VI BRICK THERMAL MANAGEMENT

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Overview:

VI BRICKs allow access to the advantages of Vicor's V•I Chip technology with increased options for thermal management. High operating efficiency minimizes heat loss, and the thermally enhanced low profile package features an easily accessible, electrically isolated thermal interface surface.

Proper thermal management pays dividends in terms of improved module and system MTBFs, smaller size and lower product life-cycle costs. The following pages provide guidelines for achieving effective thermal management of Vicor's VI BRICKs.

Efficiency and Dissipated Power:

A VI BRICK module takes power from an input source and provides regulation and/or current multiplication of the output power for delivery to a load. Not all of the input power is converted to output power however; some is dissipated as heat within the modules. The ratio of delivered output power to module input power is defined as the module's efficiency. Efficiency is a basic figure of merit that can be used to relate power dissipation directly to module output power.

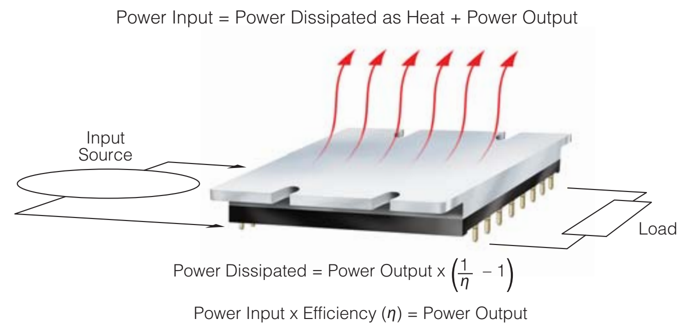

Figure 1 — Dissipated power

The first step in evaluating cooling requirements is to calculate worst-case dissipation based on module efficiency and worst-case anticipated load power. Clearly, higher efficiency will translate into lower power dissipation and simplify the cooling problem. Vicor VI BRICKs have some of the highest efficiencies in the industry, with typical efficiency up to 97%.

Removing Heat From VI BRICK Modules:

Heat is removed from VI BRICKs through the flat metal baseplate on top of the module and through the module pins. The baseplate is thermally coupled to, but electrically isolated from, all internal heat-generating components. The basic thermal design problem is to transfer heat from the baseplate into the surrounding environment as a means of maintaining baseplate temperature at or below rated maximum.

Heat energy is transferred from regions of high temperature to regions of low temperature via three basic mechanisms; radiation, conduction and convection.

Radiation. Electromagnetic transfer of heat between masses at different temperatures.

Conduction. Transfer of heat through a solid medium.

Convection. Transfer of heat through the medium of a fluid; typically air. All three of these heat transfer mechanisms are active to some degree in every application. Convection will be the dominant heat transfer mechanism in most applications. Nondominant effects will provide an added contribution to cooling; in some cases, however, they may result in undesirable and unanticipated thermal interactions between components and subassemblies.

All three of these mechanisms should be given consideration when developing a successful cooling strategy.

Radiation:

Radiant heat transfer occurs continuously between objects at different temperatures that are exposed to each other. The net effect on the temperature of an individual part is dependent on a great many factors, including its temperature relative to other parts, relative part orientations, surface finishes and spacing. The difficulty in quantifying many of these factors, combined with the universal presence of radiant energy exchange, makes calculation of radiational temperature effects both a complex and generally imprecise task.

Temperature differentials encountered in practical applications of VI BRICKs are never large enough to cause radiational cooling to be the dominant heat transfer mechanism. Radiation will account for less than 10% of total heat transfer in the majority of cases. For these reasons, the presence of radiant cooling is often assumed to provide safety margins over and above the dominant cooling mechanism, and detailed consideration of its effects are neglected. A valid assumption, in most cases, is that the module will be warmer than its surroundings and radiant energy transfer will aid cooling. In some cases, however, nearby objects (micro processors, power FETs, etc.) may be much hotter than the module and net radiant energy transfer may actually increase the module's temperature. Surveying the relative positions and estimated temperatures of modules and surrounding parts is advisable as a means of anticipating the potential effects of radiant transfer. In cases where hot components are in close proximity to the module, the use of interposing barriers can generally moderate undesirable radiational heating effects.

Conduction:

In most applications, heat will be conducted from the baseplate into an attached heat sink or heat conducting member and through the module pins to the PCB. Cooling of the module through the board is a function of how much copper is surrounding the module, how much air is passing over that copper, and how much heat is coupled into the PCB from surrounding components. For the purpose of this application note, it will be assumed that there is no cooling of the modules due to the PCB and that all of the cooling occurs through the baseplate.

Heat conducted across the interface between the baseplate and mating member will result in a temperature drop which must be controlled. As shown in Figure 2, the interface can be modeled as a "thermal resistance" in series with the dissipated power flow. The baseplate temperature will be the sum of the temperature rise in the interface and the temperature of the member to which the baseplate is attached.

Temperature rise across a surface interface can be significant if not controlled. The area of the interface should be as large as possible, and the surface flatness of the attached member should be within 5 mils. Thermal compound or a thermal pad should be used to fill surface irregularities.

Thermal resistance across surface interfaces can be held to under 0.2˚C/Watt with proper measures for VI BRICK DC-DC converters and under 0.4˚C/Watt for VI BRICK PRM and BCM/VTM.

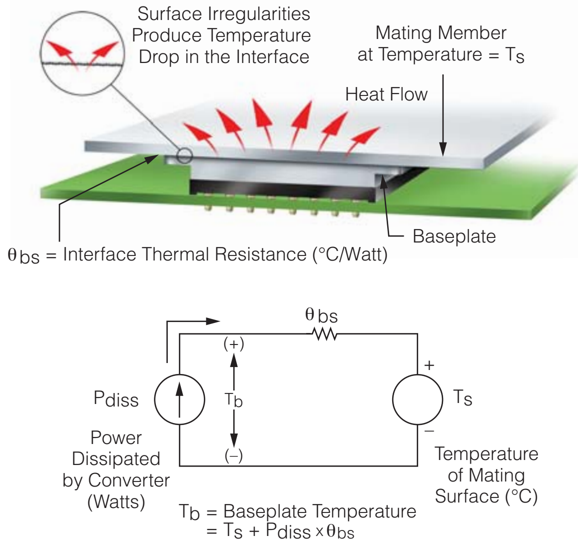

Figure 2 — Baseplate thermal considerations

Many applications require that heat be conducted from the baseplate of the module to a "remote" dissipative surface via a thermally conductive member. The resulting baseplate temperature will be the sum of the temperature of the dissipative surface, the temperature rise in the heat conducting member, and the rises across the two surface interfaces. The thermal resistance of the conductive member is proportional to its length, and inversely proportional to both its cross-sectional area and thermal conductivity (Figure 3). Minimizing total temperature rise is dependent on controlling interface resistance, as described above, and controlling the thermal resistance of the transfer member through appropriate material selection and dimensioning.

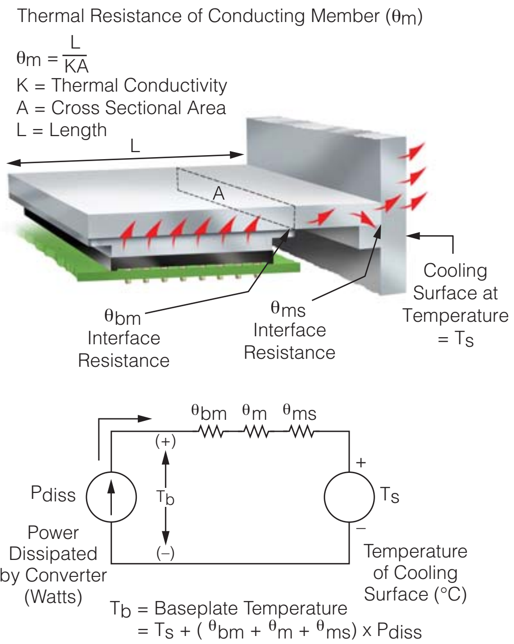

Figure 3 — Interface thermal considerations

Convection:

Convective heat transfer into air is a common method for cooling Vicor modules. "Free" or "natural" convection refers to heat transfer from a dissipative surface into a cooler surrounding mass of otherwise still air; forced convection refers to heat transfer into a moving air stream.

The convection cooling model is shown in Figure 4. Baseplate temperature depends on the temperature of the air, total dissipated power and the values of two thermal resistances; the thermal resistance of the surface interface between the baseplate and the heat sink, and the heat sink-to-air thermal resistance. Surface interface resistance can be minimized as discussed under Conduction. The heat sink-to-air resistance is dependent on a variety of factors including heat sink material and geometry, air temperature, air density and air flow rate. Fortunately, thermal resistance data is available for a very wide range of standard heat sinks for use in both free and forced convection applications. The following sections will provide guidelines for both free and forced convection cooling of Vicor VI BRICKs.

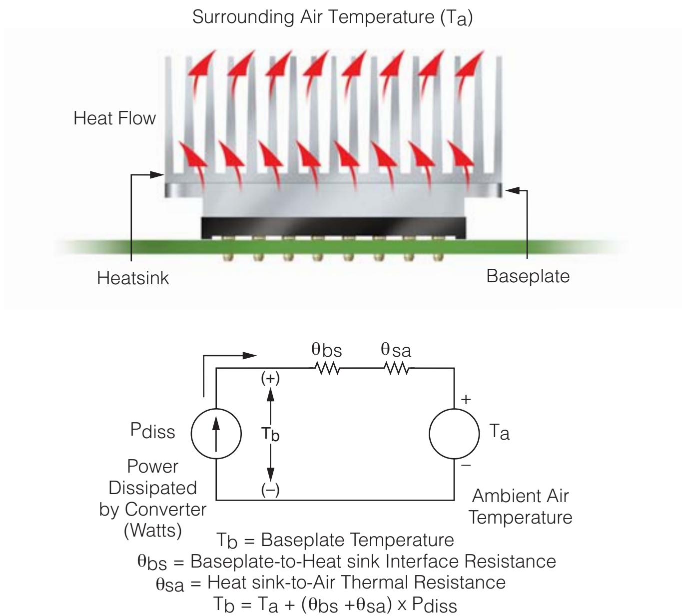

Figure 4 — Heat sink thermal considerations

Free Convection:

The benefits of free convection include low cost of implementation, no need for fans, and the inherent reliability of the cooling process. Compared to forced air cooling, however, free convection will require more heat sink volume to achieve an equivalent baseplate temperature

To select a suitable heat sink for free convection cooling, follow these steps:

1. Determine the power to be dissipated by the heat sink. This should be based upon module efficiency and worst-case module power output using the formula given in the section on Module Efficiency and Dissipated Power (Figures 1).

   $$\text{Power Dissipated} = \text{Power Output} \times \left(\frac{1}{\eta} - 1\right)$$

   $$\eta = \text{efficiency} = \frac{P_{out}}{P_{in}}$$

2. Determine the surface interface thermal resistance. Use of thermal compound or a thermal pad is recommended to minimize thermal resistance. This information is available on the VI BRICK data sheets.

3. Referencing Figure 4, we can derive the following formula for heat sink-to-air thermal resistance:

   $$\Theta_{sa} = \left(\frac{T_b - T_a}{P_{diss}}\right) - \Theta_{bs}$$

   T_a = Worst case anticipated operating ambient air temperature.
   Θ_{bs} = Surface interface thermal resistance, from Step 2.
   P_{diss} = Worst-case power dissipation, from Step 1.
   T_b = Baseplate temperature.

   Start with a value of Tb = 100°C to determine the maximum acceptable heat sink-to-air thermal resistance.

4. Select several heat sinks that appear physically acceptable for the application. Using data provided, obtain values for their free convection thermal resistance, preferably at worst-case ambient temperature, Ta. If values obtained are less than the value calculated in Step 3, go on to Step 5. If the values are greater, then either a physically larger heat sink will be required or a different cooling method will need to be used (i.e., forced air, etc.).

5. Select the heat sink with the lowest available thermal resistance consistent with space limits. Keep in mind that small reductions in baseplate temperature produce dramatic improvements in MTBF.

6. Baseplate temperature can be estimated by using the following formula:

   $$T_b = T_a + P_{diss} \times (\Theta_{bs} + \Theta_{sa})$$

7. Test to verify that performance is in line with expectations.

Heat sink data is almost always given for vertical fin orientation. Orienting the fins horizontally will reduce cooling effectiveness. If horizontal mounting is mandatory, obtain relevant heat sink performance data or use forced convection cooling. Free convection depends on air movement caused by heat-induced density changes. Thermal resistance data is dependent on the heat sink fins being completely exposed to the ambient air without any significant interference to air flow at the ends of or along the length of the fins. If packaging will tend to block or baffle air movement over the fins, a larger heat sink might be required. In the worst case, free convection may be ineffective. Make sure that the fins are well exposed to ambient air.

It is not necessary to limit the size of the heat sink to the size of the baseplate. Heat sinks with footprints larger than the baseplate area can often be used to advantage. In the latter case, heat must be conducted along the base surface of the heat sink to get to the outer fins, so don't count on achieving full cooling capability. Also, several modules can be mounted to a common heat sink, but cooling calculations must now take into account total power dissipation with consideration given to possible localized overheating if worst-case module power dissipations are greatly imbalanced.

Forced Convection:

Forced air can make a great difference in cooling effectiveness. Heat sink-to-air thermal resistance can be improved by as much as an order of magnitude when compared to free convection performance, by using suitable heat sinks. Consider the following data for baseplate-to-air thermal resistance (no heat sink) of VI BRICK modules at various airflow rates:

Airflow	VI BRICK DC-DC Baseplate to Air Thermal Resistance	VI BRICK PRM Baseplate to Air Thermal Resistance	VI BRICK VTM/BCM Baseplate to Air Thermal Resistance
Free Air	6.5°C/W	8.8°C/W	7.7°C/W
200 LFM	4.0°C/W	6.3°C/W	5.8°C/W
400 LFM	3.0°C/W	4.8°C/W	4.5°C/W
600 LFM	2.5°C/W	3.9°C/W	3.8°C/W
800 LFM	2.2°C/W	3.4°C/W	3.2°C/W
1,000 LFM	2.0°C/W	3.1°C/W	2.9°C/W

Table 1 — Baseplate to Air Thermal Resistance (no heat sink)

Forced air implies the use of fans. Many applications require that fans be used to achieve some desired combination of overall system reliability and packaging density. Industrial environments will require filters that must be changed regularly to maintain cooling efficiency, and neglecting to change a filter or the failure of the fan could cause the system to shut down or malfunction.

The steps involved in selecting a heat sink / fan combination for forced convection are essentially the same as those followed for free convection, with the additional requirement that the heat sink and fan be matched to achieve desired heat sink-to-air thermal resistance. Attention must also be paid to proper channeling of fan airflow so that maximum utilization of its cooling capability is realized. Selection of a heat sink / fan combination involves the following three steps:

1. Determine maximum acceptable heat sink-to-air thermal resistance by following the first three steps of the heat sink selection procedure given in the Free Convection section.

2. Selection of a heat sink / fan combination requires that forced convection data for both the heat sink and fan be available. Forced convection characteristics for heat sinks define both heat sink-to-air thermal resistance and pressure drop through the heat sink as a function of airflow.

Fan characteristics define airflow as a function of pressure drop. The intersection point of the airflow versus pressure curves for the fan and heat sink will define the operating airflow through the heat sink (Figure 5). The heat sink-to-air thermal resistance for this airflow may be read directly off the airflow versus resistance curve for the heat sink.

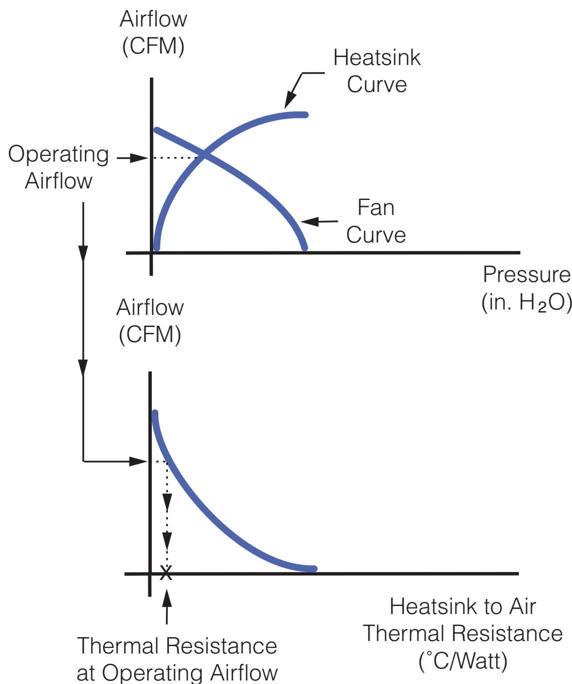

Figure 5 — Airflow vs. resistance

Finding and interpreting the operating point requires consideration of the following:

Units of pressure drop are generally given in inches of water. Units of fan airflow are in cubic feet per minute (CFM). Occasionally metric units are used, but conversion is straightforward.

Heat sink airflows may be given either in CFM or LFM (linear feet per minute). The conversion between LFM and CFM is dependent on the cross-sectional area through which air is flowing: CFM = LFM X Area

The cross-sectional area between the fins is the area through which the total airflow must pass (Figure 6). Correct interpretation of heat sink data requires that only the airflow through this area be considered. Simply pointing a fan at a heat sink will clearly not result in all of the flow going through the cooling cross-section of the sink; some channeling of air is usually required to get the full benefit of fan output. The fan curves give output in CFM versus pressure drop.
Fan pressure drop is the total of all drops encountered by the fan airflow. The heat sink, any ducting that is used, and air entry and exit channels all contribute to pressure drop. Pressure drop represents the work done by the fan in moving air through a region, so care should be taken to minimize unproductive pressure losses. Ensure that air entry and exit locations and internal air channels are not unduly constricted, and avoid sharp turns in airflow paths.

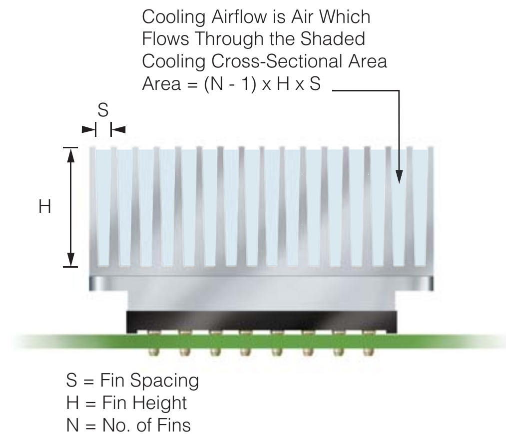

Figure 6 — Heat sink cross section

The thermal resistance that was determined by overlapping the fan and heat sink curves will represent an optimistic estimate since it assumes that all the fan output flows through the heat sink cooling cross section, and that all the pressure drop occurs along the heat sink. If the estimated thermal resistance is close to the minimum value determined in

Step 1, then it is likely that a larger fan or different heat sink is required. This will not be a problem in most cases; relatively modest heat sinks and fans usually provide ample cooling. Careful channeling and ducting of airflow as a means of both maximizing flow through the cooling cross-section of the heat sink and minimizing extraneous flow of air around the sink is well worth the small extra design effort required. Every degree of improvement in baseplate temperature results in significant improvement in MTBF. If you are paying for a fan, you may as well leverage it for all that it is worth.

3. Steps 5 through 7 in the Free Convection section will complete the heat sink selection process. Select the fan / heat sink combination with the lowest thermal resistance consistent with cost and space constraints, calculate the estimated baseplate temperature and test to verify.

Definitions:

Tmax = maximum baseplate temperature (Available from VI BRICK data sheets)

T_a = ambient temperature

η = efficiency = $\frac{P_{out}}{P_{in}}$

(Available from VI BRICK data sheets)

Θ_{bs} = baseplate-to-heat sink thermal resistance (Available from VI BRICK data sheets)

Θ_{sa} = heatsink-to-air sink thermal resistance (Available from heat sink manufacture)

Thermal Equations:

$$P_{diss} = \text{dissipated power} = P_{out}\left(\frac{1}{\eta} - 1\right)$$

$$\text{Airflow (LFM)} = \left(\frac{\text{CFM}}{\text{Area}}\right)$$

$$\text{Maximum output power} = \frac{T_{max} - T_a}{\Theta_{sa}\left(\frac{1}{\eta} - 1\right)}$$

$$\text{Maximum thermal impedance} = \frac{T_{max} - T_a}{P_{out}\left(\frac{1}{\eta} - 1\right)}$$

$$\text{Max. ambient temp.} = T_{max} - \Theta_{sa} \times P_{out}\left(\frac{1}{\eta} - 1\right)$$

$$\text{Temperature rise} = \Theta_{sa} \times P_{out}\left(\frac{1}{\eta} - 1\right)$$

$$\text{Thermal drop} = \Theta_{bm} \times P_{out}\left(\frac{1}{\eta} - 1\right)$$

Typical Examples:

Example 1. Determine the maximum output power for a 300 W, VT048A320T009FP VTM module, no heat sink, delivering 32 V in 400 LFM at a maximum ambient temperature of 45°C.

$$\text{Maximum output power} = \frac{T_{max} - T_a}{\Theta_{sa}\left(\frac{1}{\eta} - 1\right)}$$

T_{max} = 100°C
T_a = 45°C
Θ_{sa} = 4.5°C/W
η = 96% = (0.96)

$$\text{Maximum output power} = \frac{100 - 45}{4.5\left(\frac{1}{0.96} - 1\right)} = 293\text{ W}$$

Example 2. Determine the maximum heat sink thermal impedance for a 220 W, DC048B240T022FP DC-DC module, with thermal pad, delivering 24 V at 200 W.

Max. heat sink thermal impedance =

$$\Theta_{sa} = \frac{T_{max} - T_a}{P_{out}\left(\frac{1}{\eta} - 1\right)} - \Theta_{bs}$$

T_{max} = 100°C
T_a = 55°C
P_{out} = 200 W
Θ_{bs} = 0.18°C/W
η = 92% = (0.92)

Max. heat sink thermal impedance =

$$\Theta_{sa} = \frac{100 - 55}{200\left(\frac{1}{0.92} - 1\right)} - 0.18 = 2.4°C/W$$

Thermal Curves:

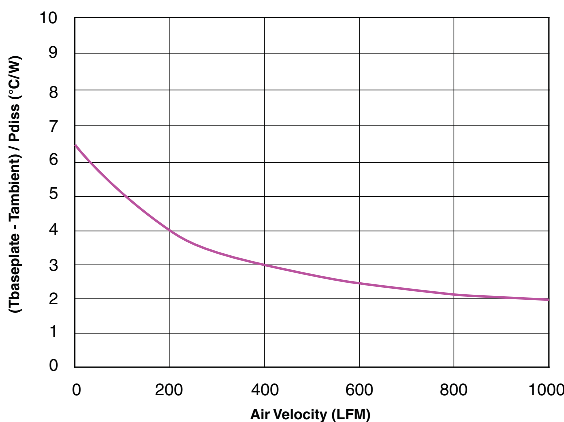

Figure 7 — Baseplate to air thermal impedance DC-DC module

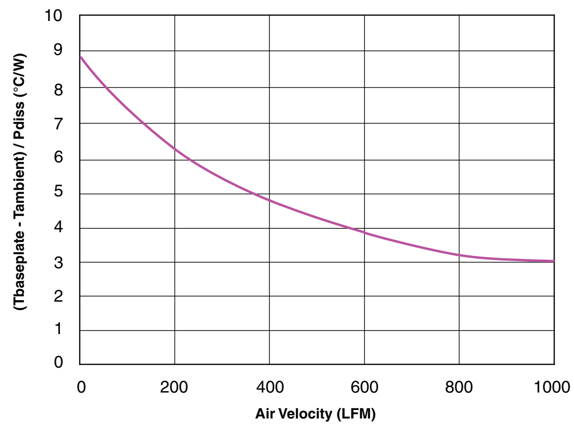

Figure 8 — Baseplate to air thermal impedance PRM module

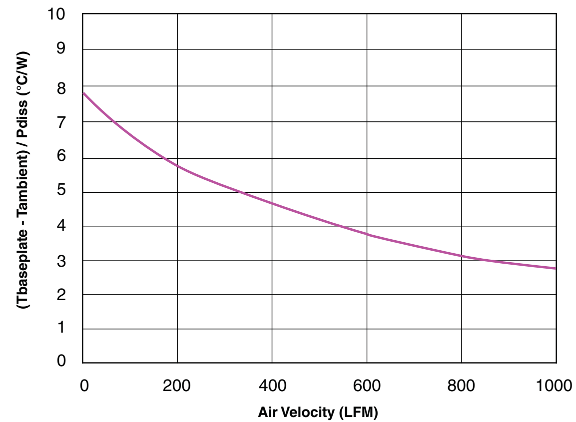

Figure 9 — Baseplate to air thermal impedance VTM/BCM module

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