power with heavier loads. V_{CE} cannot be reduced beyond the point of saturating the transistor because this would result in the inability to maintain regulation.

Note the shunt resistor R_{MIN} at the output. This resistor is present, because the minimum load current is zero. With zero load current, the transistor's V_{BE} circuit would not be complete, and the transistor would be in cut-off. Maintaining the transistor in the active mode enables it to respond quickly to changes in V_{CE}. A 1-kΩ resistor is added to the output in parallel with the load to guarantee a minimum output current of 4.9 mA so that the transistor remains active.

The regulator's power dissipation is a function of the input voltage and the load current. Table 17.1 summarizes the best- and worst-case power dissipation figures. Substantially lower power dissipation can be observed as compared to the shunt regulator discussed previously. The best-case power of 93 mW is less than 260 mW for the shunt circuit. The worst-case power of 669 mW is also much less than the shunt regulator's 1,490 mW. As expected, the majority of the power is dissipated by the TIP31 pass transistor when the load current and V_{CE} are at their maximum. The other components dissipate so little power that their thermal analysis is unnecessary in most situations.

TABLE 17.1 Series Regulator Power Dissipation

Component	V_{IN} = 10 V I_{LOAD} = 0 mA	V_{IN} = 15 V I_{LOAD} = 45 mA
R_{LIMIT}	19 mW	88 mW
Zener diode	25 mW	53 mW
R_{MIN}	24 mW	24 mW
Transistor V_{CE}	25 mW	504 mW
Total	93 mW	669 mW

The TIP31's maximum collector current is 3 A, well over our 49-mA operating point.* It is also rated for 2 W at an ambient temperature of 25°C and for 40 W at a case temperature of 25°C. These specifications imply that the device is intended to be used with a heat sink under more than lightly loaded conditions. Our present application has the transistor dissipating roughly one-quarter of the power rating without a heat sink at 25°C. However, if we want the circuit to be usable up to 40°C, some additional consideration is necessary. The TIP 31 data sheet does not provide detailed thermal resistance information, only a power derating curve versus case temperature and a maximum junction temperature of 150°C. Additional information is not needed if a heat sink is used, because the thermal resistance of the heat sink would be known, which would allow the determination of the case temperature for a given power dissipation. Knowing the case temperature would allow using the power derating curve to determine the safe operating limits of the transistor.

In the absence of information that applies specifically to our application, some estimates will have to be made. First, the transistor is being operated at one-quarter of its rating at 25°C. This probably provides sufficient margin at 40°C. Second, we can use thermal resistance information from other semiconductors packaged in a TO-220 package as a first-order approximation of the TIP31's characteristics. Other TO-220 devices have θ_{JA} = 65°C/W. Using this information, the transistor would experience a 33°C rise over ambient for $T_{J(MAX)}$ = 73°C. While this is only an approximation, it is less

* TIP31 Series, Fairchild Semiconductor, 2000, p. 1.

than half the rated $T_{J(MAX)}$ of 150°C. These estimates point in the right direction. However, the best approach is to confirm these findings with the manufacturer. Semiconductor manufacturers' application engineers are able to answer such questions and provide advice on matters that are not explicitly addressed in a data sheet.

As with the Zener shunt regulator, this circuit is relatively loose in its accuracy of V_{OUT} over varying temperature and load. The Zener voltage reference itself will drift with temperature, but its current is nearly static, so there will not be much drift with changing current. The transistor's V_{BE} changes with temperature and current as well. If these drawbacks have you wondering how accurate voltage regulators are ever constructed, the answer lies in various compensation schemes that involve more components. However, the biggest contributor to accurate voltage references and regulators is the integrated circuit, because an IC enables the pairing of transistors with closely matched physical and thermal characteristics. When transistors and diodes are fabricated on the same slice of silicon within microns of each other, they are nearly identical, and they operate at the same temperature. Close matching enables transistors and diodes to largely cancel out each other's undesired variations when arranged in specific configurations.

A series regulator can also be designed to provide a regulated constant current instead of constant voltage. Current sources are useful for battery chargers, among other applications. Figure 17.8 shows such a circuit using a PNP transistor. Once again, the variable input/output differential is taken up by the transistor's V_{CE}, although it is the output that is allowed to float with a constant current. A floating output voltage is necessary, because an ideal current source supplies constant current regardless of the impedance that it is driving. A higher load impedance results in a higher voltage output according to Ohm's law. This is the converse of a voltage source wherein constant voltage is desired at variable current. Real current regulators, of course, have limitations on the range of V_{OUT} for the circuit to remain in regulation, just as we have already observed that voltage regulators are subject to current limitations.

The TIP32 is chosen for this circuit, because it is a mature BJT with characteristics similar to the TIP31. Power circuits that require both NPN and PNP transistors sometimes use the complementary TIP31 and TIP32 pair. This current regulator functions by establishing a fixed voltage drop across R_{SET}, thereby establishing a fixed emitter current. Assuming negligible base current, the collector current drives the load with the same current. An emitter-base loop is established with a reference voltage provided by the 1N4728A Zener diode. Per loop analysis, $V_{ZENER} = I_{OUT}R_{SET} + V_{BE}$, assuming that the base current is negligible. When the Zener reference and V_{BE} are fixed, R_{SET} establishes the regulator's output current. R_{LIMIT} picks up the voltage difference between V_{IN} and V_{ZENER} and thereby serves as the Zener diode's current limiter.

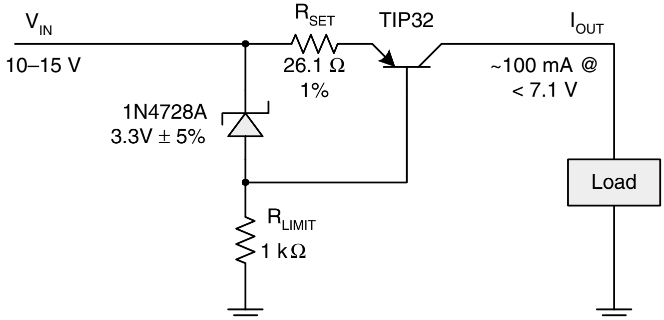

FIGURE 17.8 PNP current regulator.