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All-Star Expanded-Scale AC Voltmeter

Monitor your line voltage with this high-performer.

With the stress being put on our electrical distribution systems, the voltage delivered to your house may widely vary from the nominal 120 volts. While inexpensive digital voltmeters are now widely available, it doesn't make sense to keep one tied up monitoring line voltage, not to mention feeding it batteries every few days.

A standard analog multimeter scale, say 0 to 250 volts, is neither easy to read nor particularly accurate. Hence, I decided to create an expanded-scale AC voltmeter, reading between 110 volts and 135 volts. This idea isn't original — a vacuum tube version was available from RCA in the 1950s — but it's still a nice addition to the shack.

Theory of operation

The principle behind an expanded-scale voltmeter is simple — by floating one end of a voltmeter with a precision voltage reference, we can increase resolution and accuracy.

Suppose we want to measure the voltage of a battery that we know is somewhere between 5 and 6 volts DC. The simplest method, of course, is to set your voltmeter to the 0 to 10-volt scale and connect it across the battery terminals.

If you have a typical analog multimeter, you will have an accuracy of about 2% of full scale, in this case 0.2 volts. If the "true" battery voltage is 5.5 volts, your meter could read anywhere between 5.3 and 5.7 volts and still be within its rated accuracy.

Suppose that you also have an accurate 5.000-volt power supply. By using it as a reference and reading the difference between the voltage standard and the unknown, you can use a lower voltmeter scale and significantly improve measurement accuracy.

In this case, you can use the 0 to 1-volt scale on the voltmeter, as the voltage reference "cancels out" 5.000 volts

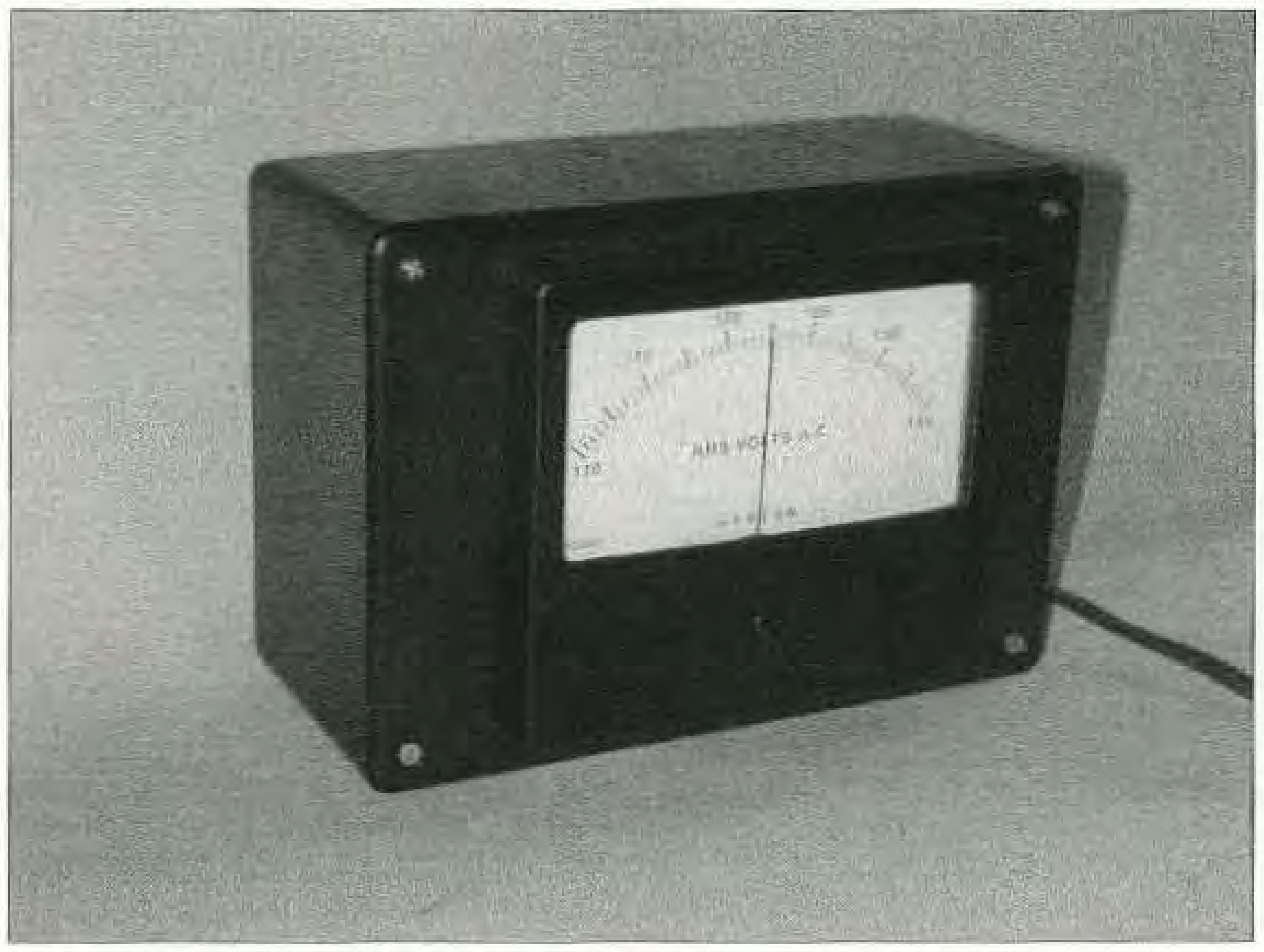

Photo A. The completed unit.

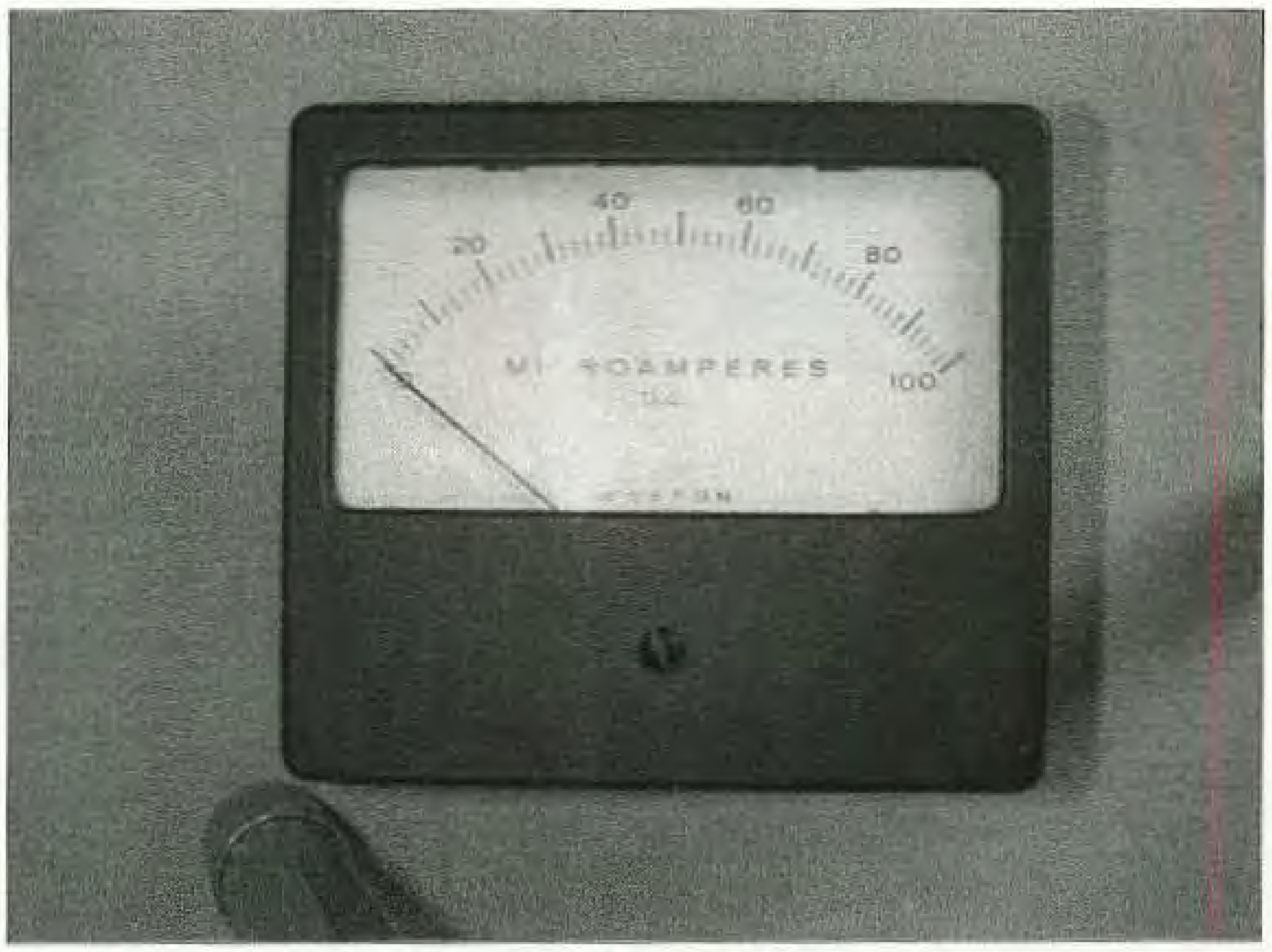

Photo B. I started with a Weston 0–100 μA meter.

Photo C. *View after disassembling meter case and removing scale plate.*

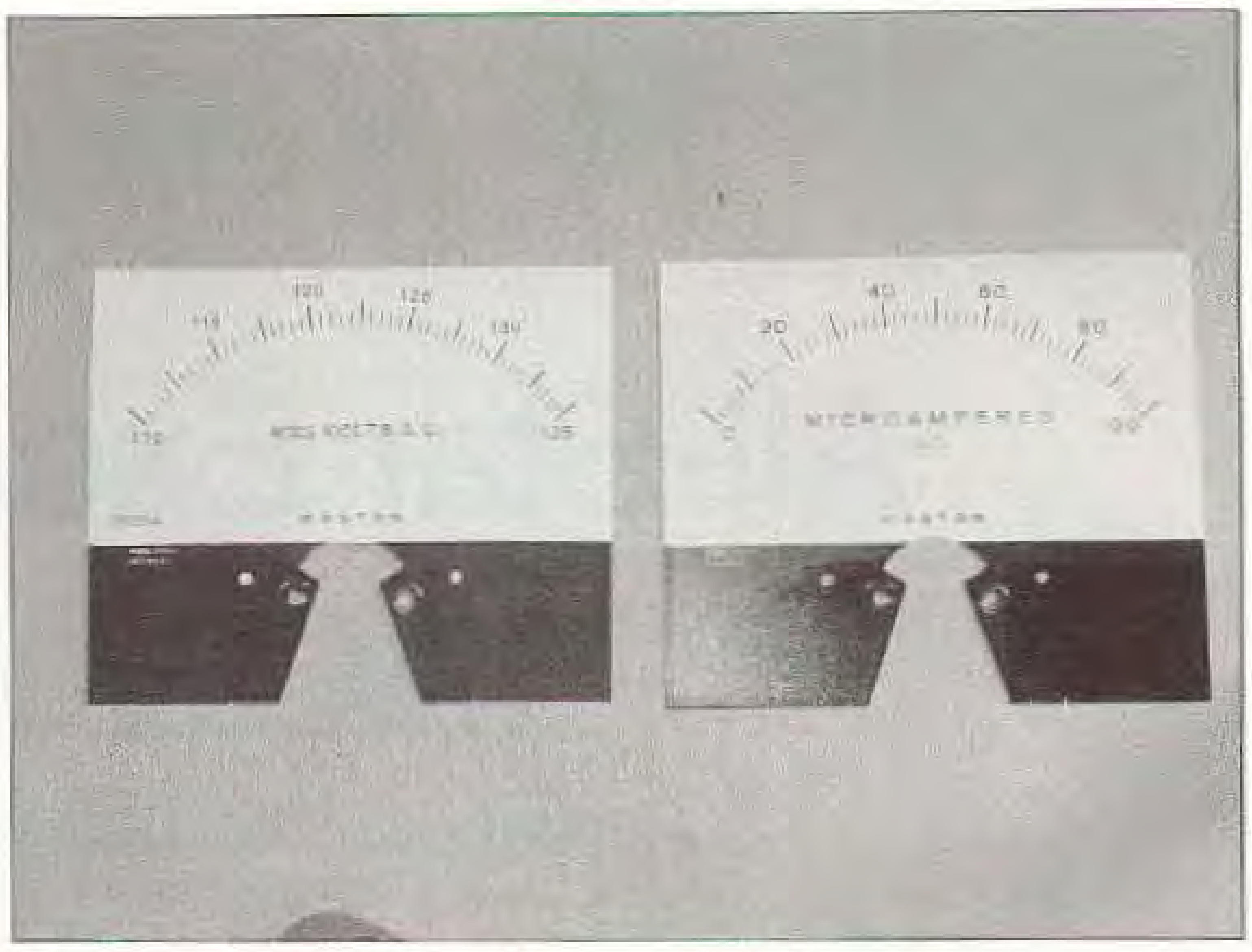

Photo D. *The original and new paper scales.*

of the unknown voltage. Using the same 2% voltmeter as before, the error is now only 0.02 volts (2% of the 1-volt full scale). A perfect voltmeter would read 0.50 volts, to which must be added the reference voltage. The limits of accuracy are now 5.48 and 5.52 volts, an order of magnitude improvement in error from the simple measurement technique. The voltmeter scale has, in effect, been recalibrated to read 5.00 to 6.00 volts, with an accuracy not 2% of full scale, but 2% of the difference between the maximum and minimum limits of the meter. This is the principle behind the expanded scale voltmeter.

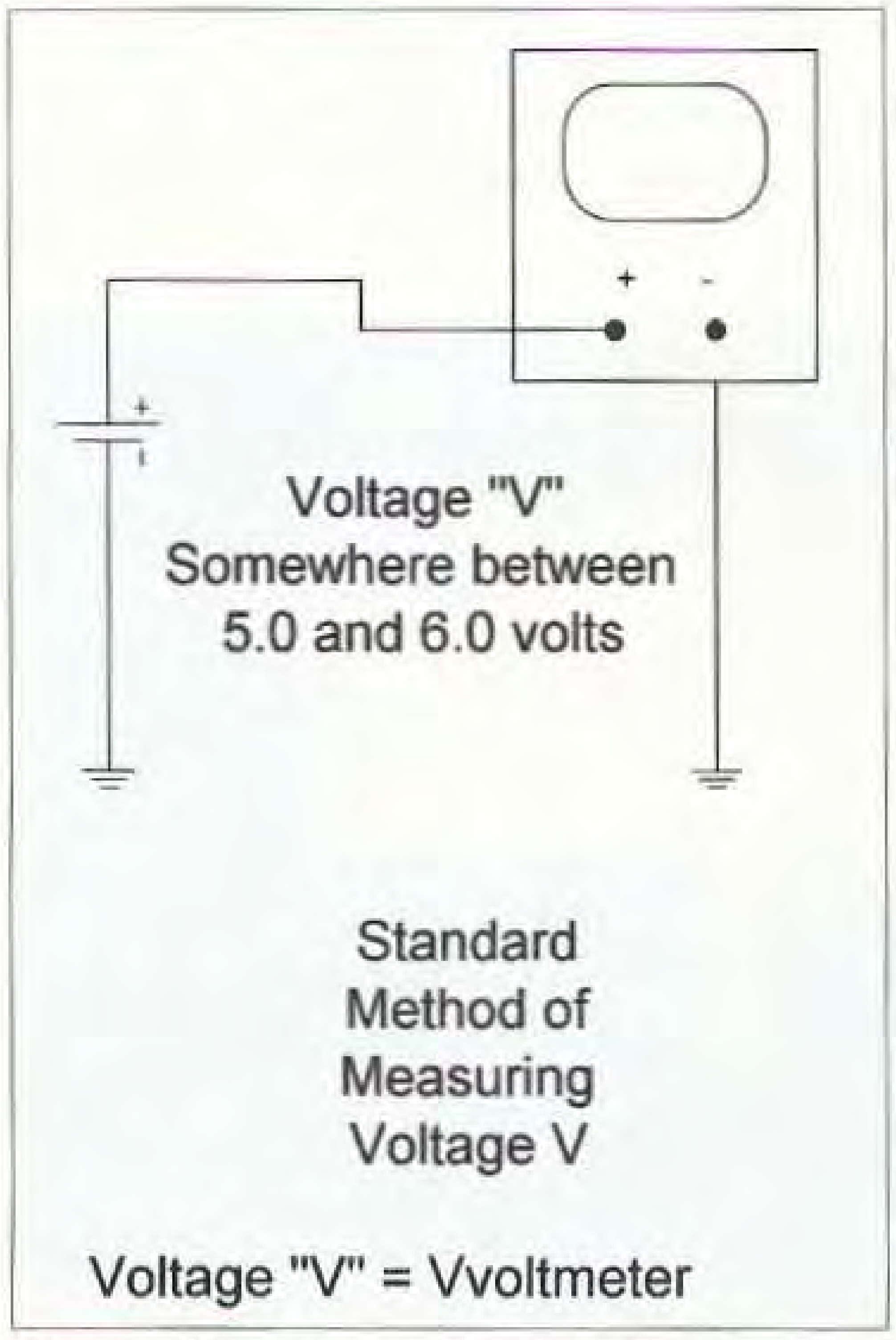

Fig. 1. *Voltmeter on 0–10-volt scale.*

Of course, this assumes that the reference voltage is accurate, as its error budget must be added to the voltmeter error. We'll take care of that in calibrating the overall instrument.

To extend this concept to an expanded scale AC voltmeter reading, we just need one more step; a rectifier to convert the AC voltage to DC.

Circuit description

Since this is a junk box project, the circuit description will concentrate on concepts so that the builder can adjust important parameters to match the available components.

The left-hand portion of the circuit produces a stable DC reference voltage of about 5.1 volts. The right-hand portion of the circuit produces a DC voltage proportional to the AC line voltage. The meter and series adjustment resistors (R2 and R3) measure the difference between the DC reference and the DC proportional voltage.

Reference voltage source

T1 is a small low-voltage transformer. I used a Stancor SW210, rated at 5-0-5 volts at 110 mA. The two secondary windings are connected in series to yield 10 VAC and feed a full-wave bridge rectifier, U1. The bridge I used is rated at 1 A, 400 V, but anything over 100 volts should be satisfactory. The objective is to produce around 15 to 20 volts to feed the reference subcircuit (Q1, R1, and D1) when the line voltage is at the lower limit you have selected for the meter. This circuit only draws a few milliamperes, so you may see much more output voltage than expected, based only on the transformer rating. For example, my SW210 transformer should result in around 13 VDC, but in fact at only 100 volts line voltage, I measured 17.4 volts. Small transformers have significant series resistance and the output voltage will soar under light loading.

As a safety measure, both the primary and secondary of T1 are fused.

A transformer with a 12.6-volt secondary should work fine without any other changes in the circuit. If you have a 6.3-volt transformer, use a voltage doubler.

Q1 and R1 form a constant-current source, with the current set by the value of R1. Current flowing through R1 biases the gate of Q1 negative. Any change in current causes an offsetting change in Q1's bias thereby restoring the original current. I used an MPF102, but most N-channel JFETs should work in this circuit.

This simple circuit is quite effective, with a 50% increase in drain voltage causing less than a 2% change in current.

D1 is a 1N751A 5.1-volt zener diode. By feeding the zener through a constant-current source, instead of a simple resistor, we can further stabilize the reference voltage. I selected a 5.1-volt zener as the reference because zener diodes in this voltage range exhibit the lowest voltage change with temperature.

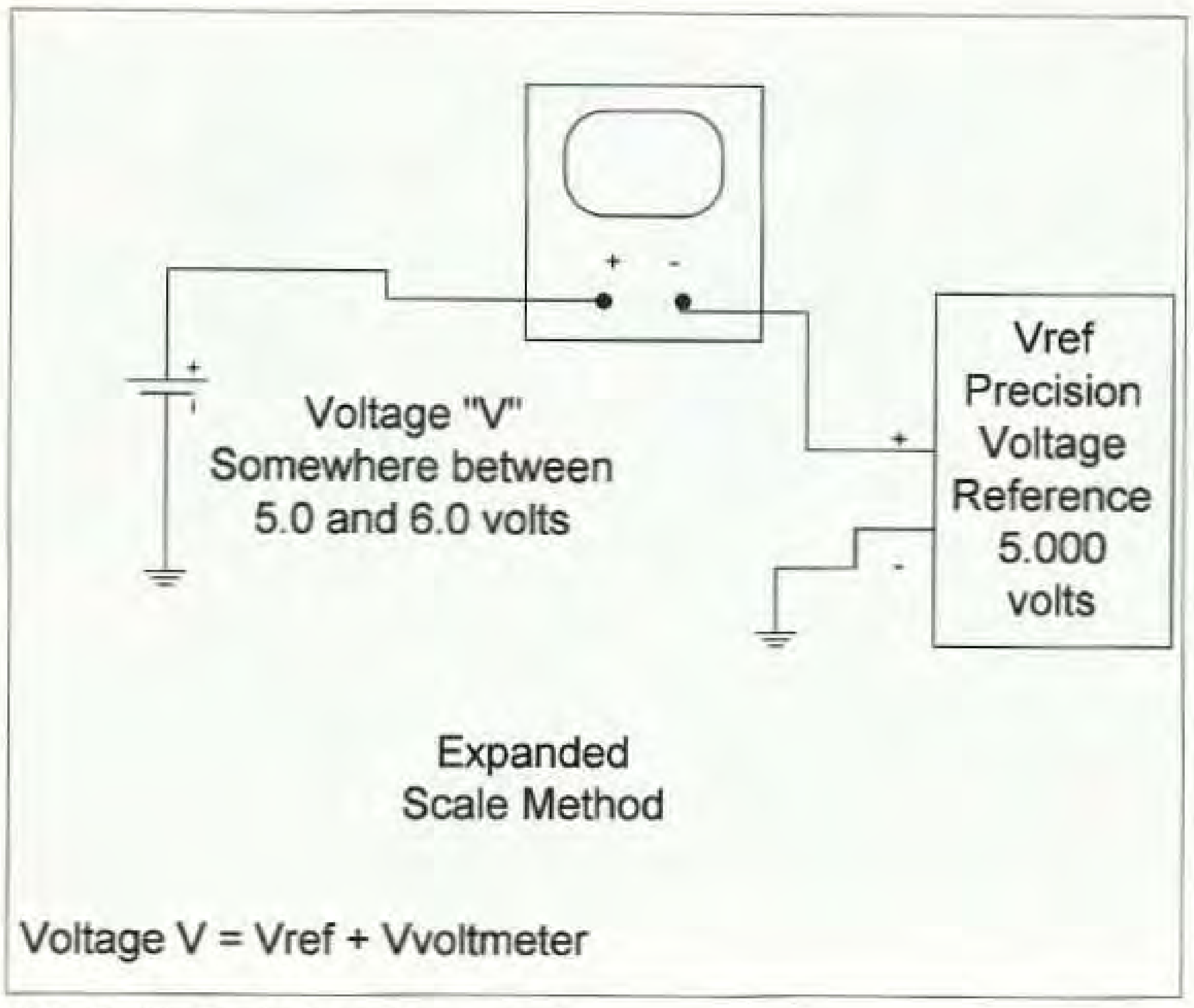

Fig. 2. Expanded-scale method.

An added refinement is to set the current through D1 to a value that minimizes changes in zener voltage with temperature. For the 1N751A, 5 mA produces essentially zero voltage change over the temperature range –25°C to +125°C.

Due to unit-to-unit variation in FET characteristics, it is necessary to select R1 to produce 5 mA through D1. Start with 270 ohms for R1 and measure the current. (You can just measure the voltage across R1 and calculate the current with Ohm's law — divide the voltage across R1 by its value in Ohms.) If the current is below 5 mA decrease R1, or increase it if the current is above 5 mA. A zener current between 4 and 5 mA will be fine. You could, of course, use a 1k pot and adjust it to produce 5.0 mA, but since this is a "select once and forget" adjustment, hand selection of an appropriate R1 works just as well.

If you don't want to use the constant-current zener approach, a 78L05 low-power 5-volt reference can be substituted. However, a 78L05 has a typical line regulation of 10 mV, or about 0.2%. This is not as good as I measured for my circuit, but provides reasonable results.

The combination of constant-current source and zener yields a remarkably stable voltage reference. Varying the AC input voltage from 100 volts to 135 volts only shifts the zener voltage 500 microvolts, representing a 0.01% shift in the 5.1-volt reference.

Proportional DC voltage

R5, R6, and R7 form a voltage divider, fed from the input line voltage. A variable sample of the line voltage is rectified by D4 and partially filtered by C2.

The component values shown in the schematic will work for a meter sensitivity between 50 µA and 500 µA . If your meter requires 1 mA or more current, it may be necessary to reduce R5 and R7 proportionally.

R5 dissipates about 0.5 watts at maximum line voltage and hence should be rated at 2 watts or more. Since the value of R5 directly affects the sample voltage, it should be a metal film resistor for good temperature stability. R7 should also be stable, but since R5 swamps its effect on accuracy, a standard carbon film resistor is acceptable.

C2 and R4 are selected to provide some filtering of the rectified sample voltage, but not complete filtering. About 1.5 volts p-p of ripple can be measured across C2. The reason C2 is intentionally small is to permit the meter to react to short fluctuations in line voltage. If you have an under damped meter and can see the pointer responding to the term ripple, increase C2.

R6 is used to adjust the meter to zero at the minimum desired voltage reading. With a 100 µA meter, the values shown permit setting the meter zero between 90 volts and 125 volts.

In building the expanded scale meter, I first tried to derive the proportional voltage from the secondary of T1. Unfortunately, I found that the particular transformer that I used did not yield an acceptable sample voltage — most likely due to core saturation — with a maximum error of 2.8%. In contrast, sampling the input line voltage as shown in the schematic produces less than 0.1% error.

Meter

The meter section of the circuit consists of R2, R3, D2, D3, and M1.

R2 is adjusted to calibrate the meter to a full-scale reading, while R3 is a safety resistor to prevent M1 from experiencing excessive current during adjustment of R2. D2 and D3 are an additional safety measure and shunt excess current away from the fragile meter coil.

The R2 and R3 values will be driven to some extent by your selection of M1.

R3 should be selected to limit the maximum current through M1 to a safe value should R2 be inadvertently set. The maximum difference between the reference and the sample voltages is about 1.25 volts if your meter is set for the range 110 to 135 volts. The 100 µA meter I used has a series resistance of 2.5 kΩ. In the absence of R3, therefore, the maximum current through M1 would potentially be 1.25 volts/2.5 kΩ

Photo E. The rescaled meter looks as good as the original.

Photo F. Key ingredients for "Manhattan-style."

= 500 µA. This is a bit high for comfort, so a series resistor of 1.2 kΩ was used at R3. The series resistance is now a minimum of 3.75 kΩ and the corresponding current is 333 µA, a more reasonable value. A further safety measure consists of the back-to-back diodes D2 and D3 across the meter. These limit the maximum current through M1 to 280 µA based on the 2.5 kΩ internal meter resistance and a diode knee voltage of 0.7 volts.

Should R7 open up, a substantial increase in voltage might be seen across the meter. In this case, D2 and D3 will protect the meter movement. In addition, when the meter is powered up or powered down, the different charging and discharging rates of C1 and C2 will cause the meter to pin negative for a few seconds. D2 and D3 will prevent damage to the meter during this time.

Rescaling the meter

The following discussion assumes that the meter you have selected is not sealed and can be disassembled. My experience with "unsealing" sealed meters is not good.

Prepare a clean, clutter-free working place and assemble the tools you will need. A set of jeweler's screwdrivers, small pliers, and a miniature wrench set will be helpful. Many of the parts are quite small and a headband magnifier is quite helpful as well. A small plastic box to store the removed parts is a good idea.

I started with a Weston 0–100 µA meter.

Carefully disassemble the meter case and remove the scale plate.

We will now make a new meter scale, print it, and attach it to the back of the old meter place.

There are several methods to make a new meter scale. I originally started with the excellent meter scale software written by James Tonne WB6BLD, available at his Web page [http://www.qsl.net/wb6bld/]. After developing the scale I wanted, I printed it on a sheet of transparent plastic and overlaid it on the meter scale plate I had removed from my meter. Much to my surprise, I found that Weston had used nonlinear spacing and that the spacing between calibration marks varied as much as 20% from one end of the meter to the other. Although WB6BLD's software permits some nonlinear adjustment, it wasn't possible to get an accurate fit to the old scale.

So, I reverted to an old tried and true method. I made a 200% enlargement of the meter face on a copier. Using 200% enlargement, my Weston meter scale almost filled an 8-1/2- x 11-inch page to create a working master. Using typist's correction fluid, I blanked out the old numbers and the term "Microamperes D.C.," keeping the scale on the working master. Using Microsoft Word, I then prepared new numbers and an identifying legend for the meter. I used a font close to the original and adjusted its size and tracking to match the 200% enlargement. I then cut the numbers and legend out and pasted them onto my working master, using typist's correction fluid to mask any stray marks. A trick to avoid shadows from the pasted up bits is to paint the edges of the paste-up with typist's correction fluid. When you are satisfied with the working master, make a copy at the reverse of the original enlargement. Since I used 200% enlargement, I needed 50% reduction. It's worth checking the reduction against the original meter scale at this point, since the enlargement and reduction scales on copy machines are not always accurate. It may be necessary to play with the reduction factor a bit in order to obtain an exact duplicate of the original. Copy machines also often have a bit of "differential stretch" whereby the enlargement and reduction factors are slightly different for vertical and horizontal dimensions. When you are done, it should be possible to overlay the new scale on the original meter plate and have the dial lines align as exactly as can be seen using a magnifier. You will also get the best appearing results if the copy paper you use is bright glossy white. I used paper intended for inkjet printers and the scale turned out brighter than the original white paint.

If you have a flatbed scanner attached to your computer, you could scan in the meter face and edit it electronically.

The new paper scale is then attached to the back of the original metal scale plate. I used a repositionable artist's spray adhesive so that I could remove the paper scale if I misaligned it. Use the mounting place screw holes to align the paper scale on the mounting plate. The ultimate accuracy of your rescaled meter depends on your ability to exactly align the paper scale, so work carefully when mounting the paper scale. Re-attach the scale plate with the new scale to the front. Make sure that the meter pointer is not binding on the paper and that bits of paper have not fallen into the meter workings.

Re-assemble the meter cover, ensuring that the mechanical zero screw engages the adjustment tang.

Note that I've labeled the meter "RMS Volts AC." Since the circuit actually responds to the rectified average voltage, this is not a true RMS reading meter. However, it is calibrated for RMS voltage, assuming the line voltage is sinusoidal, a reasonable assumption for normal AC line voltage.

My decision to keep the original scale drove my choice of minimum and maximum voltages. The original meter had 50 division marks with main divisions every 10 marks. If I chose 1 volt per division mark, my meter would span 50 volts, which is larger than necessary. If I instead used 0.2 volts per division mark, my span would be only 10 volts, a bit small. I compromised with 0.5 volts/division for a span of 25 volts. I decided to use 110 volts as the zero point and 135 volts as full scale. This gives even 5-volt divisions for the main scale, but awkward half-volt values for in-between points.

Construction

Since we are dealing with power line frequencies, a variety of construction techniques will work. A printed circuit board is certainly not necessary, and was not made since the particular meter and components used will likely vary so much from builder to builder.

The expanded scale meter shown in the illustrations uses copper pads on glued PC board, also known as the "Manhattan-style" construction, popularized by Wes Hayward W7ZOI. An excellent description of the nuts and bolts of Manhattan-style construction can be found at K7QO's Web page [http://www.qsl.net/k7qo/].

For those unfamiliar with this construction approach, it uses circular copper pads, punched out of scrap printed circuit board stock, glued onto the main PC board. Place a drop of "Super Glue" on the back of the pad and position it. In a few seconds it will be bonded to the main board.

The completed circuit board is mounted on the back of the meter, using the two meter terminal studs. It's necessary, of course, to remove the copper foil from the area around the meter lugs. I used a milling machine, but you could etch it chemically, or cut it out with an Exacto knife and peel the copper from the fiberglass substrate.

Don't rely upon the pads to hold heavy components. I used a TyWrap® to secure T1 to the board. C1 is held in place by a couple dots of hot-melt glue. The fuse holders are secured by 6-32 hardware. I also used quick disconnects on the AC line so that I could easily remove the board while testing circuit modifications.

I used a Radio Shack plastic box to house the meter and board. Since this project involves line voltage, it is

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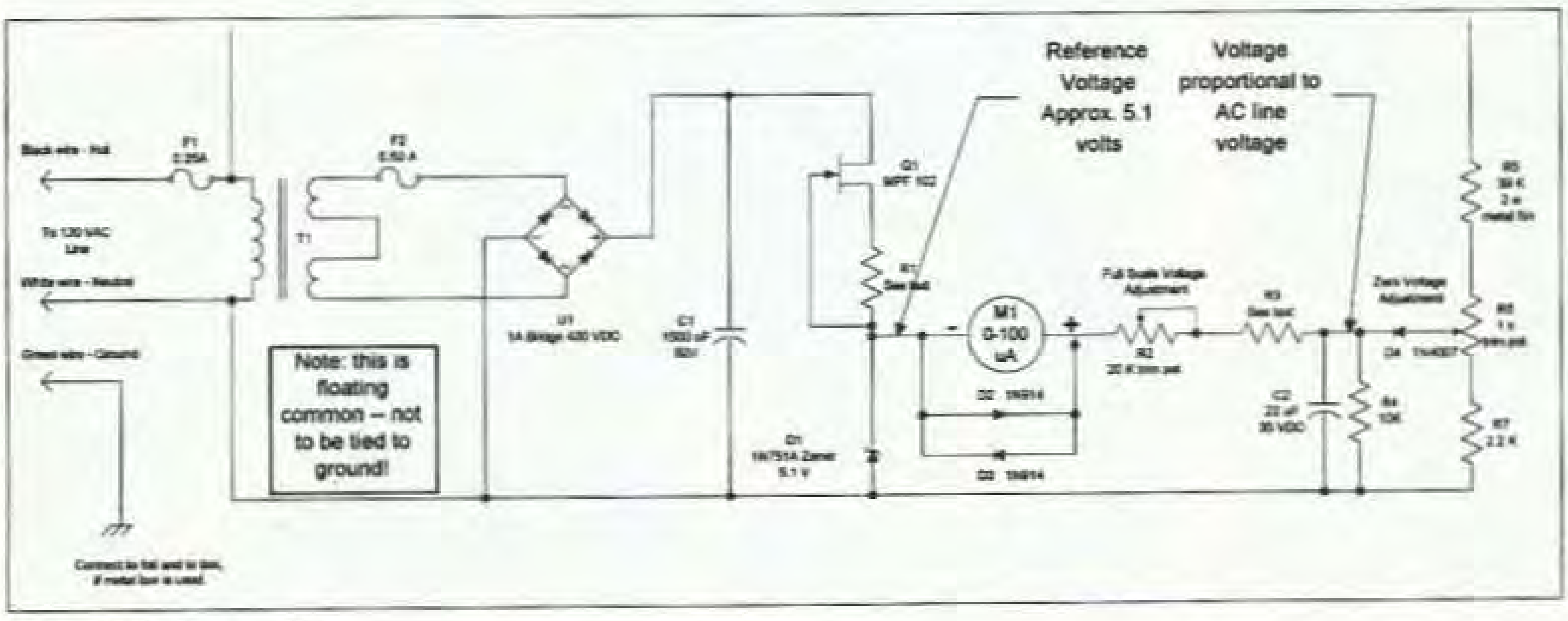

Fig. 3. Schematic.

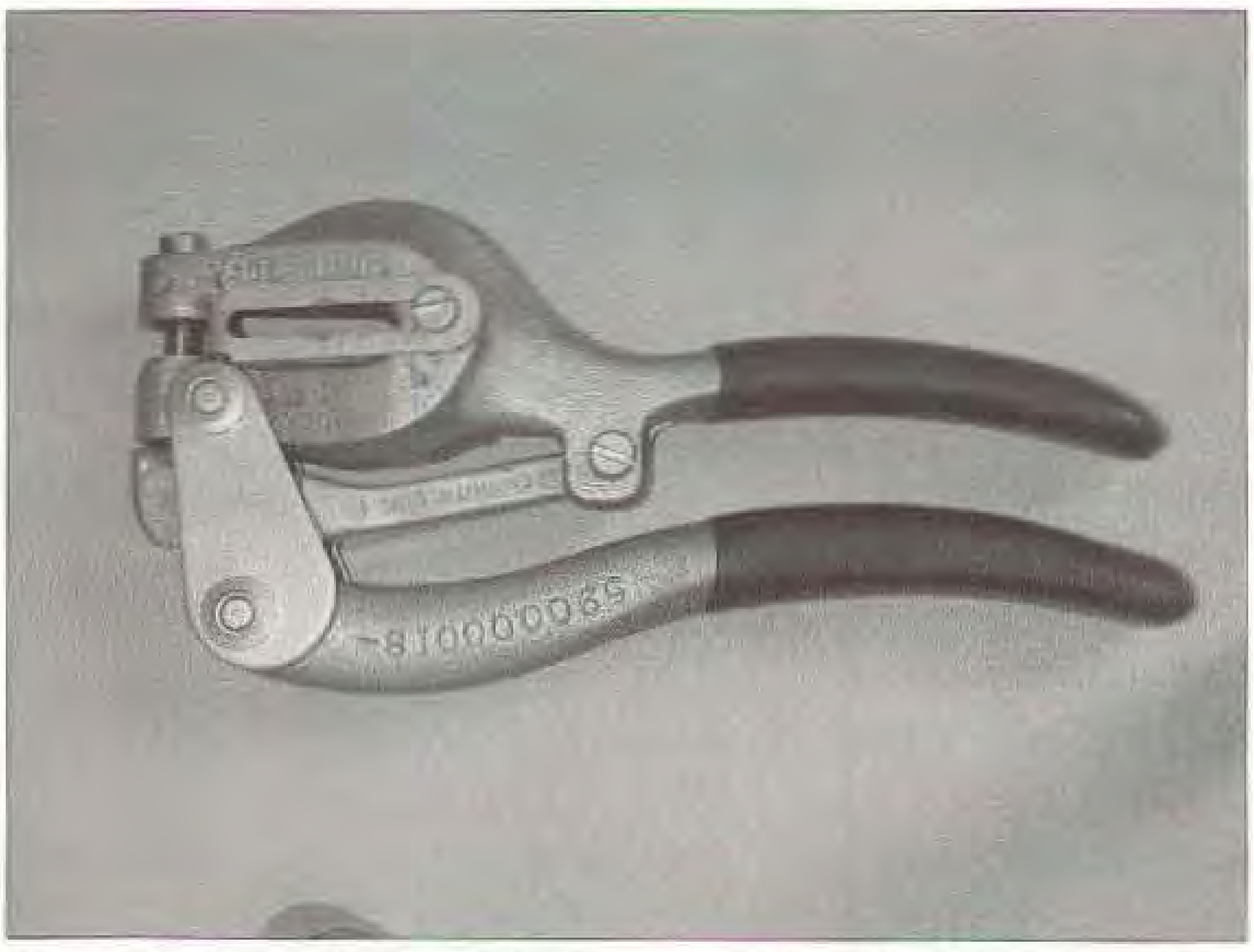

Photo G. I punched out the copper pads with a Roper-Whitney No. 5 Junior hand punch.

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important to protect against inadvertent contact with potentially lethal voltage. The plastic box provides an additional layer of protection. Note also that one side of the AC line is common with the negative side of the low voltage reference DC supply. While normally I would have used the copper foil of the main PC board for the negative low voltage DC connection, this would mean that one side of the AC line was connected to what is usually considered "ground." This could lead to an unpleasant surprise or worse. If you use my wiring technique, please use a 3-wire (hot, neutral, and ground) line cord and connect the ground (green wire) to the copper foil of the board. The photos show a two-wire line cord that I use with an isolation transformer for testing and calibration. If you use a metal box to house this project, the box should also be connected to the AC line ground wire.

Checkout and calibration

After construction, carefully check your wiring for errors. If you use the Manhattan-style construction, check the resistance between the PC foil and the rest of the circuit. This should be an open circuit.

Disconnect M1 from the circuit for the following initial checkout.

Connect the circuit to a variable AC power source, such as a VARIAC® and place an accurate digital voltmeter across the AC line. Please remember that a standard VARIAC is not isolated from the AC line and that inadvertent contact with the AC line can cause severe shock or injury. Please be careful! I strongly recommend using an isolation transformer between the VARIAC and the expanded scale voltmeter at any time when the case is open and voltage is exposed.

Always unplug the meter from the VARIAC before attaching or detaching clip leads! The steps below require you to measure voltages and adjust potentiometers whilst AC line voltage is applied. Please be careful during this process! Remember the old rule of keeping one hand in your pocket when working around dangerous voltages.

Set the VARIAC to the "zero" voltage level you have selected. Check the voltage across D1 with an accurate digital voltmeter. It should be 5.1 volts ±0.25 volts. (If you haven't already determined the proper value for R1, do so now.) Note this value as V_{ref}. Increase the VARIAC to the voltage level you have established as the "full scale" voltage. The actual voltage level is not so important. It is much more important that V_{ref} should be essentially unchanged as the AC line voltage is varied. If V_{ref} changes more than a few millivolts, you have a problem with Q1, R1, or D1. (My prototype changed only 0.5 millivolts.)

Move your digital voltmeter to read the voltage across C2. Set the VARIAC to the zero voltage level you have selected. Adjust R6 through its range. You should see the voltage across C2 vary from 4 volts (or less) to 6 volts (or more). Set R6 so the voltage across C2 is equal to V_{ref}. If you can't obtain this range of voltage adjustment, check R5, R6, R7, D4, R4, and C2 and the associated wiring.

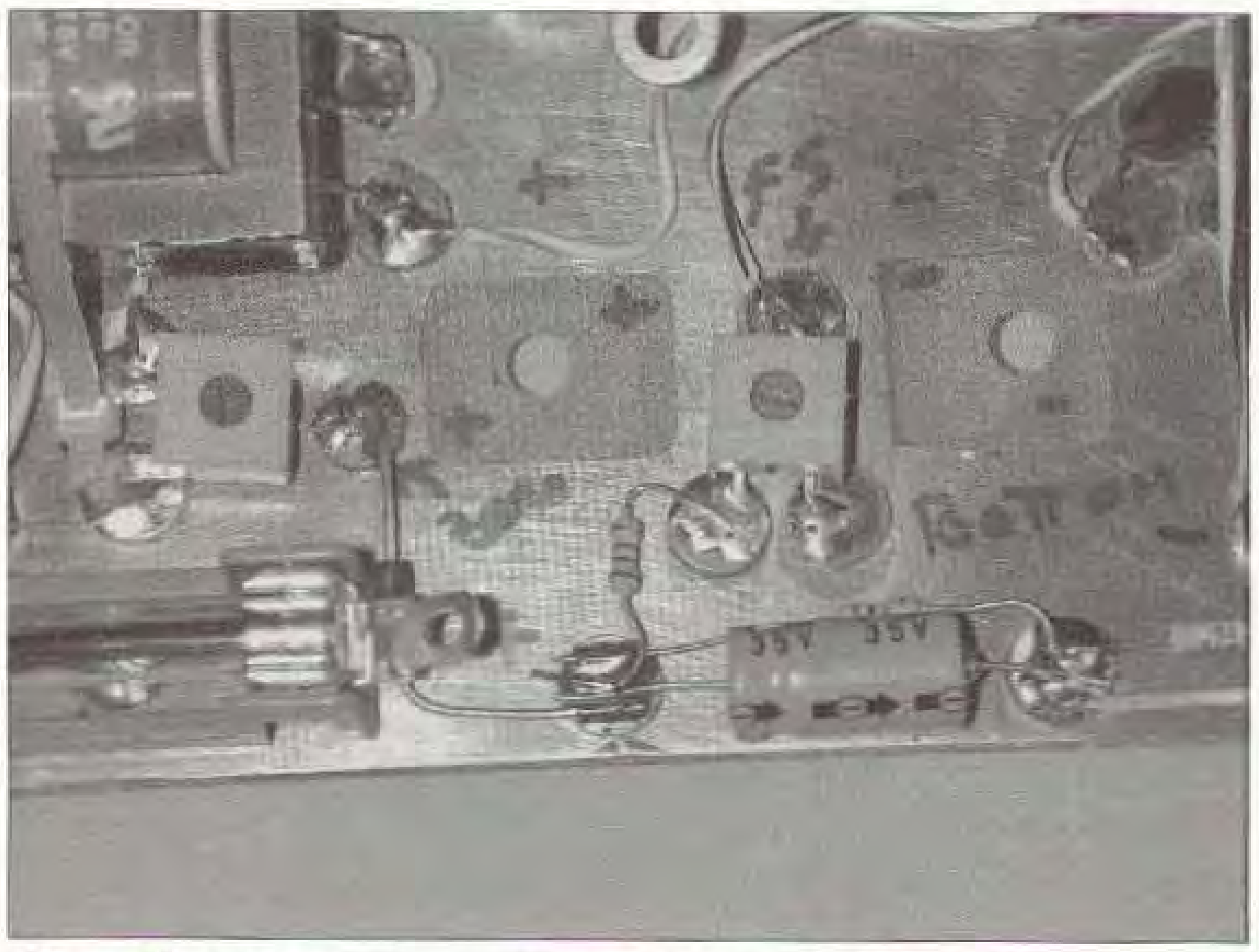

Photo H. Wiring techniques can be seen here.

Photo I. More wiring.

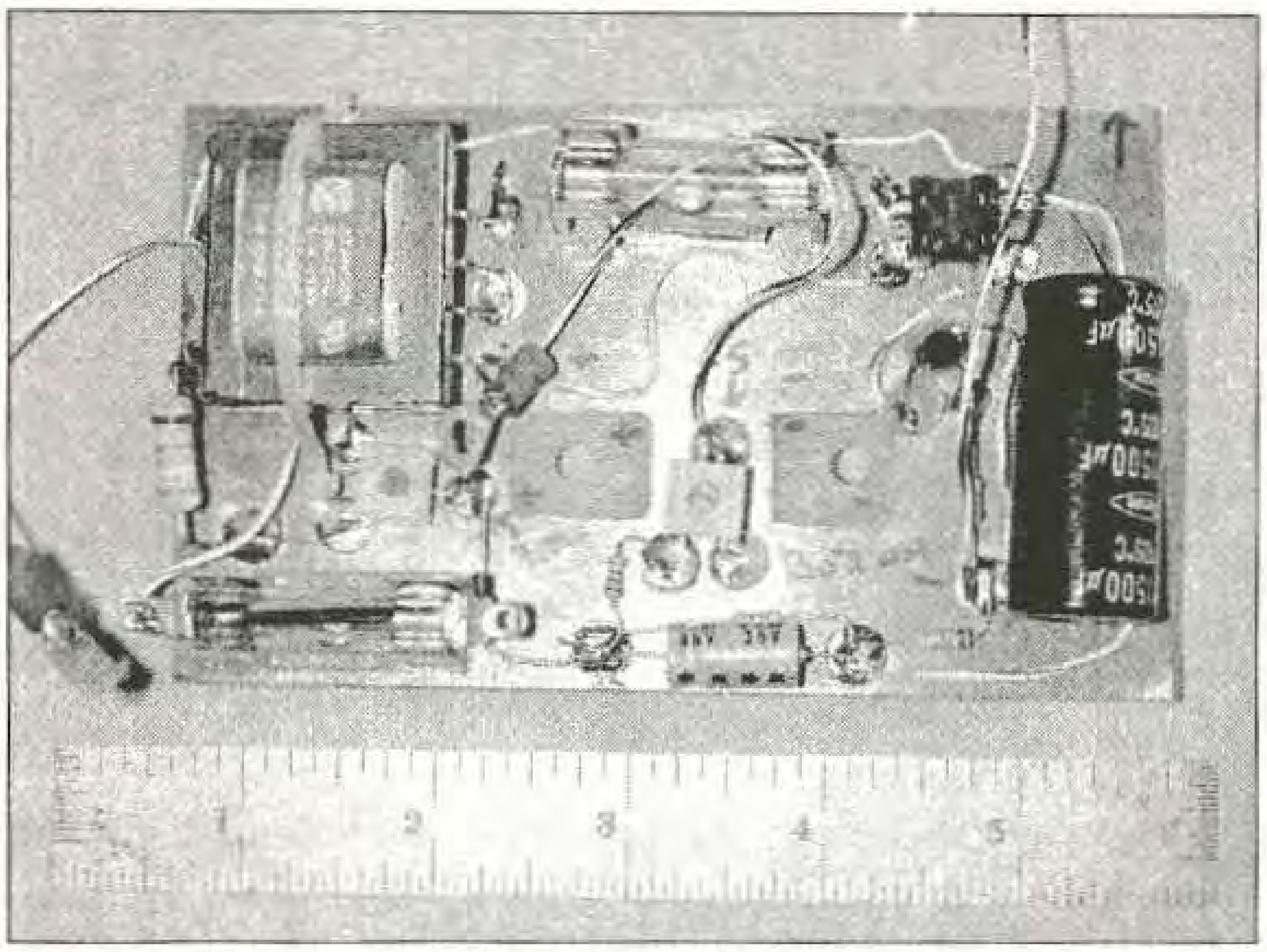

Photo J. *The completed circuit board is mounted on the back of the meter, using the two meter terminal studs. It is necessary, of course, to remove the copper foil from the area around the meter lugs. I used a milling machine, but you could etch it chemically, or cut it out with an Exacto knife and peel the copper from the fiberglass substrate.*

Disconnect the circuit from the VARIAC.

Preset R2 to midrange and connect M1 into the circuit.

Reconnect the circuit to the VARIAC and set the AC line voltage to the zero voltage level you have selected.

Using a nonmetallic adjustment tool carefully adjust R6 to zero the meter. Use a nonmetallic tool to help reduce the risk of contacting line voltage.

Increase the AC line voltage to the full-scale value and, using the nonmetallic adjustment tool, adjust R2 carefully until the meter reads full scale.

It may be necessary to repeat the R2/R6 adjustment once or twice, as they interact slightly.

Disconnect the circuit from the VARIAC and install in the box.

Check the accuracy of your meter at several points over its scale range. I found that my expanded-scale voltmeter is within 0.2 volts of my HP 3468 precision digital meter at the worst point and that almost all readings are within 0.1 volt.

Of course, the accuracy of your expanded scale meter is directly tied to the accuracy of the digital voltmeter used in calibration. A standard, "run-of-the-mill" digital voltmeter obtained for a few dollars may be surprisingly inaccurate when reading AC voltage. I recently received a "free" 3-1/2-digit DVM when ordering some equipment. This DVM is rated as ±0.8% of reading and ±3 digits on the 0–200 VAC scale. For 125 V, therefore, the error limit would be 1.3 volt. If you can borrow a more accurate DVM, such as a Fluke 187 or 189 (±0.4%, ±40 digits; resolution 0.01 volts), the error will be reduced to 0.9 volts. Even a laboratory-grade instrument, such as the HP 3468, is only specified to be within 0.727 volts when reading 125 volts. However, when reading AC line voltage, my Fluke 189 agrees with my HP 3468 within 0.05%, while the "free" DVM diverges from the Fluke 189 and HP 3468 by about 1%.

One point noted when calibrating the expanded-scale meter is that the AC line is not particularly stable; appliances cycling off and on in the house can cause 0.5-volt variations. Hence, some degree of "eyeball averaging" may be necessary when calibrating the meter.

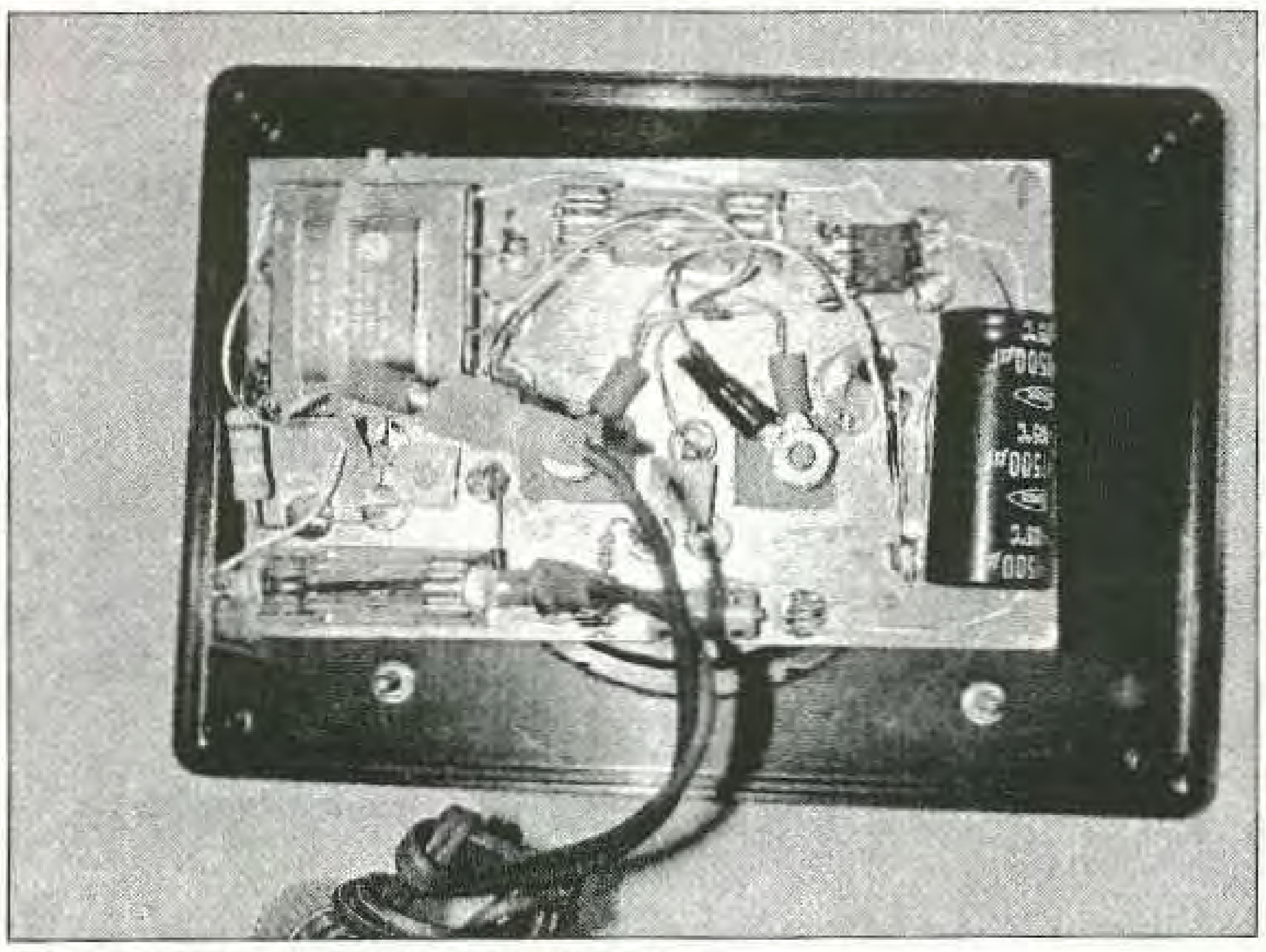

Photo K. *The board installed in place.*