POWER PAGE

PP45 *Revised February 1997*

THERMAL MANAGEMENT
DC-to-DC Converters, PD150 Series

This application note discusses thermal management of Powercube PD150 series DC-to-DC converters. As with any power electronic circuitry, a small portion of input power will be dissipated as heat. The amount of heat dissipated is dependent on the output load and converter efficiency. With efficiencies of 80% to 90%, the PD150 series converters minimize heat loss, easing the thermal design requirements.

Prudent thermal management will result in long term reliable operation and allow maximum power utilization in a minimum amount of space.

Reasons for thermal management include:

- Maintain case temperature below maximum
- Improve Reliabilty (MTBF)
- Maximize Efficiency
- Utilize maximum available output power

Power Dissipation & Efficiency

The primary goal in the thermal design is to predict and control the converter's baseplate temperature. Operating temperature, as measured at the center of the baseplate, must be less than +100°C for normal operation. The converter's power dissipation (at maximum operating output load) must be determined.

To calculate how much power is generated in the converter, efficiency and output power must be known. Efficiency is the ratio between the total power output and the total power input. Note that this stated efficiency is for a 75% load. Use the normalization curve of figure 1 to determine the efficiency at other loads.

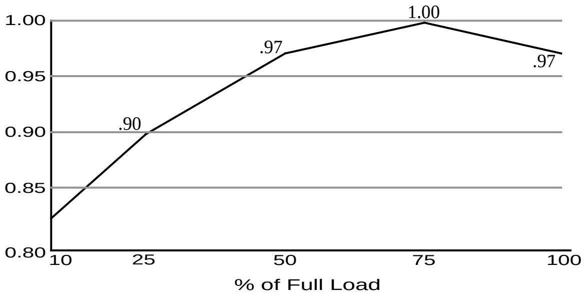


Figure 1. Normalized Efficiency vs. Load

Example: Determine the efficiency of a PD150-048-15 module operating at 75 watts output power.

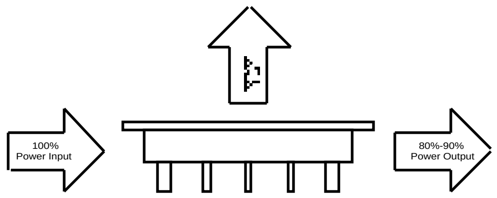
From the PD150 datasheet – page 4, the efficiency of this module at 75% of full load is 84% minimum. Now we must calculate the efficiency at the reduced output power. The full power output of this module is 125 watts. With the module operating in this application at 75 watts, the converter is working at 75/125=60% of full load. From the normalized efficiency curve of figure 1, the worst case efficiency will be 84% x 0.98 = 82.3%.

The *power dissipation* is a function of *output power* and converter *efficiency*, as shown in Figure A.

Calculation of power dissipation is shown in the example below.

Example: Determine the power dissipated in a PD150-048-15 module operating at 75 watts output power.

P_{OUT} = 75 watts
η = 82.3% (0.823)
P_{DISS} = 16.1 watts



$$\text{Power Dissipation} = P_{IN} - P_{OUT} = P_{OUT}\left(\frac{1}{\eta} - 1\right)$$

$$\text{Efficiency} = \eta = \frac{P_{OUT}}{P_{IN}}$$

Figure A. Power Dissipation

Figure 2 shows converter power dissipation plotted as a function of output power, at nominal efficiencies of 80%, 85% and 90%.

Converter efficiency will typically vary from 80% to 90% depending on the specific input and output voltage option selected. Generally, higher output voltage models result in higher efficiencies.

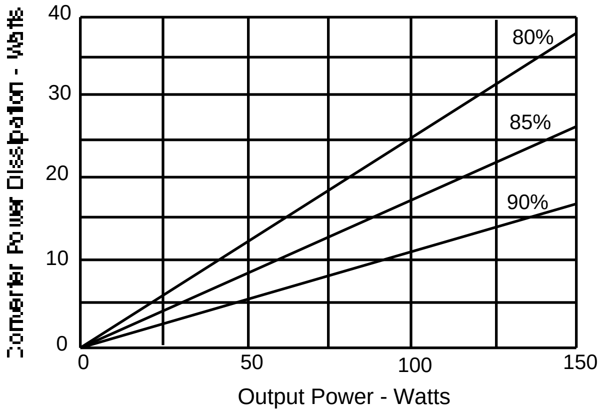


Figure 2. Power Dissipation vs Output Power

As shown in Figure 2, a change in efficiency from 80% to 90% cuts the dissipated power (heat) in half, reducing the thermal cooling requirements in half as well. Conversely, the converter can deliver twice the output power with the same cooling configuration.

Output Power vs Temperature

To utilize the maximum output power as specified in the data sheet (PD150 – page 4), the converter baseplate temperature (T_B) must be kept below the specified maximum of 100°C. For a given cooling configuration, the available output power will be *derated* with increasing ambient temperature (derate to zero at 100°C).

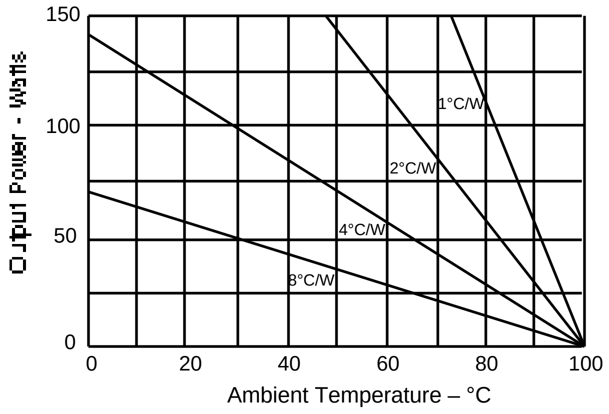


Figure 3. Output Power Vs Temperature

Figure 3 shows maximum power output with a nominal converter efficiency of 85% as a function of ambient temperature, for four different thermal resistance paths (1, 2, 4 & 8°C/W).

Figure 4 shows maximum converter power dissipation as a function of ambient temperature, for four different thermal resistance paths (1, 2, 4 & 8°C/W). The power dissipation (P_D) can be calculated as shown in Figure A, and plots vs converter efficiencies of 80%, 85% and 90% are shown in Figure 2.

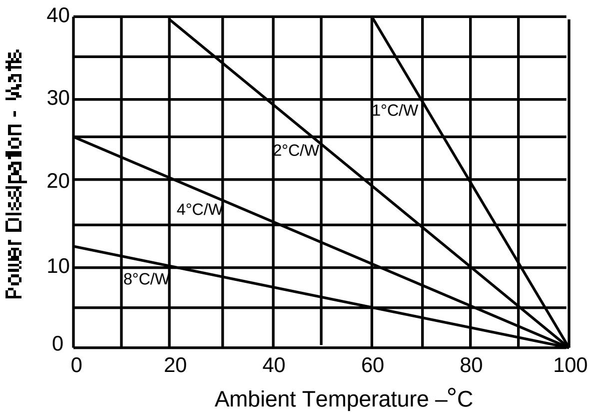


Figure 4. Power Dissipation vs Temperature

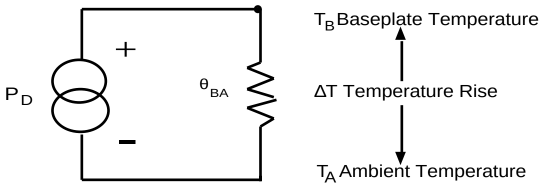
Since Figures 3 and 4 essentially show power for a constant specified maximum baseplate temperature of 100°C, it is imperative to operate below the plotted levels, keeping the temperature below 100°C. Reducing the baseplate temperature will increase the long term reliability while providing added design margin.

The plot for thermal resistance of 8°C/W indicates typical converter operation using Natural Convection (Free Air) with no additional heatsink. A thermal resistance of 1°C/W represents the use of additional heat sinking with a "best case" thermal conductivity.

Thermal Circuit Model

An equivalent thermal circuit model for the converter is shown in Figure 5. The relationship between Temperature Rise (ΔT), Thermal Resistance (θ) and Power Dissipation (P_D) may be stated as follows:

$$\Delta T = P_D \times \theta$$



$\Delta T = P_D \times \theta_{BA}$
ΔT = Temperature Rise "T_B - T_A" (°C)
P_D = Converter Power Dissipation (Watts)
θ_{BA} = Thermal Resistance - Baseplate to Ambient (°C/W)

Figure 5. Thermal Circuit Model

The basic thermal model is analogous to Ohm's Law as shown in Table 1. This basic model is used to determine the converter's baseplate temperature rise (above ambient) as a function of converter power dissipation and the thermal resistance path from case to ambient.

Thermal Model	**Electrical Equvalent**
Temperature Rise (ΔT)	Voltage (V)
Power Dissipation (P_D)	Current (I)
Thermal Resistance (θ)	Electrical Resistance (R)

Table 1 Thermal & Electrical Relationship

Thermal Resistance

The *baseplate to ambient* thermal resistance θ_{BA} can vary greatly depending on the heat transfer method and configuration. As indicated in the PD150 data sheet, θ_{BA} can vary from 1.5 to 8.3 °C/W. This number reflects a typical range of cooling configurations from *Forced* Air Convection to *Natural* (Free) Air Convection (without heatsink).

Adding a conductive member (such as a heat sink) to the thermal path produces an added *interface* thermal resistance (θ_{BS}) to the total path. The PD150 data sheet specifies a typical value of 0.4 °C/W for θ_{BS} , which could be more or less depending on such factors as interface surface flatness, the use of thermal pads (such as Grafoil®) and torquing of baseplate fasteners.

Thermal resistance (θ_{BA}) is the sum of all thermal resistances in the thermal path from *baseplate to ambient*. When a heatsink is attached to the converter baseplate, two distinct thermal resistance paths must be added:

$$\theta_{BA} = \theta_{BS} + \theta_{SA}$$

θ_{BA} = Thermal Resistance - Baseplate to Ambient (°C/W)

θ_{BS} = Thermal Resistance - Baseplate to Heatsink (°C/W)

θ_{SA} = Thermal Resistance - Heatsink to Ambient (°C/W)

Any additional thermal resistance paths must be added to the total thermal resistance calculation. An application which conducts heat from the converter baseplate to a remote dissipating surface through a thermally conductive member would add two additional paths to the total:

$$\theta_{BA} = \theta_{BM} + \theta_{M} + \theta_{MS} + \theta_{SA}$$

θ_{BA} = Thermal Resistance - Baseplate to Ambient (°C/W)

θ_{BM} = Thermal Resistance - Baseplate to Member (°C/W)

θ_{M} = Thermal Resistance - Member (°C/W)

θ_{MS} = Thermal Resistance - Member to Heatsink (°C/W)

θ_{SA} = Thermal Resistance - Heatsink to Ambient (°C/W)

Methods of Heat Transfer

Heat (due to power dissipation) is removed from the metal baseplate of the converter to its surrounding environment. There are 3 basic thermal mechanisms to transfer heat:

- Conduction
- Convection (Natural & Forced)
- Radiation

In most applications heat is removed by a combination of all mechanisms. The Thermal Resistance in the above model (θ_{BA}) is a measure of the ability of all combined thermal mechanisms to transfer heat away from the converter's baseplate. A higher Thermal Conductivity will result in a lower Thermal Resistance, hence a lower baseplate temperature rise.

The selection of heat transfer method(s) used to transfer heat from the converter will depend on factors such as:

- Converter Power Dissipation (P_D @ Max. Load)
- Max. Operating Ambient Temperature (T_A).
- Max. Operating Baseplate Temperature (T_B).
- Space available - physical constraints
- Surrounding Air Movement
- Proximity of other heat generating elements
- Cost

At low power levels while operating at low ambient temperatures, Natural Convection (free air) without an additional heat sink would be adequate. At moderately higher temperatures and/or power levels, additional baseplate heat sinking would be required, utilizing Forced Air Convection or if space permits, Natural Convection could be used. Heat can also be transferred via Conduction to a chassis, bulkhead or other thermal member if desired.

Conduction

Heat is transferred through a solid medium by *conduction* and is the most fundamental of all thermal mechanisms. Most of the heat dissipated within the converter is coupled via conduction to its integral metal baseplate. The baseplate is electrically isolated from, but thermally closely coupled to, all internal heat dissipating components. The baseplate also acts as a heat spreader to help reduce the thermal resistance to the next thermal interface.

The "Conduction" thermal mechanism is primarily a means to conduct heat from one point to another. Ultimately, the heat will be transferred via Convection or Radiation to the ambient environment. Most thermal dissipators (heat sinks) rely on Conduction to spread the heat over a larger area to maximize Convection and Radiation thermal conductivity.

The thermal resistance of a uniform conducting medium is defined as:

$$\theta = \frac{L}{KA}$$

θ = Thermal Resistance (°C/watt)
L = Length (inch) or (mm)
A = Cross Sectional Area (inch^2) or (mm^2)
K = Material Thermal Conductivity

$$\left(\frac{\text{watt}}{\text{inch}\bullet{}^\circ\text{C}}\right) \quad \text{or} \quad \left(\frac{\text{watt}}{\text{mm}\bullet{}^\circ\text{C}}\right)$$

The formula above can be used to estimate the thermal resistance of a conductive member between the converter baseplate and a remote dissipating surface.

To optimize the transfer of heat by conduction, the following rules apply:

- Use materials with high thermal conductivity (e.g. copper or aluminum).
- Utilize an optimum cross sectional area (Avoid thin areas).
- Keep the thermal path as short as possible.
- Maintain flat contact with the converter base plate to minimize thermal resistance. (Grafoil®, which can be purchased from Thermalloy, or equivalent conductive pad, or thermal grease will help). When properly mounted, a thermal resistance of 0.4°C/watt between the baseplate and the mounting surface is expected.

Baseplate Interface Thermal Path: An *interface* thermal resistance path is present at the junction of each conductive media (e.g., between baseplate and heatsink). It is important for the media to maintain close intimate contact with each other to minimize thermal resistance. The thermal resistance of *still air* is very high ... more than 5000 times that of aluminum. An air gap of 10 mils across an area of (2" x 2") would yield a thermal resistance of 3.5 °C/W, significantly reducing the effectiveness of the mating heatsink or thermal member.

When attaching a heatsink or thermal conducting member to the converter, an attempt should be made to minimize the *baseplate to heatsink* thermal resistance. The following guidelines should be observed:

- Maintain flat and smooth surfaces.
- Maintain maximum contact area.
- If practical, use thermal joint compound or thermal pad, such as an electrically & thermally conductive Grafoil® pad.
- Torque fasteners (if used) according to fastener size and type to maximize clamping pressure (#6 bolt: 6-8 in.-lbs., #4 bolt: 4-5 in.-lbs.).

Convection

Heat transfer by *Convection (Natural or Forced)* involves the transfer of heat to a surrounding fluid by conduction, typically air. This mode of heat transfer is dependent on a number of variables and is somewhat complex to calculate. Surface area, temperature gradient, thermal conductivity of fluid (air), velocity of fluid (air), fluid (air) density and other variables affect convection.

Most heat sinks dissipate a majority of the heat through convection. Due to variations and complexity, it is best to use the thermal resistance data supplied by various heat sink vendors.

Natural Convection: *Natural Convection* is sometimes also referred as *Free Convection*. Natural Convection is easier to implement than Forced Convection, but at the expense of increased thermal resistance.

Natural Convection produces its own air velocity, due to the local heating of air at the heatsink surface. The air density is reduced when heated, causing it to rise, thus causing the air movement. Natural Convection is not as effective at higher altitudes due to air density reduction.

"Free Air" movement across a thermal dissipator is required to perform adequately. "Still Air" would be unacceptable, and result in ultimate thermal runaway (until shutdown). This would occur with a converter mounted (without thermal contact) within an enclosed box.

The thermal conductivity will generally increase with an increase in power dissipation. Hence the thermal resistance will decrease. Therefore, most heatsink vendors will plot temperature rise vs power dissipation for Natural Convection. The thermal resistance can be calculated:

$$\theta_{SA} = \Delta T / P_D$$

θ_{SA} = Thermal Resistance - Sink to Ambient (°C/Watt)

ΔT = Temperature Rise (°C)

P_D = Power Dissipation (Watts)

To maximize the transfer of heat by Natural Convection the following rules apply:

- Mount heat sinks so the maximum length of convection surfaces (fins) are in the vertical plane.
- Place the heat sink above the converter, allowing air to rise above.
- Provide sufficient enclosure ventilation for natural convection of the air.
- Note that close heatsink fin spacing will reduce the effectiveness of the heat sink.

Forced Convection: Forced Convection implies the use of fans to increase the air movement across the heatsink area. Heatsink to air thermal resistance can be improved by as much as a factor of 10 when compared to Natural Convection.

This may be the way to go when operating at high ambient temperatures, operating at high power levels, or when space is at a premium. Of course fans are not without their problems. They are noisy, and in dirty environments they often require filters. They can also cause an unreliable power system if the filters are not changed frequently or the fan itself fails. Therefore proper care must be exercised when fans are used.

Heatsink vendors will either plot thermal resistance vs air velocity or plot temperature rise vs power dissipation for various air velocities. Thermal resistance θ_{SA} can be calculated using the formula shown in the Natural Convection section.

Heatsink airflow specification is usually given as a function of air velocity in *linear feet per minute* (LFM). Fan specifications are usually given as a function of air volume in *cubic feet per minute* (CFM). Conversion from volume to velocity is as follows:

Velocity (LFM) = Volume (CFM) / Area

Area is the cross sectional area through which the cooling air passes.

A small amount of airflow (200ft/min) will have a significant impact on reducing heatsink to ambient thermal resistance. Increasing the airflow from 200ft/min to 1000ft/min will reduce the thermal resistance only by a factor of 2. Airflow above 1000ft/min does not significantly reduce heatsink thermal resistance.

To maximize the transfer of heat by Forced Convection the following rules apply:

- Keep low power components upstream
- Space heatsink fins closer together than in a Natural Convection design.
- Channel the flow of the air through the spaces between the fins of the heat sink.

Radiation

Thermal radiation is the transfer of heat by electromagnetic radiation (primarily in the infra-red wavelengths). Radiation is the only means of heat transfer between bodies separated by a complete space vacuum.

Radiation will be a minor contributor to the overall thermal link in most power converter applications. When using Forced Air Convection, radiation will contribute less than 10%. When using only Natural (or Free Air) Convection, radiation's contribution will be less than 30%.

Many factors contribute to thermal radiation efficiency, such as temperature differentials, surface area, and surface emissivity. Black anodized aluminum is a good thermal medium to take advantage of radiated heat. A heatsink with a large area for a given volume will take maximum advantage of radiation.

It is best to use the effects of radiation as a "safety margin" in the thermal design, since its contributions to heat transfer will normally be small, is difficult to quantify, and requires a relatively larger heatsink area to be efficient.

Thermal Design

Thermal design involves the following:

1. Determine the converter's *power dissipation* (P_D) for the worst case load.
2. Determine the maximum operating *ambient temperature* (T_A).
3. Determine the converter's maximum operating "design" *baseplate temperature* (T_B). To maximize long term reliability (MTBF), a value lower than the absolute maximum specified (100°C) should be selected.
4. Use the thermal model (Figure 5) to calculate the minimum required "baseplate to ambient" *thermal resistance* (θ_{BA}). This will include the sum of all thermal paths (e.g. including baseplate to heatsink thermal resistance (θ_{BS}).
5. Determine the method of cooling (e.g. Natural Convection or Forced Convection) based on space available and thermal resistance requirement.

Thermal Design Example: Find the heatsink requirements for a Powercube PD150 series converter with the following requirements:

Given:

Model PD150-048-15 (48V/15V)
P_{OUT} = 75 watts
η = 82.3% (0.823) … see example on page 1
T_B = 85°C (Maximum allowable is 100°C)
T_A = 45°C
θ_{BS} (Baseplate to Heatsink) = 0.4°C/W

Calculate:

$$P_D = P_{OUT}\left(\frac{1}{\eta} - 1\right) = 75(1.21 - 1) = 16W$$

$$\theta_{BA} = \Delta T / P_D = (85°C - 45°C) / 16W = 2.5\ °C/W$$

$$\theta_{SA} = \theta_{BA} - \theta_{BS} = (2.5\ °C/W - 0.4°C/W) = 2.1\ °C/W$$

Find Heatsink:

In the above example we need a heatsink with a thermal resistance of 2.1 °C/W (or less).

With a Forced Air Convection of >500 LFM, we could use a Thermalloy model 6571B, 6528B, 6527B or 6526B heatsink.

With a Natural Convection (Free Air) , we could use a Thermalloy model 6510B or 6517B heatsink.

If space is available, heatsinks with a larger footprint than the converter could be used, to further reduce the thermal resistance.

Other heatsink vendors include: Aavid, IERC and Wakefield Engineering.

Thermal Design Equations

$$\Delta T = P_D \times \theta_{BA}$$

$$\theta_{BA} = \Delta T / P_D$$

$$\theta_{BA} = \theta_{BS} + \theta_{SA}$$

ΔT = Temperature Rise "$T_B - T_A$" (°C)

P_D = Converter Power Dissipation (Watts)

θ_{BA} = Thermal Resistance - Baseplate to Ambient (°C/W)

θ_{BS} = Thermal Resistance - Baseplate to Heatsink (°C/W)

θ_{SA} = Thermal Resistance - Heatsink to Ambient (°C/W)

T_B = Baseplate Temperature

T_A = Ambient Temperature

Velocity (LFM) = Volume (CFM) / Area

Power Dissipation (P_D) = $P_{IN} - P_{OUT} = P_{OUT}\left\{\frac{1}{\eta} - 1\right\}$

Efficiency = $\frac{P_{OUT}}{P_{IN}} = \eta$

Output Power (P_{OUT}) = $\frac{\Delta T}{\theta_{BA}\left\{\frac{1}{\eta} - 1\right\}}$

ΔT = Output Power (P_{OUT}) $\cdot\ \theta_{BA}\left\{\frac{1}{\eta} - 1\right\}$

$\theta_{BA} = \frac{\Delta T}{\ }$