%	40%	60%	80%	100%
	$P_{d,comp}$ (Watts)				
Devices:					
FET#1	0.05	0.18	0.42	0.75	1.18
FET#2	0.03	0.12	0.30	0.51	0.80
IC#1	0.01	0.02	0.05	0.10	0.15
...	...	...	...	...	...

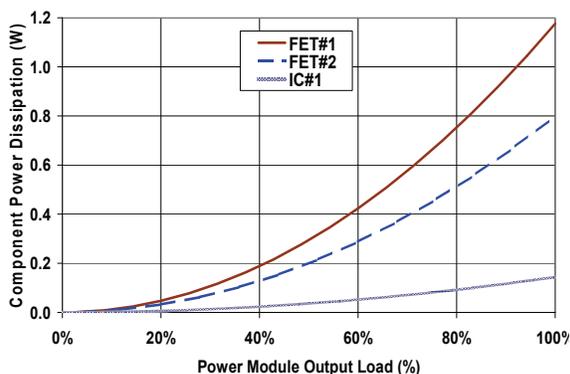


Fig. 3. Example of component power dissipation curve.

## Test Setup and Instrumentation

Traditionally, power modules were tested in a bench-top wind tunnel as depicted in Figure 4. Since this tunnel did not have heating devices, tests were usually conducted only at room ambient temperature. The results were then extended using linear extrapolation for higher ambient temperatures by shifting the "temperature margins". Due to the distinctive thermal characteristics of open-frame modules as mentioned in the previous section, thermal testing at room ambient temperature alone is not enough to adequately quantify the thermal performance of an open-frame module. As demonstrated by the example data shown in Figure 5, linear extrapolation based on room ambient temperature tests can cause significant errors at higher ambient temperatures. Therefore, tests must be conducted in the full ambient temperature range, normally 20°C~85°C. This task may be accomplished in a closed-loop wind tunnel as shown in Figure 6. The closed-loop wind tunnel can provide uniformly heated airflow with temperatures ranging from room ambient to ~90°C and velocities from 50~800 ft/min (0.25 to 4m/s). Details of a typical wind tunnel are as follows:

- Test section cross-section: 12"x12"
- Velocity uniformity: 5%
- Temperature uniformity: 5%
- Ramp-up rate: 2 °C/min
- Ramp-down-rate: 2 °C/min
- Test section accessibility (including IR): yes

An anemometer is used for air velocity measurement. The following requirements should be met in choosing an anemometer:

- Range: 0~1000 ft/min
- Accuracy: 3% of reading or 3 ft/min
- Resolution: 1 ft/min

The sensor (hot-wire) should be protected and the probe should be robust enough to endure steady-state ambient temperatures up to 85°C and frequent changes in probe

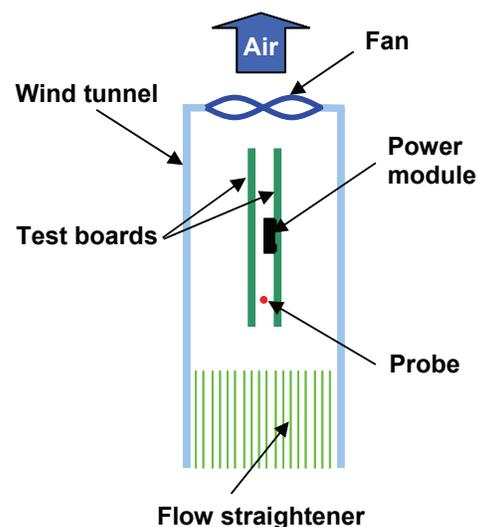


Fig. 4. Sketch of a bench-top wind tunnel.

location. The anemometer should also be re-calibrated annually with a certificate of calibration and traceability to a standards body such as the US National Institute of Standards Technology (NIST).

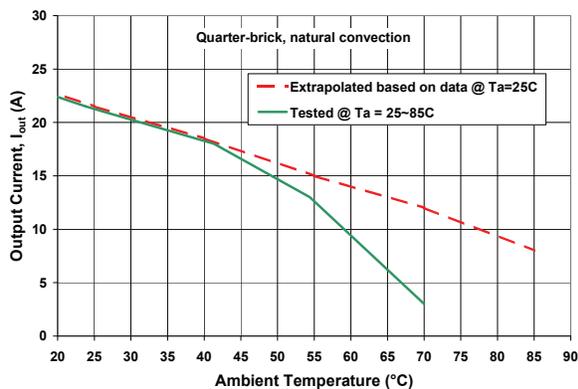


Fig. 5. Example showing errors due to linear extrapolation from room-temperature measurements.

An IR (InfraRed) camera is used for identifying hot zones and components, and for dynamic assessment of the thermal characteristics of a power module while operating conditions are varied. Unlike traditional temperature-measurement devices, the accuracy of an IR camera depends very much on parameter settings such as emissivity, background correction, distance and media compensation, and humidity compensation. To achieve quality IR images, the camera need to have a thermal sensitivity of 0.1°C, a spatial resolution of 2.0 mrad and a field of view of 24° x 18° with a minimum focus distance of 0.3 m.

Thermocouples are used for measuring component case (body) or lead temperatures as well as ambient temperatures. In the temperature range we are interested (-50°C ~ +150°C), there are many options available for thermocouple selection. It is preferred, however, to use fine-gauge (36G or 30G) T-type thermocouples for better accuracy as well as affordable cost. This type of thermocouple has a temperature measurement range of -200°C ~ +350°C with an accuracy of 1°C or 0.75%. It is important to understand that the thermocouples must be calibrated by the

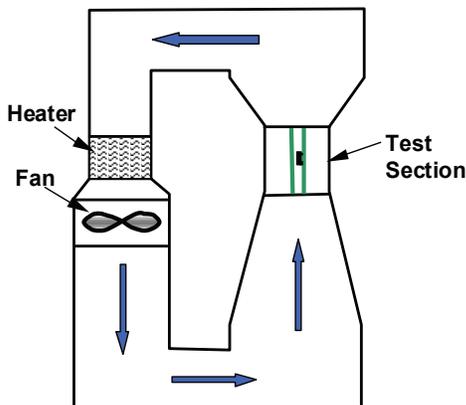


Fig. 6. Sketch of a closed-loop wind tunnel

manufacturer according to the standard reference tables in ITS-90 of the US National Institute of Standards Technology (NIST).

A data logger (data acquisition unit) and a PC are used for data acquisition and control. The recorded data should include component temperatures, ambient and atmospheric temperatures, module input and output voltages and currents, air velocities and other wind tunnel parameters. The data logger should meet the following requirements:

- Number of channels: ≥ 20
- Temperature accuracy: 1°C.
- Temperature resolution: 0.1°C.
- Scanning speed: 50 channels/s

### Testing Considerations

We use a preliminary IR test to find out the overall temperature distribution of a power module and to determine which components are to be thermocoupled for the actual characterization tests. The module may be operated at half-load under both natural convection and forced convection conditions. At least one IR image, like the one shown in Figure 7, should be taken for each of the conditions.

Infrared (IR) imaging can be a very effective tool when used properly. However, care must be taken in setting all the parameters, especially, the emissivity. When the emissivity is set incorrectly, the IR measurement error can be significant. Figure 8 shows the estimated IR temperature reading error due to incorrect emissivity setting. In general, all components in the module do not have the same emissivity. Painting the module black and using the emissivity of the paint could solve the problem of emissivity variation. But the paint alters the module's thermal characteristics causing additional error. Since we use an IR camera only for preliminary testing to identify the hot components and not for obtaining exact temperature readings, the test module need not be painted. The recommended global emissivity to be used in the preliminary IR test is 0.95.

Based on the IR images, the critical components are identified and thermocoupled. These are either the

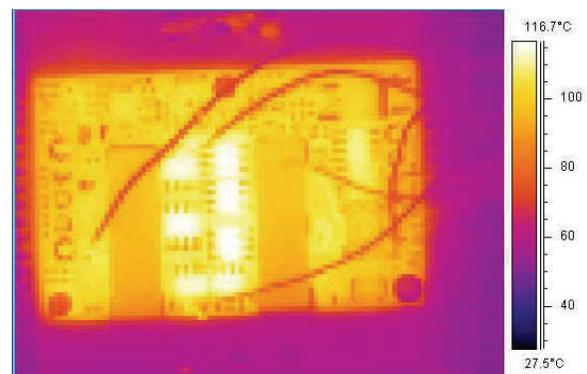


Fig. 7. Example of an IR image obtained from thermal measurements on a power module.

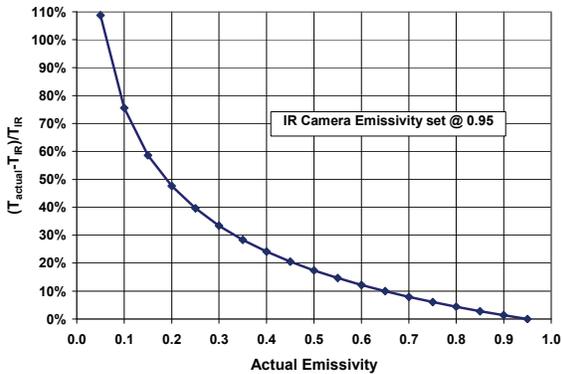


Fig. 8. Estimate of IR imaging error due to incorrect emissivity setting.

hottest components or those that have greater sensitivity to temperature limits. The selected components should include at least one component from each of the following key groups: input MOSFETs, output MOSFETs, transformer/inductor cores, optocoupler and control ICs. Depending on the test module, ten to twenty components may need to be thermocoupled. For transformer cores, unleaded semiconductor devices and PWBs, thermocouples are always attached to the hottest part of the body in accordance with the IR images. For leaded semiconductor devices, thermocouples can be placed on the case, lead or tab (as shown in Figure 9). However, the point of attachment depends how the manufacturer defines the junction-to-case thermal resistance,  $R_{jc}$ . This is critical to obtaining the correct junction temperature,  $T_j$ , from the measured case/lead temperature,  $T_c$ . To get the best results, it is strongly recommended that thermocouples be attached to the devices in the same manner as the devices are tested for their  $R_{jc}$  value, and following the procedure described by the device manufacturer.

The adhesive used for bonding the thermocouples to the devices must have excellent adhesion and thermal stability (non-flowing under heat). In addition, it should also possess good thermal conductivity as well as good electrical insulation. To minimize the effect of attachment on measurement accuracy, it is recommended that the adhesive applied is no more than the smallest amount needed for a robust attachment.

Before collecting data, the wind tunnel used for testing must be fully profiled with respect to both velocity and temperature to ensure satisfactory uniformity and stability. This test should be conducted at least once for

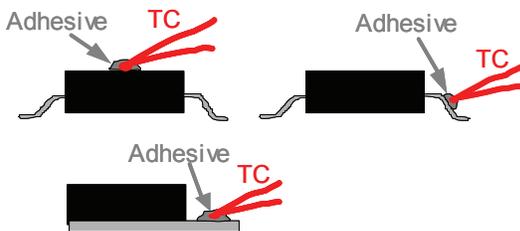


Fig. 9. Thermocouple attachment.

each test module. The test module and test boards should be in place as they are supposed to in the actual testing of the module. The test is run at air velocities of 100 ft/min (0.5m/s) and 800 ft/min (4m/s), and at wind-tunnel temperature of 70°C. Uniformity and stability are gauged after the set point is reached and has stabilized. For uniformity, measure both velocity and ambient temperature at five horizontal locations that are 0.5” apart (see next section for sensor locations). The readings should be within 5%. For stability, take five readings for both velocity and ambient temperature over a period of 30 minutes. Again, the readings should be within 5%. The formal data collection cannot be started unless these conditions are satisfied.

The location of the air velocity and ambient temperature sensors should be clearly specified because any variation in sensor locations would be the source of inconsistency in the test results. The objective is to place the sensor where it truly represents the norm of the undisturbed incoming channel flow. Measurements and simulations have proven that airflow near a power module in a typical wind tunnel setup is highly non-uniform. Figure 10 shows the flow distribution in front of the module. It clearly indicates that in order to gauge the undisturbed incoming flow, the sensor needs to be placed at least 3 inches (7.62cm) from the module.

When the board spacing is 1” or less (see next section for board spacing details), we recommend that the sensor be placed in between the two test boards at a distance of 3” from the test module and 0.5” away from the test board as shown in Figure 11. When large heat sinks are used and the board spacing is greater than 1”, the sensor should be placed in the middle between the two boards.

The test-board spacing has some effect on test results. As demonstrated by the example shown in Figure 12, smaller board spacing seems to help the module run cooler under both natural convection and forced convection conditions. The phenomenon is, however, caused by different mechanisms. Under natural convection conditions, this is due to the so-called “chimney effect”. Once spacing is greater than the boundary layer thickness, further increase in spacing makes no difference. Under forced convection, it is owing to the single-point air velocity measurement, which does

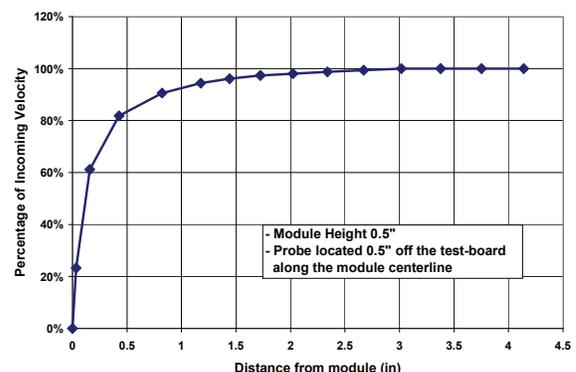


Fig. 10. Example of air velocity profile in front of a module.

not define the total volumetric airflow. When the board spacing becomes smaller, the test unit (module and boards) presents more flow resistance, resulting in less airflow and a lower measured velocity between the test boards. During the actual testing, however, one would keep boosting up the fan speed until the measured velocity reaches the setpoint, which in fact delivers more airflow to the system, resulting in better cooling than in the case of larger board spacing. The board spacing may vary based on the applications. However, it is essential to specify the spacing clearly so that others would interpret the data accordingly. For consistency, we use a 1" spacing for open-frame modules without heat sinks

Component temperatures in open-frame modules vary considerably and the limiting component also tends to be different as the module-orientation changes. The traditional two-orientation (longitudinal and transverse) testing is not sufficient to have a complete representation of the module's thermal performance. The example shown in Figure 13 clearly indicates that, for open-frame modules, all four orientations must be tested. Because of the large variation in component temperatures in open-frame modules, it is necessary to test and collect data at various output load (current) levels for a given flow and ambient temperature condition. Then, characteristic curves for all the key components can be established and analyzed for a more accurate thermal evaluation, as shown in Figure 14.

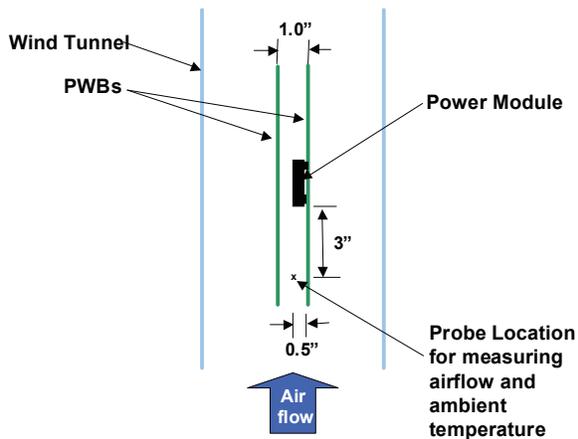


Fig. 11. Typical test setup and airflow sensor location.

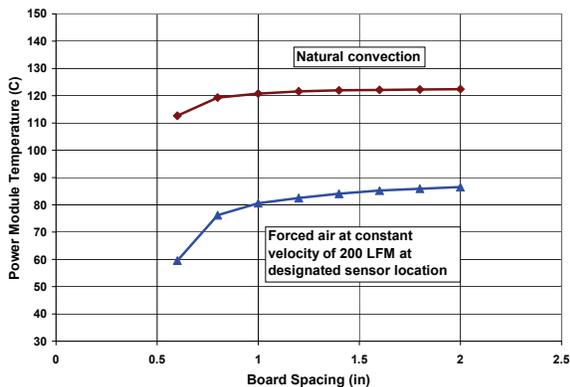


Fig. 12 Example of effect of board spacing.

## Thermal Derating Method

The actual junction temperature of a semiconductor device depends on the power level as well as the operating environment. Therefore, simply adding a fixed number (whether it is 1~2°C or 10~20°C) to the measured component case temperature to obtain the junction temperature will lead to significant inaccuracy in the evaluation of the power module's thermal performance.

The essence of the new derating method is to obtain accurate estimates of the actual junction temperatures,  $T_j$ , of the key components under various conditions. It involves several steps as described below.

### Step 1.

Establish a nonlinear characteristic curve as shown in Figure 14 for each of the critical components based on test data, where measured component temperature  $T_c$  is plotted as a function of the output current (or power). For each airflow condition, one set of curves is generated.

### Step 2.

Based on the data collected from the module designer, define the relationship between the component power dissipation  $P_{d,comp}$  and module

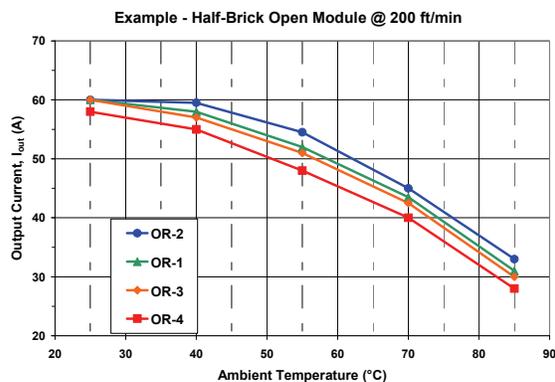


Fig. 13. Example of effect of module orientation.

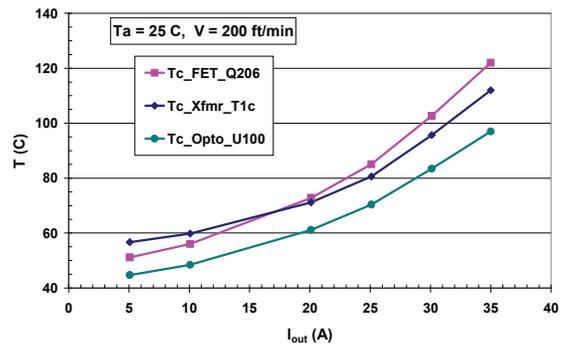


Fig. 14. Example of nonlinear characteristic curve of component temperature versus output current.

output current  $I_{out}$  for each critical component,

$$P_{d,comp} = f(I_{out}),$$

which is typically a nonlinear curve as shown in Figure 15(a). This reflects the fact that component dissipations of some critical components, e.g. the output MOSFET switches in most low-voltage output power converter stages, vary approximately with the square of the output current.

**Step 3.**

The temperature difference between the component junction and case can be calculated and plotted as a function of the power dissipation as shown in Figure 15(b), using the following equation,

$$\Delta T_{jc} = P_{d,comp} \times R_{jc},$$

where  $R_{jc}$  is the junction-to-case thermal resistance of the component. By combining the power dissipation curve presented in the last step, it is easy to obtain  $\Delta T_{jc}$  as a function of the output current as shown in Figure 15(c).

**Step 4.**

Calculate and plot the actual junction temperature  $T_j$ , as shown in Figure 15(d), for each of the critical components based on the measured case temperature  $T_c$ ,

$$T_j = T_c + \Delta T_{jc},$$

An example of the junction temperature as a function of the output current in a real power module is given in Figure 16. The measured case temperature is also shown. It is obvious that the temperature difference between  $T_j$  and  $T_c$  is not a constant, nor is it negligible when the power module is operated at high output current level ( $\Delta T_{jc} \approx 15^\circ\text{C}$  at  $I_{out} = 35\text{A}$  for the particular device shown in Figure 16).

**Step 5.**

Apply the proper temperature constraint for each of

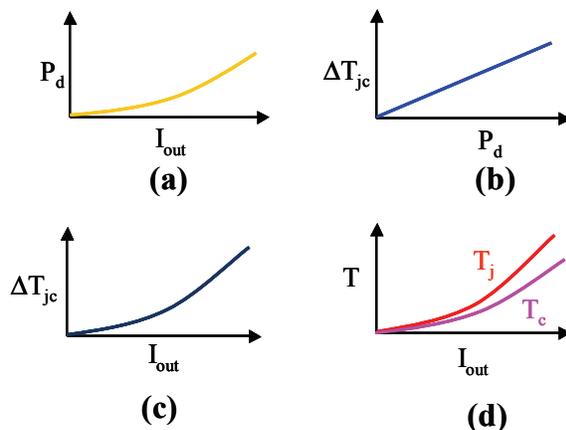


Fig. 15. Component junction temperature as a function of the output current.

the critical components. The first component reaching its temperature limit determines the maximum module output current  $I_{out}$  under that particular operating condition. Using the same example given in Figure 16, the temperature limit for that device is set at  $T_{j,max} = 125^\circ\text{C}$ , which results in maximum output current capability of 32A for this power module under the particular operating condition of 200 ft/min airflow and  $25^\circ\text{C}$  ambient temperature. If  $T_c$  instead of  $T_j$  is used, the maximum output current capability would be incorrectly estimated to be 36A (12.5% larger). However, that would cause the junction temperature to be in excess of  $140^\circ\text{C}$ , far above the permitted  $T_{j,max} = 125^\circ\text{C}$ .

**Step 6.**

Steps 1 through 5 are for one particular operating condition. To obtain a complete thermal evaluation of a power module, these steps should be repeated for all operating conditions, which include airflow, ambient temperature, module orientation and test board spacing.

**Derating Constraints and Other Considerations**

Derating constraints are the maximum component temperatures used to determine a module's maximum

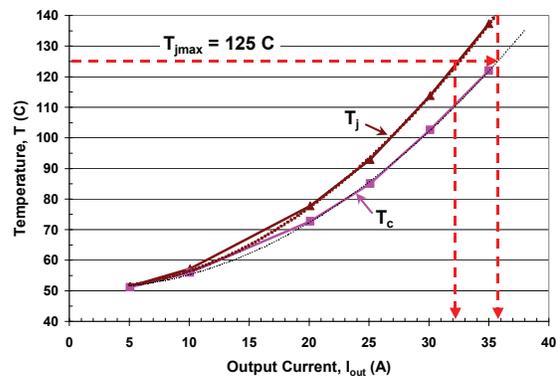


Fig. 16. Example of actual junction and case temperatures for a standard SO8 MOSFET.

output under a certain operating condition. A summary of the common derating constraints is given in Table.2.

Table 2. Derating Constraints

Device	Critical T	Typical value	Recommended value
Semiconductor	$T_{junction}$	125 °C	125 °C
FR4 PWB	$T_{surface}$	120 °C	130 °C
Magnetics core	$T_{body}$	120 °C	130 °C
Opto-coupler	$T_{body}$	100 °C	110 °C

For semiconductor devices (FETs, ICs, etc.), most suppliers specify  $T_{j,max} = 150^{\circ}\text{C}$ . Power module makers, however, have been using  $T_{j,max} = 125^{\circ}\text{C}$  due to concerns about long-term reliability. Until there is solid proof that raising  $T_{j,max}$  from  $125^{\circ}\text{C}$  to  $150^{\circ}\text{C}$  would not compromise on reliability, we need to stick with  $T_{j,max} = 125^{\circ}\text{C}$  for our thermal evaluation purposes.

One exception to semiconductors is the opto-coupler, which has very small power dissipation but very large junction-to-case thermal resistance. Device manufacturers usually specify a maximum operating ambient temperature of  $100^{\circ}\text{C}$  instead of a maximum junction temperature. This is traditionally translated into a maximum body temperature of  $100^{\circ}\text{C}$ . But realizing that there is always a certain difference between the body and the ambient temperatures, it is reasonable to use  $110^{\circ}\text{C}$  as the maximum body temperature for thermal derating purposes.

FR4 PWBs are limited by their UL ratings, which has been  $120^{\circ}\text{C}$  until recently when PWB manufacturers provided data indicating that a maximum temperature of  $130^{\circ}\text{C}$  can be used. For magnetic cores, it has also been limited to  $120^{\circ}\text{C}$  due to concerns about “thermal runaway” at higher temperatures. Our experiments, however, show that there is no abrupt change in the thermal characteristics between  $120^{\circ}\text{C}$  and  $130^{\circ}\text{C}$ . Hence,  $130^{\circ}\text{C}$  is used as the limiting temperature for magnetic cores.

As discussed previously, it is important to understand that the difference between  $T_j$  and  $T_c$  is not a constant, or even a linear function of the output current. It depends on the component package as well as on operating conditions (output current and airflow). For a standard SO-8 MOSFET, this difference ( $\Delta T = T_j - T_c$ ) could be as small as 1 or  $2^{\circ}\text{C}$  under natural convection and very low output current when the dissipation is small, but as large as 15 to  $20^{\circ}\text{C}$  under forced convection and high output current (see Figure 17). Considering that the junction temperature  $T_j$  plays a major role in determining the performance and reliability of the module, it is essential to calculate  $T_j$  based on the actual power dissipation and the measured component case temperature  $T_c$ . Under no circumstances, one can assume a small  $\Delta T_{jc}$  (such as 1 or  $2^{\circ}\text{C}$ ) for all operating conditions.

Another parameter that requires extra attention is the component junction-to-case thermal resistance  $R_{jc}$ , which is usually tested by the semiconductor device manufacturer on a small FR4 board (typically  $1'' \times 1''$ ) in a natural convection environment. Our experimental data indicates that  $R_{jc}$  is significantly different when the device is mounted on an IMS (Insulated Metal Substrate) board or a much larger multi-layer FR4 board with high copper content. Therefore, it is important to carefully examine the application condition against the specified test condition before using the  $R_{jc}$  value provided in the data sheet. When the application condition is significantly different from the manufacturer’s test condition, one should either seek assistance from the manufacturer for the specific  $R_{jc}$  value, or test it using a semiconductor

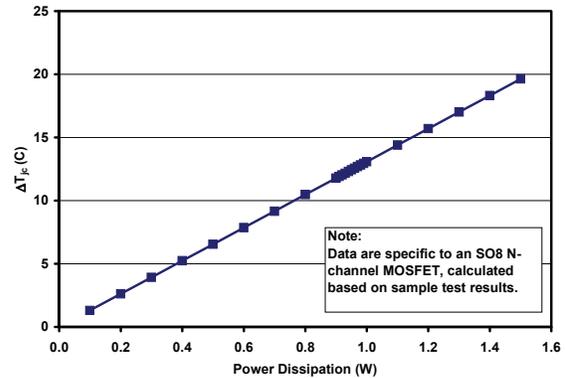


Fig. 17. Example of junction-to-case temperature difference for a standard SO8 MOSFET.

thermal analyzer. A semiconductor thermal analyzer uses the variation in a diode forward voltage drop with temperature as a means of estimating temperatures. Then, the temperature difference is calculated by

$$\Delta T = a + b \times \Delta V,$$

where  $a$  and  $b$  are constants and  $\Delta V$  is the measured forward voltage drop of the junction. This method is direct, non-intrusive and widely implemented.

## Data Presentation

Traditionally, power module thermal derating charts are presented in the form of power dissipation vs. ambient temperature as shown in Figure 18. To mechanical or thermal designers, it makes no difference whether power dissipation, total output power or output current is used as the independent variable because they are all related to each other. To users of power modules, however, output current or output power makes more sense than power dissipation. We recommend using output current in the derating chart for single-output-voltage modules (shown in Figure 19) and output power for multi-output-voltage modules.

Another difference between the charts in Figures 18 and 19 is the shape of the curves. With the traditional derating method, tests are conducted at room ambient temperature and data are linearly extrapolated at higher ambient temperatures. The derating curves are actually straight lines and all converge at  $100^{\circ}\text{C}$ , which is the derating constraint – the maximum module case temperature. With the new derating method, tests are conducted in the full ambient temperature range and there is no need for data extrapolation. Furthermore, the thermal performance is judged based on the actual junction temperatures of individual components. As a result, the nonlinear nature of the module’s power dissipation over ambient temperature is accurately recorded and represented in the derating chart.

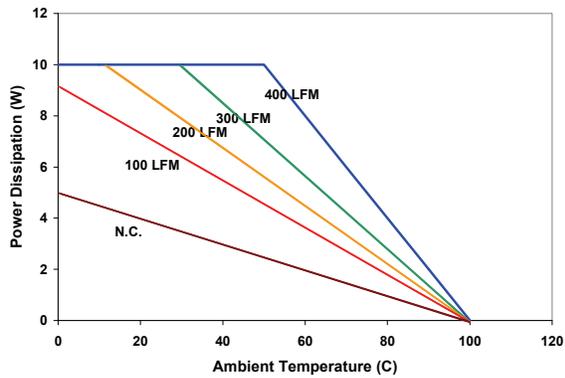


Fig. 18. Example of a conventional derating chart.

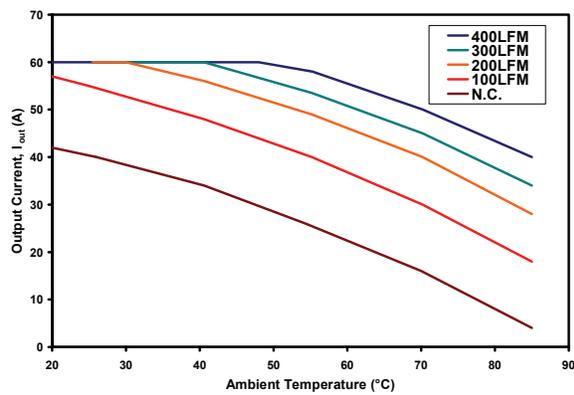


Fig. 19. Example of derating chart for an open-frame module.



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