THERMAL CONSIDERATIONS FOR DC/DC CONVERTERS

All power converters—AC/DC, DC/DC and DC/AC—consume power that is dissipated internally as heat. This heat must be removed from the power-dissipating component in the converter in order to keep its functioning temperature low and other critical components at relatively low constant temperatures. The Arrhenius equation for reliability (see References) indicates that the failure rate of a power device will increase by 3 to 5 times for a 25°C increase in temperature. The ever-increasing demand for higher power density converters delivered at low cost forced manufacturers to push the limits in converter efficiency and minimal size. High efficiency will allow higher power density for a given volume package, but will also force the high-density converter to operate at a higher junction temperature.

Function integration and high-switching frequencies and efficiencies make it possible to minimize the volume of converters to a point where feature converters could be a single silicon die with all control and power components. The generated heat is removed from power-dissipating components, such as power transistors, rectifiers and magnetics, by different heat conduction techniques. Heat is conducted from the junction of the device to the surface of the case in a converter through different materials such as the PCB, potting material and the case itself. Each of these materials present a resistance to the heat as it passes through them. Minimizing the so-called “thermal resistance” from the junction to the surface increases the rate of heat flow. DC/DC converter manufacturers use different packaging techniques to minimize thermal resistance while reducing production cost.

The power dissipated in a converter can be calculated from its efficiency:

$$\eta \text{ in } \% = \frac{P_{OUT}}{P_{IN}}(100), \quad \textit{or} \quad P_{IN} = \frac{P_{OUT}}{\eta}$$

$$P_{DISSIPATED} = P_{IN} - P_{OUT} = \frac{P_{OUT}}{\eta} - P_{OUT} = \frac{P_{OUT}(1-\eta)}{\eta}$$

NOTE: The efficiency varies with input line, output load and operating temperature.

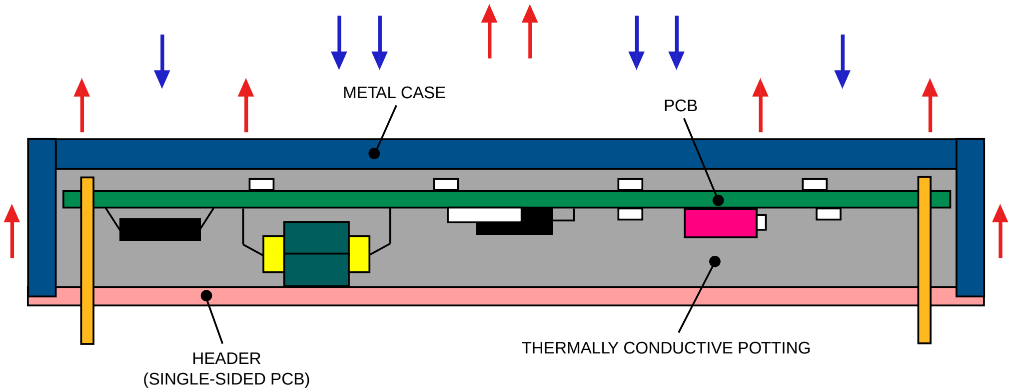


FIGURE 1

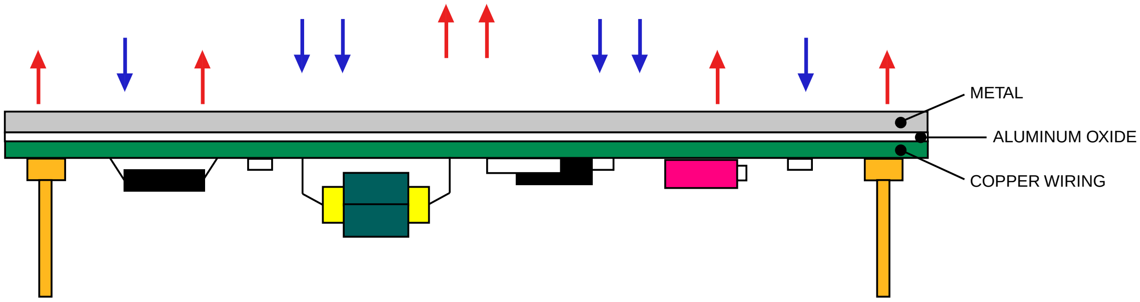
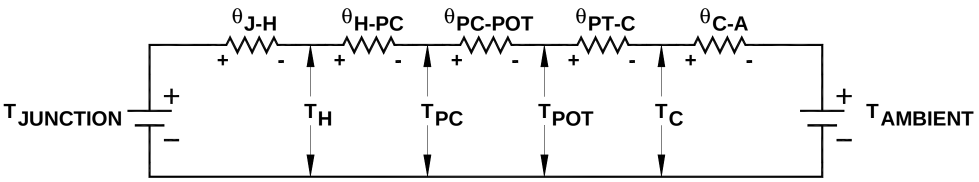


FIGURE 2

In Figure 1, the converter is assembled on a FR-4 PCB and is potted with a thermally conductive material in a metallic case. Figure 2 shows a converter with the same footprint as that in Figure 1. Its metallic base—usually aluminum or stainless steel—is isolated with a 1-mil thermal-conductive isolator; copper is then deposited for the components installation. Single- or dual-sided PC wiring is available. The thermal resistance is minimized and the bare base plate is used as a heat sink. The open-frame construction of the converter has two notable advantages over the package in Figure 1. The first is low cost, which is specifically designed for automated production; and the second is the minimum possible thermal resistance from function to the case. It also has two major disadvantages: the first is its high EMI/RFI radiation, and the second is that if offers 50% less surface area for heat conduction.

In Figure 3, a simplified one-dimensional equivalent heat flow circuit is presented. Voltage sources are replaced by temperature sources and the DC current is the heat flow. It should be pointed out that the heat is not a one-dimensional vector. Even though current follows the least resistive path, heat is conducted in all directions. For a three-dimensional heat flow study, the Fourier law should be used.

For marketing reasons, some manufacturers will not publish the thermal resistance, $\theta_{C\text{-}A}$, of a given converter. For low-power density converters, the value of the thermal resistance is not necessary if the converter operates without derating over its temperature range. For high power density converters, manufacturers specify cooling techniques or derate the converters above a given temperature point. (See Figure 4.) To protect converters in case the cooling in a system fails, designers incorporate thermal protection circuitry turning the converter off when its temperature exceeds some preset temperature value.



θ = Thermal resistance through a medium

T_J = Junction temperature

$\theta_{J\text{-}H}$ = Thermal resistance of the junction to device heat sink

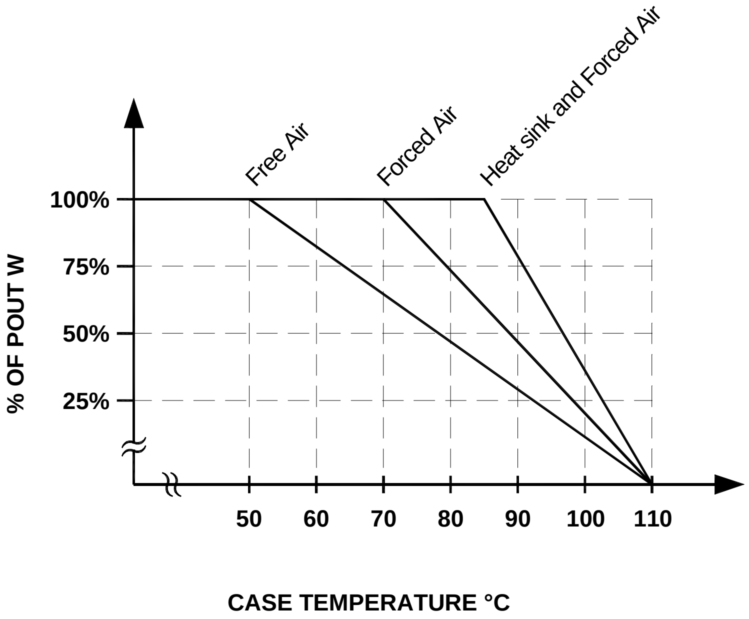
$\theta_{H\text{-}PC}$ = θ of printed circuit board

θ_{PT} = θ of potting material

$\theta_{PT\text{-}C}$ = θ of potting to case

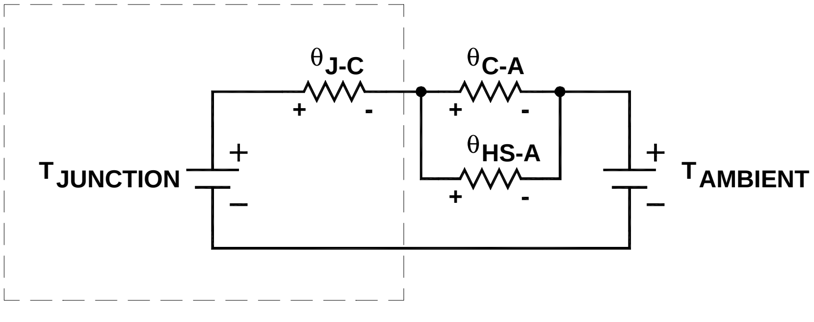
$\theta_{C\text{-}A}$ = θ of case of the converter to ambient

FIGURE 3



Derating of a converter under different cooling conditions. $T_j \geq 110+(\theta_{j\text{-}C})P_{DISSIPATED}$

FIGURE 4



Equivalent circuit for reducing the thermal resistance, $\theta_{C\text{-}A}$, of the converter through installation of a heat sink. Note the thermal resistance, $\theta_{C\text{-}A}$, of the converter and of the heat sink, $\theta_{HS\text{-}A}$, are in parallel and the new case thermal resistance is the parallel combination of the original case to ambient thermal resistance of the converter and the $\theta_{HS\text{-}A}$ of the heat sink.

FIGURE 5

Referring to Figure 3, the junction to case thermal resistance is relatively constant; the only variable thermal resistance is that from the case to ambient. This resistance can be reduced by using forced air convection or parallel connect some other thermal resistance to reduce θ_{C-A} of the converter. In Figure 5 an aluminum heat sink with a thermal resistance given in °C/W/in is installed on the case of the converter. The new value of the case to ambient resistance, θ_{C-A}, under ideal interface conditions will be the parallel combination of the converter θ_{C-A} and that of the heat sink.

This equation indicates that Q is proportional to the surface area of the conducting surfaces, therefore by adding a heat sink on the case of the converter, its surface area and the rate of heat transfer increases. The thermal resistance from the case of the converter to heat sink, θ_{C-H}, is overlooked when a heat sink is improperly installed.

Experiments have shown that only 2% to 5% of the total area of two flat surfaces conduct heat. Forcing a heat sink onto the converter may increase the conducting area but it may also reduce it by bending or deforming either or both surfaces. To increase the conducting area, heat sink manufacturers offer thermal grease, thermal epoxy and microfiber impregnated with thermally conductive material such as alumina oxide, alumina nitride or Grafoil.

The selected material must have high thermal conductivity and must be flexible to fill all the voids between the two conducting surfaces. If rigid thermal epoxy is used to connect the two surfaces, the coefficient of thermal expansion (CTE) of the epoxy and the two conductive surfaces should be matched in order to avoid the formation of cracks or heat sink separation if the whole assembly is subjected to few thermal cycles.

The rate of heat transfer, Q, is given as:

$$\boxed{\mathbf{Q = H \cdot A \cdot \Delta T}}$$

where Q = Rate of heat transfer in W
H = Coefficient of heat transfer in $W/m^2 \cdot K$
A = Surface area of heat transfer in m^2
ΔT = Temperature difference between two conducting surfaces

HEAT TRANSFER BY RADIATION

In free or forced air-cooled systems, heat transfer by radiation is not a great contributor in cooling a DC/DC converter or any other power device. Such applications include automotive and chemical processing where air, dust and water may come in contact with the electronic circuits. These electronic circuits must be protected from the elements.

When potting is not used for shielding and cooling, and the system is operating in a still air environment, heat transfer by radiation is the only way heat is transferred from the power devices.

From Boltzmann’s equation, the total heat transfer is given as:

$$\boxed{\mathbf{Q_{RTotal} = k \cdot e(T_0^4 - T_A^4)}}$$

where k = Boltzmann’s Constant
e = emissivity of a surface between 1.0 and 0.8
T_0 = radiating surface temperature
T_A = ambient

The radiated heat transfer from a surface to ambient is given as:

$$\boxed{\mathbf{Q_{RTotal} = e \cdot hr \cdot A_S(T_S - T_A)}}$$

where hr ≅ 0.0037W/in² °C (hr is the coefficient of radiated heat transfer)
A_S = surface area in in^2
T_S = surface temperature in °C
T_A = ambient temperature in °C

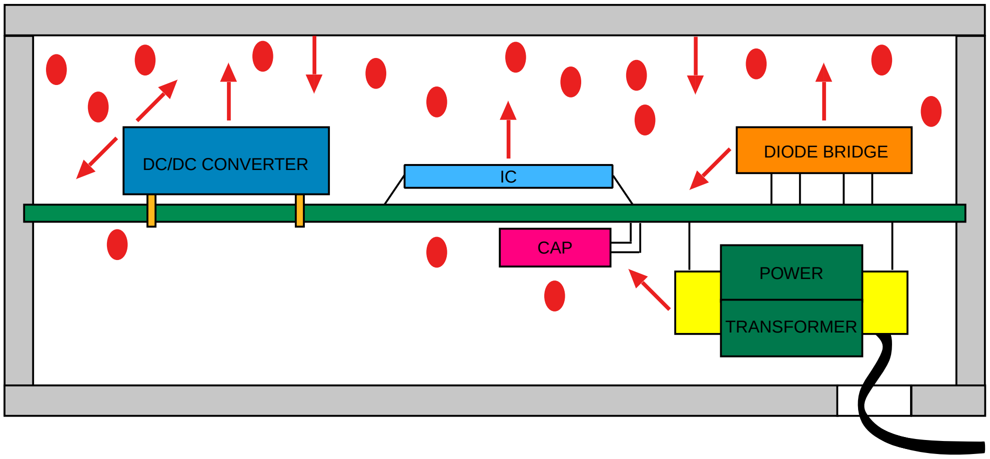


FIGURE 6A. Example of thermal runaway in an enclosed system
DO NOT DESIGN SUCH AN ENCLOSURE!

The various components powered by a DC/DC converter inside an enclosure also radiate heat (see Figure 6A). The heat radiated from hot components will be transferred to surrounding components. The net effect is that the enclosure becomes an oven and if the hot air is inside the enclosure, thermal runaway is imminent.

One must realize that the reason the enclosed system may experience thermal runaway is *NOT* only due to the DC/DC converter but the total power dissipated from all the components inside the enclosure, which of course, includes the DC/DC converter. A common misconception is that by using a higher efficiency DC/DC converter, the problem will be solved. The best solution to solving and preventing the problem is through reduction in the total dissipated power inside the enclosure or through the use of thermal management techniques. Design a box like the one in Figure 6B if the system must be in a sealed enclosure.

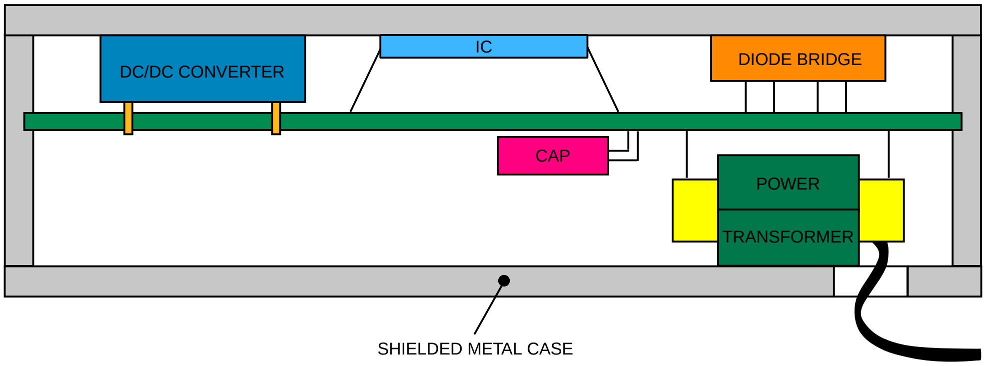


FIGURE 6B. Better design for an enclosed system

Examples

CASE 1: FREE AIR

A 15W DC/DC converter must operate continuously at 70°C in a free-air convection environment. Its properites include 80% efficiency and thermal resistance, $\theta_{C\text{-}A}$, of $7°C/W_{DISSIPATED}$.

Its internal dissipated power is: $P_{DISSIPATED} = \frac{P_{OUT}*(1-\eta)}{\eta} = \frac{15*(1-0.8)}{0.8} = \frac{3}{0.8} = 3.75W$

Its case temperature is given as: $T_{CASE} = 70°C + 3.75W(7°C/W) = 70°C + 26.25 = 96.25°C$

If the maximum operating case temperature of this converter is 100°C, the converter will survive but its MTBF will be 50% to 80% of the value given for 25°C.

CASE 2: FORCED AIR

In a forced-air environment the thermal resistance, $\theta_{C\text{-}A}$, can be 2°C/W or lower and the case temperature will be:

$T_{CASE} = 70+(3.75)(2) = 77.5°C$.

CASE 3: FREE AIR & HEAT SINK

A heat sink is placed on the case of the converter with an $\theta_{H\text{-}A} = 6°C/W$ and the interface material has a thermal resistance of $\theta_I = 2°C/W$. Find the total thermal resistance and the case temperature:

$$\theta_{TOTAL} = \frac{7(2+6)}{7+(2+6)} = \frac{56}{15} = 3.73 \qquad T_{CASE} = 70+(3.75)(3.73) \cong 84°C$$

NOTE: The thermal resistance of the case is in parallel with the series combination of the thermal resistance of the interface and the heat sink.

Do's & Don'ts

DO'S

1. Operate the converter at maximum efficiency (40% to 80% load).
2. Remove obstacles to allow free- or forced-air convection.
3. Minimize thermal resistance from case to ambient.
4. Use thermally conductive potting for industrial or automotive environments if the air circulation is restricted.

DON'TS

1. Operate converter with less than 10% full load.
2. Restrict airflow around power devices.
3. Design high-density PCB if cooling is not available.
4. Use shield enclosures for your system such as plastics or metal.

Heat Sink Manufacturers

AAVID Thermal Technologies, Inc. (www.aavid.com)
AAVID Thermalloy (www.aavidthermalloy.com)
ChipCoolers, Inc. (www.chipcoolers.com)
Thermagon, Inc. (www.thermagon.com)
Wakefield Engineering, Inc. (www.wakefield.com)

References

"Thermal Computations for Electronic Equipment", Gordon N. Ellison, Van Nostrand Reinhold.
"Electronic Materials Handbook (Volume 1 Packaging)", ASM International.
"Modern MOS Technology", ONG, McGraw-Hill.

Metric Conversion Guide

TEMPERATURE

TO CONVERT FROM	TO	MULTIPLY BY
°F	°C	5/9·(°F-32)
°R	°K	5/9
°F	°K	5/9·(°F+459)
°C	°K	°C+273

THERMAL CONDUCTIVITY

TO CONVERT FROM	TO	MULTIPLY BY
Btu·in/s·ft^2·°F	W/m·°K	519.2
Btu/ft·h·°F	W/m·°K	1.73
Btu·in/h·ft^2·°F	W/m·°K	0.1442
cal/cm·s·°C	W/m·°K	418.4

Tables

THERMAL CONDUCTIVITY OF MATERIALS AT ROOM TEMPERATURE

MATERIAL	W/m·°K
Aluminum (Pure)	216
Alumina	29
Copper	380
Epoxy Fiberglass (PCB)	0.26
Gold	296
Silver	410
Iron	80

AVERAGE THERMAL CONDUCTIVITY BETWEEN TWO CONDUCTIVE SURFACES (Without interface fillers, no force applied)

MATERIAL	W/m·°K
Metal to metal	220
Ceramic to metal	45
Plastic to metal	2.5
Ceramic to ceramic	25
Any surface to air	0.04

HEAT TRANSFER COEFFICIENT

CONVECTION	W/m^2·°K
Free air	5
Forced air	50