

An Evaluation of Board-Mounted Power Module Packages

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This Technical Note is based on a paper presented at
the Applied Power Electronics Conference 2002

Abstract

We compare the characteristics of four BMP packages with a focus on thermal performance. Using experimental and simulation methods, the air-flow regime is found to be particularly important in determining which package provides superior thermal performance. For single-board medium-power designs, air flow velocities of less than 1 m/s (200 ft/min) allow potted modules to run cooler while air velocities greater than 2 m/s (400 ft/min) tend to allow open-frame modules to operate cooler. For dual-board designs, however, open-frame modules appear to outperform potted modules even at natural convection. Other attributes that are of interest to BMP users, such as cost, manufacturability, and ease of use, are discussed. We also propose a new method to obtain thermal derating characteristics of open-frame modules.

I. Introduction

Today, distributed power architectures are widely used in powering a variety of applications in computing and communications. One of the salient features of this approach is to have electronic power conversion be located on board the electronics being powered. This has led to a major new class of power electronic products called board-mounted power (BMP) modules. These are typically DC-DC converters that provide load-level voltages from a nominally 48 V or 24 V input at power levels from below a watt to as high as 600 W in a single package. Over the years, advances in components, circuits and packaging have resulted in BMP modules with higher efficiency, smaller size, lighter weight and lower profiles. Since these improvements have come with switching frequencies remaining relatively constant in the few-hundred kHz range, the packaging of BMP modules has become more challenging today than ever before as a result of the constant increase in power density.

The first BMP modules used open-frame ceramic substrates that provided a high-thermal-conductivity path to the components. Subsequently, FR4 substrates were utilized, with potting or encapsulation of the modules being used to improve heat transfer from the components. Today, open-frame modules have become popular again, driven by their low-cost characteristics. Examples of open-frame and potted modules used today are shown in Figure 1.

While the open-frame design has advantages such as lower profile and weight, simpler manufacturing process and potentially lower cost, there are design tradeoffs regarding their thermal performance as well as robustness and long-term reliability. In fact, while there has been considerable marketing hype touting open modules and their absence of heat sinks, there has been very little data obtained from an impartial analysis of the characteristics of different BMP packages. As a result, many users of BMP modules are often confused when it comes to selecting the right module for their specific application. The purpose of this paper is to attempt an assessment of BMP packages based on scientific analysis and experimental data, thereby providing useful information to BMP users as well as BMP designers. Four major BMP packages, as shown in Figure 2, are evaluated with respect to their thermal performance and other attributes: single-board potted (without metal base-plate, Figure 2a), dual-board potted (with metal base-plate, Figure 2b), single-board open-frame (Figure 2c) and dual-board open-frame (Figure 2d).

Section II compares the thermal performance of single-board potted versus open-frame modules, while comparisons between dual-board potted and open-frame modules are discussed in Section III. A summary comparison of other attributes such as mechanical robustness, safety conformance, ease of manufacturing and relative cost is given in Section IV. Since open-frame modules have recently become popular, we also provide a new methodology for thermal derating of such modules in Section V. Conclusions and a summary are provided in Section VI.

I. Introduction (continued)



Figure 1. Pictures of an open-frame module (a), and a potted module (b).

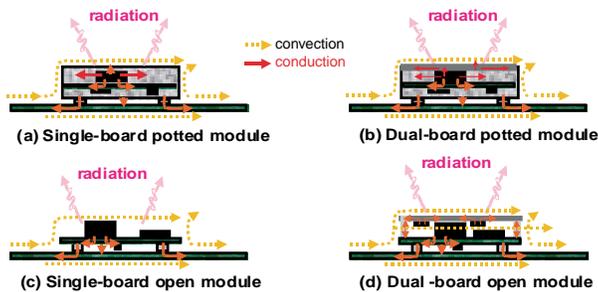


Figure 2. Drawings of four popular BMP packages showing construction details and heat transfer mechanisms.

II. Thermal Performance of Single-Board Potted vs. Open-Frame Modules

It is often assumed that an open-frame module thermally outperforms an equivalent potted module, because the former has its components exposed to air therefore having “more heat transfer surface area”. This is only partially true under certain circumstances, because air cooling of electronic devices also involves many other important factors that are usually overlooked or misunderstood, such as flow regime (laminar or turbulent), flow domain distribution, material properties and geometrical configurations (such as board spacing, component spacing and arrangement). Just having a larger surface area does not mean more effective heat transfer, and consequently does not automatically result in better thermal performance. To perform a more objective evaluation, we have to understand the physics that govern the heat dissipating process, and deliberately examine all the contributing elements.

A. Methodology

The approach adopted in this paper combines experimental techniques with simulation tools that use computational fluid dynamics (CFD) methods for simultaneously analyzing both heat transfer and air flow. The particular advantage of using simulation is that a detailed prediction of both airflow and temperatures at various positions within the test application can be easily determined. Once validated, such a method is far superior in accuracy and completeness to traditional approaches such as using smoke in wind tunnels that only qualitatively describes flow, or using infra-red cameras to measure and visualize a crude surface temperature map of the module.

The modules investigated were of the half-brick size with medium power output. Both potted and open-frame modules were single-board designs with the potted module encapsulated in an aluminum case. No external heat sink was used for either module, thus allowing for a “face-to-face” comparison. Board spacing was set at 25.4mm (1in) and airflow was monitored at a location 76.2mm (3in) upstream of the module and 12.7mm (0.5in) off the load-board. Component temperatures were measured with standard calibrated thermal couples. The CFD tool used was FLOTHERM from Flothermics, Inc.

B. Flow Considerations

The flow regime, laminar or turbulent, determines the flow characteristics which dictates thermal performance. Flow regime is categorized by a dimensionless number called Reynolds Number, which is defined [1] as

$$Re = UL/\nu, \tag{1}$$

where, U is the nominal air velocity, L the characteristic length, and ν the air viscosity. For typical BMP applications, the airflow can be classified as channel flow or internal flow. The air velocity is usually measured between the PWB boards at a certain distance from the BMP module. The board spacing can be used as the characteristic length in calculating the Reynolds Number. For channel flow, the transition from laminar to turbulent occurs at $Re \approx 2100$ [1], which is equivalent to airflow of around 1.27m/s (250 ft/min) with a board spacing of 25.4mm (1in).

In the laminar-flow regime, the pressure head is usually low, and not large enough to fully penetrate into the spaces between all the components of an open-frame module. In most regions, air velocity between the components is not significant in terms of convective heat transfer. Instead, the components are masked with a thin film of air, called the laminar boundary layer where heat conduction dominates [2].

II. Thermal Performance of Single-Board Potted vs. Open-Frame Modules (continued)

B. Flow Considerations (continued)

As a result, an invisible air envelope at low air velocities actually encompasses an open-frame module when laminar flow is present. As commonly known, air, with a typical thermal conductivity of roughly 0.025 W/m-K, is a poor thermal conductor, leading to poor conduction through the laminar boundary layer. By contrast, a potted module has encapsulant (thermal conductivity of 0.25-0.30 W/m-K, roughly ten times better than air) to help conduct heat from the heat-generating components to the metal case. The metal case functions as an extended heat transfer surface, in a manner similar to a heat sink. therefore there is no reason to assume that open-frame modules have any thermal advantage over the potted modules at low laminar airflow.

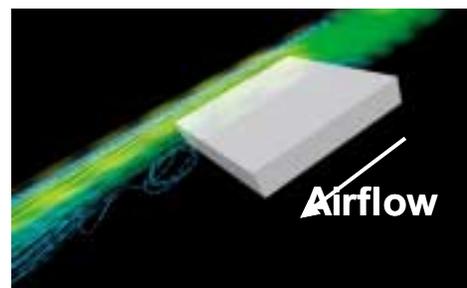
In the flow transition region of 1.27-1.9 m/s (250-375 ft/min), some more air penetrates between the components of an open-frame module, increasing the local convective heat transfer coefficients and effective surface area while the heat-sinking effect of a potted module does not increase proportionally. As a result, the thermal performance of an open-frame module tends to improve and eventually break even with or even exceed that of the potted module at some point in this flow region.

When the flow turns to full-scale turbulent (greater than 2 m/s (400 ft/min)), air thoroughly penetrates between components with significant speeds, as can be seen in the visualizations obtained from simulation depicted in Figures 3 and 4. All the exposed component surfaces are now completely involved in convective heat transfer. It is expected that open-frame modules would outperform potted modules in high airflow.

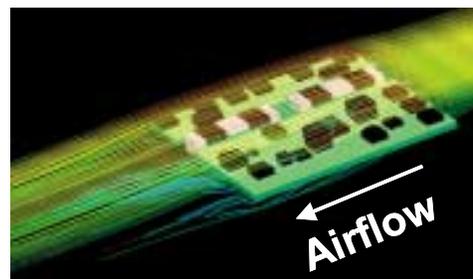
C. Modeling and Testing Results

The analyses given in last section are verified by the CFD-modeling results of single-board open-frame and potted modules with identical layout and power dissipation, shown in Figure 5. Both the maximum and average component temperatures are compared. The airflow conditions range from 0 (natural convection) up to 4 m/s (800 ft/min). When air velocities are less than 1 m/s (200 ft/min), the potted modules show better thermal performance, with both maximum and average component temperatures being lower than the open-frame case. Between 1 m/s (200 ft/min) and 2 m/s (400 ft/min), there is virtually little difference between the two modules. The break-even point occurs around 1.27 m/s, which happens to be the transitional point from

laminar flow to turbulent flow. Beyond 2 m/s (400 ft/min), the open-frame module gradually exhibits better performance with both average and maximum component temperatures being lower than that of the potted module in both open-frame and potted forms. The tested average component temperature as a function of airflow is shown in Figure 6. Again, the potted module demonstrates better performance at natural convection and low airflow while the open-frame module is superior at high airflow, a similar pattern observed in both the modeling and experimental results.



(a)



(b)

Figure 3. Visualization of air flows of a potted module (a) and a single-board open module (b) at 2 m/s (400 ft/min)



Figure 4. Air velocity vector map for an open module at 2 m/s (400 ft/min)

II. Thermal Performance of Single-Board Potted vs. Open-Frame Modules (continued)

C. Modeling and Testing Results (continued)

It should be pointed out that the data in Figure 5 and Figure 6 are specific to the modules in discussion. Other designs may perform differently with regards to magnitude of the temperature difference and the break-even point as the layout and power dissipation deviate. However, it is believed that the general trend will remain. The important message here is that flow regime plays a critical role in electronic cooling. As clearly demonstrated by the examples discussed above, the flow regime is what is responsible for the different thermal characteristics of potted and open-frame modules.

D. Other Observations

There were some other interesting facts discovered through the CFD simulations, and it is worthwhile to briefly remark on a few of the findings.

- The flow field around a power module (open-frame or potted) is highly non-uniform and much more complex than is commonly assumed. Even in an open-frame module, most of the air goes around the module with the highest velocity occurring right above the module. This translates into a high percentage of total heat dissipation from the top surface of the module. Also, in view of the notable non-uniformity of airflow, it is important to define the exact location of the velocity probe when specifying airflow.

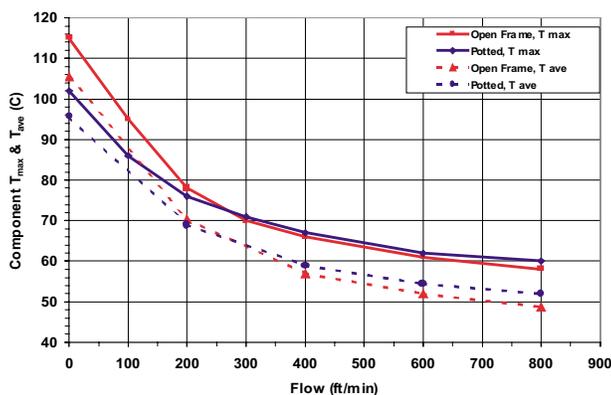


Figure 5. Component temperatures as a function of flow velocity for single-board potted and open modules (CFD modeling)

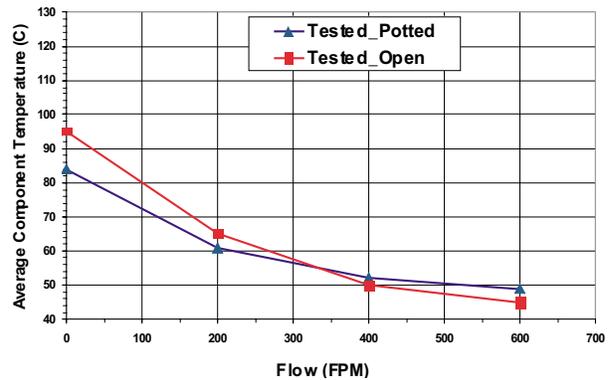


Figure 6. Average component temperatures as a function of flow velocity for single-board potted and open modules (tested)

- Air velocity between components in an open-frame module is often overstated at low incoming airflow. It was found that with a 1 m/s (200 ft/min) incoming airflow, the average air velocity between components is 0.25 m/s (50 ft/min), similar to that in a typical natural convection case [3].
- Contrary to common assumptions, there was no evidence that variation in component profiles (heights) of an open module could cause turbulence when incoming flow is in the laminar regime.
- It is generally assumed that a potted module would have more negative impact on a smaller adjacent device than an open-frame module. However, based on the simulation of a standard SO-8 MOSFET positioned right behind a power module, it was discovered that an open-frame module is not much better than a potted module. The adverse “shadowing” effect on this SO-8 device is equivalent in both cases.
- It was also discovered that a potted module does not always create a significantly higher flow resistance to a system than an open-frame module. As a matter of fact, there is little difference between the two types of modules at low to medium airflow. The distinction becomes significant only in the high airflow range (≥ 3 m/s (600 ft/min)).

III. Thermal Performance of Dual-Board Potted Module vs. Dual-Board Open Module

A half-brick dual-board module was tested in both its open-frame and potted forms to determine which operates better under various conditions. The module tested was a 58 x 61 x 12.7mm (2.3 x 2.4 x 0.5in) module that had an FR4 board with embedded magnetic windings and an IMS (Insulated Metal Substrate) board with power semiconductors mounted on it. The nominal spacing between the FR4 and IMS boards was about 5.8mm (0.23in) while the gap between the module and its test board was about 3.8mm (0.15in).

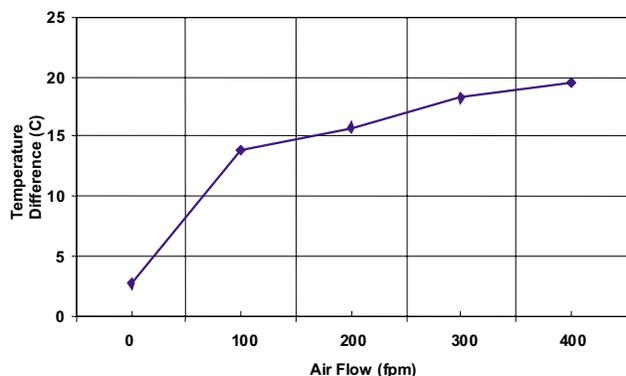


Figure 7. Average component temperature difference between dual-board potted and open-frame modules ($T_{\text{potted}} - T_{\text{open}}$)

With the dual-board design, the open-frame version not only gets some help from air flowing between the FR4 and IMS boards, but more importantly, it has the metal plate to fully take advantage of the enhanced convection on top of the module where the air velocity is the highest. In contrast, the potted version has a relatively smaller surface area and increased thermal resistance for some of the components than the dual-board open module. Both factors tend to lead to higher temperatures for the same thermal and electrical conditions. Figure 7 shows the tested results in temperature difference as a function of the airflow between the two versions.

In a natural convection environment, the two versions operate comparably, with less than 3°C difference in average component temperature. Under forced convection conditions, however, the open-frame version significantly outperforms the potted version. Even at 0.5 m/s (100 ft/min) airflow, the average component temperature difference is almost 15°C. As the air speed increases, the difference in temperature rise becomes greater. When airflow is in the fully turbulent region

(2 m/s (400 ft/min)), component temperatures in the open-frame version are roughly 20°C cooler than in the potted version.

IV. Comparison of Other Attributes

Table 1 shows a summary comparison of some other attributes that are of interest to both users and manufacturers of BMP modules. Attaching external heat sinks to modules is one way of increasing power dissipation capability at a particular airflow level. It is relatively straightforward to attach heat sinks to the potted BMP packages and the dual-board open-frame package. On the other hand, the uneven profile of the single-board open-frame module makes it more complicated to attach a heat sink with good thermal contact. One approach is to attach a baseplate with thermally-conductive filler material placed between the baseplate and the module. This allows attachment of a heat sink to the baseplate, providing increased thermal dissipation capabilities. The potted modules provide good mechanical robustness since the components are encapsulated and enclosed in a case. The dual-board open-frame module is slightly better than the single-board open-frame module because the upper board acts as a partial shield.

Safety conformance of all modules is adequate meeting or being better than requirements. The potted modules have the best conformance since it is not possible to come into contact with the components inside the module. The dual-board open-frame module also reduces access to the components from the top. On the other hand, the single-board open-frame module allows direct contact with the components unless a baseplate is attached to the module.

In comparing manufacturing complexity, the potted modules are the most complex since the sequence consists of assembly of one or two boards followed by placing them in a case and encapsulating the components with a thermally-conductive filler material. The dual-board open-frame module requires the interconnection of the two boards after they are separately assembled. By contrast, the single-board open-frame module has the simplest manufacturing process since all that is needed is to assemble the components on the single board. In comparing cost of the different BMP packaging approaches, the single-board open-frame module has potentially the lowest cost because of its simplicity of construction. However, depending on the power density level, a single-board design may entail higher levels of integration and more expensive components in order to fit the entire circuitry on the board. Thus, overall cost may be higher for those single-board designs pushing the frontiers on efficiency and power density.

IV. Comparison of Other Attributes (continued)

Table 1. Comparison of other attributes

	Single-board potted module	Dual-board potted module	Single-board Open-frame module	Dual-board Open-frame module
Heat-sinking	Yes	Yes	Difficult	Yes
Mechanical robustness	Good	Good	Average	Fair
Safety conformance	Excellent	Excellent	Adequate	Good
Manufacturing process	Complex	Complex	Simple	Moderate complexity
Customer assembly –SMT Placement –Environmental –Cleaning –Rework	Good Protected Compliant Complex	Good Protected Compliant Complex	Difficult Can be contaminated Special drying Simple	Good Can be contaminated Special drying Moderate
Cost	Moderate	Moderate	Potentially low	Moderate

V. Method for Assessing Thermal Performance of Open-Frame Modules

Open-frame modules have unique thermal characteristics that deserve special treatment in testing as well as in the thermal derating process. Despite the upsurge in open-frame designs in recent years, there has not been a standard characterization process in the industry. As a matter of fact, there is very little published literature that describes objective investigations in this area. This has caused confusion among customers regarding testing procedures and interpretation of data published in module-manufacturer data sheets. In this section, we attempt to look into some of the special aspects of open-frame modules based on our experience and to provide a more accurate and practical methodology for performing thermal evaluations.

The traditional method of using the module case temperature as an indicator for assessing thermal performance of potted modules [4], is not applicable to open-frame modules, since the components are not in direct thermal contact with one another. Furthermore, based on our extensive experience, open-frame modules have the following characteristics:

1. The component that limits thermal performance of the module varies depending on operating conditions. In addition, module orientation with respect to airflow is also critical.
2. Temperature difference among components become larger than in the potted-module case, and therefore all important components need to be monitored during thermal testing.
3. Thermal performance becomes more sensitive to the location of both velocity and ambient temperature sensors.

4. Spacing between test boards and wind tunnel configurations are more likely to influence thermal testing.
5. The maximum component junction temperature $T_{j,max}$ and component power dissipation $P_{d,comp}$ become more critical in the derating process.
6. 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.

Based on these observations, a new thermal characterization method along with special testing considerations is proposed here for open-frame modules. This new method involves the following key steps:

1. For each critical component, define the relationship between the component power dissipation $P_{d,comp}$ and module output current I_{out} ,
$$P_{d,comp} = f(I_{out})$$
2. Establish a nonlinear characteristic curve as shown in Figure 8 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. 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, increase with the square of the output current.
3. Calculate and plot the actual junction temperature T_j for each of the critical components [5], where R_{jc} is the junction-to-case thermal resistance of the component.

$$T_j = T_C + (P_{d,comp} \times R_{jc})$$

(3)

V. Method for Assessing Thermal Performance of Open-Frame Modules (continued)

4. Apply the proper temperature constraints for the critical components. The first component reaching its temperature constraint determines the maximum module output current I_{out} under that particular operating condition.

It is important to understand that the difference between T_j and T_c is not 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 °C under natural convection and very low output current when the dissipation is small, but as large as 15 to 20 °C under forced convection and high output current. Considering that the junction temperature T_j plays a major role in determining the reliability of the module, it is incorrect to assume that T_j is approximately equal to T_c under all conditions.

Another parameter that requires extra attention is the junction-to-case thermal resistance R_{jc} , which is usually tested by the semiconductor device manufacturer on a small FR4 board (typically 25.4 x 25.4mm (1 x 1in)) in a natural convection environment. Our experimental data indicated 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 beneficial to carefully examine the application condition against the specified test condition before using the R_{jc} value provided in the data sheet.

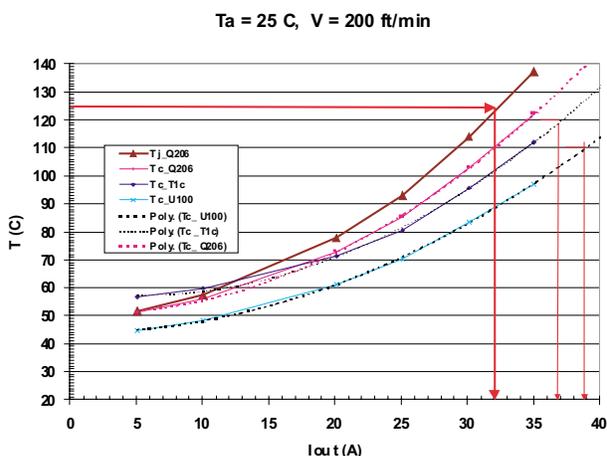


Figure 8. Example of nonlinear characteristic curve of component temperature versus output current.

Special considerations are needed when testing open-frame modules because they exhibit distinct thermal characteristics and are more susceptible to experimental variations. We have found that the following practices are helpful in performing a more objective and accurate thermal assessment:

1. The wind tunnel used for testing must be fully profiled with respect to both velocity and temperature to ensure satisfactory uniformity and stability.
2. Open-frame modules should be tested at all ambient temperatures. Linear extrapolation based only on room ambient temperature data would produce large errors at high ambient temperatures.
3. Infrared (IR) imaging can be a very effective tool for temperature readings when used properly. However, care must be taken in setting all the parameters, especially, the emissivity. Painting the module black could solve the problem of emissivity variation, but one has to realize the impact of paint on the module's thermal performance. In practice, we use an IR camera for preliminary testing where hot zones and components are identified, while thermocouples along with an automated data acquisition system are used for precise temperature readings to obtain the actual thermal derating characteristics.
4. When using thermocouples for leaded semiconductor devices, there is always the question as to where the thermocouple should be attached — the body, the lead, or in some cases, the metal tab. The point of attachment depends on the way that the manufacturer specifies R_{jc} . 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} values, and following the procedure described by the device manufacturer.
5. The locations 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 in between the two test boards at a distance of 76.2mm (3in) from the test module and 12.7mm (0.5in) away from the test board as shown in Figure 9.
6. A single-point air-velocity measurement is a simple and quick indicator but is not adequate to define the actual amount of airflow. We recommend using a volumetric flow measurement in addition to the single-point air velocity measurement.

V. Method for Assessing Thermal Performance of Open-Frame Modules (continued)

7. Component temperatures in open-frame modules vary considerably and the component that limits thermal performance 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 picture of the module's thermal performance.
8. The test-board spacing also has a significant effect on a module's thermal performance. This spacing may vary based on the applications. However, it is essential to specify the spacing clearly so that others would interpret the data accordingly. We use a 25.4mm (1in) spacing for open-frame modules without heat sinks.
9. Because of the enormous variations in component temperatures of open modules, it is necessary to test and collect data at various output current levels for a given flow and ambient temperature condition so that characteristic curves for all the key components can be established and analyzed for a better thermal evaluation.

VI. Summary and Recommendations

It is clear from the previous discussions that many factors go into an evaluation of BMP modules. To choose the right power module, one has to understand the specific application and compare modules with respect to thermal performance, cost, ease of use, heat-sinking capability and safety conformance. From a thermal standpoint, single-board open-frame modules, though popular, do not necessarily outperform equivalent potted modules under all condition. As a matter of fact, under natural convection or very low airflow, potted modules do even better than open modules. However, when the airflow is sufficient, a single-board open-frame module would run much cooler than a potted module. In comparing dual-board design, it seems that a dual-board open-frame module always thermally surpasses a dual-board potted module. Overall, given a certain application where both open-frame and potted modules can be accepted, cost may be the key factor in determining which one is preferred. For applications where board spacing is a constraint, single-board open-frame modules are favored due to their lower profiles.

Understanding the airflow and heat-dissipation process is key to an impartial assessment of BMP modules. Good testing and derating practices will ensure accurate and unambiguous results that can be easily understood by others and can be repeated whenever needed. In selecting power modules, it is important for users to understand that good-looking derating curves do not always guarantee actual performance unless the testing conditions and parameters are clearly specified.

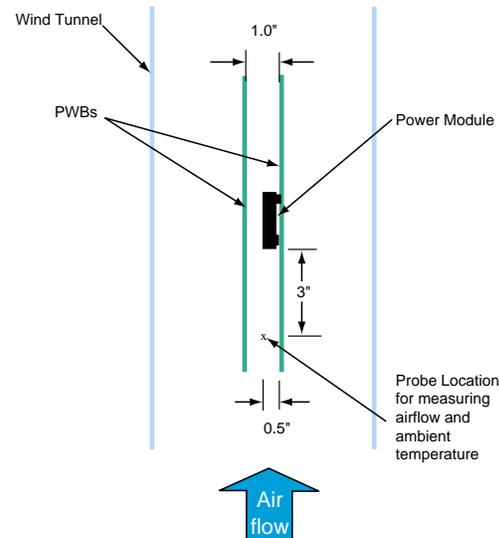


Figure 9. Typical test setup and airflow sensor location

Acknowledgment

The authors would like to thank David Stevens of Tyco Electronics Power Systems for his invaluable input regarding many of the issues discussed in this paper. We also thank Mike Otrupcak and Jon Maresca of Tyco Electronics Power Systems for their assistance in some of the experiments.

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Printed in U.S.A.

May 2002
TN02-001EPS

