# STABLE, LOW-COST REFERENCE POWER SUPPLIES

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*Design of a "standard" voltage supply for small laboratories or shops, using economy-grade transistors as temperature-compensating diodes. May be used as a d.c. or a.c. calibrator to monitor small voltage changes.*

A VERY stable voltage source of known value can be a useful addition to any lab or shop. It can help you calibrate instruments or serve as a comparison to monitor very small voltage changes. Imagine having your own complete reference supply with the following characteristics: 1. Temperature coefficient less than 0.002%/°C; 2. Operating stability better than 0.03% even with line-voltage fluctuations of ±15%; and 3. Warmup time less than two minutes.

The least expensive unit you could buy would cost far more than the components for the basic unit described here. Even if you buy all the parts new, you will spend less than $10.00. The secret of its low cost is in utilizing one characteristic of some economy-grade transistors.

### Basic VR Diode Regulation

Let's start by looking at the diode VR (voltage regulator) circuit of Fig. 1. Voltage supply $V_1$ and resistance $R1$ establish bias current $I_1$ through the VR diode according to the operating load line drawn on the diode's characteristic curve.

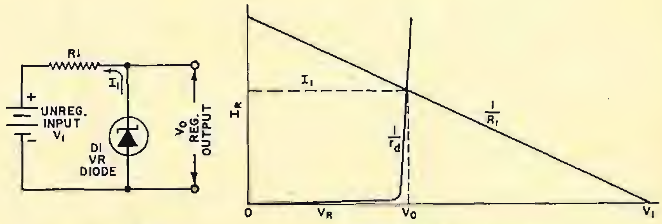
We would like to obtain an output voltage, $V_O$, which remains constant. Two sources of output-voltage variation or error are input voltage and operating temperature. Let's see what we can do to reduce output error, even though input voltage or operating temperature may vary.

First, consider what happens as the value of unregulated input voltage $V_1$ is changed. If $V_1$ increases, the load line just assumes a new position—parallel to the former one and above it. The result is an increase in current flowing through the diode, which causes a slight increase in the voltage drop across it. The change in $V_O$ will equal the product of the current change times $r_d$, the dynamic resistance of the diode.

To reduce the output-voltage variation, we might try reducing $r_d$. For a particular VR diode, we could increase bias current $I_1$ since $r_d$ is somewhat a function of bias current. Unfortunately, this would just cause a larger variation in $I_1$ with any change in $V_1$ so we would gain very little improvement in the control of $V_O$. We might also try decreasing the slope of the load line. This would necessitate a higher value of $R1$ and a higher value of $V_1$. However, if the percentage of variation in $V_1$ remained the same, we would still gain little. We need a better way.

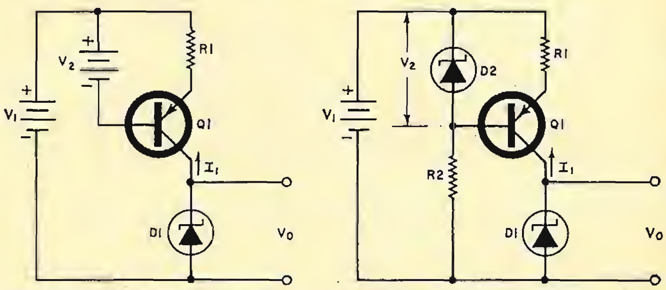
We can replace $R1$ with a constant-current device such as the transistor circuit of Fig. 2. As long as we keep voltage $V_2$ constant, the emitter current of $Q1$ stays at a fixed value. If the current gain of $Q1$ is relatively high, collector current is just about equal to emitter current and also remains constant. In a practical circuit, $V_2$ can be developed by a second VR diode—$D2$ in Fig. 2B.

The second source of output-voltage variation in the basic regulator circuit of Fig. 1 is the temperature co-




(A) SIMPLE CIRCUIT (B) OPERATING CHARACTERISTICS

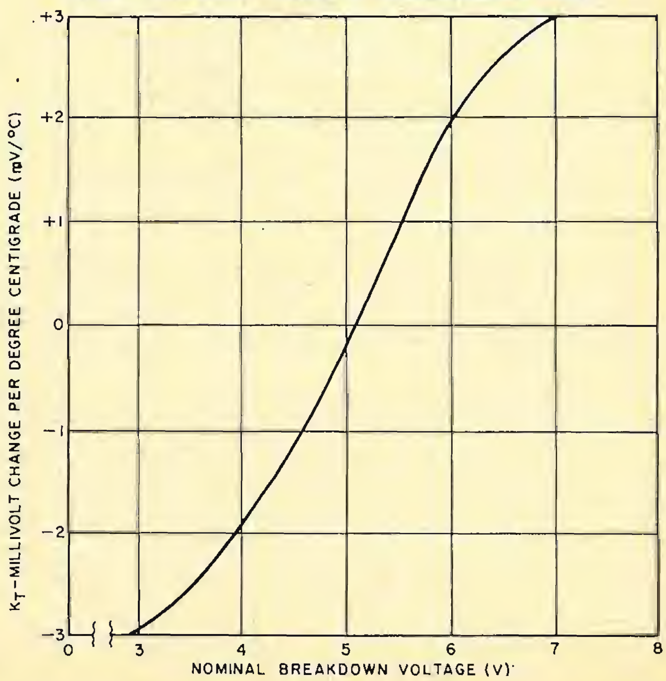
**Fig. 1. The simplest diode-type voltage regulator circuit.**




(A) BASIC CIRCUIT WITH ADDITIONAL FLOATING SUPPLY (B) CIRCUIT USING A SECOND VR DIODE TO DEVELOP $V_2$

**Fig. 2. Adding constant-current regulation for bias current.**

**Fig. 3. A graph of temperature coefficient versus breakdown voltage. This curve is typical of voltage-regulator diode.**



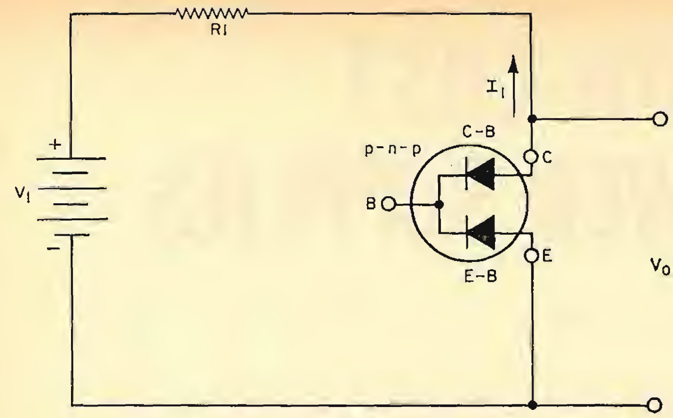



Fig. 4. Any transistor is equivalent to two diodes, back-to-back. A temp-compensated regulator is in circuit like this.

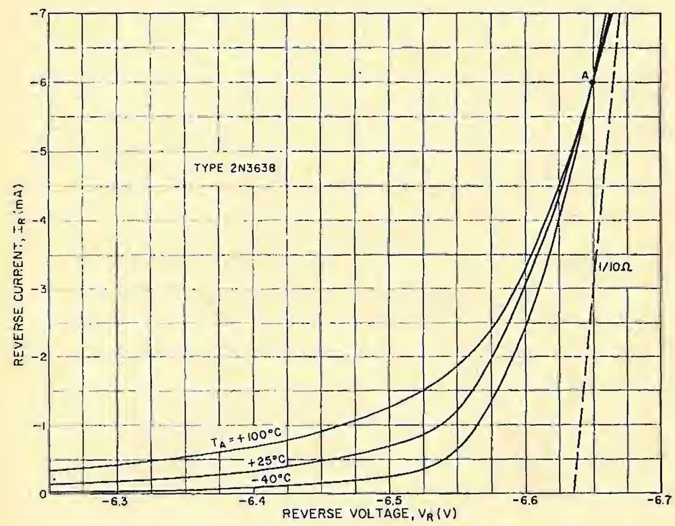



Fig. 5. At crossover point A, temperature coefficient is zero.

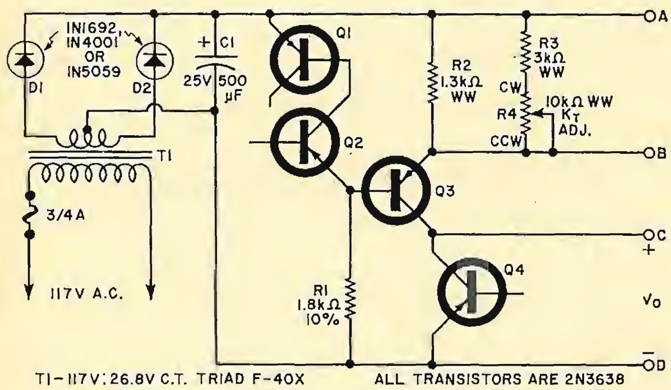



Fig. 6. Basic regulator circuit with 5-volt constant output.

efficient of the VR diode. The value and polarity of this temperature coefficient (or $K_T$), normally expressed in millivolts per degree centigrade (mV/°C), depends on the diode breakdown voltage. Fig. 3 shows a graph of typical values.

Very-low-voltage diodes (less than about 5 volts) exhibit a negative $K_T$, while higher voltage units have a positive $K_T$—one whose value increases with breakdown voltage. It is possible to find VR diodes, with just the right breakdown voltage, which show almost zero $K_T$ over a wide range of temperatures. However, you can't just go to a distributor and buy them. Besides, the cost of even "economy" VR diodes is considerably higher than for the plastic-encapsulated transistors we will discuss in a moment.

There is another solution to the temperature-error problem. Since budget limitations of the small lab or the experimenter preclude purchasing temperature-compensated VR diodes, we might consider constructing a temperature-compensated diode of our own. Let's see what is involved.

## Temperature-Compensating a Diode

The basic temperature-compensation procedure consists of intentionally introducing a temperature error which is exactly equal in value but opposite in sign to that inherent in the diode.

As shown in Fig. 3, VR diodes with breakdown voltages greater than about 5 volts have a positive $K_T$, *i.e.*, the voltage drop across the junction *increases* with increasing temperature. It is also a fact that an ordinary forward-biased silicon diode has a *negative* $K_T$ (voltage drop across it *decreases* with increasing temperature). The value of $K_T$ may be between 1 and 2.5 mV/°C, depending on the level of bias current $I_1$ in relation to the area of the junction.

In a commercial temperature-compensated unit, a VR diode is carefully mated with a forward-biased diode having just the right $K_T$ at the desired current level. The two diodes are then carefully tied together inside the same package to make sure both operate at exactly the same temperature.

Generally speaking, making such carefully compensated VR diodes is beyond the capability of the small lab. Even if we were to find two well-matched diodes we could not put them in the same package, and performance over a range of temperatures would be only fair, at best.

Don't give up, though. Fortunately, the emitter-base (E-B) junction in a *p-n-p* diffused silicon planar epitaxial transistor has a breakdown voltage typically between 6 and 7 volts. We can use it, then, as our VR diode. This is in the proper range to have a $K_T$ of approximately +2 mV/°C. All we need to go with it is a forward-biased diode that we can place in very close contact with the E-B junction we are using as a VR diode. We *have* another diode—the collector-base (C-B) junction. It is about as close to the E-B junction as it can be.

What happens if we connect the terminals of the transistor as shown in Fig. 4? (The *p-n-p* transistor is shown symbolically as a two-diode equivalent, which it is.) The C-B diode is forward biased and the E-B diode is reverse biased. If $V_1$ is large enough, the E-B diode will be biased in the breakdown region by current $I_1$.

The processes used in making this type of transistor are generally controlled with care. As a result, both diodes are uniform from unit to unit of the same type. As a matter of fact, measuring the collector-emitter voltage on several hundred *Fairchild* 2N3638 *p-n-p* transistors with $I_1$ equal to 5 mA indicated that 92% of the units were within a spread of ±0.17 volt. This represents a tolerance of ±2.5%, which is far closer than we would likely find for a standard VR diode type. The cost is *much* less.

Fig. 5 shows the breakdown-voltage characteristic curves for a typical 2N3638 under different temperature conditions. The terminals were connected as shown in Fig. 4. Note that the curves for all three temperatures intersect at point A. This represents the optimum bias point for minimum temperature coefficient.

The bias current which yields the desired near-zero $K_T$ is of course a function of breakdown voltage. Transistors having a collector-emitter reverse breakdown of −6.6 volts at a test current of −5 mA should be biased at −7 to −7.5 mA. Current should be reduced to −4 or −4 mA for transistors with −6.8-volt breakdown.

As can be seen from the curves of Fig. 5, the $K_T$ of our unit may be controlled by varying the bias current slightly. This makes it possible to *adjust* the $K_T$ to a very low value. Notice that as long as the bias current for a typical unit of Fig. 5 is maintained within a ±10% spread, we still get a $K_T$ of less than 0.001%/°C!

To achieve the very low temperature coefficient of which this approach is capable, it is also necessary to control the $K_T$ of the bias current since this could create a temperature error greater than the one compensated for. To meet the 0.001%/°C performance stipulated above, we must keep the level of bias current within 0.1%/°C. If we carefully adjust the current through our home-brew compensated VR diode, we can produce an intentional temperature error which is equal in size but opposite in sign to the net sum of any other temperature errors. The result can be a very tight $K_T$ for the package.

### Operating Circuits

A practical circuit for a stable reference supply is shown in Fig. 6. $Q1$, $Q2$, $Q3$ and $R1$, $R2$, $R3$, $R4$ make up the constant-current bias source for $Q4$ which is the transistor being used as our temperature-compensated VR diode.

In order to produce a bias current that is stable with temperature, the E-B diode of $Q1$ (biased in a forward direction) and $Q2$ compensate for any change in $V_{BE}$ for $Q3$. The net voltage across $R2$ therefore remains constant with temperature.

$R4$ provides a means of adjusting the temperature coefficient of the over-all supply by varying the bias current. A lower-than-optimum bias current gives a negative $K_T$ while a higher value yields a net positive $K_T$.

Resistors $R2$ and $R3$ should be wirewounds to prevent temperature problems. They need not be precision units—in fact, *Ohmite* "Brown Devil" power resistors will work quite well.

Terminals A and B are provided to compensate for external loading. If, for example, a load resistance of 10,000 ohms is to be tied to the output, we can make the bias current through $Q4$ constant (and thus hold the output voltage) by increasing the current output from $Q3$. This is easily done by connecting a resistor, of the same type and value as the load, between A and B. This technique not only allows for correction of most output-voltage error which might result from loading, but also keeps the $K_T$ of the output voltage constant. Load resistances down to about 2500 ohms are practical.

The basic reference supply in Fig. 6 provides a very stable voltage of approximately 6.7 volts at an output resistance of approximately 10 ohms. Adding one of the output circuits of Fig. 7 will permit an adjustable output voltage.

Using the simple potentiometer of Fig. 7A at the output gives us a way to vary the output voltage. We would need to compensate for the loading effects of $R5$ either by placing a 5000-ohm wirewound resistor between A and B or by changing $R2$ to 1000 ohms. The output voltage will not be calibrated but it will be very stable and thus may be used as a reference to measure small voltage changes, as will be discussed later.

By using the more elaborate output circuit of Fig. 7B, we can obtain output voltages that correspond to the readings of a multi-turn dial attached to the 10-turn potentiometer used for $R7$. (The open-circuit output voltage will be one-half the dial reading on a 0-10 basis.) Calibration potentiometer $R5$ permits us to adjust the full-scale voltage to exactly 5 volts. For the output voltage to be accurate, no appreciable loading of the output is permissible. Maximum output resistance is approximately 1700 ohms.

Fig. 8 shows a circuit that permits 0-10 volts output. The open-circuit output voltage corresponds exactly to the dial reading of the counter associated with $R7$. Two home-made temperature-compensated VR diodes are connected in series to permit the higher output voltage. The maximum output resistance is 3300 ohms.

### Construction Hints

Before assembling your reference supply, measure the breakdown voltage of all the 2N3638 transistors. Use the circuit of Fig. 4 with $V_1 = 22\frac{1}{2}$ volts and $R1 = 3300$ ohms.

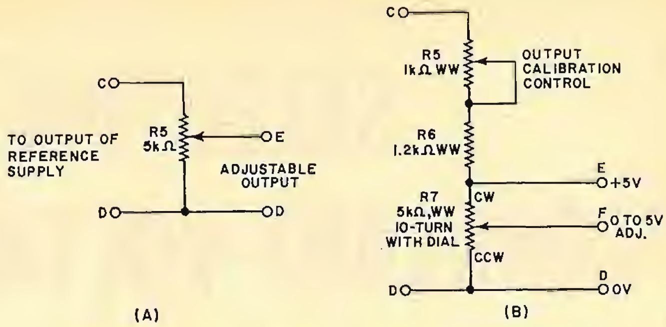



Fig. 7. Output circuits for reference supply. (A) Simplest version. (B) Precision-type output control with calibration.

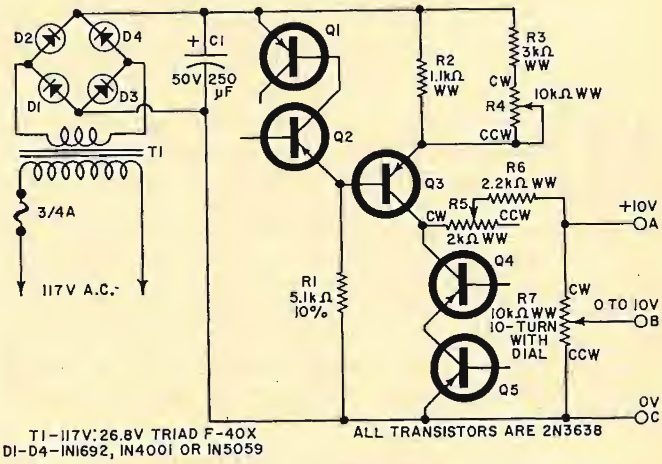



Fig. 8. Complete 10-volt constant-voltage reference supply is independent of temperature, due to low-cost transistors wired as temperature-compensated voltage regulator diodes. Parts for elaborate version cost under $25, with a precision dial.

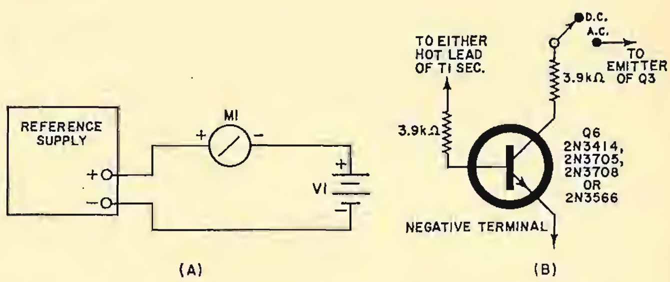



Fig. 9. Accessories. (A) Hookup to adjust temp-compensation pot. (B) Chopper circuit, so supply can make a.c. measurements.

This allows you to spot any maverick units by making sure the breakdown voltages of the transistors to be used as temperature-compensated VR diodes ($Q4$ in Fig. 6 and $Q4$ and $Q5$ in Fig. 8) are between 6.55 and 6.75 volts.

Circuit layout is not critical, although best performance is obtained when all the transistors are mounted close together so they operate at the same temperature.

### Calibration and Adjustment

Precise adjustment of temperature coefficient can be accomplished while monitoring the output voltage as ambient temperature is varied. Fig. 9A shows a possible test arrangement. $V_1$ must be a relatively stable power source, at least during the test. $M1$ is a v.o.m. set for its lowest current range. Be sure to get the polarities of the meter and the supplies correct. The reference-supply output should be adjusted until the two values are exactly equal (no meter deflection) at room temperature.

Now place the power supply in an oven which has been heated to about 100°C (212°F on your wife's oven control) and allow it to stabilize for 5 to (*Continued on page 79*)

## Reference Power Supplies

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10 minutes. Do not change the output voltage setting of the reference supply, and make sure the temperature of the $V_1$ supply hasn't varied much.

Note which direction the change in reference-supply voltage takes, if it changes, to determine which way you should adjust $R4$. If the output voltage *increased* in value, indicated by an upscale reading on $M1$, then you have a *positive* temperature coefficient which may be corrected by *decreasing* the bias current. This is done by turning $R4$ counterclockwise.

The procedure is repeated until you obtain the desired $K_T$. The adjustment isn't critical unless you want the ultimate in temperature stability. In fact, you would probably get an $K_T$ of less than 0.003%/°C by just setting $R4$ to center position or replacing $R2$, $R3$, and $R4$ by a single 1000-ohm wirewound resistor.

Precise voltage calibration requires an external voltmeter of adequate accuracy. If one is not available, you can obtain fairly good results by using three 1.345-volt mercury cells in series for $V_1$. Set the reference-supply dial to 4.035 volts and adjust the calibration potentiometer for a zero reading on $M1$.

A typical application of this type of supply is to permit monitoring a small fluctuation in voltage. The arrangement used is the same as shown in Fig. 9A. Initially, the reference-supply output is adjusted to give a zero reading on $M1$. Now any variation in the $M1$ reading indicates a change in voltage, $V_1$. The value of the change will be indicated on $M1$ directly. With my v.o.m. used for $M1$, I can see a change of less than 2 mV out of 10 volts; that's a 0.02% change!

With the voltage output calibrated, the arrangement may be used as a differential voltmeter to measure any unknown source under practically no-load conditions. Again the configuration of Fig. 9A is used. The output of the reference supply is adjusted until $M1$ reads zero. The value of the unknown voltage is read from the dial of the reference supply.

Calibrating voltmeters, recorders, or d.c. oscilloscopes is a snap when the output voltage of the reference supply is accurately known. You can add the simple chopper circuit shown in Fig. 9B to your supply. It permits calibrating a.c. voltmeters or scopes with a peak-to-peak square-wave voltage whose value is equal to the output of the reference supply. If you include this feature in your packaged unit, provide a switch to remove the chopper when you use the supply as a d.c. reference. ▲