Cold Plate Technology Comparison

By **Greg Caswell**

New types of energy, such as wind and solar power, are being utilized more prevalently and hybrid cars/buses are being identified as a means of reducing carbon dioxide emissions resulting from the use of fossil fuels. Electronic systems like frequency converters for wind power and train utilization are required to provide ever higher levels of energy savings. As such, IGBT (insulated-gate bipolar transistor) modules required for power conversion and motor control are becoming more and more important. Similarly, as our society becomes increasingly more dependent on information-oriented, digitized data, there is an increasing need for uninterruptable power supplies (UPS).

IGBTs are generally used as switching components in these applications. Although these devices are usually very efficient, their operation can be significantly impacted by conduction and switching power losses. Therefore, the heat generated must be conducted away from the IGBT devices themselves. The IGBT module characteristics will differ according to the particular application, but higher efficiency and downsizing are common requirements.

The National Renewable Energy Laboratory (NREL) states "the barrier to developing next-generation power electronics is cooling at high heat fluxes (up to 100 W/cm^2) at high temperatures (>125 °C) in compact (low-volume), lightweight power electronics packages. Advanced heat transfer techniques must be used to overcome such barriers and challenges in next-generation power electronics cooling."[1]

Previously, aluminum heat sinks would have provided sufficient conduction. But, with the higher power levels associated with IGBTs, cold plate technologies offer better thermal transfer capabilities.

This white paper compares and analyzes two distinct cold plate technologies with regard to their thermal transfer capabilities and then translates that information into an analysis of both random failure and integrated circuit (IC) wearout reliability to show the 8-12.25X lifetime improvement achievable for the IGBT devices/modules, with respect to random failures and a 27-44X improvement with respect to IC wearout.

Selecting the right cold plate technology, when cooling is required, involves getting the appropriate answers to several questions: What is the maximum permitted junction temperature for the IGBTs being implemented in the product? What is the maximum junction temperature allowed to achieve the IGBT life cycle requirement? What cold plate technologies are available? What are the comparative costs of the cooling methods — can you reduce the number of IGBTs with improved cooling? How reliable is the cooling method? How much physical space is there for cooling?[2]

Answering these questions provides insight into why it is vital to implement the best cold plate technology to reduce heat levels and enhance reliability.

Figure 1 shows two of the IGBT modules that have been improved with the use of cold plate technology.

Mitsubishi IGBT Module

Semikron Module

Figure 1. Two IGBT modules enhanced by cold plate technology

/ TUBED COLD PLATE

The tubed cold plate configuration is shown in Figure 2. Components can be mounted on both sides of this compact and lightweight cold plate, making it ideal for applications where heat loads are moderate and space is at a premium.

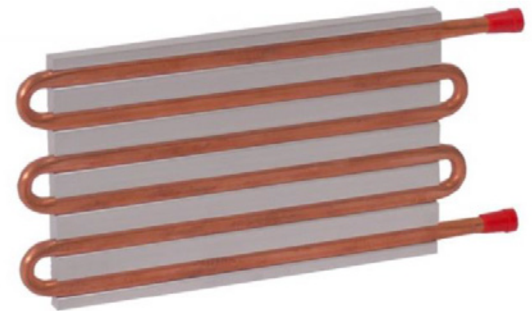


Figure 2. Tubed cold plate configuration[3]

/ VACUUM BRAZED COLD PLATE

The vacuum brazed cold plate configuration contains a high-performance corrugated aluminum fin brazed into the cavity beneath the mounting surface of the cold plate. The fin creates turbulence, which minimizes the fluid boundary layer and reduces thermal resistance. Figure 3 is a pictorial of the vacuum-brazed cold plate configuration.

Figure 3. Vacuum-brazed cold plate configuration[4]

/ NORMALIZED PERFORMANCE CURVES

Thermal resistance is normally expressed as °C per Watt. Thermal resistance describes how much hotter the surface of a cold plate is relative to the temperature of the fluid flowing through the cold plate, under a given thermal load. The lower the thermal resistance, the better the performance of the cold plate.

/ DETERMINING IGBT RELIABILITY

The relationship between reliability and the IGBT junction temperature is shown in Figure 4. Clearly, reliability is increased if the junction temperature is maintained at the lower values. This observation is directly linked to the cold plate technology's ability to reduce and maintain the lower IGBT device junction temperatures.

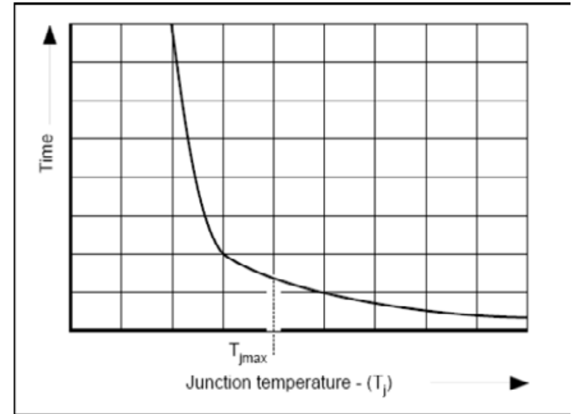


Figure 4. Relationship of IGBT device junction temperature to reliability (time). Image from Dynex Semi[2]

Figure 5 shows the typical stackup for an IGBT construction, with the die being soldered to the top of a direct bond copper (DBC) substrate, which is in turn bonded to a copper base plate. The base plate is then bonded to the cold plate. As such, it is the accumulation of the thermal resistances that drives the ability of the IGBT module to remove heat and improve performance.

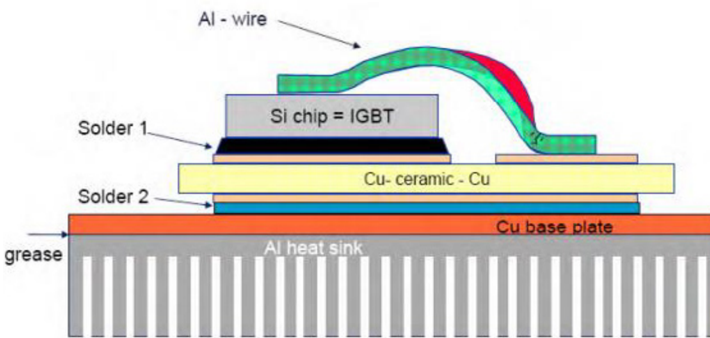


Figure 5. Cross-sectional depiction of IGBT construction[5]

The layers of the stack-up, each with differing thermal characteristics, have a great impact on the heating and cooling rates of the module, which can significantly impact its performance. Consequently, the failure mechanisms associated with IGBT modules are directly related to their packaging and particularly their cold plate technology.

Published data has demonstrated that the tubed cold plates have a thermal-resistance range of 0.11-0.45 °Cin²/W, while the vacuum-brazed cold plates would have a thermal resistance of 0.04-0.11 °Cin²/W in a typical operational environment.[10,11,12,13] Clearly the vacuum-brazed approach exhibits a significantly lower thermal resistance, which in turn will reduce the thermal impact on the IGBT devices. Translating this information into a reliability comparison is the next step in demonstrating the improved performance of the vacuum-brazed cold plate technology.

/ GETTING THE HEAT OUT

It is useful to understand the necessity of removing the heat from an IGBT module. For the purposes of this paper, we will look at a typical IGBT application to show the significant levels of power involved and how much of that power translates into heat.

$$P_{loss(cond)} = DI_{on}V_{on}$$

D is the fraction of time the switch is ON

For IGBT: $V_{on} = V_{CE(sat)}$

Conduction Loss

$$P_{loss(sw)} = \frac{1}{2} I_{on} V_{off} (t_{on} + t_{off}) f_{sw}$$

f_{sw} is the switching frequency

Switching Loss

Power losses in IGBT modules are characterized by conduction and switching losses. For example, a measure of power is converted into heat when the device is on (conducting), and some heat is also generated when the IGBT is switching from an on to an off state. The total loss in the module is the sum of these properties. Conduction losses and switching losses can be derived by the following two formulas, respectively.[7]

The following formula defines the parameters for determining the static thermal model for conduction.

$$Q = \frac{T_1 - T_2}{R_{th}} \quad \text{where} \quad R_{th} = \rho_{th} \frac{l}{A}$$

Where:

Heat Flow Rate = Q (W)
Temperature = T (°C)
Thermal Resistance = Rth (°C/W)
Thermal Resistivity = ρth (°C-m/W)

Similarly, the following formula addresses the heat loss with respect to convection.

$$Q = \frac{T_1 - T_2}{R_{th}} \quad \text{where} \quad R_{th} = \frac{1}{hA}$$

Where:

Heat Flow Rate = Q (W)

Temperature = T (°C)

Thermal Resistance = Rth (°C/W)

Heat Transfer Coefficient = h (W/°C-m^2)

Applying this information to an example results in the following analysis of a 160 kVA, six-IGBT device configuration as shown in Figure 6. The thermal losses are shown in Figure 7.

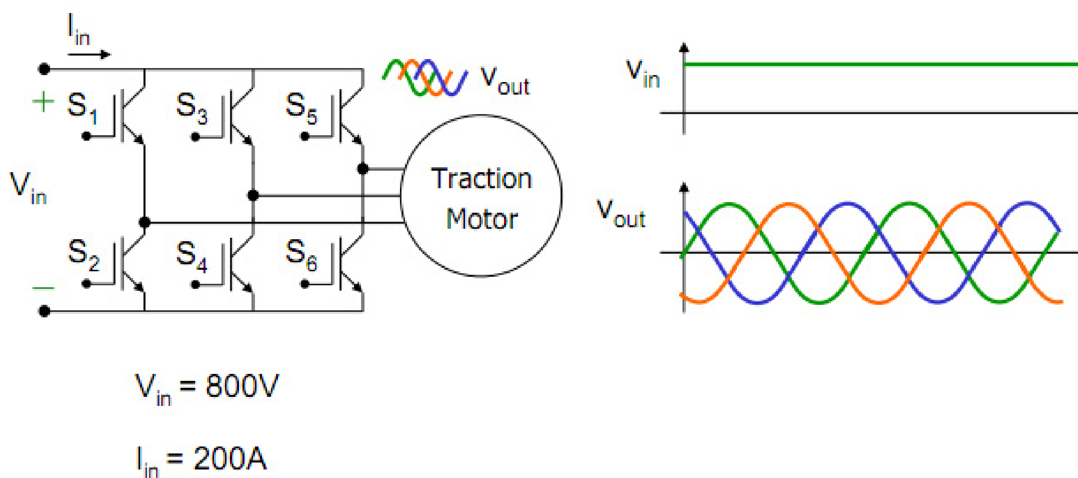
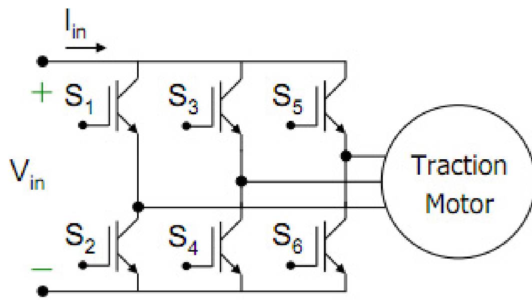


Figure 6. A six-IGBT module[7]



Circuit Parameters	Device Parameters
V_{off} = 800V	SKiM459GD12E4
I_{on} = 200A	$V_{CE(sat)}$ = 2V
D = 0.33	t_{on} = 150ns
f_{sw} = 10kHz	t_{off} = 400ns

Losses per IGBT

$$P_{loss(cond)} = DI_{on}V_{CE(sat)} \quad = 133\text{W}$$

$$P_{loss(sw)} = \frac{1}{2} I_{on} V_{off} (t_{on} + t_{off}) f_{sw} \quad = 440\text{W}$$

$$P_{loss,1} = P_{loss(cond)} + P_{loss(sw)} \quad = 573\text{W}$$

Losses in Six IGBTs

$$P_{loss,all} = 6 \times P_{loss,1} = 3440\text{W}$$

Figure 7. Loss analysis of IGBT module[7]

Applying this information to the following formula yields the thermal resistance of the module.

$$R_{th(s-a)} = \frac{T_{J(\max)} - T_A - P_{loss,1} R_{th(j-s)}}{P_{loss,all}} = 0.014°\text{C/W}$$

/ RELIABILITY ANALYSIS

As any product progresses through its life cycle and passes through its early failure phase, the failure rate becomes nearly constant, and the modules enter their normal life period. This period is characterized by a typically constant failure rate and is referred to as the normal life of a product or component. It is during this period of time that the lowest failure rate occurs.

As components begin to fatigue or wear out, failures occur at increasing rates.[8,9] Wear out in IGBT modules is usually caused by the breakdown of electrical components that are subject to physical wear and electrical and thermal stress.

This time frame in the life cycle is what this paper will focus on, with respect to identifying the improved reliability as a function of the vacuum-brazed cold plate technology.

Reducing the temperature is the key to enhanced reliability and longevity in operation. The best way to assess the impact of temperature is to utilize a modified Arrhenius equation to do so.[6]

The equation below models acceleration due to temperature and is referred to as the Arrhenius equation, which relates how increased temperature accelerates the age of a product as compared to its normal operating temperature.

$$A_f = e^{\left(\frac{Ea}{k}\left\{\frac{1}{T_u} - \frac{1}{T_t}\right\}\right)}$$

A_f = acceleration factor

EA = activation energy in electron-volts (eV)

k = Boltzmann's constant (k = 8.617 x 10-5 eV/Tk)

T_k = Kelvin

T_u = reference junction temperature, in degrees Kelvin (K = C + 273)

T_t = junction temperature during test, in degrees Kelvin

e = 2.71828 (base of the natural logarithms)

Thermal cycling has the most profound effect on product life. The acceleration factor due to thermal cycling is given by the Coffin-Manson equation below.

$$A_F = \left(\frac{\Delta T_l}{\Delta T_f}\right)^{1.9} \left(\frac{F_f}{F_l}\right)^{1/3} e^{\left\{\frac{Ea}{K}\left(\frac{1}{T_{max\,f}} - \frac{1}{T_{max\,l}}\right)\right\}}$$

ΔT_l = lab temperature difference between highest and lowest operating temperature

ΔT_f = field temperature difference between on and off state

F_f = cycle frequency in the field (cycles/24 hours). Minimum number of six.

F_l = cycle frequency in the lab. Minimum number of six because most failures occur in the first four hours.

/ LIFETIME RELIABILITY IMPACT

As previously noted, published data has shown that the thermal resistance of the tubed cold plates range from 0.11-0.45 °Cin²/W and the brazed cold plates from 0.04-0.11 °Cin²/W. Failures for IGBT devices typically fall into two categories, that of random oxide failures and also long-term wear out of the devices themselves. The Arrhenius equation will address the former while the Coffin-Manson equation the latter.

Using the thermal resistance information and the calculations indicate that the random failure mode results in a temperature rise for the tubed cold plate is 94 °C and the rise for the brazed cold plate is 33 °C when the low end of the thermal resistance ranges are utilized. This translates to an 8X improvement in life with the brazed cold plate approach with respect to random failures. If we carry this forward to the wearout analysis, the improvement in life is 27X longer than the tubed cold plate approach (using 50 °C as the coolant temperature). If the coolant is at 25 °C then the wearout improvement is 44X.

If we look close to the high end of the thermal resistance range that of 0.42 °Cin²/W for the tubed approach and 0.11 °Cin²/W for the brazed approach, the resultant temperature rise for the tubed cold plate is 248 °C while the brazed technology results in a rise of 71 °C. Clearly, the tubed approach would require a significantly larger cold plate to offset the temperature rise so that it is not beyond the maximum operating temperature of the IGBTs.

At these higher end temperatures, the brazed cold plate technology has a 12.25X improvement in life than the tubed approach. The wear out calculation is not meaningful, as the tubed approach can't provide adequate cooling when the module size is a constant.

/ THE ABILITY TO HANDLE MORE POWER (USING UP THE NEW THERMAL MARGIN)

As a result of this improvement in thermal properties, the power level of the IGBT module could be increased almost 3X before reaching the temperature rise of the tubed cold plate, again keeping the cold plate size a constant. Similarly, fewer IGBTs would be needed to achieve a certain level of power due to the improved thermal characteristics of the IGBT module.

/ SUMMARY

The brazed cold plate technology offers a major improvement in life for an IGBT module from both the perspective of random failures and IC wear out. The temperature reductions achievable provide this margin and result in a product that will outperform the tubed cold plate technology.

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