APEX MICROTECHNOLOGY

THERMAL TECHNIQUES

APPLICATION NOTE 11

POWER OPERATIONAL AMPLIFIER

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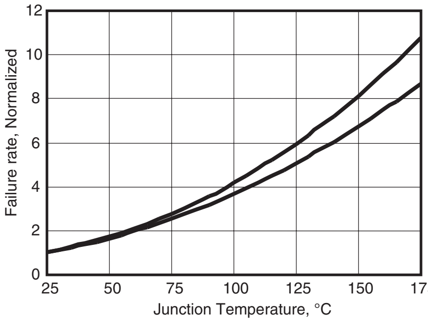
THERMAL MANAGEMENT

As power op amps shrink in size and become more powerful, the importance of a good thermal design is more critical than ever. Most importantly, reliability is a direct function of internal component temperatures and dissipated power. Furthermore, as the amplifier case rises above 25°C, derating factors do not just reduce the allowable power level. Voltage and current offsets drift, current limits change and, sometimes even dynamic performance is affected. This application note discusses thermal management starting with actual dissipation vs. allowable dissipation, the common cooling options, how to achieve maximum performance with sound mounting techniques, as well as the benefits of thermal capacity.

Thermal management techniques must be applied to remove as much heat as possible from the semiconductor junction, thereby maintaining minimum operating temperatures and maximum reliability. A further goal is to minimize the effects of the removed heat on other devices. Figure 1 shows the average of bipolar and MOSFET power transistor failure rates at elevated temperatures relative to operation at 25°C. All electronic components encounter similar increased failure rates.



This data was extracted from the base failure rate tables of MIL-HDBK-217F, Notice 2, revision of 28 February, 1995.

FIGURE 1. MTBF vs. Temperature.

MAXIMUM POWER RATING

Your new home stereo system boasts 200W. Industrial amplifier #1 claims 100W audio output. Industrial amplifier #2 claims 67W internal dissipation.

Your challenge is to determine which of these is the most powerful. With a 115V input current rating of only 0.4A, we can dismiss the stereo. Analysis of the industrial amplifiers requires we either find internal dissipation for amplifier #1 or find maximum audio output for amplifier #2. Power Design is the tool for this work once circuit details become known (load impedance, supplies and a few other amplifier specifications). Figure 2 illustrates the general concept that there could be almost a 2:1 ratio between output power and internal power for AC signals and about 3:1 for DC signals (even assuming a purely resistive load).

	Pint	Pout	Vout	Iout	Tcase	Tjunction
AC (rms)	59W	100W	20V	5A	85°C	138°C
DC (peak)	72W	200W	28.3V	7.07A	98°C	200°C

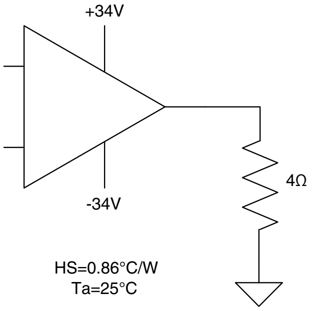


FIGURE 2. What Wattage Number Should be Applied to This Circuit?

With internal dissipation of industrial amplifier #1 being only 59W when delivering its maximum output of 100W, #2 is the power champion because at 100W output it still has 8W reserve as far as internal dissipation is concerned. The second concept to note in Figure 2 is that DC signals result in higher temperatures than AC signals. This is because with AC signals, each power transistor has a half cycle to cool while the opposite polarity transistor does the work. The bottom line on power ratings: All of the four wattage numbers above accurately describe the circuit, but the actual number can vary better than 3:1, depending on definitions.

Θ_{JC} is the thermal resistance from junction to case. With these ratings (one for DC and a more advantageous one for AC) output power capability for any type circuit can be easily determined. A great deal of effort has been put into minimizing this thermal resistance. It is the major specification affecting power handling capability. When allowing for a case temperature of 25°C and maximum junction temperature, the maximum internal dissipation rating is developed.

$$P_{MAX} = (T_{JMAX} — 25°C) / \Theta_{JC} \qquad (1)$$

This rating is consistent with rating methods of most transistor manufacturers and should not be confused with advertised output power which is highly application dependent. Before using this rating, check for factors which might degrade the rating such as actual ambient temperature (T_R), heatsink thermal resistance (Θ_{HS}) mounting, and in some cases, an isolation washer.

$$P_{MAX} = (T_{JMAX} — T_A)/(\Theta_{JC} + \Theta_{HS} + \Theta_{HSC}) \qquad (2)$$

Equation 2 gets back to the real world where a real heatsink is used, the interface between amplifier and heatsink is not prefect, ambient temperature may not be ideal, and reliability requirements may not allow junction temperatures up to data sheet maximums. Read the heatsink data sheet carefully. There are multiple thermal ratings for heatsinks because they vary with power level, sometimes with orientation and always with flow rate (air or liquid). Thermal interface rating between cases and heatsinks are built into Power Design and can be found on the Apex Accessories Information data sheet.

WASHERS AND WASHERS

The most common is the thermal washer mounted between the amplifier and the heatsink. It's prime objective is to enhance thermal conduction compared to a bare joint. This is the washer which MUST NOT BE COMPRESSIBLE. Using a compressible washer on a metal can type package VOIDS THE WARRANTY. The most common of these washers is an aluminum substrate with a thermal coating on each side. Thermal performance of these washers is at least as good as a joint with properly applied thermal grease. Advantages over grease include removal of operator variables on performance (too thick, too thin, missing coverage), and not being messy. When electrical isolation is required, similar washers with a Kapton substrate provide isolation at the expense of additional thermal resistance on the order of 2x. These washers are not reusable. When replacing an amplifier, the old coating residue should be removed from the heatsink to avoid buildup and possible amplifier damage.

The second washer type used in mounting power devices is the compression washer used under the head or nut of the mounting screw. These may be (in order of effectiveness) Belleville washers, split lock washers or tooth lock washers. One of these washers should be considered when the equipment would be regularly subjected to temperatures where humans would require protective clothing.

SYSTEM LAYOUT

Thermal management starts with determination of actual dissipation and should result in a layout of an optimized thermal system to convey the heat to the ambient environment. In systems using natural convection, heat sources should be separated as widely as possible. In contrast, systems using high velocity air or liquid cooling perform optimally when localizing these devices. Understanding convection and radiation may help avoid layout related problems. Since convected heat rises, it is best to place the heat sources near the top of the enclosure and avoid having temperature sensitive circuits above or near the heat sources. The hot air should flow in its natural vertical direction using vertical board and fin orientation. Heatsinks should be oriented so air can pass freely over all the fins.

MOUNTING THE AMPLIFIER

The design of the amplifier mounting must:

1. Provide the required thermal path from amplifier to ambient.
2. Maintain intimate contact between amplifier and heatsink surfaces.
3. Maintain amplifier lead positions with respect to a PCB, socket or wire.

Occasionally, an Apex amplifier will not require a heatsink. If this appears to be the case, double check the thermal calculations, and then proceed to use cage jacks, socket or soldering leads directly on the pins to finish the design.

Figure 3 shows common mounting layouts for metal can type packages. While the PC board example shows the use of cage jacks, this is drawing would also apply when soldering the pins directly to the PCB. Note that in this example, either the heatsink is supporting the PCB or the PCB is supporting the heatsink. In this latter case, if the heatsink is more than four square inches (in the same plane as the PCB), consider the configuration in Figure 4 where heatsink mass places less stress on the PCB in the immediate area of the amplifier when subjected to shock or vibration.

Figure 5 shows the preferred mounting method for the DIP10 products. Number 4 hardware is first used to mate the amplifier to the flat surface of the heatsink. Do not forget the thin layer of thermal grease spread evenly over this area. The heatsink/amplifier assembly can now be mounted to the PCB with (usually) #6 hardware. A spacer length of 0.25" plus a washer at least 0.02" (almost all washers are thicker than this) will insure amplifier components do not touch the PCB.

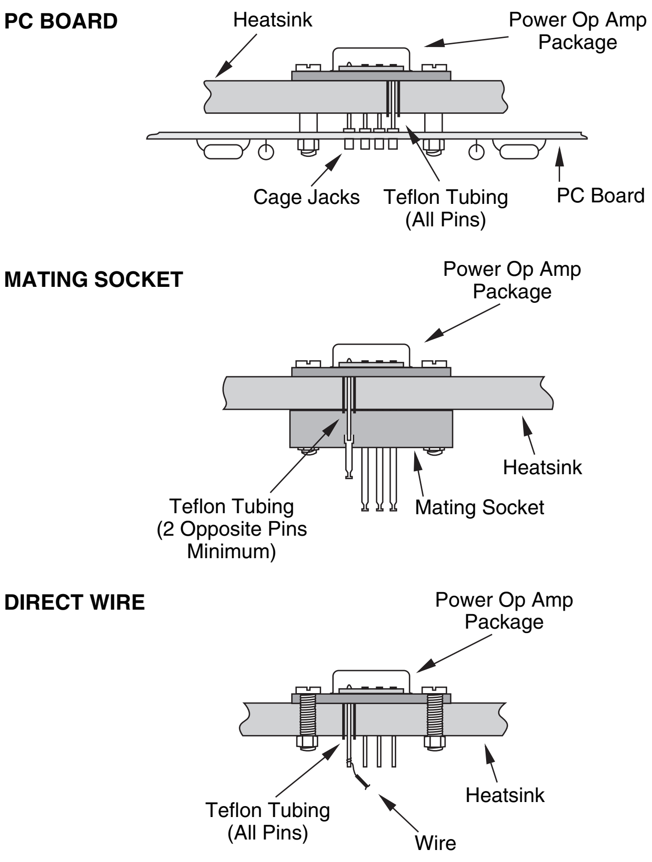


FIGURE 3. Mounting Techniques (Cross Section Views)

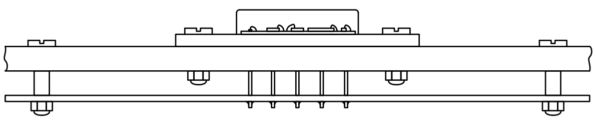


FIGURE 4. Large Heatsinks Need More Support.

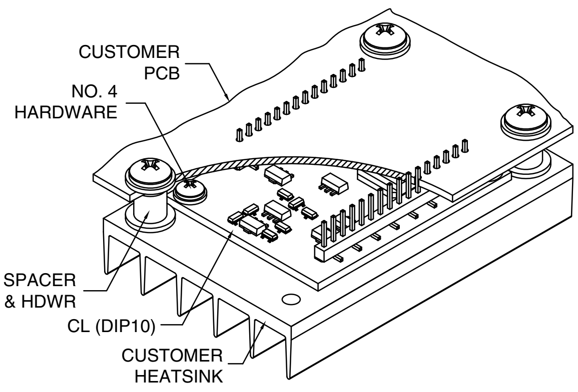


FIGURE 5. Preferred mounting for CL (DIP10) packages.

When DIP10 packages are mated with very small heatsinks (about the same size as the amplifier and fins of 1" or less, the method in Figure 6 may be used.

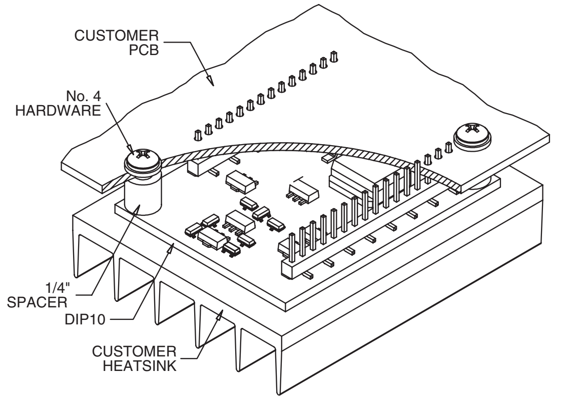


FIGURE 6. Mounting CL (DIP10) packages to very small heatsinks.

Generally, The BC series amplifiers are used in systems requiring large power delivery. As discussed in the previous section, large heatsinks may often necessary to keep the amplifier cool while delivering significant power. The mechanical assembly of the printed circuit board, BC amplifier, and heatsink deserves some discussion.

The heatsink should be the main structural element that supports the amplifier and the PCB. The BC pins and most circuit card material are not strong enough to support a heatsink of any significant size. Failures are likely to arise by doing so - circuit traces may crack, pins may bend and lose contact with sockets, and solder joints may weaken and lose effectiveness. Figure 7 shows one acceptable arrangement where the PCB and heatsink are supported by standoffs to some structural element. The BC amplifier is attached to the heatsink with 2 screws. Cage jacks or solder connections may be used for the electrical connection to the pins. Half-inch standoffs provide stable support of the heatsink above the PCB.

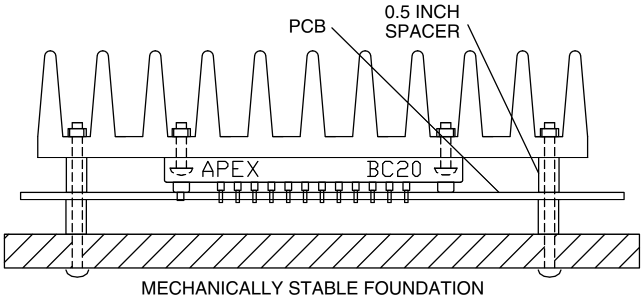


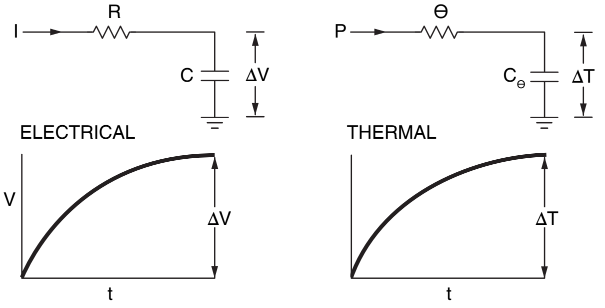
FIGURE 7. Heatsink is not mechanically supported by the PCB or the BC Amplifier.

Commercial heatsinks usually specify a surface finish of 63 micro inches, flatness of 4mils/inch in the direction of extrusion and 6mils/inch perpendicular to the direction of extrusion. This is marginal but generally considered acceptable for packages up to about 1 square inch. Apex procures all heatsinks with flatness specified at 2mils/inch. This forces a machining operation on the mounting surface, resulting in less than 1mil/inch actual flatness. We recommend this approach when specifying a heatsink, whether it is a normally an off the shelf model, a custom designed heatsink or uses structural members of equipment as a heatsink. Do not forget to require deburring of all holes. When amplifier pins go through the heatsink, specify a hole for each pin of the amplifier. A single hole or cutout for all the pins will thermally isolate the amplifier from the heatsink.

Aging of this thermal interface has proven to be no problem, as long as the mechanical assembly is not disturbed. If disassembled, clean off grease or washer coating material from both amplifier and the heatsink, reapply and reassemble.

THERMAL CAPACITY

The power levels that can be achieved in the pulse mode of operation are elevated far above those of steady state operation. This is due to the thermal capacity of the heatsink. As heat is first applied, the rate at which the case temperature increases can be compared to its electrical equivalent, the voltage build up on a capacitor of a R-C network. Figure 8 displays this analogy.



$dQ = id_t = C2V$
$I \bullet R = V$

$dq = C_\Theta d(\Delta T) = Pd_t$
$P \bullet \Theta = \Delta T$

FIGURE 8. Electrical and Thermal Models.

Thermal capacity is the amount of heat needed to raise the temperature of the given object 1°C. The generally published parameter for materials is specific heat given in calories/gram, so multiplying by grams yields calories. Multiplying this by 4.186 will convert to watt-seconds, again for a 1°C change. The thermal time constant (Tau) is the product of the thermal capacity and the thermal resistance. This time constant defines the rate at which the material reaches thermal equilibrium. The time required to achieve 95% of the final temperature is three time constants.

To illustrate the principle, aluminum has a density of 2.7gr/cm³ and a specific heat of .22calorie/gram/°C (times 4.186 = 0.921watt-seconds/gram/°C). The Apex HS05 heatsink weighs 18.3 ounces (518.8grams) and has a thermal resistance (free air) of 0.85°C/W. Thermal capacity of the heatsink is then 0.0921 • 515.8 or 478watt-seconds/°C. Finally, the time constant of the HS05 with a free air mounting will be 478 • 0.85, or 406 seconds.

Adding a fan to the application reduces thermal resistance, but thermal capacity remains constant, meaning the time constant will be proportional the thermal resistance. Graphs for the HS05 indicate 500 feet/minute linear air flow produces a thermal resistance of 0.3°C. The new time constant is 478 • 0.3, or 143 seconds.

If power is applied as a single pulse, the case temperature follows the curve in Figure 4. The Δ T in °C for both heating and cooling follow these equations :

$$\Delta T_{HEAT} = W^*\Theta_{HS}\,(1-e^{-t/tau}) \qquad (3)$$

$$\Delta T_{COOL} = \Delta T_{HEAT}(e^{-t/tau}) \qquad (4)$$

The Figure 9 (next page) curve indicates that thermal capacity plays a major role when the duty cycle is extremely low.

Figure 10 (next page) shows the initial response to application of repetitive pulses. The pulse train is repetitive when the duty cycle does not allow the circuit to return to its initial temperature between pulses. The following procedure will predict operating temperatures after the heatsink has reached equilibrium. Peak power is multiplied by duty cycle to arrive at average power. The average temperature of the case will be $T_A + (P_{AVERAGE} \bullet \Theta_{HS})$. To determine the peak power, the pulse duration and

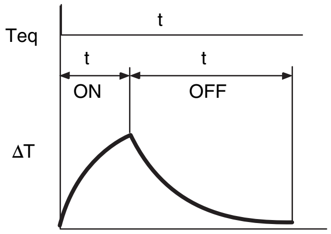


FIGURE 9. Single Pulse Response.

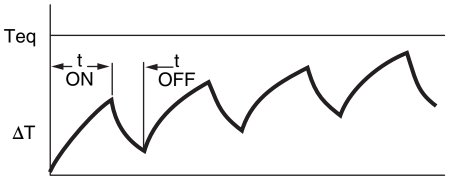


FIGURE 10. Repetitive Pulse Response.

time constant are substituted into equation 3 above. Then 1/2 Δ heating is added to average temperature to yield the maximum case temperature. This case temperature should be used in conjunction with the SOA curves to determine the maximum power available from the device.

CONCLUSION

Thermal management optimizes space, cost and size for your power levels and temperature range. When properly applied, it will get the heat out and keep your circuits cool; thereby, maintaining the highest possible reliability and performance.

For easy calculations of this information see the spreadsheet EE Friend at www.apexmicrotech.com.