Thermal Management for Linear Regulators

by Kieran O'Malley

The thermal characteristics of regulators depend on their operating environment and the system's load requirements. Because irreversible changes occur at a faster rate in packaged devices at elevated temperatures, it is essential that the regulator's operating temperature be minimized. This article reviews thermal calculations for single and dual output regulators, the effect of heat sinking and gives several step-by-step examples of correct package selection.

Introduction

When an IC is operating, its on chip devices dissipate power in the form of heat. In a regulator, the bulk of the power is dissipated as heat from the power or pass transistor. The heat generated depends on the amount of current passing through the power transistor (the load current), and the voltage across it.

The heat that is generated on the die flows through its package and into the surrounding air. The heat must be removed at a sufficient rate to keep the regulator's transistor junction temperatures below the temperature beyond which damage may occur. Most manufacturers of silicon based ICs specify this temperature, T_J(max) as 150°C.

The maximum power dissipation of an IC package is:

$$P_D(max) = \frac{T_J(max) - T_A(max)}{R\Theta_{JA}} \qquad (1)$$

where:

T_J (°C) = maximum recommended junction temperature,

T_A (°C) = ambient temperature of the application, and

$R\Theta_{JA}$ (°C / W) = junction-to-ambient thermal resistance of the package, and any other heat dissipating materials.

Both T_J(max) and T_A(max) are listed in the Absolute Maximum Ratings section of the device's data sheet. T_A(max) is usually between 70°C and 125°C for regulators.

$R\Theta_{JA}$, the thermal resistance between the IC junctions and the external or ambient surroundings, is specific to an IC's package type. It quantifies how much the die's junction temperatures will rise for each Watt of power the IC dissipates into still air. The $R\Theta_{JA}$ value is listed in the Package section of the data sheet for each available package. From equation 1 its obvious that a package with a lower $R\Theta_{JA}$ has better power handling capability. (Note that some IC data sheets specify a figure called a derating factor, GΘ. It is the reciprocal of RΘ.)

Selecting the right power package for a regulator requires calculating the regulator's maximum power dissipation and then checking that against equation 1 to insure that the junction temperatures in the IC will remain below 150°C.

Calculating Power Dissipation in a Single Output Linear Regulator

The maximum power dissipation for a single output regulator (Figure 1) is

where

$$P_D(max) = \left\{V_{IN}(max) - V_{OUT}(min)\right\} I_{OUT}(max) + V_{IN}(max) I_Q \qquad (2)$$

V_{IN}(max) is the maximum input voltage,

V_{OUT}(min) is the minimum output voltage,

I_{OUT}(max) is the maximum output current, and

I_Q is the quiescent current the regulator consumes at I_{OUT}(max).

Once the value of P_D(max) is known, equation 1 can be

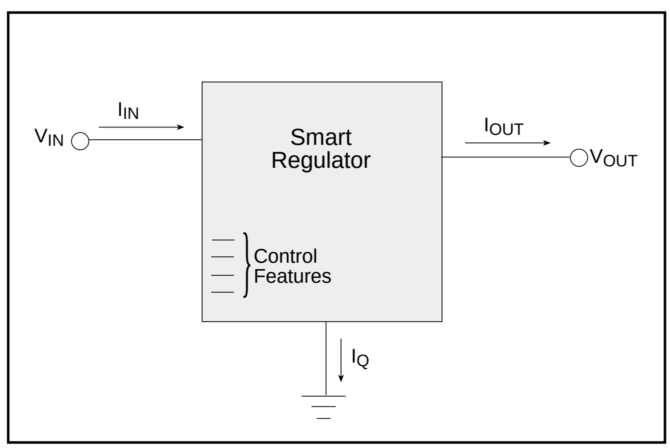

Figure 1: Single output regulator with key performance parameters labeled.

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rewritten to determine the maximum permissible value of $R\Theta_{JA}$ or:

$$R\Theta_{JA} = \frac{150°C - T_A}{P_D} \quad (3)$$

The value of $R\Theta_{JA}$ can then be compared with those in the package section of the data sheet. Those packages with $R\Theta_{JA}$'s less than the calculated value in equation 3 will keep the die temperature below 150°C.

In some cases, none of the packages will be sufficient to dissipate the heat generated by the IC, and an external heatsink will be required.

Selecting a Package for a Single Output Regulator

Assume that a linear regulator, the CS8121, will be operating under the following conditions:

V_{IN}(max)	10V
V_{OUT}(min)	4.8V
I_{OUT}(max)	200mA
T_A(max)	85°C

The following steps will ensure that the right package is chosen.

Step 1: Determine I_Q from the data sheet performance curve (Figure 2). Find the maximum output current on the graph's X axis. Locate the intersecting point on the curve whose temperature is the same or lower than the application's T_A(max). In this case, I_Q = 2.25mA for I_{OUT} =200mA at T_A(max)=25°C and I_Q = 1.7mA @T_A(max) = 125°C. For 85°C, the value of I_Q = 2.25mA is chosen as the worst case possibility.

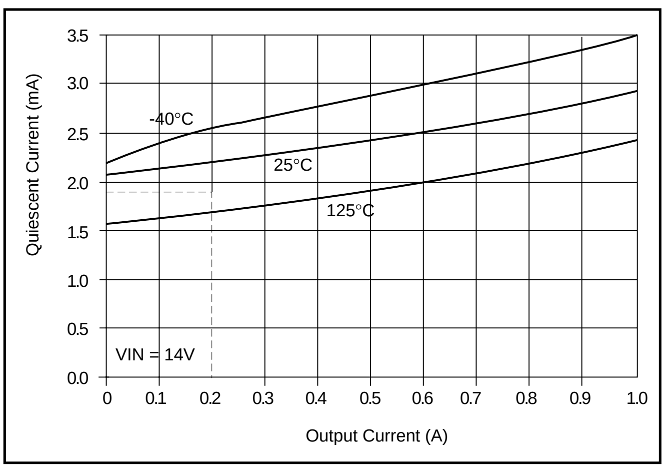

Figure 2. Quiescent Current over Temperature for CS8121

Step 2: Calculate the maximum power dissipation in the IC using equation 2 and the values provided above.

$$P_D(\text{max}) = \{10V - 4.8V\}\, 200mA + 10V(2.25mA)$$
$$= 1.0625W$$

Step 3: Calculate the maximum allowable $R\Theta_{JA}$ using equation 3.

$$R\Theta_{JA} = \frac{150°C - 85°C}{1.0625W} = 61.2°C / W \quad (3)$$

The CS8121 is available in three packages. Each package has the following thermal characteristics.

Table 1: Thermal Characteristics of CS8121 Power Packages

Package	$R\Theta_{JA}$	$R\Theta_{JC}$
TO220	50 °C / W	3.5°C / W
14 lead SO narrow	125 °C / W	30°C / W
8 lead PDIP	100 °C / W	52°C / W

Step 4: Choose the correct package. Compare the value of $R\Theta_{JA}$ from the calculation in step 3 with the ratings for the available package options.

According to Table 1, the only package that can meet this level of power dissipation without a heat sink (the only package with a lower $R\Theta_{JA}$) is the TO220 package with its $R\Theta_{JA}$=50°C / W.

In the above application, one of the packages was able to handle the power dissipation requirement, but there will be instances where none of the packages have a sufficiently low $R\Theta_{JA}$. In those cases, a heat sink must be attached to the package. The heat sink effectively increases the surface area of the package to improve the flow of heat away from the IC and into the surrounding air.

Heat Sinks

Each material in the heat flow path between the IC and the outside environment will have a thermal resistance. Like series electrical resistances, these resistances are summed to determine the value of $R\Theta_{JA}$.

$$R\Theta_{JA} = R\Theta_{JC} + R\Theta_{CS} + R\Theta_{SA} \quad (4)$$

where

$R\Theta_{JC}$ = the junction–to–case thermal resistance,
$R\Theta_{CS}$ = the case–to–heatsink thermal resistance, and
$R\Theta_{SA}$ = the heatsink–to–ambient thermal resistance.

$R\Theta_{JC}$ appears in the package section of the data sheet. Like $R\Theta_{JA}$, it too is a function of package type. $R\Theta_{CS}$ and $R\Theta_{SA}$ are functions of the package type, heatsink and the interface between them. These values appear in heat sink data sheets. For these examples, we will assume that the package and the heatsink are in still air.

Selecting a Package and a Heatsink for a Single Output Regulator

Let us assume that we are still using the CS8121 but the maximum input voltage has been increased to 12V. The new requirements are:

V_{IN}(max)	12V
V_{OUT}(min)	4.8V
I_{OUT}(max)	200mA
T_A(max)	85°C

With these new requirements , I_Q(typ) remains at approximately 2.25mA (Figure 2). Power dissipation is higher due to the higher input voltage.

$$P_D(\text{max}) = \{12V - 4.8V\}\, 250mA + 12V(2.25mA)$$
$$= 1.83W$$

and the maximum allowable $R\Theta_{JA}$ becomes

$$R\Theta_{JA} = \frac{150°C - 85°C}{1.83W}$$

$$= 35.5°C / W$$

From Table 1 it's apparent that none of the package options have a low enough $R\Theta_{JA}$. A heat sink will be required. (Figure 3)

To select the appropriate heat sink and interface, one first determines the value of the term $R\Theta_{CS} + R\Theta_{SA}$ as follows.

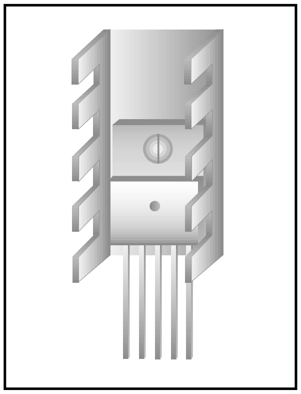

Figure 3. TO220 package with bolt on heatsink.

Step 1: Look up the value of $R\Theta_{JC}$ for the package. The values appear in Table 1 above and in the package section of the data sheet. $R\Theta_{JC}$ for the TO220 is 3.5°C / W.

Step 2: Determine the value of $R\Theta_{CS} + R\Theta_{SA}$ by substituting for the $R\Theta_{JC}$ of a TO220 package and the calculated value of $R\Theta_{JA}$ in to equation 4.

$$R\Theta_{CS} + R\Theta_{SA} = 35.5°C / W - 3.50°C / W$$
$$= 32°C / W$$

The combined value of the heatsink and interface thermal resistance ($R\Theta_{CS} + R\Theta_{SA}$) must be less than or equal to this value.

Step 3: Choose the interface material, if any, find its $R\Theta_{CS}$ and subtract it to find the maximum acceptable $R\Theta_{SA}$ for the heatsink. In this case we selected a KON-Dux™ pad from AAVID Thermal Technologies[1]. It has a $R\Theta_{CS}$ of approximately 0.021°C / W.

$$R\Theta_{SA} = 32°C / W - 0.021°C / W$$
$$R\Theta_{SA} = 31.97°C / W \approx 32°C / W$$

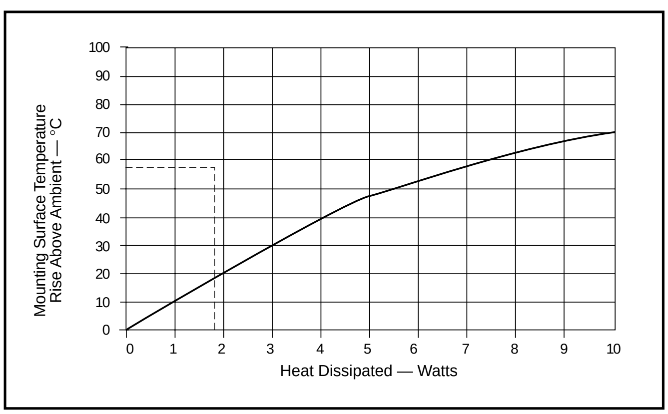

Figure 4. 504222 heatsink performance curve from AAVID Thermal Technologies product selection guide.

Step 4: Select the right heatsink. Each heatsink has a performance curve which shows its heat dissipation capability in still air (Figure 4).

We have already chosen a TO220 package. To select an appropriate heat sink we consult the performance curve for the AAVID Thermal Technologies 504222 low profile model. It shows the temperature rise of the package mounting surface as a function of power dissipation: e.g. if 2 watts is dissipated, the surface temperature only rises about 20°C above ambient (Figure 4). Locate the value of the power dissipation, P_D (1.83W) on the X axis of the graph (Heat dissipated - Watts). Then locate the value of allowable heatsink temperature rise above ambient on the Y axis of the graph. The allowable temperature rise in this case is 58.56°C (1.83 x 32).

Consulting Figure 4, we see that the heat sink curve lies below the allowable temperature rise so it will work in this application.

Heatsinking Surface Mount Packages

Suppose that your application requires a surface mount package rather than a through hole package. There are several options for heatsinking a surface mount package. One can use a traditional heat sink such as that described above. However if the amount of heat sinking is more modest, the heat can be drawn out through the package ground pins into a large copper area on the printed circuit board.

In this application, the micropower CS8101 regulator in a surface mount package must meet the following performance specifications:

V_{IN}(max)	10V
V_{OUT}(min)	4.9V
I_Q(typ)	70µA
I_{OUT}(max)	80mA
T_A(max)	125°C

Solving equations 2 and 3 for this application, P_D=0.41W and $R\Theta_{JA}$=61°C / W. $R\Theta_{JA}$ for the 16 lead batwing surface mount package is 70°C / W. Therefore, a heat sink will be required if the surface mount package is used.

With the copper foil method of heat sinking, the heat is drawn through the package's ground pins into a copper foil sink on the surface of the printed circuit board. (The foil is usually connected to electrical ground.) Figures 5A

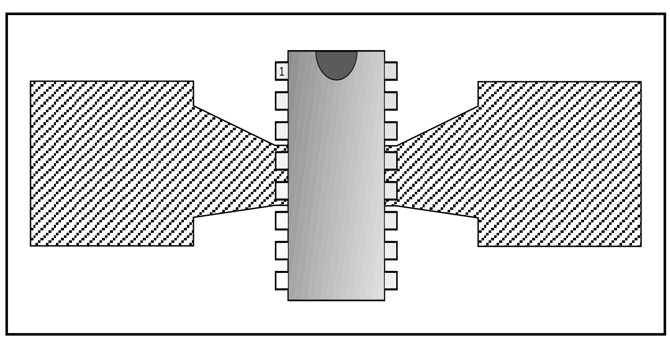

Figure 5A: Geometry of copper foil extending from central ground pins on surface mount package.

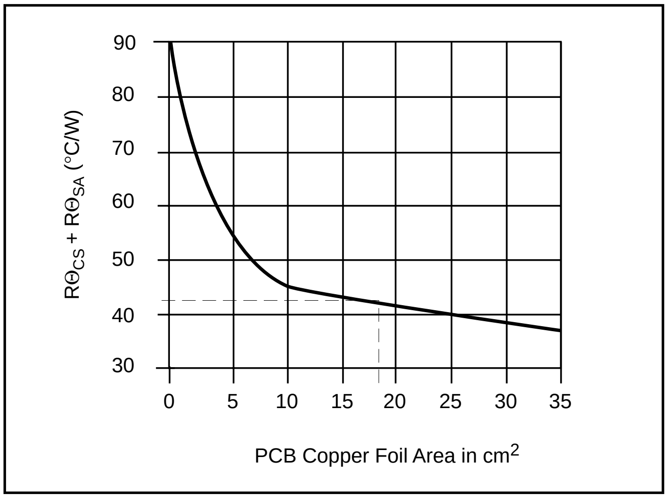

Figure 5B: Heatsink performance curve for PCB copper foil.

and 5B show a typical copper foil geometry and the thermal resistance of a 35µ thick foil of this material as a function of its area. Determining the size of the copper foil sink is done as follows.

Step 1: Solve equation 4 for the term $R\Theta_{CS} + R\Theta_{SA}$, substituting $R\Theta_{JC}$=20°C / W for a 16 lead batwing SOIC.

$$R\Theta_{CS} + R\Theta_{SA} = 61°C/W - 20°C/W$$
$$= 41°C/W$$

Step 2: Locate the value of the thermal resistance needed ($R\Theta_{CS} + R\Theta_{SA}$) on the Y axis in Figure 5B. Find the intersection of the Y value with the curve and then read down to the X axis. The value on the X axis is the total area of the heatsink that is required. In this case the area is 18cm^2. Each wing of the heatsink is 9cm^2 or 3cm on a side.

Calculating Power Dissipation in a Dual Output Regulator

The previous examples show how package and heat sink selections are made for a single output regulator. The calculations are slightly different for a dual output regulator. In this application we assume the IC and heatsink will be in still air. If air is forced over the heat sink, heat dissipation will be improved in relation to the rate of air flow. Consult any heatsink manufacturers' data book for details on heat flow effects.

The calculation for a dual output regulator is similar to that for a single but it includes the power dissipation term for the second output (Figure 6).

$$P_D(max) = \{V_{IN}(max) - V_{OUT1}(min)\}I_{OUT1}(max) + \{V_{IN}(max) - V_{OUT2}(min)\}I_{OUT2}(max) + V_{IN}(max)I_Q \quad (5)$$

In the following example, we see the power dissipation component contributed by the second output and determine whether a heat sink is required for the application.

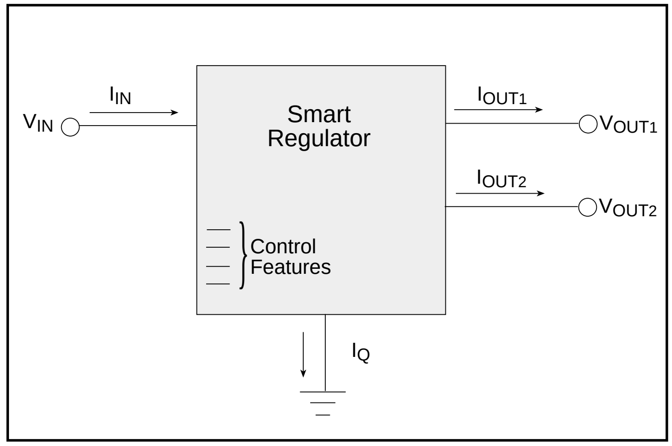

Figure 6. Dual output CS8167 with key performance parameters labeled.

The dual output CS8167 in a TO220 power package must operate under the following system conditions:

V_{IN} (max)	10V
V_{OUT1}(min)	7.6V
I_{OUT1}(max)	250mA
V_{OUT2}(min)	4.85V
I_{OUT2}(max)	35mA
I_Q(typ)	60mA
T_A(max)	55°C

Step 1: Calculate the power dissipation for the IC under worst case conditions using equation 5 and the above system specifications.

$$P_D(max) = (10V - 7.6V\}250mA + \{10V - 4.85V\}35mA + (12V)60mA$$
$$= 0.60W + 0.180W + 0.72W$$
$$= 1.5W$$

Step 2: Calculate the maximum permissible thermal resistance for the IC package using equation 3.

$$R\Theta_{JA} = \frac{150°C - 55°C}{1.5W}$$
$$= 63.3°C/W$$

Step 3: Compare the calculated value of $R\Theta_{JA}$ with the $R\Theta_{JA}$ of the TO220 package in Table 1. Since the TO220 package $R\Theta_{JA}$ is 50°C / W, the regulator will not require a heat sink in this application.

Power Packages

Linear regulators are available in a variety of power packages (Figure 7). There are the traditional metal tab SIPs (TO220's) and surface mount fused lead (batwing) packages mentioned in the previous examples, as well as the overmolded TO220 and the surface mount D^2 Pak. The

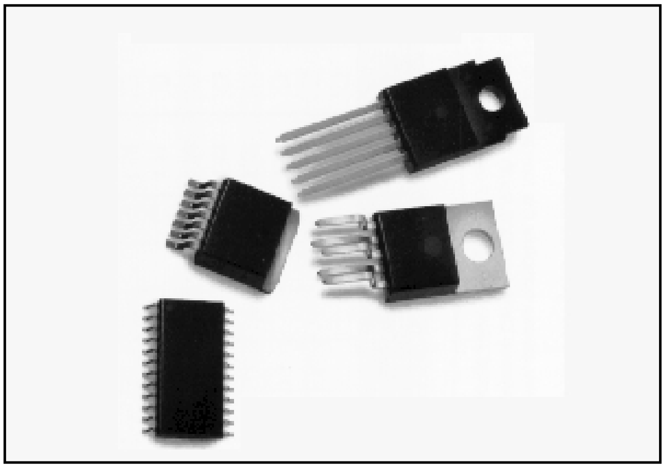

Figure 7. CSC Linear Regulators are available in (clockwise) overmolded TO220, standard TO220, surface mount batwing and D^2 surface mount packages.

epoxy covering on the metal tab in the overmolded TO220 package serves as an electrical insulator so that the tab can be bolted to an ungrounded heat rail.

The surface mount D^2PAK is a compromise solution that retains some of the heat handling capability of the TO220 package while satisfying the need for a better surface mount power package. The metal tab of the D^2 Pak can be connected to metal foil on a printed circuit board to enhance its heat dissipation.

Summary

Determining an appropriate package for a regulator in a particular application depends on knowing key system specifications: maximum input voltage, maximum load current, highest ambient operating temperature and minimum output voltage. The maximum quiescent current, maximum power dissipation and maximum junction to ambient thermal resistance requirements follow from these.

If a chosen package can't meet the worst case thermal resistance requirements, heatsinking will be necessary to keep IC junction temperatures below 150°C. Heatsinking in the form of bolting to a heat rail, attaching a metal heat sink or adding copper foil underneath surface mount and through hole packages are all options.

Failure to determine the proper operating specifications, miscalculation of the power dissipation requirements or improper heat sink selection can have catastrophic effects.

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(1) Heat Sink data was provided by
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