The Solar Control-ar

A solar panel charge controller for all seasons.

by Joel R. Donaldson WB5PPV

My home is on wheels. My ham shack is on wheels. I live in an old motor home, often staying for months in remote areas that lack any AC power. I'm no rugged old geezer when it comes to creature comforts, however. My idea of roughing it is having to warm something up on the gas stove, instead of cauterizing it in the microwave. Given this affinity for modern gadgets (and my inability to convert my Yaesu to operate on propane gas), I've been forced to come up with alternate ways of obtaining electricity for my comfort and pleasure. My RV came equipped with a big, stupid Onan generator. It uses a little less than a gallon of fuel for every hour of operation, regardless of whether or not it's powering anything. It's cranky to start on cold mornings. It interferes with my TV and HF reception. During weekly skeds on 20 meters, I find myself shouting into the microphone to make myself heard over it. It hunts, surges, and revs for no apparent reason. It sets off my smoke alarms, even when it isn't actually on fire. In short, it stinks. Literally.

After several months of power generation aggravation, I bought a combination inverter/battery charger so I wouldn't have to run the generator all the time. It's coolness incarnate! It's 85 to 90 percent efficient, and completely silent. You have 120 volts AC whenever you want, with the flick of a switch. Yep, I'll only have to run the generator for several hours a day now, just long enough to recharge the RV batteries, right? Well, not exactly. As it turns out, you can only rapid-charge a lead-acid battery up to about 75 percent of its total capacity. After that, the last 25 percent takes a *long* time, regardless of how big your battery charger is. Try to save some time by really cranking up the charge current and all you get is a boiling battery with melted plates. Great. Now I can run the generator for two hours to build up the bulk of the battery charge, and then run it for another four or five hours just to top it off. Or I can shut it down after several hours and live with undercharged batteries, right?

Well, not exactly. As it turns out, an excellent method for prematurely ruining a lead-acid battery is to consistently undercharge it. In the process of discharging, the lead plates in a battery are converted to lead sulfate. If the battery is promptly and fully recharged, this sulphation is almost completely driven back into solution, leaving the plates essentially unchanged. However, if the battery is not completely recharged, the sulphation hardens into a form that is eventually not removable with any amount of recharge. When this happens, there is less plate area available in which chemical reactions can occur, and the battery permanently loses capacity. The process continues until the battery can't hold any charge at all, and . . . it's toss time!

So much for quick charges with the generator. I really need a scheme that provides a gentle, continuous low-current battery charge over long periods of time, say maybe five to eight hours, something that is quiet, doesn't stink or guzzle gasoline, is easy to maintain, and doesn't need to be attended while it's doing its thing.

Well, you know what the answer had to be.

Shortly after I mounted four 53 watt Siemens solar panels on the roof of the RV, I began to search for a good charge controller. I looked at both the store-bought and the roll-your-own types. Most charge controllers don't exactly teeter on the leading edge of technology, but the way some of them work is still kind of neat. Unfortunately, all of them I looked at suffered from at least one of the following maladies:

•1. They were expensive.

•2. They were either incapable of controlling a large number of solar panels (typically being limited to a maximum of 8 to 15 amps), or they wouldn't work with anything less than a large number of panels.

•3. They were inefficient, with a significant percentage of the panel array's total power output being wasted as heat within the charge controller.

•4. They lacked truly useful metering capabilities.

•5. They lacked sufficient adjustability, or the adjustments wouldn't stay put.

•6. They couldn't be manually bypassed in case of failure or for routine battery equalization.

•7. They had little (if any) immunity to strong RF fields.

With these problems in mind, I set out to design my own controller. In addition to avoiding everyone else's pitfalls, I had to make the final design simple and use readily-available parts. Because several hundred to several thousand amp-hours of storage batteries represent a considerable investment, the design also had to be reliable. No one wants to leave their house, RV or repeater site unattended for an extended period, only to later discover that the controller has failed in the "on" position, indefinitely subjecting their batteries, inverter, radios and other appliances to the full 18 to 20 volts produced by their solar panels. Or, just as bad, failed in the "off" position, with the batteries totally Tango Uniform.

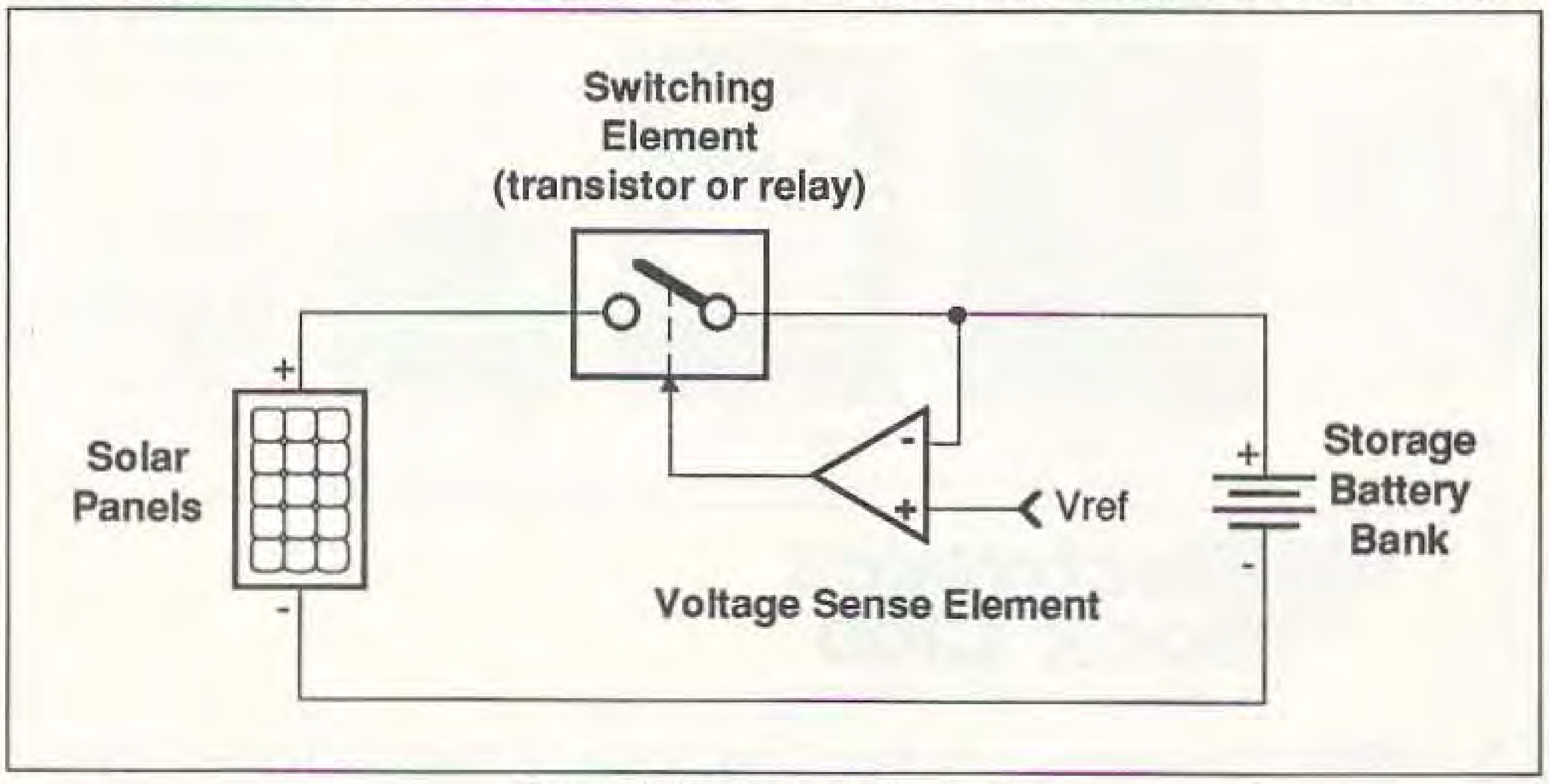

Figure 1. Series control scheme.

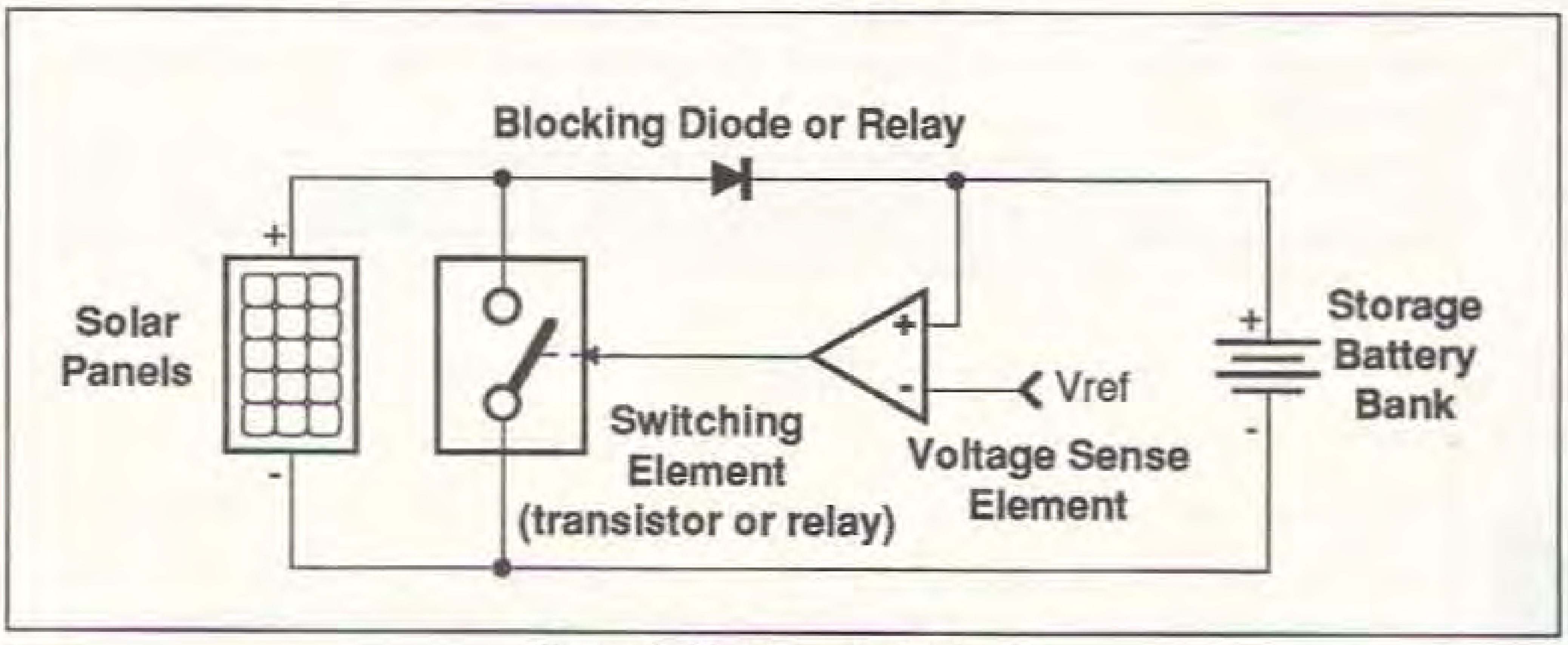

Figure 2. Shunt control scheme.

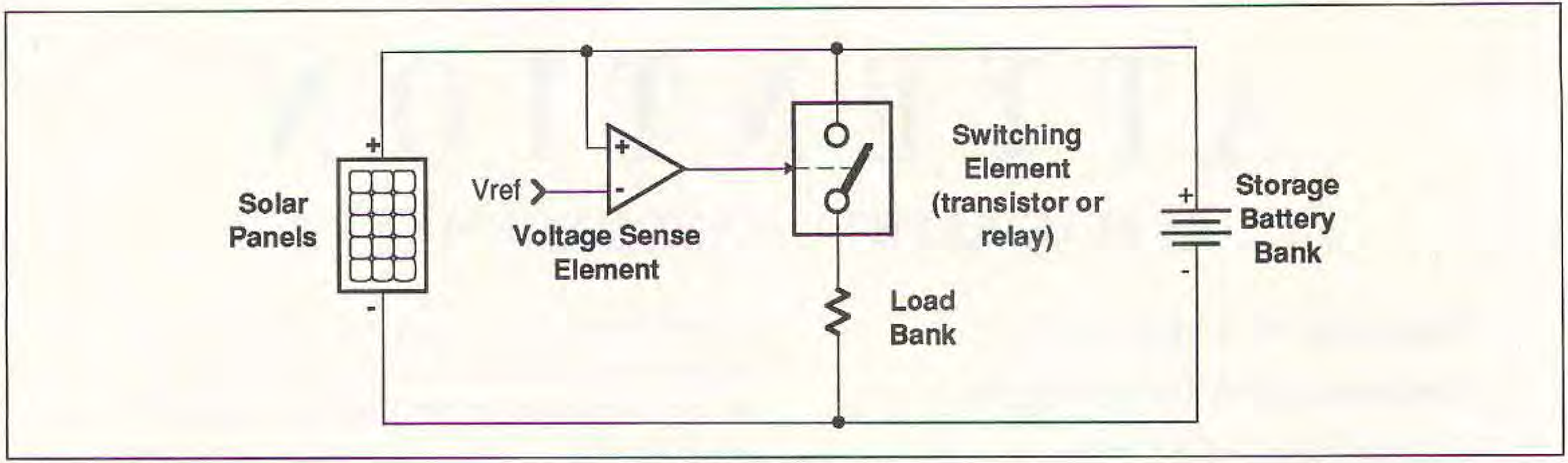

Figure 3. Diversion control scheme.

Series Control Scheme

In my survey of what's already out there, I found that one of three different techniques may be used in the typical charge controller to limit the solar panel's output upon completion of battery charge. Each technique has its own advantages and disadvantages.

See Figure 1. *The series-regulated* approach uses a switch in series (surprise!) with the solar panel output to disconnect the solar panels from the batteries as soon as the desired level of charge is reached. The biggest advantage of this scheme is probably its simplicity. As with the other approaches, the actual switch may be a relay contact, or one or more power transistors. The relay-types cycle on and off at long intervals (from several minutes to several hours, typically), while designs that use power transistors may cycle at rates up to several tens of kHz, à la Pulse Width Modulation.

Shunt Control Scheme

The *shunt-regulated* approach shorts out the solar panels as soon as the batteries are charged. Solar panels, being essentially constant-current sources, are in no manner harmed by being shorted indefinitely. The output voltage just drops to almost nothing as the current increases only very slightly above its normal value. With a really low-impedance shunt switch, the shorted-out power dissipation can be held to very low levels. Note that a blocking diode or secondary switch is used in conjunction with the shunt switch in order to avoid also shorting out the connected batteries (definitely something to avoid!). Although the additional diode or switch complicates this approach somewhat, it still has the advantage of being a relatively simple scheme to implement.

Diversion Control Scheme

Unlike the previous techniques, the diversion-regulated approach doesn't attempt to prevent energy from reaching the battery as it reaches full charge, but instead siphons off excess energy so as to maintain the desired battery voltage. As the batteries top off, the controller automatically switches a load bank across them, so as to keep the voltage from

Approx.Full-Scale Current (Amps):	R2 Resistance (Ohms):	Length 14 Ga. Wire: (Inches):
5	0.0100	47.54
10	0.0050	23.77
15	0.0033	15.85
20	0.0025	11.89
30	0.0017	7.92
50	0.0010	4.75

Table 1. Meter shunt details (see text).

climbing any higher. As the load bank starts to overwhelm the output from the solar panels, the battery voltage begins to drop, eventually reaching a point at which the load bank is automatically disconnected. This connection-disconnection process continues as long as the solar panels are producing a surplus of power, thereby preventing overcharge. A big advantage of these controllers is that they don't care what sort of power source is actually doing the battery charging; all they are concerned with is keeping the battery voltage from exceeding a set value. This makes them useful in situations where solar battery charging is supplemented by other charging sources (like wind chargers or water turbines). No matter how many different charging sources you add to a battery bank, just one diversion regulator will control them all, as long as the combined current output from all sources does not exceed that of the regulator or the load bank attached to it. The biggest disadvantage of this scheme is probably the load bank requirement, which forces you to figure out what you are going to do with any surplus power produced by the system.

One nice thing about all three of these techniques is that once the batteries have reached a state of complete charge, the excess solar energy does not necessarily have to be discarded but can be instead used to power other lower-priority loads. In the case of the series and shunt regulation schemes, all you have to do is substitute a power diversion switch for the existing disconnecting or shorting switch. For diversion regulation systems you just connect your alternate load in place of the controller's load bank. Any electrical load will suffice, so long as it is tolerant of frequent disconnects from power. In the case of diversion regulation, the load must also be ever-present, and must be large enough to be capable of swamping the output of the solar panels on even the sunniest of days. Good potential candidates for load banks would include water pumps (you can always stand a little more water in the stock tank as soon as the batteries finish charging), cooling fans (keep the wife and the chicken coop cool) and, in larger solar installations, hot water pre-heating or electrical generation of hydrogen gas (for later use as a fuel).

Note that all three of these regulation techniques are typically implemented with saturated on-off switching. Theoretically, you could incrementally adjust the amount of voltage or current being produced by your panels as the battery charge increased, using pass transistors biased in a linear mode. The biggest practical disadvantage to this technique probably lies in the tremendous amount of heat that would be generated by the pass transistors at any point between saturation and full cut-off. All that heat would have to be dissipated somewhere, and at the very least would result in increased size and cost, due to a rather herky heat sink! So, linear regulation is probably not as well suited to the constant-current nature of solar cells as it is to power sources with essentially unlimited supply currents (like batteries and AC mains). The sole

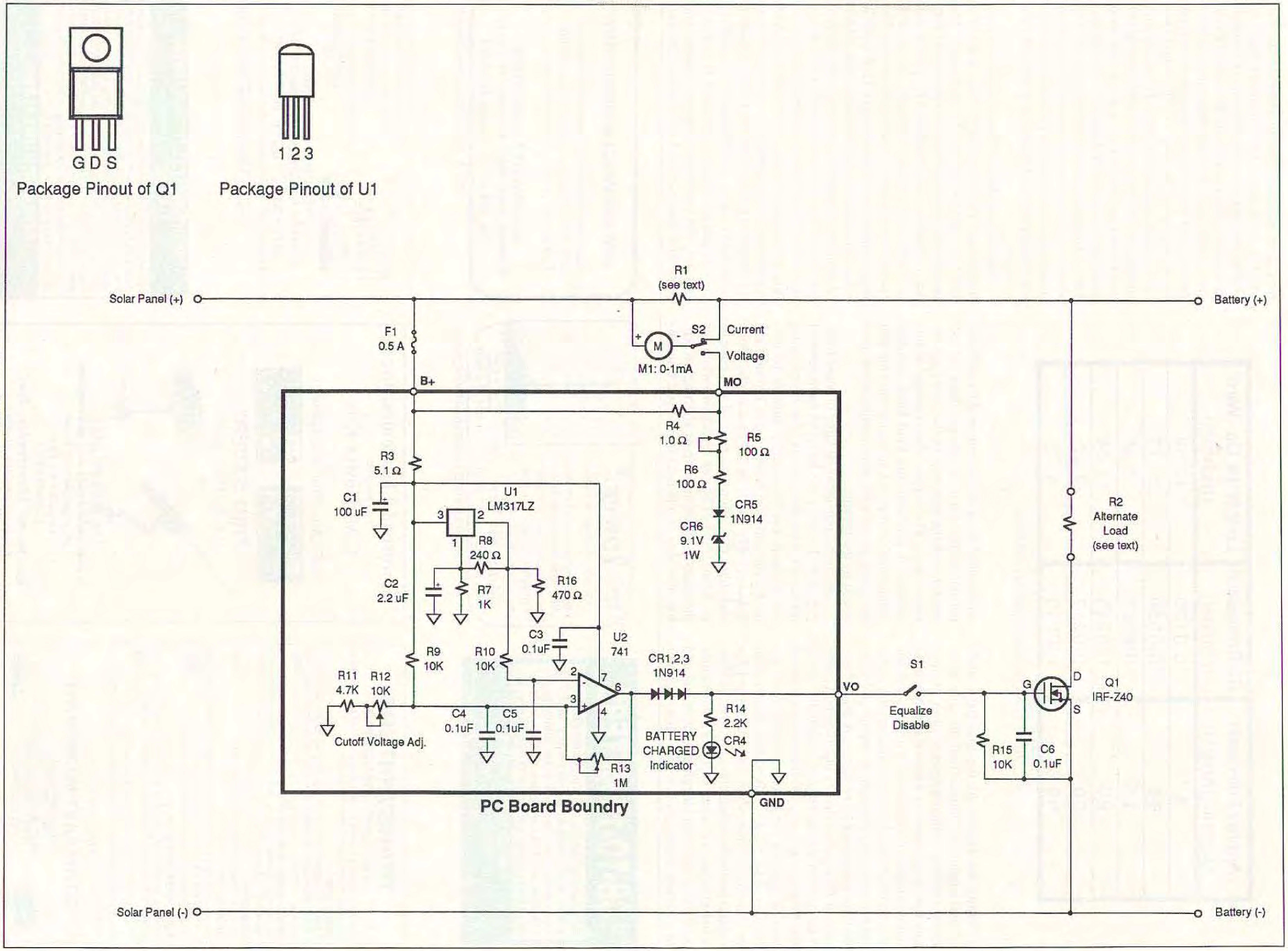

Figure 4. Charge controller schematic.

exception might be in controllers for very small solar arrays, where heat dissipation could be more easily managed.

Anyway, this survey provided a good starting point for my own design. For the switching element, I considered using relays, power BJTs, and power FETs. A power relay looked good from a cost standpoint (you can buy a fog lamp relay at Wal-Mart for less than $4, and you don't need a heat sink), but the reliability of the contacts would always be suspect. High power FETS are easier to use than BJTs, and are very reasonably priced, so they looked like the best choice. As for the actual circuit configuration, I considered several factors important.

First, the use of a transistor in a series switch arrangement would mean that some power would be wasted in the voltage drop across the transistor when the battery was being charged. This would reduce the efficiency of the charge controller somewhat. Likewise, the use of a shunt switch arrangement would mean that some power would be wasted in the voltage drop across the blocking diode.

Second, the power being dissipated across these components (in either configuration) is significant for rather long periods of time (whenever the sun is shining and the batteries are not fully charged), which could shorten their life expectancy. A diversion regulation scheme avoids these two problems because no switching or blocking device is employed between the solar panels and the batteries, and the diversion load switching device is only operated for brief periods *after* the battery has reached full charge. This implies good efficiency and reliability. Since no blocking diode or series switch is used, there will be some loss of efficiency with this arrangement, due to nighttime solar panel reverse leakage current (typically 15 mA per 50 watt panel), but this is more than offset by the higher daytime efficiency. So there you have it—an FET-switched diversion regulator it is!

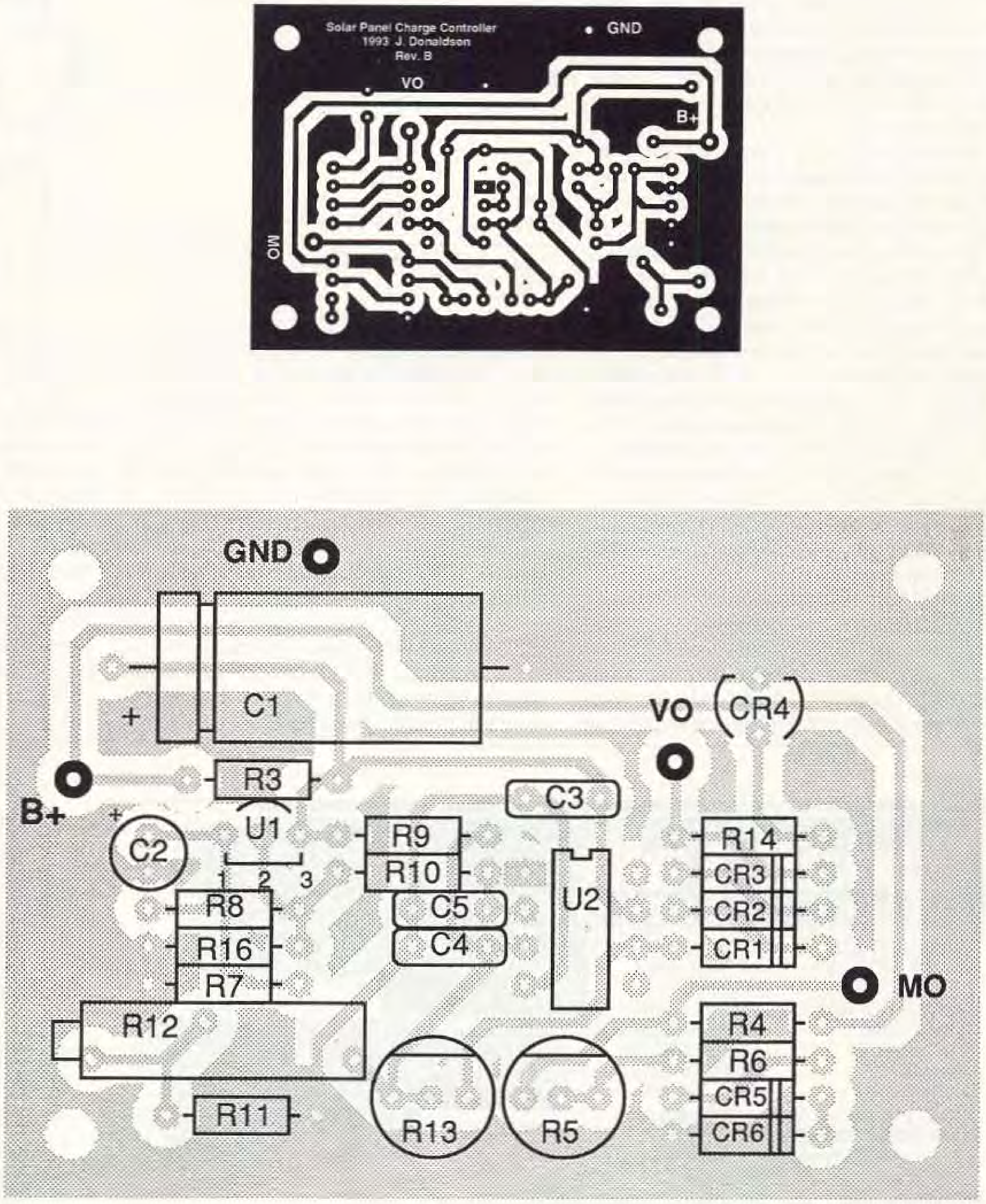

Figure 5. PC board foil pattern (100%) and parts placement diagram (200%).

From that point on, the design was pretty straightforward. In referring to the schematic, you'll see that U2 compares the battery voltage with a reference developed by U1, and turns on Q1 as soon as the battery voltage exceeds the level set with R12. Q1 in turn grounds the alternate load (R2), which swamps the output current being produced by the solar panels. Note that since the LM317LZ can't regulate a voltage that approaches its input value (e.g., the battery voltage), it is instead set to a lower reference voltage (approximately 6.5 volts). The R9/R11/R12 pair scale the battery voltage down to a value roughly comparable to this reference. Since the 741 is incapable of output voltage swings completely to ground, CR1, CR2 and CR3 are used to prevent the volt or so of output normally present at U2 from keeping Q1 turned on. In order to easily fine-tune the charge cutoff voltage and to improve the controller's resistance to mechanical vibration, a multi-turn trimmer is used for R12 (10 to 15 turns works nicely). The voltage difference between termination and resumption of battery charging (e.g., the charger's hysterisis) is adjustable via pot R13.

In addition to driving Q1, U1 also directly drives the "BATTERY CHARGED" indicator LED. Note that unlike some other charge controller designs, this LED is not lit until *after* the battery reaches full charge.

A single International Rectifier 50 amp

power FET is specified in the Parts List; it is available from Digi-Key (701 Brooks Ave. South, P.O. Box 677, Thief River Falls MN 56701-0677; telephone 1-800-DIGI-KEY for a free catalog) for around four dollars. Other smaller FETs can be substituted for lower power handling requirements, or several FETs can be paralleled in extremely large installations. I like using a well-oversized FET, for reliability reasons.

The metering circuit I chose measures the amount of current produced by the solar panels, and also determines battery voltage. The vast majority of the charging current is borne by R1, while a small portion of it is diverted through the meter. Since the meter uses a 1 mA movement, the voltage drop across R1 never exceeds 50 mV, thereby minimizing power losses and heat dissipation. Physically, R2 consists of a small coil of 14-gauge household wire, the exact length of which is determined by the desired full-scale reading of the meter. I set mine up for a full-scale current of 14 amps, but Table 1 lists the appropriate lengths for some other full-scale values. I chose 14-gauge because it is readily available in most hardware stores. Solid is preferred over stranded.

To read battery voltage, R4, R5, R6, CR5 and CR6 are used in a voltage-scaling circuit that allows the meter to read from approximately 10 volts no-scale to 16.5 volts full-scale. The expanded voltage scale is important because there is typically less than 1 volt of difference between the output of a fully-charged and a fully-discharged lead-acid battery. Any small variations within that 1 volt range would be difficult to read on an analog meter, unless the meter scale was expanded to remove the useless 0 to 10 volt range of readings. (Whether your battery reads 10 volts or something less than 10 volts is immaterial; in either case you have a damn dead battery on your hands!) On the top end of the scale, the normal charge-cutoff voltage for a lead-acid battery can range as high as 14.8 volts, with equalization being safely performed at up to 16.5 volts (see the sidebar on battery charging). This value sets the desired upper range of measurement. For temperature stability, current is always applied to CR6. This represents a small continuous battery load (less than 20 mA under most conditions), but buys some improvement in meter accuracy.

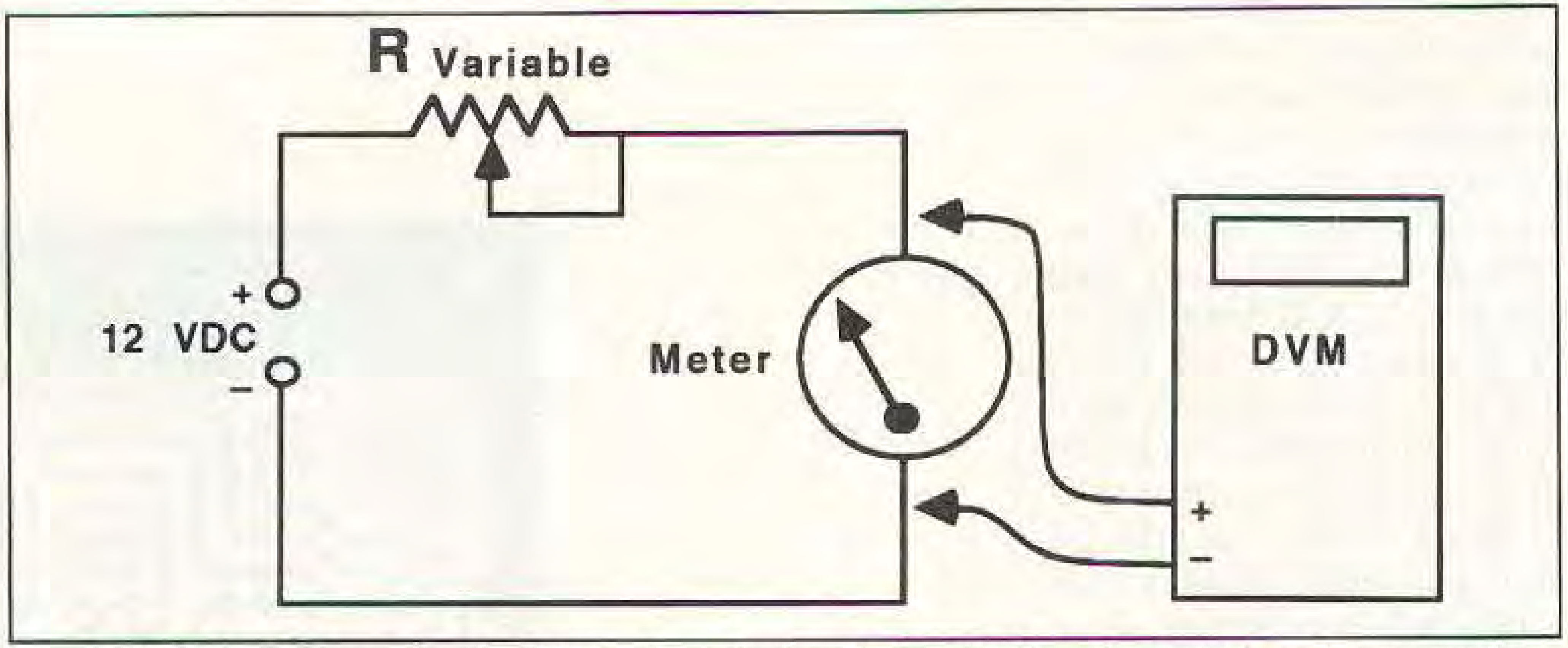

Figure 6. The precise value for R1 can be calculated after finding the meter's resistance value.

For ease of construction, a printed circuit board layout has been provided. Almost all of the components carrying low currents mount on it, while the components requiring heavy-gauge wire mount in what ever type of enclosure you desire. I mounted mine in a wall paneling cutout, using the aluminum cover from a bakelite experimenter's box as the front panel. These covers are available without the rest of the box from Digi-Key for under $2. Make sure that the PC board is mounted so that R12 and R13 can be easily adjusted with everything buttoned together.

If a "live" diversion load will not be used in your installation, R2 can consist of 12 volt light bulbs (headlamps for high current applications; #1141 bulbs for smaller installations), or power resistors. I recommend that the load be spread among several individual resistors or bulbs so that if one burns out, the controller will still function (although at some reduction in overcharge protection). Also, if bulbs are used, be sure to pick a bulb with long life (e.g., 1,000 hours for the #1141, versus only 200 hours for the similar-appearing #1156 bulb). Using 24 volt bulbs in a 12 volt system will also greatly extend reliability, although more bulbs will be required. High-power load resistors can be easily built from scratch with nichrome heating wire (available at most hardware stores), and mounted in ventilated metal boxes, tin cans, etc.

To calibrate the meter for battery voltage, set R5 and R13 at the middle of their ranges, and switch S2 to the voltage scale. Disconnect any alternate load. Apply +10 VDC to the battery terminals and allow CR6 to warm up for a few minutes before proceeding. Adjust R5 to just below the point at which some meter deflection starts to occur. Gradually increase the voltage at the battery terminals, noting and recording the resulting meter readings. (These readings can be used later in relabeling the meter face, if desired). As you increase the voltage, verify that the meter pegs out at a little over 16.5 volts of input. Next, set the input voltage to the desired battery charge cut-off value, and adjust R12 until the BATTERY CHARGED indicator lights up. There are no adjustments for calibrating the current scale; the current readings can be read off an ammeter connected in series with the positive battery wire, once the controller is installed and hooked up to the panels and batteries. Again, the current readings can be recorded for later use in relabeling the meter face.

During installation, I recommend providing fusing between the charge controller and the batteries, located as close to the batteries as possible. In some larger solar installations, you might want to consider remote-mounting the meter and PC board, if it will save you any appreciable length of heavy-gauge (bulky and expensive!) wire. If going that route, simply mount the PC board, S1, S2, F1, and the meter in a box located for viewing convenience, and mount everything else somewhere directly between the solar panels and the batteries. Small-gauge wiring (e.g., telephone cable) can then be used to connect the two boxes.

After the controller has been installed, readjust R12 for proper charge cut-off voltage. The difference between charge cut-off and turn-on voltage is set with R13, and will vary with battery size and loading. Normally, R13 should be adjusted so that CR4 does not cycle more than several times a second under light battery loads, but should never fail to resume charging when battery voltage drops below approximately 13 volts. There is some interaction between the settings for R12 and R13, so several readjustments may be necessary to get the desired charge cut-off and resumption voltages.

The controller is heavily bypassed for RF interference rejection. For best RF rejection, it is suggested that separate wiring be used to connect the radio(s) to the batteries. A metal enclosure for the controller also helps and, finally, a 100 μH RF choke can be added in series with the fuseholder in particularly stubborn situations.

If you have access to a computer, laser printer, and drawing or drafting software, you can relabel the meter face in a very professional manner. First, recreate the physical dimensions and markings of the old meter face with your drawing program. Next, substitute your recorded voltage and current readings for those of the existing meter face, in the corresponding positions on the meter scale. Finally, use your laser printer to print the new meter face on large adhesive-backed label paper (Avery 5165 or equivalent), and stick the new face over the old one. Very spiffed!

In conclusion, I think you'll find that this controller is the best battery banger for your buck. It's efficient, reliable, and has all the useful tweaks. Whether you're building a mansion in the middle of nowhere, sticking a TNC on top of the local mole hill, or just need a little something to keep your Argonaut's trolling motor battery from boiling dry, this little baby will do the job.

A Few Words About Batteries

While most other components in an alternate energy system are virtually indestructable and maintenance-free (with the possible exception of wind chargers and water turbines), the selection and maintenance of electric storage batteries can make or break the entire installation. Make your battery selection carefully and maintain it properly and it will serve you well for years. Make the wrong choice or neglect your investment and you will soon have another opportunity to make a wiser battery purchase!

Storage batteries used in most solar power applications are either lead-acid or NiCd. Lead-acid batteries can be cheaply purchased new almost anywhere, while NiCd cells are generally available only as surplus. The big advantages lead-acid cells have over NiCds are that they are more efficient to recharge (only 15 to 20 percent of the charging energy is lost, as compared to 25 to 35 percent for NiCds), they offer better voltage regulation under load, and they are usually cheaper than surplus NiCds. On the other hand, NiCds are much more tolerant of extreme discharges, and are not as prone to permanent damage due to repeated undercharge or long-term storage in a discharged state. Since the vast majority of solar installations use lead-acid batteries, most the following information will center around them.

Some Battery Basics

The lead-acid battery types that are most common in solar applications are all of deep-cycle design. This is significant, because a deep-cycle design stands up to repeated heavy discharge-recharge usage much better than a battery of ordinary automotive design does. An automotive battery is designed to deliver very large bursts of current for short periods (when starting a car), and then is immediately recharged (by the car's alternator). Most solar power applications require the battery to provide lesser amounts of current, but provide it for extended lengths of time before receiving any recharge. An automotive battery will lose a significant percentage of its full storage capacity after being heavily discharged just one time. It will typically lose 50 percent of its capacity after 20 such discharge-recharge cycles. (For our purposes, a heavy discharge is one that removes all but 20 percent of the battery's original full charge). By contrast, even the lightest duty deep-cycle battery will typically tolerate 200 to 300 such discharge-recharge cycles before reaching a similar state; some of the heavier deep-cycle designs can exceed 10,000 such cycles. It is a common mistake to purchase the "biggest batteries you can get" for a new solar installation, usually meaning size 4D or 8D truck/tractor batteries (which are conventional automotive designs). Regardless of how "heavy duty" a battery is claimed to be, if it isn't a deep-cycle design, it won't last very long in most solar applications.

The maximum storage capacity of a deep-cycle lead-acid battery is usually specified either in amp-hours or in minutes of reserve capacity. The amp-hour value refers to the number of amps a battery will deliver over a specified period of time (generally implied to be 20 hours, if not specifically stated), before the battery has discharged to a useless level (around 10.5 volts). The reserve capacity value specifies the number of continuous minutes the battery can last while delivering 25 amps, before dropping to this same 10.5 volts. As a rule of thumb, for the smaller batteries, you can multiply the number of reserve minutes directly by 0.6 to arrive at an approximate equivalent amp-hour rating for the battery. Therefore, a 50 amp-hour battery (or a battery with approximately 83 minutes of reserve capacity) can be expected to deliver at least 2.5 amps for 20 continuous hours, or at least 1 amp for 50 continuous hours. Note, however, that at current drains much higher than those specified at the 20 hour rate the capacity of the battery starts to decline due to internal losses and chemical inefficiencies at high currents. Consequently, this same battery might only be able to deliver 5 amps for nine hours (45 effective amp-hours), instead of the 10 hours (50 theoretical amp-hours) implied by the battery's amp-hour rating. Bigger batteries can deliver higher currents without incurring this effect.

Like all lead-acid batteries, the life expectancy of a deep-cycle battery is directly dependent upon how heavily the battery is discharged before being recharged. Batteries that are routinely discharged to only 20 percent of their rated capacity have a much shorter life expectancy than identical batteries that are rarely discharged below 50 percent. This same trend applies at the extremes—few batteries that are completely discharged will last for more than a few such cycles, and most batteries that are never discharged below 80 to 90 percent of their capacity will last almost indefinitely (given proper maintenance). The moral: Don't buy a 100 amp-hour battery if you are planning on routinely using all 100 amp-hours between recharges. A good rule of thumb states that a deep-cycle battery should be recharged before 80 percent of the capacity has been drained, with 50 percent being even better. Fifty percent discharge represents a good compromise between battery life expectancy and reasonable battery bank size. Therefore, you would do well to buy at least 200 amp-hours worth of batteries to meet your anticipated 100 amp-hour discharge "budget."

Ambient temperature also has a strong effect on battery performance. Most batteries are rated at around 80 degrees Fahrenheit. At higher temperatures they are capable of greater capacity, but their life span is shortened, due to the acceleration of detrimental chemical reactions. At lower temperatures, they last longer than normal (provided the electrolyte is not allowed to freeze), but their capacity drops. At 32 degrees F, typical capacity is reduced by 35 percent; at 0 degrees F, it is reduced by 60 percent; and at minus 20 degrees F,

	Charge Cutoff Voltage:	Maintenance Voltage:	Equalization Voltage:
Wet-Cell Battery @ 80° F.	14.4	13.5	16.3
Wet-Cell Battery @ 100°F.	13.9	13.3	15.8
Gel-Cell Battery @ 80° F.	14.4	13.8	(na)
Gel-Cell Battery @ 100° F.	14.1	13.8	(na)

Table 2. Non-sealed wet cell battery states.

Approx. State of Charge:	Specific Gravity:	No-Load Voltage:
100%	1.270	12.70
75%	1.250	12.50
50%	1.190	12.30
25%	1.150	12.10
DEAD!	1.120	11.80

Table 3. Suggested charge and equalization voltages for various batteries.

it is reduced by better than 80 percent. Their ability to accept a charge also drops along with the thermometer. In general, the best tradeoff between efficiency and long life occurs when the battery is maintained at around room temperature.

As a battery is discharged, the sulfuric acid solution inside each cell is gradually converted to ordinary water. Consequently, the specific gravity of this solution also drops as the battery discharges; this change can be easily measured with a hydrometer in order to determine the battery's state of charge. A good battery hydrometer includes a temperature correction scale (specific gravity versus battery charge varies somewhat with temperature), and will often provide readings that are more precise than those obtained with a voltmeter. Specific gravity readings should be taken by inserting the hydrometer suction pipe into the battery cell, squirting the electrolyte into and out of the hydrometer several times (electrolyte agitation improves accuracy), and then reading the hydrometer while the suction tube is still inserted into the cell. Keeping the suction tube in the cell while taking readings minimizes the chance of spilling the electrolyte on feet, kneecaps, or any other exposed appendages. Read the hydrometer scale at the center of the fluid inside the tube, not at the edges. Note that any heavy battery charge or discharge currents drawn just prior to taking specific gravity or voltage measurements will have an adverse effect on the accuracy of the readings. Specific gravity readings are also helpful in determining the overall health of a battery. For example, differences in specific gravity of more than 0.050 between any two individual cells in a battery generally indicate that the battery is headed for problems. By taking specific gravity readings every month or so you can catch battery problems before they cripple the entire system.

Table 2 is helpful in determining the state of charge of a battery, using either a voltmeter or hydrometer. Note that this table is applicable only to the non-sealed wet-electrolyte batteries. For obvious reasons, a hydrometer should never be used on a sealed battery (wet or gell).

What To Buy

Among the deep-cycle variants, the most common type is the RV/Marine, typically sold by hardware and department stores in automotive package (or "group") sizes 24 and 27. Typical ratings for this class of battery are 70 amp-hours (110 minutes) for the size 24, and 105 amp-hours (170 minutes) for the size 27. These batteries represent a reasonable value in smaller solar systems, or in installations where space is at a premium. However, as deep-cycle designs go, they are lightweights, with relatively short life expectancy in heavy service. This deficiency is primarily due to the use of thin lead plates used in their construction, and the low antimony content of the plates themselves. The next most common deep-cycle version is probably the golf cart/electric vehicle, typically sold through battery supply houses, some wholesale clubs, and an occasional department store (frequently by catalog only). These batteries are all of 6 volt design (you use two in series to get 12 volt banks), and typically cost a tad more per pair than a single size 27 RV/Marine battery. They provide superior service in most solar applications (due to thicker plates and higher antimony content), and probably represent the best value for small to mid-sized installations. Typical ratings are 220 amp-hours, or 400 minutes of reserve capacity.

Industrial (floor scrubber) batteries are probably best described as golf cart batteries on steroids. They are 6 volt, with much taller cases than golf cart batteries. They are typically rated at around 350 amp-hours, and they also make excellent choices for small-to-mid-sized solar applications. They are available from the larger battery supply houses, or may be special-ordered (along with ordinary golf cart batteries) from auto parts stores like NAPA. High-quality deep-cycle batteries for marine applications are manufactured by Surrette and by Rolls, in a variety of sizes. They are of very heavy construction, with very thick, high antimony content plates. Many marine supply houses stock them, and they work very well in solar applications.

For non-mobile installations, really large deep-cycle batteries are often employed. For example, 12 volt electric fork lift batteries are available with typical ratings of 1,000 amp-hours. Life expectancy is around 10 years, and the cost brand-new is under $2,000. Surplus telephone cells are also popular, with ratings of 1,200 to 2,500 amp-hours being commonplace. These cells are sold individually (each cell is 2 volts and weighs between 300 and 500 pounds). Life expectancy is greater than 20 years for new ones.

A good used set will have at least 10 years of life left in it, and is available for around $400 to $800 per 12 volt group. Gell-electrolyte (gell-cell) batteries are becoming cheaper and more popular for solar applications. Available in group 24, 27, 4D, 8D and 6 volt golf cart sizes, they offer very good performance, with virtually zero maintenance. Where ordinary "wet cell" batteries require monthly checks of electrolyte levels, the gel cells are completely sealed, with nothing to replenish. They also offer higher charging efficiency than ordinary batteries, and provide slightly higher output voltage down to complete discharge. Examples of this class of battery are the Johnson Dynasty, Exide Nautilus Megacycle, and Dryfit Prevailer/Sonnenschein/Deka brands. Don't confuse these batteries with the "maintenance-free" wet-electrolyte RV/Marine batteries being sold in some department stores under brand names such as Delco Voyager and GNB Stowaway. Unlike the true gel-cells, these batteries offer little improvement in performance over the standard RV/Marine models.

How To Keep Them Happy

Although routinely overlooked in the battery manufacturers' literature and in many references, most deep-cycle batteries (with the exception of the gell cell and other totally-sealed varieties) are benefited by a periodic, controlled overcharge, often referred to as an equalization charge. To equalize a battery, the charging is allowed to continue for some time past the point at which the battery is normally considered to be "full," taking care to avoid excessive battery heating or electrolyte boil-off. In a typical equalization cycle, the battery voltage is allowed to rise to approximately 16 volts, where it is maintained for up to eight hours by adjustment of the charging current. This process helps to mix up the electrolyte, which otherwise tends to "stratify" (e.g., separate into overlapping layers of acid and water). It is also useful in removing some sulfate deposits. When performed properly, equalization doesn't make the battery boil over, but does produce fairly vigorous bubbling. At the termination of this cycle you can expect to add some water. Most battery manufacturers consider one equalization charge a month to be appropriate for batteries that are in a continuous state of charge and discharge; less often is adequate for batteries that see a lot of standby service. Due to the generation of considerable gas that accompanies this process, equalization should *never* be performed on a sealed or gell-electrolyte battery. (Because their electrolyte is gelled, stratification is generally not a problem with gell-cells, anyway). Also, most 12 volt appliances will not tolerate 16-plus volts, so remember to disconnect everything before you equalize. Table 3 summarizes the suggested charge and equalization voltages for various batteries.

Finally, remember that lead-acid batteries generate highly explosive gasses. The larger the battery bank, the more gas produced. Don't mount any battery in an unvented location, and avoid any sparks or open flame around the battery (particularly during and shortly after recharging). Making or breaking electrical connections at the battery terminals is particularly dangerous. Battery explosions often shower large areas with acid. Wear eye, face and skin protection, and give the bank plenty of time to "air out" before attempting any maintenance or inspection.

And a Few More Words About Solar Panels

If you are buying new solar panels, you will probably find that models in the 47 to 65 watt range represent the best value (e.g., most watts per dollar), if that size range will serve your needs without overkill. This range is where the sales volume currently lies for large-scale power production (e.g., for homes and small businesses). Excellent quality is the rule throughout the industry, with limited warrantees typically ranging from 10 to 12 years. Actual expected life is anyone's guess, but figures of 20 to 30 years are routinely tossed around. There isn't too much standardization in panel sizes among the offerings from different manufacturers, so pick your brand and mounting hardware carefully. Also, the power density (amount of power produced per square inch of panel area) varies subtly from one model and manufacturer to the next. This means that in some applications where space is very limited, Model X might meet performance objectives where Model Y wouldn't. In picking a panel model, you should consider the anticipated temperature operating range of the panels, the efficiency of your charge controller, and your battery maintenance requirements. As the temperature of a solar panel rises, its output voltage drops. If your panels will be located in a very hot climate and/or are mounted in such a manner as to hinder air circulation around both surfaces, you should limit your panel selection to models that offer the highest charging voltages (typically around 17 volts at rated output current). Some of the lower-voltage "self-regulating" panels are designed to be used without a charge controller in applications where the load attached to the battery is anticipated to be constant enough to avoid boiling dry the electrolyte. Since the output voltage of these panels has been intentionally reduced, the likelihood of battery damage is small. Unfortunately, so is the likelihood of ever fully recharging the battery. High temperature becomes even more important if you will be periodically equalizing your batteries, since this process can require better than 16 volts under full load from the panels.

Finally, if the output voltage of your panels is marginal under hot conditions, a charge controller with excessive internal losses may aggravate the problem. Try to pick a controller that has less than 0.5 volts of drop under your maximum anticipated charge current (the controller described in the accompanying article has virtually no internal losses). If you will be buying your panels surplus, you are pretty much stuck with what's available. If possible, obtain permission to return the panels for a refund if an initial test shows that they are producing considerably less than their new rated current and voltage. Look for water leaks in the seams of the panel glass. If the panel has

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Parts List

Resistors (1/4 watt 5% unless otherwase stated)

R1=Meter Shunt (see text and note below)
R2=Alternate Load (see text)
R3=5.1 ohms
R4=1 ohm
R5=100 ohm single-turn, linear taper trim pot. Bourns series #3323W or series #3362U. Available through Digi-Key.
R6=100 ohm
R7=1K
R8=240 ohm
R9=10K
R10=10K
R11=4.7K
R12=10K multiple-turn linear taper trim pot. Bourns series #3006P or Spectrol series #43P. Available thouugh Digi-Key.
R13=1M single-turn linear taper trim pot. Bourns series #3323W or series #3362U. Available thouugh Digi-Key.
R14=2.2K
R15=10K
R16=470 ohm

Capacitors

C1=100µF 25V electrolytic
C2=2.2µF 16V electrolytic
C3=0.1µF ceramic disk
C4=0.1µF ceramic disk
C5=0.1µF ceramic disk
C6=0.1µF ceramic disk

Semiconductors

CR1,2,3,5=1N914 small signal Diodes
CR4=LED
CR6=9.1v, 1w Zener diode
Q1=IRF-Z40 50 amp power MOSFET
U1=LM317LZ 3-terminal adjustable regulator
U2=741 single op-amp

Meter

M1=0-1mA

Switches

S1=SPST
S2=SPDT

Fuse

F1=0.5A

Miscellaneous

heat sink
enclosure
fuse holder

Drilled and etched PC boards are available for $3.50 plus $1.50 S&H from FAR Circuits, 18N640 Field Ct., Dundee IL 60118.

Note (Calculating R1): Due to the large amount of current and very low resistance value of R1, this resistor is best built from scratch. R1 is an ammeter current shunt, and physically consists of nothing more than a precise length of 14 gauge household wire. The proper wire length is shown in Table 1. There is nothing unusual about building it—it can be wrapped in a coil, wadded-up, or just left hanging. As shown in the schematic, meter M1 is connected through it with a couple of ordinary hook-up wires. Since the vast majority of current is carried through R1, the wires to the meter can be of most any convenient gauge.

The value for R1 can be determined after the decision is made on maximum current through shunt load R2 and the full scale meter movement current and meter resistance. All current meters have some small value of resistance. If you don't know that value, you can calculate it with a simple experiment:

Let I_M = full scale meter movement current
R_i = meter shunt resistance
I_i = maximum load current into the shunt R_2
R_M = resistance of the current meter

Take a variable resistor that has a value of 2 X 12 volts/I_M.

If the I_M current is 1 mA, then the variable resistor should be greater than 12 kΩ or approximately 30 kΩ. Connect the meter and variable resistor (*adjusted to maximum resistance*) as shown in Figure 6. Slowly adjust the resistor until the meter is reading full scale (1 mA in this example). Now measure the very small voltage drop across the meter with a DVM. This voltage drop divided by the full-scale current meter reading will be the meter resistance R_M.

Now the value of R1, the shunt resistor, can be determined for the full scale current meter with the calculated meter resistance of R_M:

$$R1 = \frac{I_M}{I_i} R_M.$$

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bare wires for electrical connections, wiggle the wires while checking the output under load to insure that the panel connections are not intermittent. A panel with faulty connections will often show sufficient output voltage under no load, but will drop to almost no output when any appreciable current is drawn. Beware of stolen panels. Some bargain panels being sold at flea markets were originally "liberated" from mountaintop radio sites or RV'ers in the desert. If the panels are engraved or otherwise marked, make sure that the seller has a believable story as to their ancestry. Take names and addresses.

In most installations, you have a choice between tracking the sun with the panels, or leaving the panels in a fixed position for the day. Auto-tracking panel mounts are commercially available (or can be fun to design and build yourself), but they do add some expense and maintenance requirements to the system. If the size of your system is marginal, buying additional fixed panels might be just as cost-effective as installing trackers. During the wintertime, much of the advantage in tracking the sun is lost, since it never rises very far above the horizon, and doesn't travel very far horizontally between sunrise and sunset. Also, on overcast days, it makes little difference which direction the panels are facing, but installing additional panels will always provide some additional output. However, if you don't use a tracking system, be sure to include provision for seasonally changing the elevation of the panels. An adjustable bracket costs little more than a fixed mount, and the improvement in power output is almost always significant. 73