Application Considerations for Hybrid Series Voltage Regulators

by W. R. Peterson

This Note describes a series of hybrid voltage regulators that can supply 5, 12, or 15 volts while delivering up to 4 amperes. These circuits, the RCA-HC4000 family, use a series pass element for regulation, and include both self-protection (foldback) and load-protection (crowbar-trigger) networks. The foldback network protects the circuit against overcurrents that would otherwise result from load-resistance decreases, either transient or steady state (catastrophic). The crowbar protection makes these circuits especially well suited for supplying a regulated voltage to loads that may be sensitive to over-voltage and expensive to repair or replace. Such loads include, for example, the logic circuits used in most computer and data-terminal applications.

CIRCUIT DESCRIPTION

The circuit of the RCA-HC4000 family, shown in Fig. 1, includes an integrated-circuit voltage regulator, ballast resistors for the internal pass transistor and for external pass transistors, the foldback circuit, and the crowbar trigger circuit.

Integrated-Circuit Voltage Regulator

Regulation, stability, and temperature compensation are achieved by use of the RCA-CA3085AH integrated-circuit voltage regulator chip. Because the CA3085AH is limited to a supply voltage of 40 volts and a feedback voltage to the inverting input of 1.6 volts, the regulated output voltage is limited to the range from 2 to 32 volts.

Resistors R2 and R3 set the output voltage because their junction provides the inverting input signal, which is approximately 1.6 volts. The regulator supplies current to the load so that the load (output) voltage is divided by resistors R2 and R3 to 1.6 volts at the inverting input. If the load resistance changes, the regulator changes the output current. The regulating action can be described as follows: because the regulator cannot change the load current instantaneously, an increase of load resistance causes an increase of output voltage. Consequently, transistor Q6 conducts more collector current. As a result, the base current

of transistor Q13 decreases; the load current then decreases, and returns the output voltage to normal.

Ballast Resistors

The values of ballast resistors R4, R8, and R9 are selected to satisfy two conditions: (1) the voltage drop across each resistor at rated current must be approximately 450 millivolts; and (2) the current conducted by each external pass element must be 1.5 times the internal pass element current. Because the transconductance of the power transistors is nonlinear, the ratio of the internal to external ballast resistors is actually 1.8. With the ballast resistors set at R4 equal to 0.165 ohm and R8 and R9 equal to 0.09 ohm, respectively, current levels are within 15 per cent of design values.

Foldback Current Limiting

Foldback current limiting is included in the HC4000 circuit to keep power dissipation within safe limits when the load resistance falls below the rated level, as shown in Fig. 2. The main advantage of foldback limiting is that the ratio of maximum power dissipation in the pass transistor during normal regulation to the maximum power dissipated during the foldback mode is typically 0.9; a conventional current-limiting circuit would require the pass transistor to conduct the rated current for all excessive loads, including shorted loads.

As indicated in Fig. 1, the foldback circuit consists of transistor Q3 and resistors R1, R6, and R7. Transistor Q3 senses the voltage across the legs of a bridge formed by resistors R6 and R7 on one side and the base-to-emitter voltage V_{BE} of transistor Q4, resistor R4, and the load resistance on the other side. Voltage V_{BE} of Q4 is included because it increases with collector current, and thus increases the circuit sensitivity. When transistor Q3 senses an overload, it conducts current away from the base of transistor Q13. This effect reduces the base drive to transistor Q2 and subsequently the voltage drop across the undersize load resistor. The voltage feedback condition reaches a stable
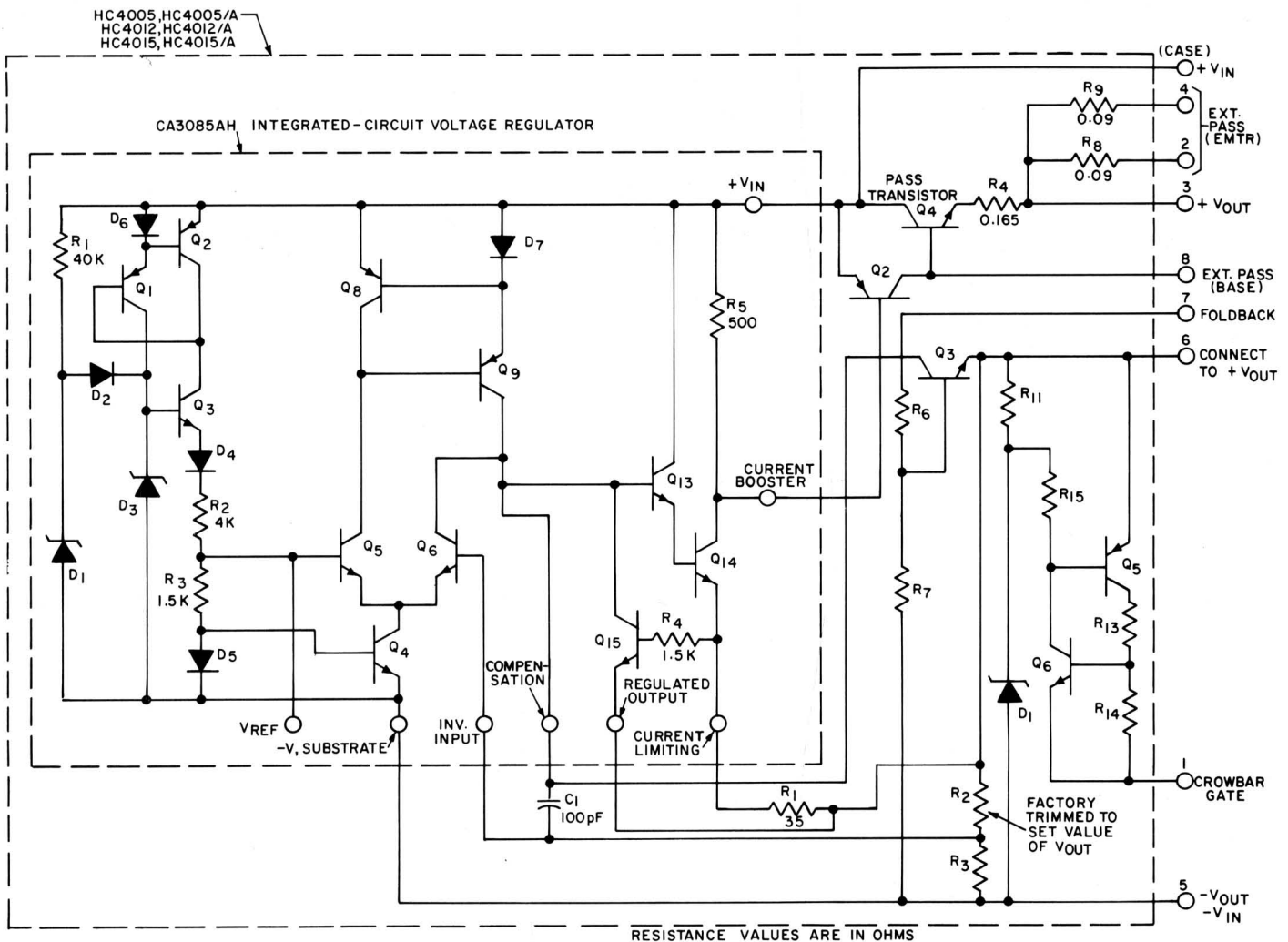
Fig. 1— Schematic diagram of the RCA-HC4000 family of
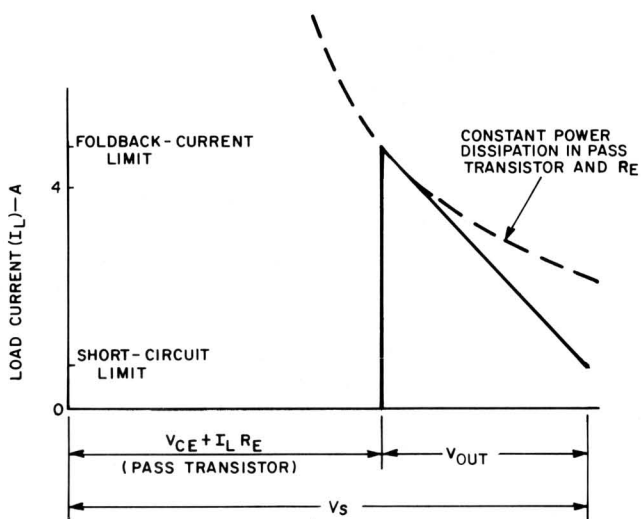series voltage regulators.

Fig. 2— Characteristic of the foldback protection circuit in
RCA-HC4000 family of voltage regulators.

point on the foldback characteristic that corresponds to the load resistance. Additional protection of transistors Q13 and Q14 is achieved by activation of the current-limiting transistor Q15, which turns on when the current through R1 reaches 20 milliamperes.

Crowbar Trigger Circuits

The crowbar trigger circuit provides gate current to an external silicon controlled rectifier (SCR) in response to an over-voltage of 130 per cent of the output value. This over-voltage may result from a spike generated by the load, from the supply, or from a short-circuited pass element. Resistor R11 and zener diode D1 provide a stable reference voltage. The voltage at the junction of these components is compared to the output voltage by transistor Q5. If an over-voltage occurs, transistor Q5 turns on and provides base current to Q6, which also turns on. This condition is regenerative; the collector currents of Q5 and Q6 are limited only by resistor R13, which limits the base current to Q6 and

therefore its collector current. Resistor R14 provides a leakage path for the collector-base junction of Q6. The crowbar output, terminal 1, is connected to the gate of an appropriate SCR. The output current always falls within the 100- to 500-milliampere range, with a typical rise time of 0.5 microsecond.

Once the SCR is turned on, the voltage across the trigger circuit is reduced to the forward voltage drop of the SCR. If the SCR fails to turn on (because of an open anode connection, for example), the crowbar trigger circuit dissipates a large amount of power P_d, determined by the following equation:

$$P_d = V_o I_G \qquad (1)$$

where V_o is the output voltage and I_G is the SCR gate current.

The trigger circuit is capable of dissipating 750 milliwatts at case temperatures up to 75°C. If it is anticipated that the power or the temperature will exceed these values, an external resistor should be connected in series with terminal 1 to limit the internal dissipation.

BASIC STRUCTURE

The basic regulator structure consists of three separate subassemblies mounted in an "eight-lead TO-3" package, as shown in Figs. 3, 4, and 5. The power pass element is mounted on a copper heat sink attached directly to the header base, and has a thermal resistance of approximately 2°C per watt. The drive circuit is mounted on the base or lower substrate and the crowbar is mounted on the upper substrate.

The base substrate is attached to the header by a thermally and electrically conductive epoxy. Electrical interconnection to the module is accomplished by reflow-soldering of solder-coated eyelets. The crowbar substrate is supported on these eyelets and electrically interconnected to the module by a reflow-soldering of solder-coated washers.
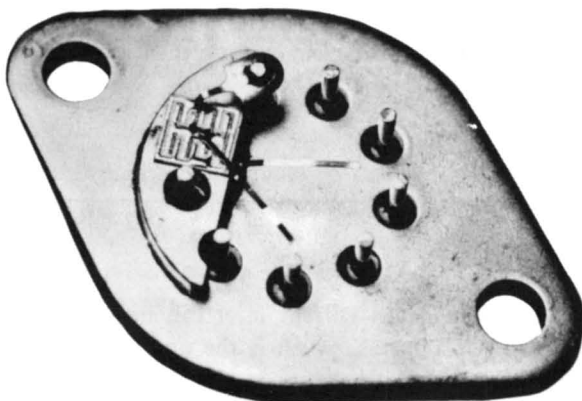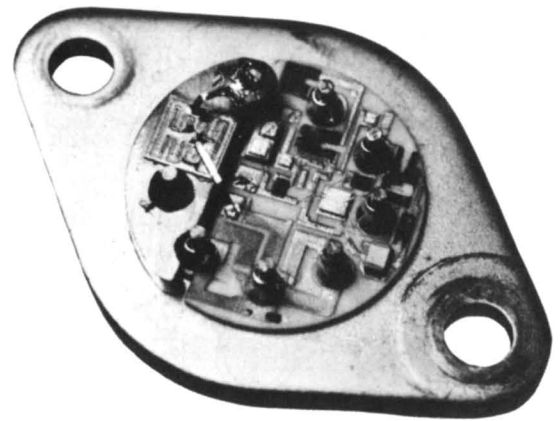

Fig. 4— *The base substrate assembled to an output.*

Additional interconnections among the three subassemblies are provided by three soldered clips and straps.

Two primary considerations determine the maximum allowable temperature of power hybrids: reliability, and material limitations. Usually, the most significant material limitation is a low-melting-point solder. However, extensive life studies have shown that the temperature of the thick-film substrate should not exceed 125°C; therefore the temperature limit of the HC4000 family of regulators is determined by reliability considerations.

The effect of lateral heat flow from the power transistor to the thick-film substrate is illustrated in Fig. 6. The junction temperature of pass transistor Q4 is 150°C (as a result of 30 watts dissipation and a heat-sink temperature of 85°C). The dissipation in Q4 causes the junction of Q2 to rise to 125°C, and also causes other components on the substrate to heat up. Because there is no source of appreciable thermal energy on the substrate, the tempera-
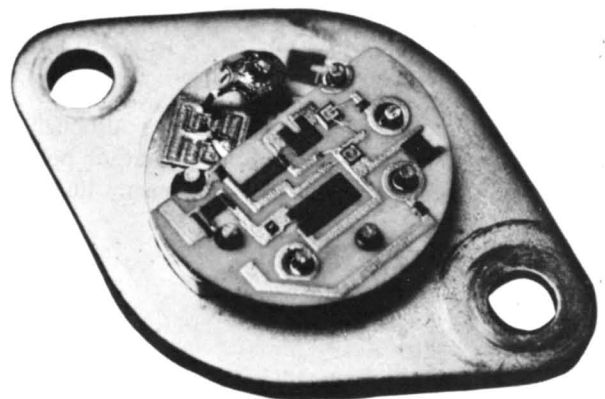

Fig. 3— *Output assembly.*

Fig. 5— *Regulator module with the crowbar circuit in place just before sealing.*

tures of the components on the substrate are determined by the temperature of the heat sink on which the regulator is mounted, and by the proximity of the components to the pass transistor. The integrated circuit (IC) is located in a cooler area of the substrate; this location minimizes output voltage drift during warm-up, because the temperature excursion of the IC is held to 75°C.
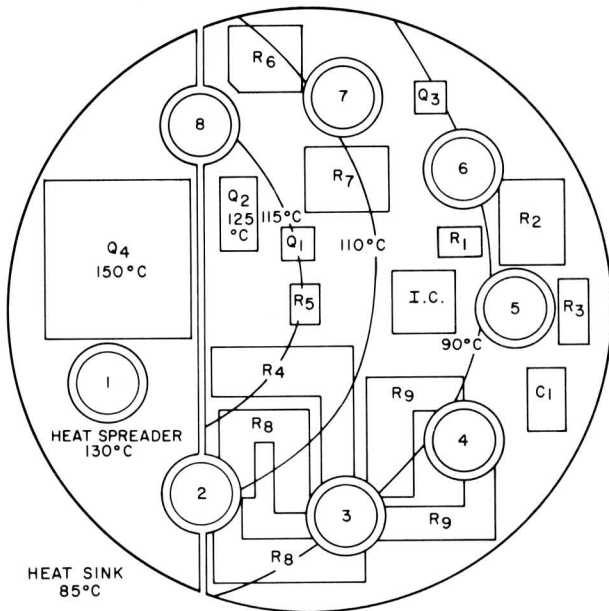

Fig. 6— Maximum operating temperature levels of the base-header assembly.

ANALYSIS OF FOLDBACK CIRCUIT

The cut-in, slope, and short-circuit levels of the foldback circuit can be derived from Fig. 7, which indicates the bridge concept of the circuit. The cut-in current can be determined from the following equation:

$$V_{BEQ3} = \frac{R_7}{R_6 + R_7} [V_{BEQ4} + I_L (R_4 + R_L)] - I_L R_L \quad (2)$$

where I_L is the cut-in current through R_L. Although the transconductance curve (Fig. 8) for the output pellet is nonlinear, the segment of interest is reasonably linear and can be expressed by

$$V_{BEQ4} = K_1 + K_2 I_L \quad (3)$$

Because the output voltage is still being regulated just before cut-in,

$$I_L R_L = V_O \quad (4)$$

Substitution of Eqs. (3) and (4) into Eq. (2) yields the following expression for I_L:

$$I_L = \frac{V_{BEQ3} + V_O - (K_1 + V_O) \dfrac{R_7}{R_6 + R_7}}{(K_2 + R_4) \dfrac{R_7}{R_6 + R_7}} \quad (5)$$

For a typical 5-volt regulator, the cut-in current is given by:

$$I_L = \frac{0.55 + 5.0 - (0.69 + 5.0) \dfrac{4.2K}{5.0K}}{(0.0525 + 0.165) \dfrac{4.2K}{5.0K}} = \frac{5.55 - 4.76}{0.183}$$

$$= 4.32 \text{ amperes}$$

The short-circuit current cannot be determined from Eq. (4) because the base-emitter junction of transistor Q3 clamps the voltage across R7. The expression for the short-circuit current can then be written as follows:

$$I_{LSC} = \frac{\left(\dfrac{V_{BEQ3}}{R_7} + I_{BQ3}\right) R_6 + V_{BEQ3} - K_1}{K_2 + R_4} \quad (6)$$

where I_{BQ3} has been determined empirically as 320 microamperes for a typical 5-volt regulator. Thus the short-circuit is given by:

$$I_{LSC} = \frac{\left(\dfrac{0.55}{5} + 0.32\right) \times 8 + 0.55 - 0.69}{0.2175} = 0.96 \text{ ampere.}$$

The slope of the foldback characteristic then is expressed as follows:

$$\frac{I_{LCI} - I_{LSC}}{V_O} = \frac{R_6}{R_7 (K_2 + R_4)} - \frac{I_{BQ3} R_6}{V_O (K_2 + R_4)} \quad (7)$$

The foldback cut-in current level can be set at values from 4.0 to 4.8 amperes, which is the upper limit for the practical range of use. However, in certain instances where the limits of temperature, power dissipation, and heat-sink thermal resistance are accurately known and where currents up to 6 amperes are necessary, the foldback sensitivity can be

reduced. This reduction is achieved by inserting an external resistance in series with terminal 7. Effectively, R6 is increased and the amount by which the cut-in current is increased can be predicted from Eq. (5) or can be found experimentally.

The limit of 6 amperes is necessary because the h_{FE} of the pass transistor drops considerably as the current increases from 4 amperes to 6 amperes, creating a borderline current level on the driver. Resistor R1 limits the load current at 6.5 amperes, although its primary function is to protect the integrated circuit from excessive currents encountered during overload. Because current-limiting results in high power dissipation, the external resistor should be trimmed for cut-in at 6.1 amperes or less when the regulator is used to deliver currents between 4.0 and 6.0 amperes.
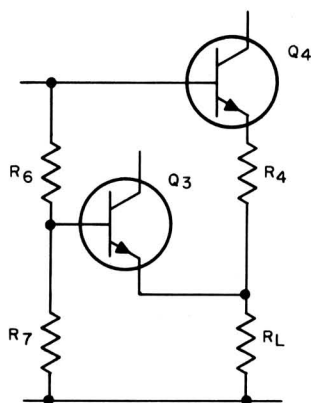
Fig. 7— Foldback bridge circuit.

POWER DISSIPATION

Maximum allowable power dissipation for steady-state operation of the HC4000 is calculated as follows:

$$P_d(max) = \frac{T_J(max) - T_C}{R_{\Theta JC}} \qquad (8)$$

where the maximum junction temperature T_J (max) is 150°C, the case temperature T_C is 25°C, and the junction-to-case thermal resistance $R_{\Theta JC}$ is 2°C/W. P_d(max), therefore, is 62.5 watts.

Actual power dissipation, P_d, is given by

$$P_d = V_{CE} I_C \qquad (9)$$

where V_{CE} is the operating collector-to-emitter voltage and I_C is the average collector current.

The p-n-p drive transistor Q2 can be used to provide drive current for external booster transistors; the additional power dissipation caused by this mode of operation must be limited to a safe value. Power dissipation in the drive transistor can be calculated as follows:

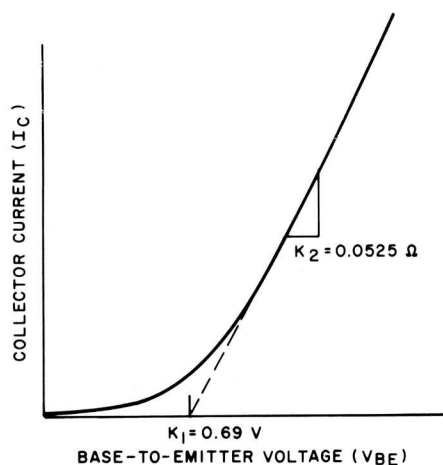$$P_{dDR} = I_{DR} [V_S - (V_o + 0.165 I_{Q4} + 0.9)] \qquad (10)$$

Fig. 8— Transconductance characteristic of pass transistor.

where I_{DR} is the base current supplied to the external boosters and V_S is the voltage supplied to the hybrid circuit. Fig. 9 shows the allowable power dissipation in Q2 as a function of its case temperature.

The worst-case power dissipation in the regulator occurs during foldback operation. Fig. 10 illustrates the foldback characteristic superimposed on the pass transistor characteristic. Power dissipation along the foldback characteristic can be determined from the following equation:

$$P_d = I_C V_{CE} = I_C [V_S - K_3 (I_C - I_{SC})] \qquad (11)$$

where

$$K_3 = \frac{V_o}{I_{FB} - I_{SC}} \qquad (12)$$

The maximum value of P_d can be found by equating its derivative to zero:

$$\frac{dP_d}{dI_C} = V_S - 2K_3 I_C + K_3 I_{SC} = 0 \qquad (13)$$

$$I_C = \frac{V_S + K_3 I_{SC}}{2K_3} \qquad (14)$$

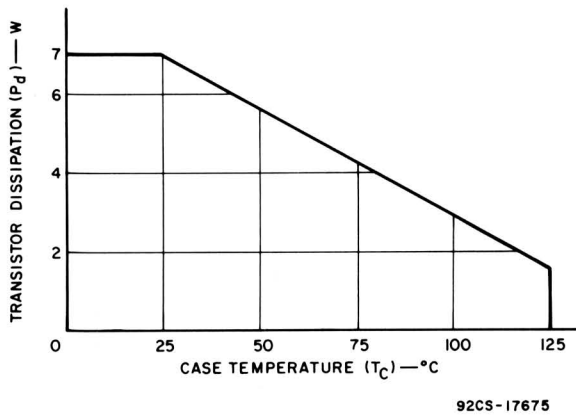$$P_d(max) = \frac{V_S^2}{4K_3} + \frac{V_S I_{SC}}{2} + \frac{K_3 I_{SC}^2}{4} \qquad (15)$$

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Fig. 9— Allowable power dissipation in driver transistor Q2 due to external drive current.

In a typical application, V_O is 12 volts, V_S is 16 volts, I_{FB} is 4.4 amperes, and I_{SC} is 1.0 ampere. Then

$$K_3 = \frac{12}{4.4 - 1.0} = 3.5$$

$$P_d(max) = \frac{16^2}{4 \times 3.5} + \frac{16 \times 1.0}{2} + \frac{3.5 \times 1.0^2}{4} = 27.2 \text{ watts}$$

$$I_C = \frac{16}{2 \times 3.5} + \frac{1.0}{2} = 2.8 \text{ amperes}$$

$$V_{CE} = V_S - K_3(I_C - I_{SC}) = 16 - 3.5\,(2.8 - 1.0) = 9.7 \text{ volts}$$

This operating condition is shown in Fig. 10. Obviously, $P_d(max)$ will occur at the foldback cut-in point for large values of V_S. The boundary condition for this value of $P_d(max)$ occurs at the level where I_C is equal to I_{FB}, which is 4.4 amperes in this example.

The thermal resistance from case to ambient, $R_{\Theta CA}$, can be determined from the following equation:

$$T_J = T_A + (R_{\Theta CA} + R_{\Theta JC})\, P_d \qquad (16)$$

$$R_{\Theta CA} = \frac{T_J - T_A}{P_d} - R_{\Theta JC} \qquad (17)$$

where T_J is 150°C, $R_{\Theta JC}$ is 2°C per watt, and P_d is the maximum power dissipation in the regulator for steady-state conditions that have a duration exceeding 4 seconds. This relationship is shown in Fig. 11 with ambient temperature T_A as a parameter. This chart can be utilized in determining the proper heat sink for each application. In some cases, the equipment chassis will be an adequate heat sink. However, lower thermal resistance can be achieved with a separate heat sink; the Thermalloy Model 6133B and Thermalloy Series 6001A-15 are recommended.
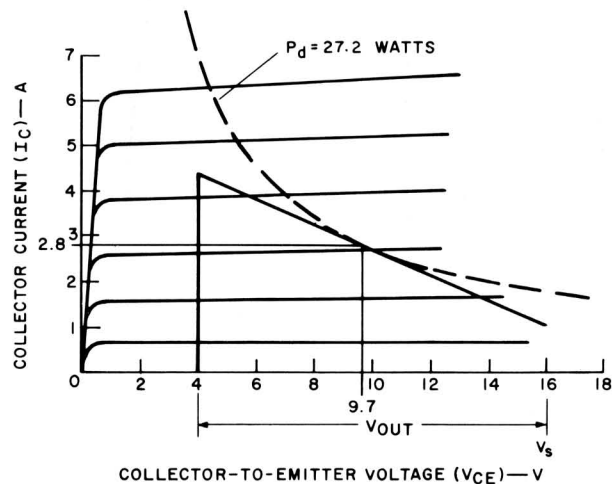

Fig. 10— Foldback and regulation load line.

OPERATING CONSIDERATIONS

Operation with External Pass Elements

The ballast resistors provide current sharing between external pass elements and the internal pass transistor. This function is shown in the 12-ampere regulator in Fig. 12, where the internal element conducts 3 amperes and each external element conducts 4.5 amperes. No serious compromise of regulator performance is caused by this method of boosting current. The external silicon controlled rectifier (SCR) for crowbar protection is also shown in Fig. 12.

Greater current capability can be achieved by utilizing the regulator in a Darlington configuration, as shown in Fig.

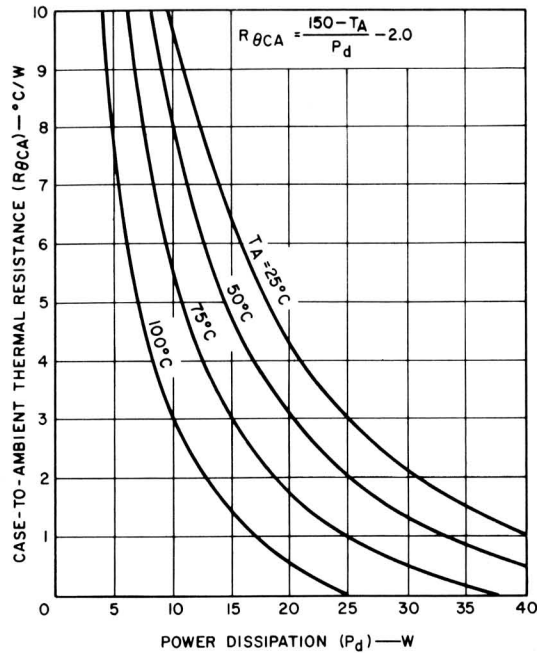$$R_{\theta CA} = \frac{150 - T_A}{P_d} - 2.0$$

Fig. 11— Heat-sink thermal resistance as a function of power dissipation at various ambient temperatures.

13. In this design the internal pass transistor drives a group of parallel transistors, the number in the group being determined by the current- and power-handling capability of the particular type. Multiplication of the 2-ampere regulator current by a reasonable group beta of 20 yields a 40-ampere regulator. The base of the external pass transistor is connected to terminal 7, the foldback sensing terminal, instead of to terminal 8. For the foldback circuit to operate properly, the voltage from terminal 7 to terminal 6 must be 1.65 volts at cut-in. To satisfy this requirement the ballast resistors must have the correct values, determined by the transconductance of the pass transistors and the desired foldback cut-in current.

The current capability of the HC4000 family of regulators can be extended above 40 amperes by addition of the external elements that were used in the 12-ampere regulator. Fig. 14 shows this method. The number of parallel transistors must be increased to provide the necessary current- and power-handling capability.

Remote Sensing

If the regulator must be located at a distance from the load, the conductors carrying the load current may contribute a significant voltage drop. This drop can bring the voltage at the load to a level below the required regulated voltage and can increase the load regulation. To avoid this condition, the regulator can be connected for remote sensing as shown in Fig. 15. The sensing current that flows into
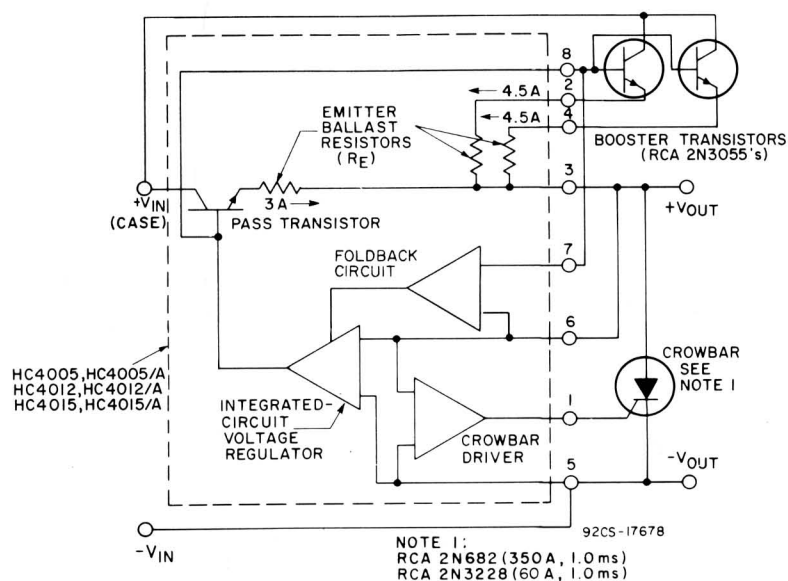

Fig. 12— RCA-HC4000 family of voltage regulator modules connected as a 12-ampere series regulator.
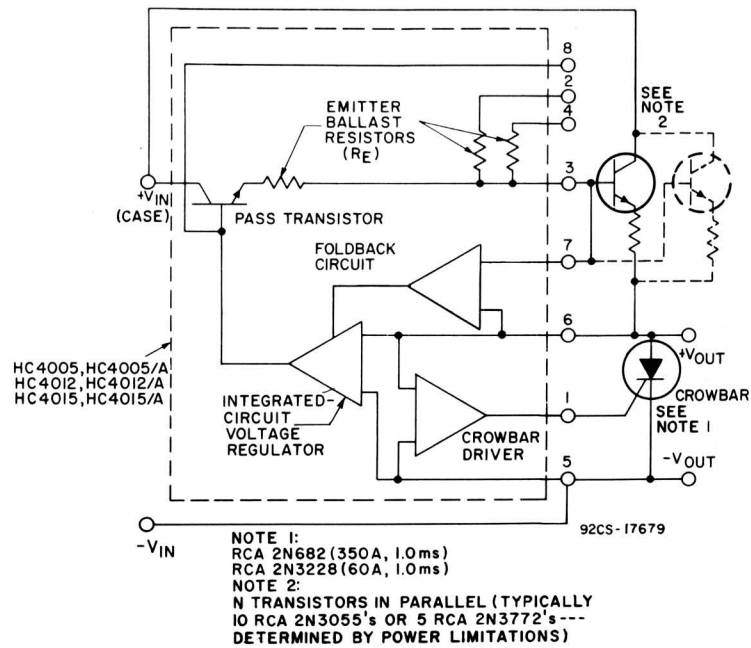
NOTE 1:
RCA 2N682 (350A, 1.0ms)
RCA 2N3228 (60A, 1.0ms)
NOTE 2:
N TRANSISTORS IN PARALLEL (TYPICALLY
10 RCA 2N3055's OR 5 RCA 2N3772's---
DETERMINED BY POWER LIMITATIONS)

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Fig. 13— RCA-HC4000 family of voltage regulator modules connected as a 40-ampere series regulator.

NOTE 1:
RCA 2N682 (350A, 1.0ms)
RCA 2N3228 (60A, 1.0ms)
NOTE 2:
N TRANSISTORS IN PARALLEL (TYPICALLY
25 RCA 2N3055's OR 12 RCA 2N3772's OR
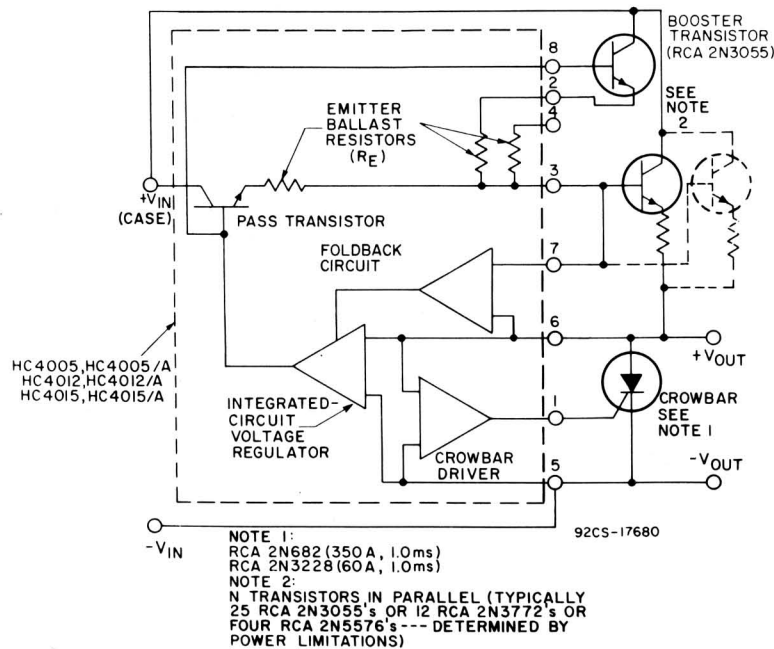FOUR RCA 2N5576's--- DETERMINED BY
POWER LIMITATIONS)

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Fig. 14— RCA-HC4000 family of voltage regulator modules connected as a 100-ampere series regulator.

terminal 6 is approximately 1 milliampere, while the current flowing from terminal 5 to ground is approximately 15 milliamperes; therefore, the voltage drop in the sensing leads is small in comparison with the voltage drop in the load conductors. Effectively, the load conductor connected on the positive side of the load becomes a resistance internal to the regulator similar to the emitter ballast resistor. The load conductor on the negative side of the load becomes a small resistance in series with the supply.
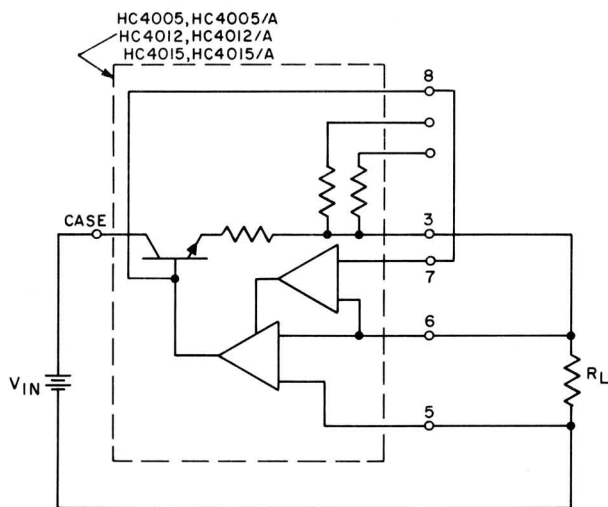

Fig. 15— Remote sensing circuit for the RCA-HC4000 family of voltage regulators.

Positive and Negative Voltage Regulation

A significant number of systems require both positive and negative voltages referenced to one particular ground. Regulated negative voltages can be provided by a negative regulator that is specially designed for that application; however the HC4000 devices, although they are positive regulators, can also provide regulated negative voltages when connected in the manner shown in Fig. 16. Regulator No. 1 provides an output voltage that is positive with respect to ground. Regulator No. 2, which is the same type of device (although any positive regulator could be used here), provides an output voltage that is negative with respect to ground. This technique requires a separate secondary winding on the power transformer to provide isolation between the two circuits.

Any number of positive regulators, regardless of output voltage, can be connected in this manner provided that there is only one common point such as ground. Use of a negative regulator eliminates the need for a separate secondary winding and full-wave bridge, but usually requires almost double current capability for the single secondary winding and full-wave bridge. For this reason, the cost of the system

that uses positive and negative regulators has only a small advantage over the system that uses all positive regulators to obtain both positive and negative regulated voltages.
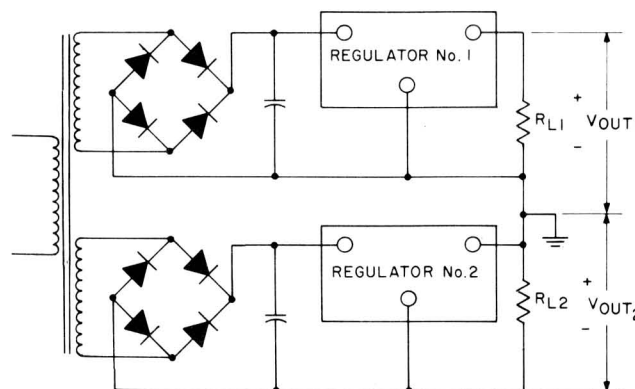

Fig. 16— Positive and negative regulation using the RCA-HC4000 family of voltage regulators.

Five-Volt Ten-Ampere Power Supply

A five-volt ten-ampere power supply is shown in Fig. 17. All of the external components were obtained from parts on hand, which explains the choice of a transformer with a 12-volt secondary. A better choice for the secondary voltage can be determined from the following equation:

$$V_{IN}(NOM) = 1.18(V_O + V_{pass}(min) + 0.5\ V_{RIPPLE}) \qquad (18)$$

This value allows a tolerance of ± 15 per cent on the average full-wave rectified secondary voltage that is identified as V_{IN}. The output voltage from this supply varies by only 2 millivolts from no-load to full-load, and by only 1 millivolt when the input voltage varies by ± 15 per cent.

Assembly and Handling

Because the collector of the power transistor in an HC4000 is connected directly to the case, some means of electrical isolation from the chassis must be provided during assembly. Isolation is usually achieved with a thin mica insulator made especially for the "8-lead TO-3" package. The resulting thermal impedance is typically 0.4°C/W.

Soldering to the terminal pins of the "8-lead TO-3" package, shown in Fig. 18, is not recommended except within the time and temperature limits specified on the data sheet. The reason for these limits is that the excellent thermal conductivity of the pins may transfer excessive heat to internal components and materials, causing immediate failure or compromising the life of the device. To avoid
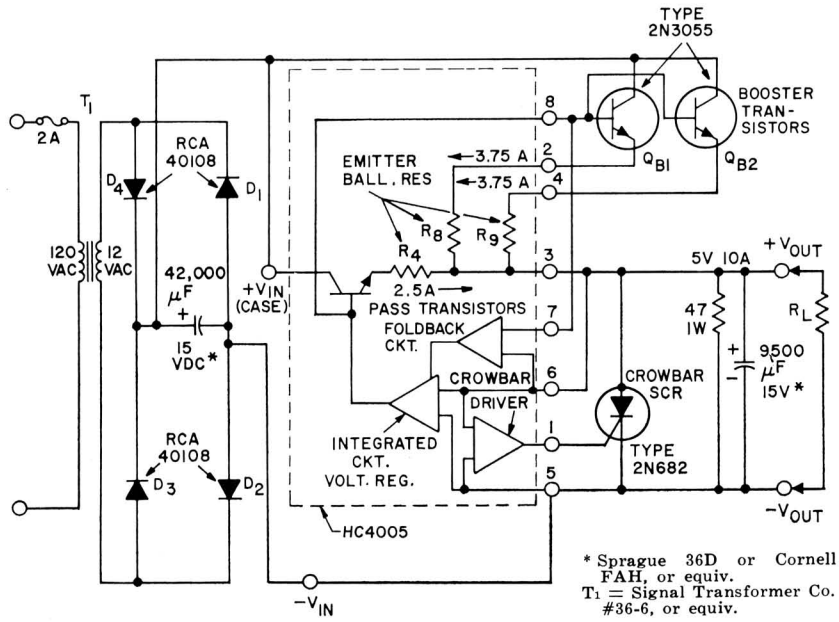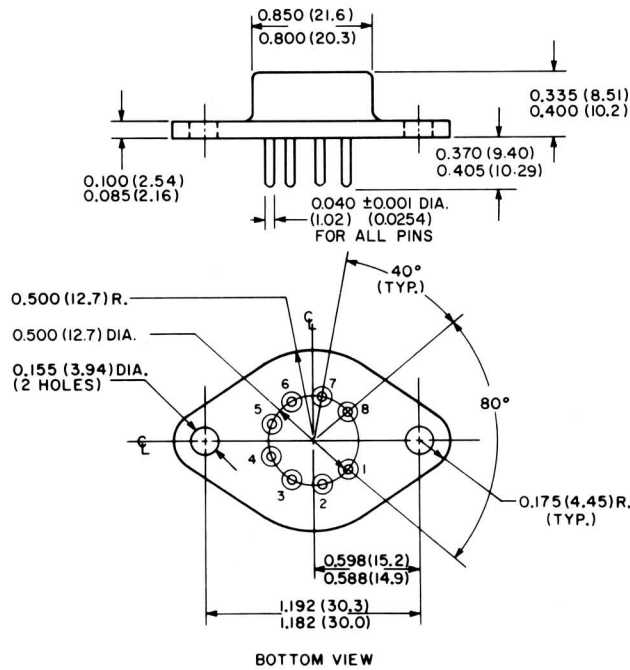
Fig. 17— A 5-volt 10-ampere supply that uses the RCA-
HC4005 voltage regulator.

BOTTOM VIEW

DIMENSIONS IN INCHES AND MILLIMETERS.
MILLIMETER VALUES IN PARENTHESES.

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Fig. 18— The "eight-lead TO-3" package used for the
RCA-HC4000 family of voltage regulators.

soldering to the pins, an "8-lead TO-3" socket* can be mounted on the heat sink or chassis, and solder connections made to the socket lugs.

For an HC4000 mounted on a heat sink, the thermal resistance can be reduced substantially by use of silicone grease or a silicone heat-sink compound such as Dow Corning 340.

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*Socket RCA DF-263A.

Cutting or bending of the pins is not recommended because these operations may crack the glass seal and thus destroy the hermeticity of the package.

REFERENCES

1. R. Engler and W. Peterson, "Design Considerations for a Hybrid Power Series Regulator", Proceedings of the 21st Electronic Components Conference, May, 1971.
2. "A 60-Watt, 20-Volt Regulated Power Supply Using a Single Pass Transistor", RCA Application Note AN-4558.

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