Design Your Own Regulated POWER SUPPLY

New IC regulators are so inexpensive and easy to use that you can build a regulated, short-circuit proof power supply for less than the old unregulated kind

INTEGRATED-CIRCUIT VOLTAGE REGULATORS have been around for quite a while, but they have been expensive and have needed lots of "outboard" parts to get them to work. Today, there's a new breed of voltage regulators here. These are low in cost ($2–5 in singles), very easy to use, and take very few outside additional parts. Some directly handle up to ¾ of an amp; others easily handle an amp or more with external pass transistors. Some are fixed-value outputs; others are variable. Some are dual pairs that give you two output voltages (one positive, one negative) out of the same package.

Why bother to regulate a power supply? For openers, the hum essentially disappears. Besides a rock-stable output voltage that is independent of temperature, line, or load variations, most designs are also short-circuit proof, shutting down or current limiting automatically. This protects the regulator and the supply against damage from shorts, and the current limiting will usually (but not always!) also protect the load from damage caused by wrong biasing or polarity mixups. Finally, a regulated power supply may actually be *cheaper* than an unregulated one, particularly if you need very low hum on the supply lines. This happens because you can usually use a much smaller filter capacitor. For instance, if you wanted a 5-volt, 200-mA supply with less than 20 millivolts of ripple, single capacitor "brute-force" filtering might take around a 80,000 μF capacitor. With a regulator, you might design a power supply with a 16-volt output and four volts of peak to peak ripple, and do the job with a 400-μF capacitor, with the regulator absorbing the "lumps" and giving a smooth output. Often times, the difference in capacitor cost is greater than the price of the regulator, particularly if the capacitor makes the case bigger, and regulated supplies can be cheaper than unregulated ones.

Of course, the problem with any power supply design is figuring out what size and voltage transformer you need, where to get it, what size capacitor to use, and how much fusing to provide. After that, we can tack a regulator onto the output.

Start with an unregulated power supply

Let's assume you're interested in output voltages that are low compared to the 117-volt power line, and are interested in currents between 50 mA and an ampere or two. Let's also assume you are working with a 60-hertz, single-phase power line, as usual. For this particular type of power requirement, the transformer-coupled, full-wave capacitor-input circuit of Fig. 1 is recommended.

The transformer drops the voltage to a chosen value and provides safety isolation. When its anode is positive diode D1 conducts and charges capacitor C. On the next half-cycle, diode D2 conducts and charges capacitor C. If there isn't too much load on the capacitor, it doesn't discharge very much between cycles and so the conduction time of each diode turns out to be *very short*. Very high currents flow very briefly during the diode conduction time and the current to the capacitor is delivered in narrow spikes. The amount of the current and the time width of the spikes depend on the load, the capacitor, and the internal resistance of the transformer, but the time spacing between the spikes is precisely half of a 60 hertz power line cycle, or a time period of 8.33 milliseconds.

Figure 1 also shows the waveform at the capacitor and the load. It is essentially a fixed dc value from which a *sawtooth* waveform is subtracted. The frequency of the sawtooth is 120 hertz (for a full-wave rectifier), and its depth depends on how fast the capacitor discharges. The greater the load for a given size capacitor, the more the capacitor can discharge between the charging current spikes and the higher the sawtooth ripple.

There are two other possible circuits, the half-wave single diode one, and the full-wave one using a single (untapped) transformer winding and a bridge rectifier. The half-wave circuit takes twice the capacitor size and has twice the peak diode current. It also takes a bigger transformer as unbalanced currents and a resultant dc flow through the transformer windings. The full-wave circuit takes four diodes instead of just two and presents an additional diode drop between load and transformer. Besides this, you can only get one voltage from any given winding, while the Fig. 1 circuit can easily get you several voltages since the transformer center tap is grounded. Thus, unless you have a good reason not to, stick with the center-tapped.

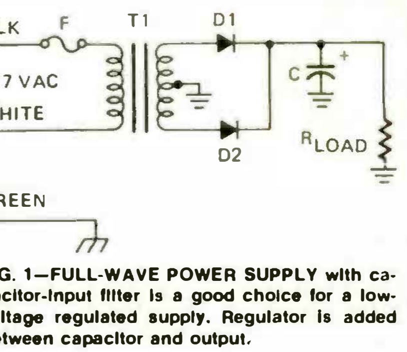

FIG. 1—FULL-WAVE POWER SUPPLY with capacitor-input filter is a good choice for a low-voltage regulated supply. Regulator is added between capacitor and output.

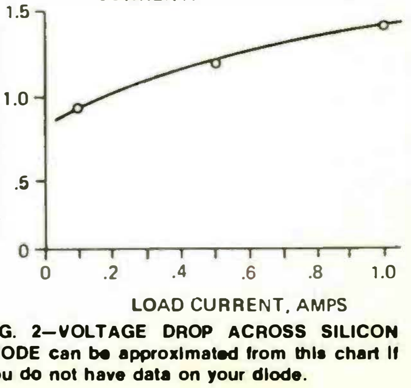

FIG. 2—VOLTAGE DROP ACROSS SILICON DIODE can be approximated from this chart if you do not have data on your diode.

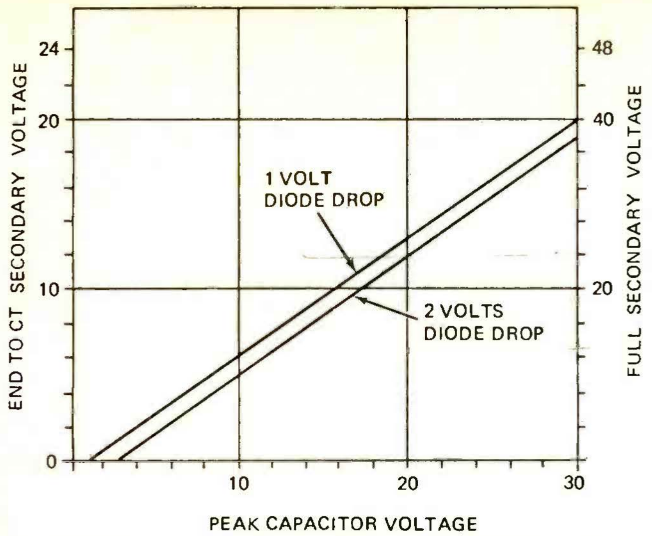

FIG. 3—TRANSFORMER VOLTAGE VERSUS CAPACITOR VOLTAGE. Remember that actual transformer secondary voltage depends on the power-line voltage level and the magnitude of the load.

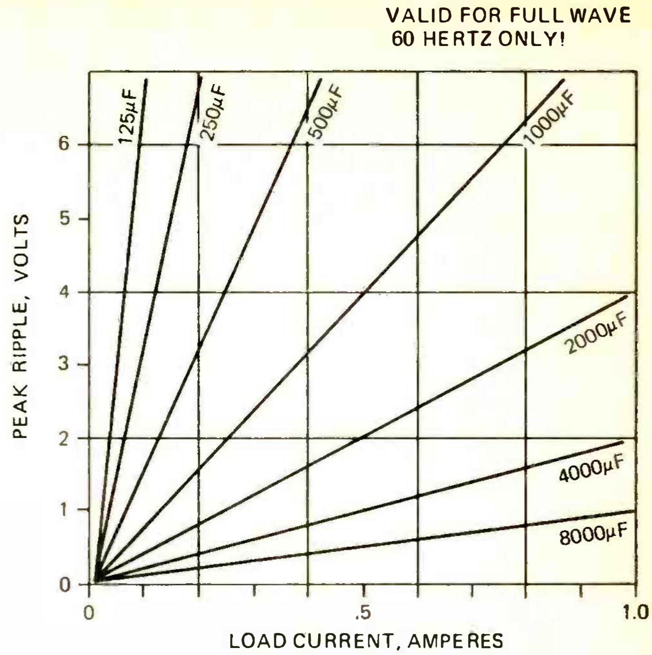

FIG. 4—PICKING THE FILTER FOR LOAD AND RIPPLE. Chart is valid for full-wave, 60-Hz supply only. Note that ripple varies inversely as capacitor value.

two-diodes, full-wave, capacitor-input circuit of Fig. 1.

Some numbers

There is no obvious "one-to-one" relationship between the transformer voltage and the output voltage. You do **not** get 6.3 volts of dc output from a 6.3-volt center-tapped-transformer, or 12.6 volts from a 12.6 one and so on. While the game isn't *quite* this simple, it is easy to calculate the voltages you need for a given output.

Let's try the calculation "frontwards" first. Suppose you had a 6.3-volt rms center-tapped transformer, and to keep things simple, suppose further that the *regulation* of the transformer itself is very good, which is another way of saying the transformer can handle the load we want it to.

Each half of the 6.3 volt winding will be providing half of 6.3 volts or 3.15 volts. This is the rms ac value. We need to find the *peak* value, for this is what charges the capacitor through the diode. The peak value is 1.41 times the rms value or 3.15 × 1.41 = 4.45 volts. (Note you can "speed math" this calculation by taking one-tenth the rms voltage, doubling it, doubling it again, and then adding the original voltage to it.)

If the diodes were perfect, we'd get a capacitor voltage of 4.45 volts. The diodes have a conduction drop, and quite a bit more than you might expect, since, *when* they are conducting, they carry *ten* to *twenty* times the average load current. Remember that the diodes only conduct briefly. If they are only on for 1/10 the time, they have to conduct ten times the current the load needs.

The accurate way to find the voltage drop is to use a data sheet for the particular diode you are using and calculating the actual conduction angle, which is a pain. Figure 2 gives you a curve that is exactly valid for a 1N4000 series diode and a conduction time of 1/10 a complete cycle. This is close enough so long as you are using any reasonable silicon power diode. From Fig. 2, we see that the drop will be around a volt for lower currents; let's use this figure. The diode drop subtracts from the available voltage, so the voltage across the capacitor is 3.45 volts. This is a peak value, from which we subtract the ripple voltage.

Figure 3 is a chart that relates the transformer voltage to the filter capacitor voltage for several values of diode drop. Use the chart directly or else use the following rules:

To find the peak output voltage:

1. Start with the transformer secondary rms voltage
2. Divide by two to get the center-tapped voltage
3. Multiply this by 1.4 to get the peak value
4. Subtract the diode drop, estimated from Fig. 2, or subtract 1 volt for lower current operation.

To find the transformer voltage:

1. Start with the peak capacitor voltage.
2. Add the diode drop
3. Multiply by 0.707 to get the rms value
4. Double this for the center-tapped rms value

It turns out that you always design for much more output voltage than you really need if you are using a regulator. The regulator has a minimum *dropout* voltage above its output it needs for proper operation. The maximum voltage is limited by regulator breakdown or power dissipation. We'll see more on this in just a bit, but first. . . .

What size capacitor?

The size of the filter capacitor and the maximum load current determine the amount of sawtooth ripple you get. The accurate analysis of this is also a pain. We can make a very good approximation if we assume our ripple sawtooth voltage recharges very fast and decreases linearly. This both simplifies the math and puts us on a conservative side of things.

With this simplification, the relationship between the load current and the capacitor size is given by:

$$\text{Load current} = \frac{V_{load}}{R_{load}} = \frac{C\times\Delta V}{8.33\times10^{-3}}$$

where:
V_{load} = Load voltage, volts
R_{load} = Load Resistance, ohms
ΔV = Ripple in volts
C = Capacitance in *farads*

Even this is a messy and confusing formula. Figure 4 gives it in graphical form. A simple way to forever remember how to calculate capacitor size is:

Use an 8000-μF capacitor and the ripple in VOLTS will Equal the current in AMPS.

Use an 8-μF capacitor and the ripple in VOLTS will Equal the current in MILLIAMPS.

Double the capacitor to halve the ripple and so on. For instance, with our rule, a 4000-μF capacitor gives us 1 volt of ripple at 500 mA, and so on. Rules-of-thumb like we are giving you may not be exactly accurate, but they are quick, easy, and they *work*. And that's all we need to worry about.

Picking the parts

The choice of a capacitor isn't too hard to make—use the best quality electrolytic you can afford, of a voltage rating at least equal to, and preferably double your output voltage. Ordinary computer-grade aluminum electrolytics are a good choice. Tantalum capacitors are an expensive luxury unless you happen on to some surplus units or are going to put your circuit into orbit. Silicon power diodes are tough and readily available. Use the 1N4001 or 1N5060 or their surplus equivalents for the 1-amp or less applications. For higher currents, use the 3-ampere diodes such as a 1N5624 or a 1N4721 or something larger.

These diodes run very hot. Their leads should be short and routed to some sort of heat radiator such as lots of foil on a PC board, or a large terminal strip. The heat removal process is mostly by conduction—out the leads. For long diode life, provide some place for this heat to go. Phenolic PC boards may char under direct heat exposure, so the epoxy-glass versions are preferred for power supply work. Also be sure that a power diode doesn't end up in direct contact with an electrolytic or the heating can shorten the capacitor's useful life.

The maximum voltage across the diode is *twice* the *output* voltage. Use a PIV rating at least double this. If in doubt, go to a 200- or a 400-PIV unit; they don't cost that much more and may be easier to get.

This brings us back to the transformer. If you possibly can, use a stock filament transformer, as these are inexpensive and easy to get. Unfortunately, these often turn out to be rather large, particularly if you are working with compact gear, and offer only a limited choice of voltages.

One source of transformers I've found extremely handy—at twice the usual filament transformer cost—is Signal Transformers, 1 Junius Street, Brooklyn, New York, 11212. They have an incredible variety of stock very small to enormous transformers, some of which mount directly on a PC board without any hardware. For instance, a PC-mount 10-Vct transformer that can handle 120 mA, measures 1¼" square by 1½" long and sells for around $4.37, plus postage.

The input fuse and third wire ground on the supply is simply good practice. Use a slow-blow fuse whose amperage is *above* 1/50th the load *power*. For instance, a 5-volt, 1-amp unregulated supply provides 5 watts at full load. Use a 5/50=0.1 ampere unit. The actual current may be found by dividing the load power and the transformer losses by the line voltage and then making some power factor adjustments and then adding a safety factor. The 1/50th load power current (measured at the capacitor—not the regulator) formula is a lot quicker and gives the same result.

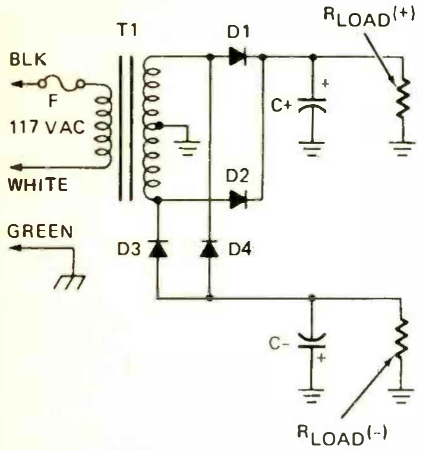

FIG. 5—NEGATIVE SUPPLY may be added to basic supply. The transformer current rating must be high enough to handle both loads.

Figure 5 shows a dual unregulated power supply, where we have added two more diodes and a new capacitor to pick up a negative voltage. You might like to use only the bottom half of this circuit if you need a negative-only supply

Adding regulation

By now, we should know how to design a power supply that has a given output voltage and a given output ripple. All we have to do now is add a regulator.

Figure 6 shows how a typical positive-only regulator may be added. The regulator senses the output voltage and then absorbs the difference between the instantaneous supply voltage and the desired output. The minimum *extra* voltage you can live with is called the *dropout voltage*, and is typically 2 to 3 volts above the regulated output voltage. Thus most 5-volt regulators need at least 8 volts to work with.

The *maximum* permissible input voltage is usually set by a breakdown limit and the allowable internal power dissipation. The load current times the extra voltage drop must be internally dissipated by the regulator. This is determined by the size of the regulator, the load, the available heatsinking, and whether external *pass* transistors are used with the regulator.

Several add-ons normally go with the regulator circuit. An output capacitor, usually in the 0.1 to 1 μF range is almost always needed for regulator stability, and it has to be a good Mylar or tantalum capacitor. The current-limiting circuitry may be internal, or you may have to add a chosen resistor to get a desired current limit. You may be able to add a voltage or a resistance to *change* the output voltage, and finally, you may be able to add external transistors to extend the current capability.

Regardless of what regulator you use, be sure and have a data sheet on hand and study it carefully. Most regulators need at least one stabilizing capacitor on the output. Almost all of the newer ones are very easy to use, but you must sit down with the individual data sheets to make sure you aren't exceeding a limit.

TABLE I
SOME LOW COST AND EASY TO USE VOLTAGE REGULATORS
(Typical unit pricing on these run from $2 to $4.)

7800 Series	Fixed voltage, positive only. To 750 mA without extra parts. 7805 is 5 V. Also available as 6 V (7806), 8 V (7808), 12 V (7812), 15 V (7815), 18 V (7818) and 24 V (7824).	
	Data Sheets from	FAIRCHILD SEMICONDUCTOR 313 Fairchild Drive Mountain View, California, 94040
	or	MOTOROLA SEMICONDUCTOR Box 20912 Phoenix, Arizona, 85036
7900 Series	Fixed Voltage, negative only. Similar to above.	
SG4501T	Dual 15 V regulator, adjustable from 8 to 24 V. To 60 mA without external transistors. 2 A or more with external transistors.	
	Data Sheet from	SILICON GENERAL INC. 7382 Bolsa Avenue Westminster, California, 92683
4195DN	Dual 15 V regulator, fixed voltage. 100 mA without external transistors. Only two external parts needed.	
	Data Sheet from	RAYTHEON SEMICONDUCTOR 350 Ellis Street Mountain View, California, 94040

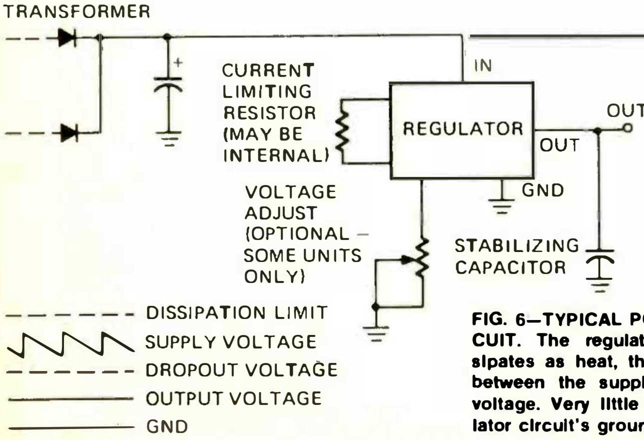

FIG. 6—TYPICAL POSITIVE REGULATOR CIRCUIT. The regulator senses and then dissipates as heat, the instantaneous difference between the supply voltage and the output voltage. Very little current flows in the regulator circuit's ground lead.

Several popular low-cost regulators are shown in Table I along with their manufacturers. Prices range from $2 to $5 if you pick the room-temperature versions and the economy package. Most data sheets have extensive applications and design information attached to them. Once again, don't try to do any regulator design without a specific data sheet on hand, for there are lots of differences between apparently similar devices.

The best way to show you how to design your own regulator circuits is with three quick examples—a fixed +5-volt 750

(Continued on page 85)

REGULATED POWER SUPPLIES
(continued from page 56)

mA logic supply, a dual plus-minus 15-volt, 100-mA op-amp supply, and finally a dual, variable, 1-amp supply you can use for general lab use. If these basic circuits can't be used directly, you should be able to adapt them to fit your custom needs pretty well.

The 5-volt, 570 mA logic supply: We'll use the fixed 7805 positive regulator for this. It internally current limits at 750 mA and should be just what we need for a TTL or DTL system power supply. The dropout voltage is 2 volts. The maximum power dissipation at room temperature with a good heatsink is slightly over 5 watts. This means the maximum permissible voltage *across the regulator* is 5/0.75 = 6.7 volts. For this circuit, the permissible range of supply voltage is then 7 to 11.7 volts. Let's aim for a 10-volt supply with 2-volts worth of ripple, splitting the difference on both ends.

First, our capacitor size. An 8000-μF and 1 amp would give 1 volt of ripple. Similarly, reducing capacitance and current by one-quarter would still give 1 volt of ripple, or 6000 μF for 750 mA. Halve the 6000 μF for double the ripple, or 3000 μF for 2 volts of ripple. We can probably cheat just a bit and get by with a 2500-μF, 15-volt electrolytic.

Output voltage at the capacitor, in absence of ripple, should be 10 volts. Add a volt for the diode to get 11 volts. Multiply
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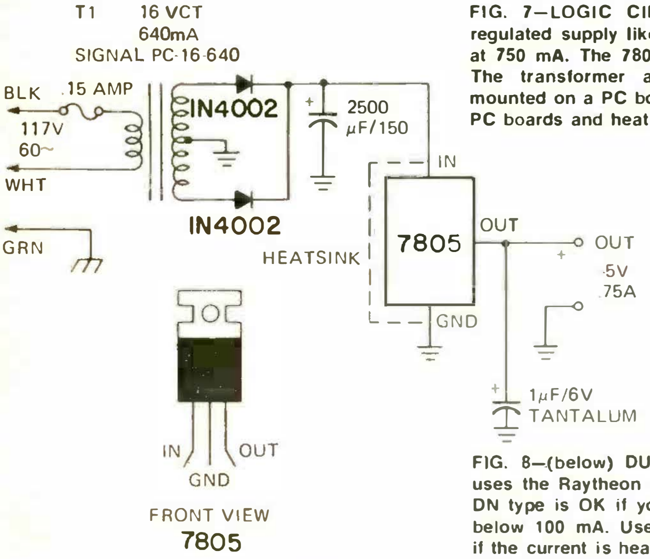
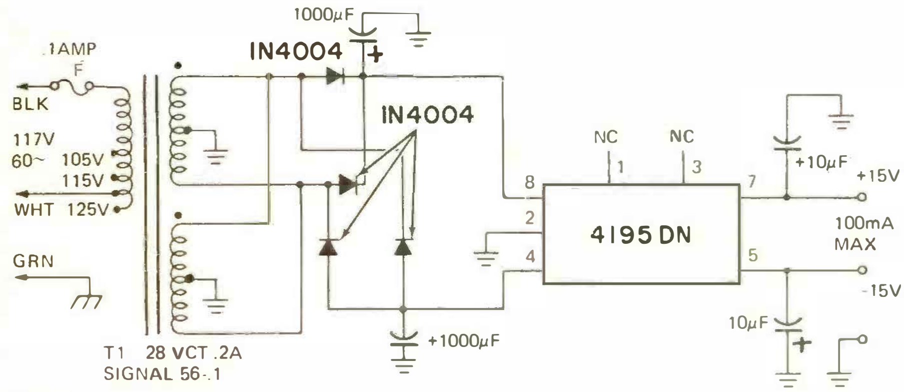


FIG. 7—LOGIC CIRCUITS often require a regulated supply like this that delivers 5 volts at 750 mA. The 7805 needs a good heatsink. The transformer and other parts can be mounted on a PC board. See text reference to PC boards and heat dissipation.

FIG. 8—(below) DUAL REGULATED SUPPLY uses the Raytheon 4195 series regulator. The DN type is OK if you keep current drain well below 100 mA. Use a more rugged regulator if the current is heavy.



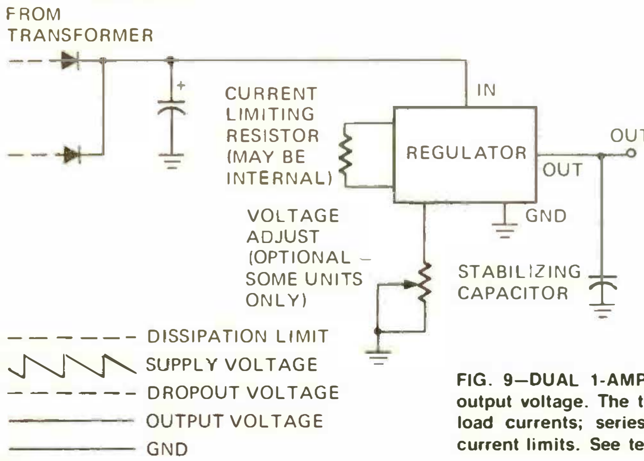


FIG. 9—DUAL 1-AMP SUPPLY has adjustable output voltage. The two transistors handle the load currents; series resistors determine the current limits. See text for details.

REGULATED POWER SUPPLIES

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by 0.707 and get 8 volts. Double this for a 16-volt center tapped transformer. We need a 16-Vct transformer at 750 mA. Let's cheat again just a bit and use a 640-mA transformer, the Signal PC16-640, 1½ × 1⅜ × 2", PC mount, and costing around $4.88, plus postage.

Figure 7 shows the circuit. A high quality 1-μF, 6-volt tantalum is used on the output for stability. The output power measured at the capacitor at maximum load is 10 volts × .750 ampere = 7.5 watts. The fuse should be 7.5/50 amp = 0.15 ampere. Load current limiting is automatic and internal. Any reasonable-sized standing-up type of heatsink can be used, or the regulator may be bolted to the case (be sure to insulate it!).

If we wanted a negative supply instead, there's several things we could do. If we *only* want a negative supply, simply call the +5 line "ground" and the common line "-5". Note that if we do this, we don't use the transformer winding for *any* other voltages, positive or negative.

Another alternative is to turn the whole circuit upside down and use a negative regulator. Devices such as the 78N05 or the 7905 have been announced and should be readily available by the time you need them.

Dual 15-volt, 100-mA op-amp supply: Would you believe only three parts? This time we use the Raytheon 4195, in the low-cost DN minidip plastic package if we aren't going to be using things at the 100-mA end too much, or in the more expensive and more powerful T or TK packages if we are.

The dropout voltage is 3 volts; the dissipation limit is 6 (with the minidip). Let's work on a 4-5 volt differential range as an input. One volt of ripple with 100 mA takes 800 μF. Let's use 1000. The input voltage has to be 20 volts (15+5). Add a volt for the diode to 21 volts. Multiply by 0.707 for rms to get 14.5. Double this for 29Vct. Use a 28-volt transformer. The Signal 56-0.1 does the job with both secondaries in parallel. Two inches square by 1¾" ($4.66 plus postage). Chassis mount this time.

This particular regulator takes larger, quality output capacitors; 10-μF tantalums are recommended. The final circuit is shown in Fig. 8. Input taps on the 56-1 transformer let you trim for optimum voltage range for your particular line voltage.

Variable 8-15-volt, 1-amp bench supply: This circuit is shown in Fig. 9. We add two pass transistors to a SG4501 regulator and properly heatsink them. About 5000 microfarads should do, and the transformer can be a 1 amp (one per side) such as the Signal 56-1. Voltage is adjusted with the potentiometer shown. You can set the current limit by changing the two 0.6-ohm series resistors. Doubling the value to 1.2 ohms gives you a 500 mA limit; 2.4 ohms a 250 mA limit and so on.

With these basic circuits as guidelines, you should be able to build up most any low-voltage regulator circuit you want. Always remember to work directly with a data sheet, provide the needed stabilizing and outboard components, and keep the input voltage to the regulator above the dropout voltage and below a value that causes excessive internal dissipation at high load currents.—*Don Lancaster* **R-E**