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COMPUTING IC TEMPERATURE RISE

WHY IC TEMPERATURES RISE

Heat is the enemy of integrated circuits—particularly power devices. Here's how to use thermal ratings to determine safe IC operation.

Excessive heat shortens the life of an IC and reduces its operating capability. Until recently, ICs were capable of operating only in low-power applications requiring perhaps a few milliwatts of power. But now, ICs handle several amperes and drive devices such as relays, solenoids, stepping motors, and LED lamps. These high power levels may increase IC temperatures substantially and are capable of destroying devices unless appropriate precautions are taken.

THERMAL CHARACTERISTICS

The thermal characteristics of any IC are determined by four parameters. Maximum allowable IC chip junction temperature T_J and thermal resistance R_θ are specified by the IC manufacturer. Ambient temperature T_A and the power dissipation P_D are determined by the user. Equation 1 expresses the relation of these parameters.

Equation 1:

$$T_J = T_A + P_D R_\theta$$

Junction temperature T_J usually is limited to 150°C for silicon ICs. Devices may operate momentarily at slightly higher temperatures, but device life expectancy decreases exponentially for extended high-temperature operation. Usually, the lower the junction operating temperature, the greater the anticipated life of the IC.

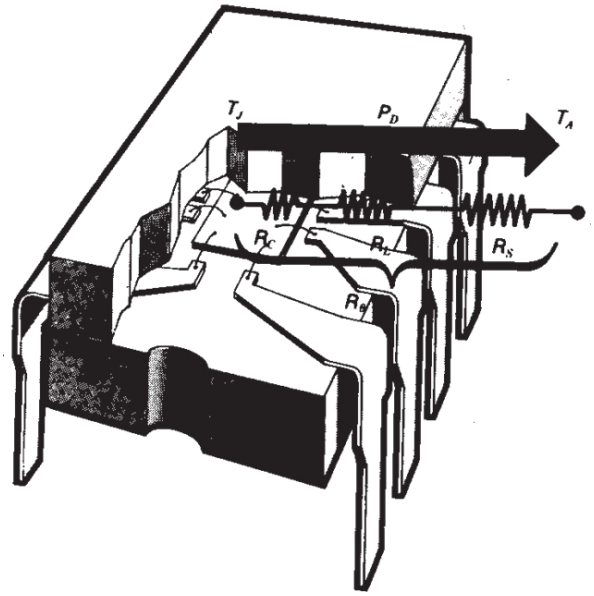


Figure 1: IC temperature T_J is determined by ambient temperature T_A, heat dissipated P_D, and total thermal resistance R_θ. This total thermal resistance is comprised of three individual component resistances: chip R_C, leadframe R_L, and heat sink R_S.

Ambient temperature T_A is traditionally limited either to 70°C or 85°C for plastic dual in-line packages (DIPs) or 125°C for hermetic devices. Again, the objective is to operate at as low a junction temperature as practical.

Thermal resistance R_θ is the basic thermal characteristic for ICs. It is usually expressed in terms of °C/W and represents the rise in junction temperature with a unit of power applied in still air. The reciprocal of thermal resistance is thermal conductance, or derating factor, G_θ expressed as W/°C. Thermal resistance of an IC consists of several distinct components, the sum of which is the specified thermal resistance.

For a typical IC, these components of thermal resistance are 0.5°C/W per unit thickness of the silicon chip, 0.1 to 3°C/W per unit length of the leadframe, and up to 2,000°C/W per unit thickness of still air surrounding the IC. DIPs are used more than any other type of packaging for ICs and copper-alloy leadframes provide a superior thermal rating over the standard iron-nickel-cobalt alloy (Kovar) leadframes. However, power ICs are also available in other packages such as PLCCs, SOICs, and power-tabs.

The power P_D that an IC can safely dissipate usually depends on the size of the IC chip and the type of packaging. Most common copper-frame DIPs can dissipate about 1.5 W, although some special-purpose types have ratings as high as 5 W.

Total IC power to be dissipated depends on input current, output current, voltage drop, and duty cycle. Thus, for many industrial digital-control ICs, logic-gate power P_I (typically less than 0.1 W) and output power P_0 must be determined to find the total power to be dissipated. Total power dissipation for these logic devices is the sum of P_I and P_0.

Equation 2:

$$P_I = n(V_{CC}I_{CC})$$

Equation 3:

$$P_0 = n(V_{CE(SAT)}I_C)$$

where V_{CC} = logic-gate supply voltage, I_{CC} = logic-gate supply ON current, $V_{CE(SAT)}$ = output saturation voltage, I_C = output load current, and n = number of logic gates. Manufacturers usually list typical and maximum values for these voltages and currents. For thermal considerations it is best to use the maximum values so that worst-case power dissipation is determined.

If the duty cycle of the device is longer than 0.5 seconds, the peak power dissipation is the sum of the logic-gate power P_I and output power P_0 for the logic ON state alone. If the ON time is less than 0.5 seconds, however, average power dissipation must be calculated from instantaneous ON and OFF power P_{ON} and P_{OFF} from:

Equation 4:

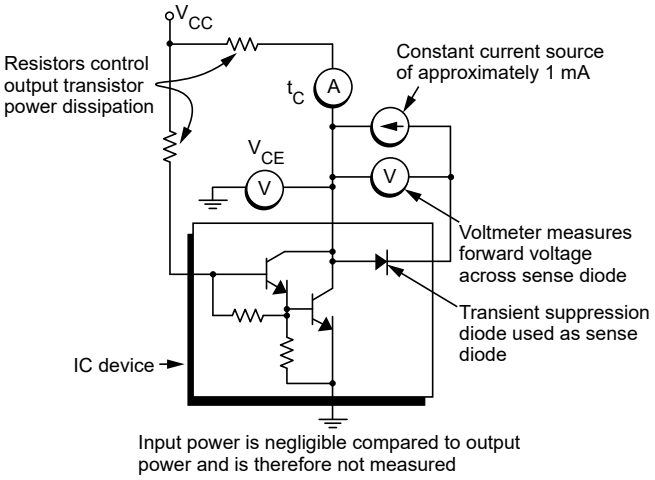
$$P_D = DP_{ON} + (1 - D)\,P_{OFF}$$

CORRECTIVE ACTIONS

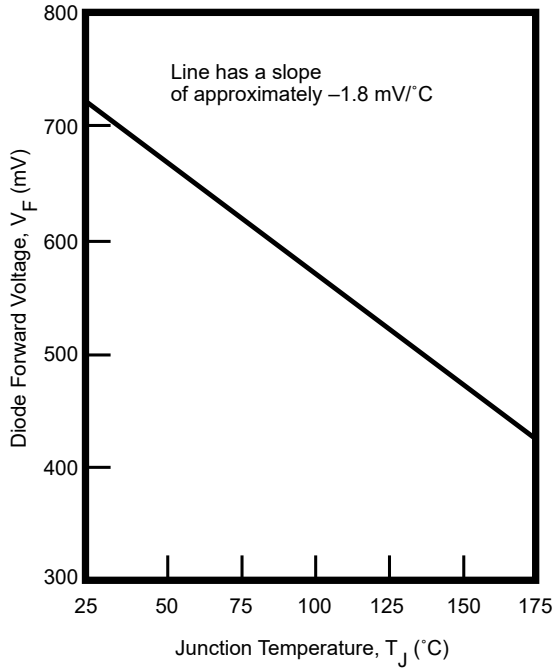
If the junction temperature or the required power dissipation of the IC is calculated to be greater than the maximum values specified by the manufacturer, device reliability and operating characteristics possibly will be reduced. Possible solutions are:

1. Modify or partition the circuit design so the IC is not required to dissipate as much power.
2. Reduce the thermal resistance of the IC by using a heat sink or forced-air cooling.
3. Reduce the ambient temperature by moving heat-producing components such as transformers and resistors away from the IC.
4. Specify a different IC with improved thermal or electrical characteristics (if available).

SETTING UP THE CIRCUIT



CALIBRATING THE SENSE DIODE



MEASURING IC TEMPERATURE

Sometimes IC junction temperature cannot be calculated readily and instead must be measured. Measurement should be made when there is insufficient data with which to calculate, when the effects of external variables such as forced-air cooling or enclosure size must be determined, or as a check on the manufacturer's specifications regarding package thermal resistance.

The most popular technique of measuring IC temperature uses the characteristic of a diode to reduce its forward voltage with temperature. Many IC chips have some sort of accessible diode—parasitic, input protection, base-emitter junction, or output clamp. With this technique, a "sense" diode is calibrated so that forward voltage is a direct indicator of diode junction temperature. Then, current is applied to some other component on the chip to simulate operating conditions and to produce a temperature rise. Because the thermal resistance of the silicon chip is low, the temperature of the sense diode is assumed to be the same as the rest of the monolithic chip.

The sense diode should be calibrated over at least the expected junction operating temperature. Apply an accurately measured, low current of about 1 mA through the sense diode and measure the forward voltage in 25°C increments after stabilization at each temperature. This calibration provides enough data for at least six points to construct a diode-forward-voltage versus junction-temperature graph at the specified forward current. A typical 25°C forward voltage is between 600 and 750 mV and decreases by 1.6 to 2.0 mV/°C.

For power levels above 2 W, it may be necessary to use more than a single transistor if only the device saturation voltage and sink current are used. If higher power is desired, keep the output out of saturation.

Measuring the sense-diode forward voltage may require a considerable waiting period (10 to 15 minutes) for thermal equilibrium. In any event, at the instant of measurement, the heating power may have to be disconnected because erroneous readings may result from IR drop in circuit common leads. Various circuit connections (such as four-point Kelvin) may be arranged to reduce or eliminate this source of error.

The IC junction temperature can be determined by comparing the voltage measurement with the internal power source against the voltage measurement with the temperature chamber.

FINDING SAFE OPERATING LIMITS

Here's how to calculate the safe operating limits for an IC. The first two examples are simple calculations involving maximum allowable power and are straightforward. The third and fourth examples are more complex and involve logic power, output power, and duty cycle.

Problem: Determine the maximum allowable power dissipation that can be handled safely by a 16-lead Kovar DIP with an R_θ of 125°C/W in an ambient temperature of 70°C.

Solution: From Equation 1, the maximum allowable power dissipation P_D for this IC is:

$$P_D = (150°C - 70°C)/(125°C/W)$$
$$= 0.64\ W$$

Problem: Determine the maximum allowable power dissipation that can be handled by a 14-lead copper DIP with a derating factor G_θ of 16.67 mW/°C in an ambient temperature of 70°C.

Solution: Because the derating factor G_θ is the reciprocal of thermal resistance R_θ, the maximum allowable power dissipation P_D from Equation 1 is:

$$P_D = (150°C - 70°C) \times (16.67\ mW/°C)$$
$$= 1.33\ W$$

Problem: Calculate the maximum junction temperature for a quad power driver wlth a thermal resistance of 60°C/W in an ambient of 70°C and which is controlling a 250 mA load on each of the four outputs.

Solution: To determine the maximum (worst case) junction temperature for this IC, the maximum total power dissipation must be determined from the data listed on the IC data sheet. The specifications are usually listed as typical and minimum or maximum values. It is important to use maximum voltage and current limits to ensure an adequate design. Common maximum values for an industrial power driver are $V_{CC} = 5.25$ V, $I_{CC} = 25$ mA, $V_{CE(SAT)} = 0.7$ V, and $I_C = 250$ mA. From Equation 2 and Equation 3, worst case logic and output power dissipation are:

$$P_I = 4\ (5.25\ V \times 25\ mA)$$
$$= 525\ mW$$
$$P_0 = 4\ (0.7\ V \times 250\ mA)$$
$$= 700\ mW$$

Thus, the total worst case power dissipation P_D is 525 mW plus 700 mW, or 1.225 W. From Equation 1, maximum junction temperature T_J is:

$$T_J = 70°C + (1.225\ W) \times (60°C/W)$$
$$= 143.5°C$$

Problem: Determine the acceptable duty cycle for a power driver with a thermal resistance of 100°C/W in an ambient temperature of 85°C and which is controlling load currents of 250 mA on each of four outputs.

Solution: From Equation 1, the allowable average power dissipation P_D for this IC is:

$$P_D = (150°C - 85°C)/100°C/W$$
$$= 0.65\ W$$

This means that there is 0.65 W limit on average power but not instantaneous power. If the duty cycle is low enough and the ON time is not more than about 0.5 seconds, the average power dissipation can be considerably lower than the peak power. The ON, or peak power, is determined from the data sheet maximum values of V_{CC}, I_{CC}, and $V_{CE(SAT)}$ at the specified load current of 250 mA. From Equations 2 and 3, logic-gate power P_I and output power P_0 for the ON state are:

$$P_I = 4\ (5.5\ V \times 26.5\ mA)$$
$$= 583\ mW$$
$$P_0 = 4\ (0.7\ V \times 250\ mA)$$
$$= 700\ mW$$

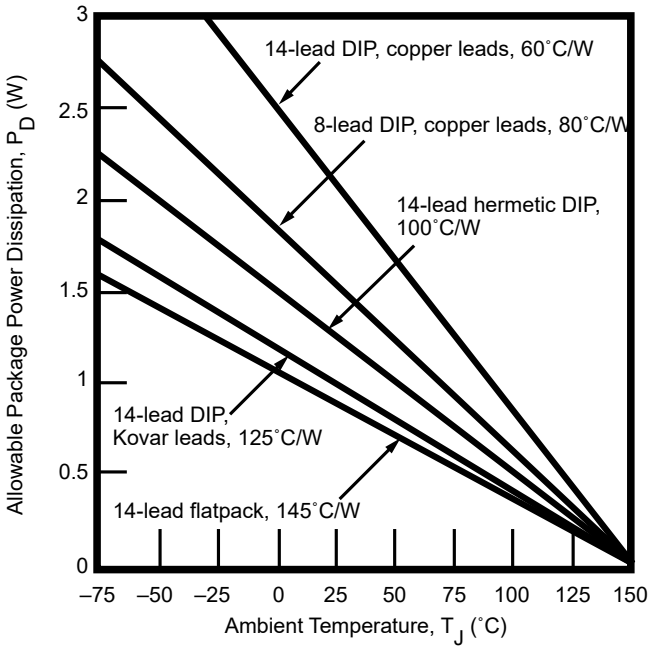
Instantaneous ON power P_{ON} is the sum of P_I and P_0 for the ON state, or 1.283 W. The OFF power is primarily the power dissipated by the logic in the OFF state and is found by using the I_{CC} maximum rated current listed on the specification sheet. The power dissipated in the output stage can be calculated from the leakage current I_C and supply voltage V_{CE}. From Equation 2 and Equation 3, logic-gate power P_I and output power P_0 for the OFF state are:

$$P_I = 4\ (5.5\ V \times 7.5\ mA)$$
$$= 165\ mW$$
$$P_0 = 4\ (100\ V \times 0.1\ mA)$$
$$= 40\ mW$$

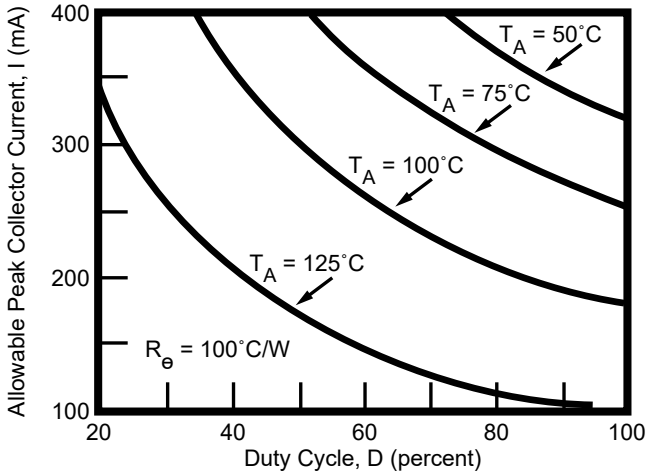
Instantaneous OFF power P_{OFF} is the sum of P_I and P_0 for the off state, or 205 mW. From Equation 4, acceptable duty cycle D is:

$$D = (P_D - P_{OFF})/(P_{ON} - P_{OFF})$$
$$= (0.65\ W - 0.205\ W)/(1.283\ W - 0.205\ W)$$
$$= 41\%$$

THERMAL RATINGS



DUTY CYCLE



WHAT THE CURVES SHOW

The junction temperature of an IC depends on several factors, including the thermal resistance of the IC and the operating duty cycle. Graphs showing the relationship of these factors are often useful in specifying an IC.

Typical thermal-resistance ratings for ICs in still air range from 60°C/W to 140°C/W. The slope of each curve on this graph is equal to the derating factor G_θ, which is the reciprocal of thermal resistance R_θ. For an ambient temperature of 50°C, a typical 14-lead flatpack with an R_θ of 140°C/W can dissipate about 0.7 W. A typical DIP, however, with 14 copper-alloy leads, can dissipate almost 1.7 W at 50°C.

The highest allowable package power dissipation shown here is 2.5 W. Other special-purpose DIP packages are available with power dissipation ratings as high as 3.3 W at 0°C (R_θ = 45°C/W). If not for package limitations, IC chip dissipation might be greater than 9 W at an ambient temperature of up to 70°C.

Although the curve for plastic DIPs goes all the way up to 150°C, they ordinarily are not used in ambient temperatures above 85°C because of traditional package limitations.

Duty cycle is important in calculating IC junction temperature because average power—not instantaneous power—is responsible for heating the IC. To convert from peak power to average power, multiply the peak power dissipation by the duty cycle. The average power rating is then used with the thermal-resistance rating to calculate the IC junction temperature. Thus, low duty cycles allow peak power to be high without exceeding the 150°C junction-temperature limit. However, this consideration applies only to ON times of less than 0.5 seconds.

Revision History

Number	Date	Description	Responsibility
1	November 17, 2022	Recreated previously released document in current template and made minor editorial changes (throughout), and adjusted equation in third problem set (page 4).	J. Henry

955 PERIMETER ROAD • MANCHESTER, NH 03103 • USA
+1-603-626-2300 • FAX: +1-603-641-5336 • ALLEGROMICRO.COM