Jack R. Smith K8ZOA
7236 Clifton Rd.
Clifton VA 20124
[JackSmith@cox.rr.com]

Build This Amazing ESR Meter

A simple project for everybody's shack.

There are only two types of electrolytic capacitors in your equipment — those that have failed and those that will fail. Only a small percentage of bad electrolytics fail as a short circuit. Rather, most dry out and gradually become less effective at their filtering, coupling, or bypassing job.

Troubleshooting a dried-out electrolytic isn't the easiest task, even if your workshop is equipped with a capacitance bridge. A relatively new test instrument, the equivalent series resistance (ESR) meter, makes this task simple. Although ESR meters are commercially available, it isn't hard to build one. This article takes you through the design and construction of a simple ESR meter.

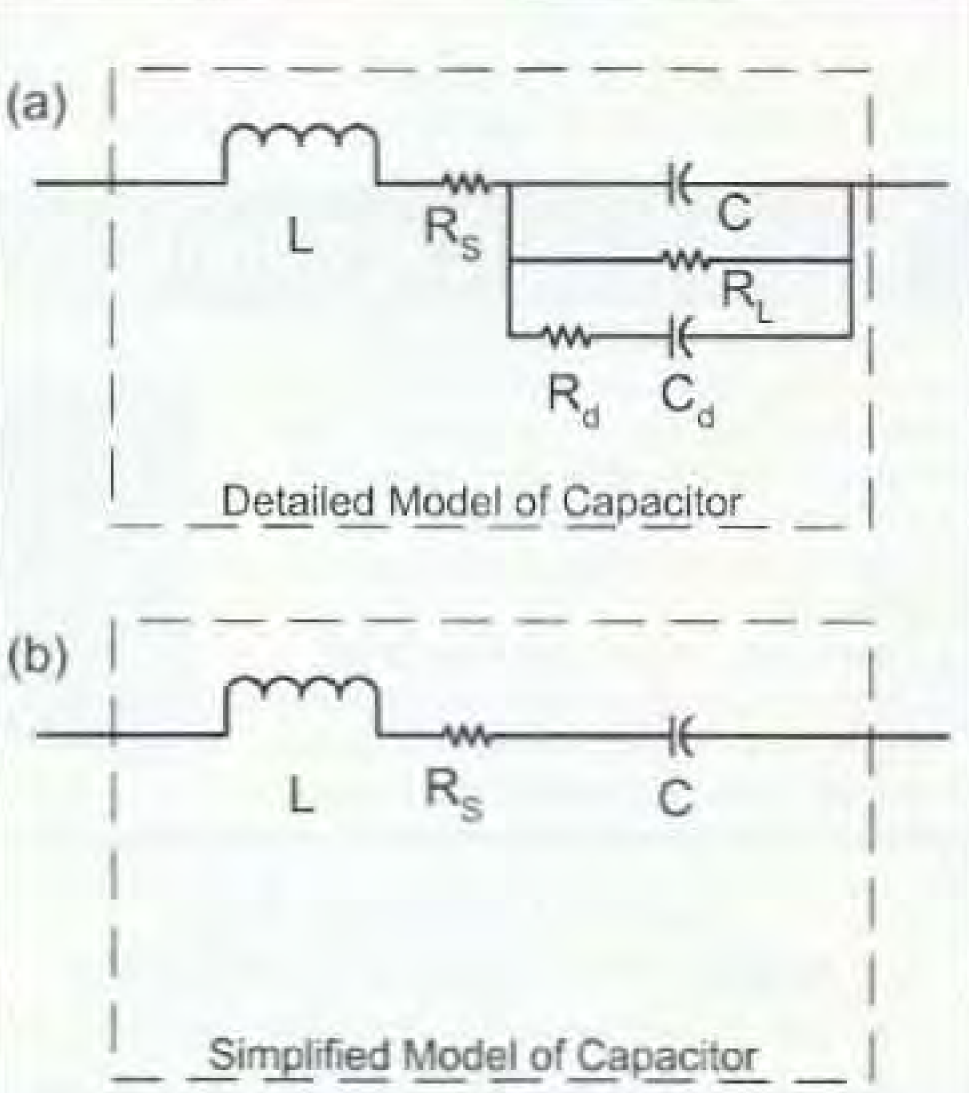

Fig. 1. *A real-life capacitor can be modeled differently depending upon the level of detail necessary.*

What is equivalent series resistance, and how do you measure it?

A real capacitor isn't the simple perfect device that the schematic symbol might lead one to believe. Two common capacitor models are shown in **Fig. 1**. We'll be concerned only with the simplified model:

- L represents the inductance of the lead wire and capacitor construction.
- R_S represents all the loss elements of the capacitor, including lead wire loss, capacitor electrode loss and dielectric loss.
- C is an ideal capacitor, with no loss and zero inductance.

As an electrolytic capacitor dries out, R_S increases, while L and C remain relatively constant. Thus, if we can measure R_S, we can detect faulty capacitors. We obviously can't measure R_S with a standard DC ohmmeter; C blocks DC current flow and at most we would measure the leakage resistance R_L in **Fig. 1(a)**.

However, suppose we had an ohmmeter that worked with AC instead of DC. With such a device, we would then measure the composite impedance Z of the series combination of the reactance of L and C and R_S. If we use a reasonably high frequency, typically 100 kHz, the reactance of L and C will be negligible in comparison with R_S for reasonable capacitance values. We can illustrate this with an example.

Consider a 10 µF nominal aluminum electrolytic capacitor. From measurements, at 100 kHz we know that C = 12.4 µF, R_S = 1.5 ohms, and L = 35 nH (including 1/2-inch leads).

Photo A. *Finished ESR meter.*

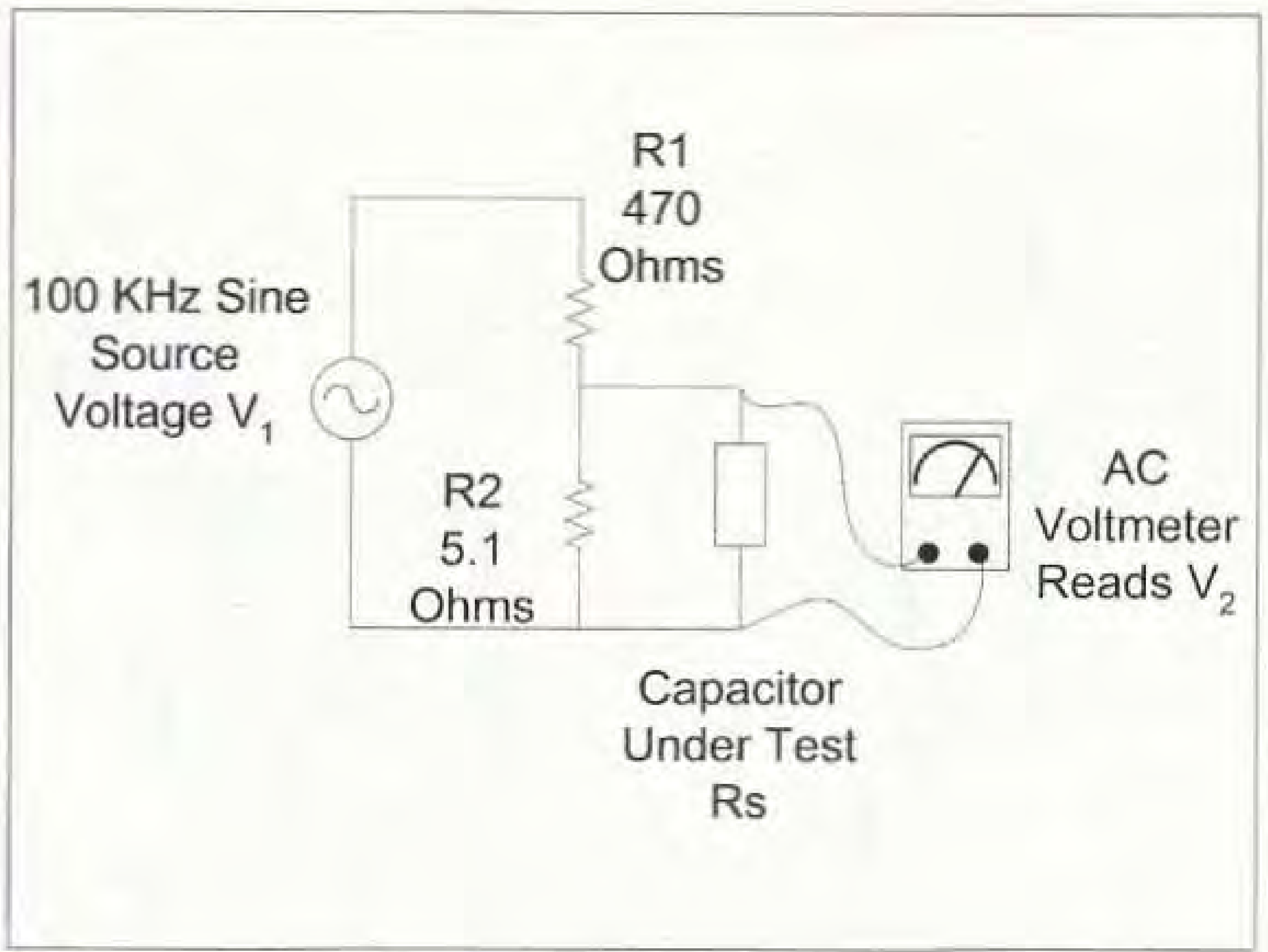

Fig. 2. The principle behind the ESR meter.

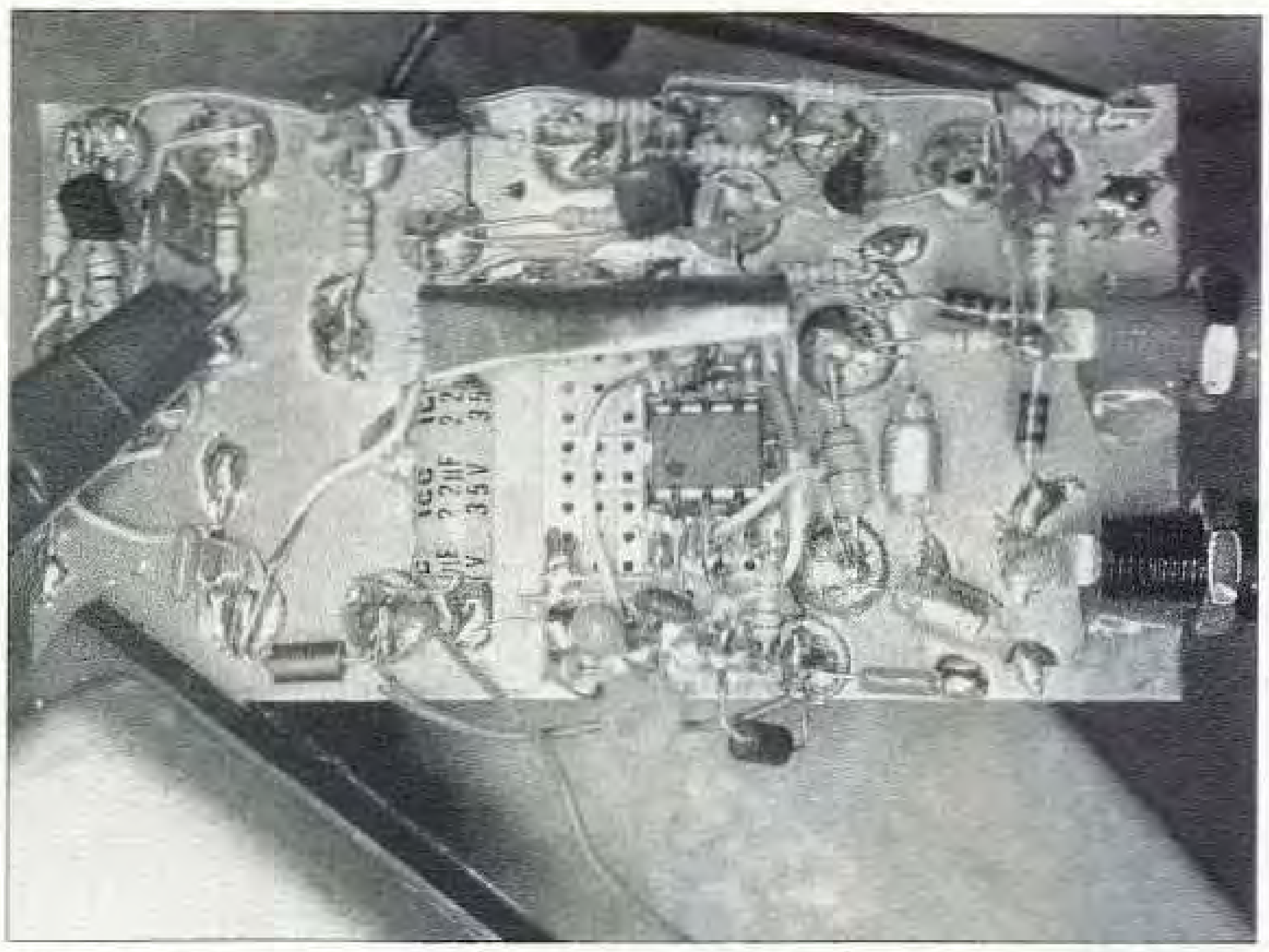

Photo B. I built the prototype using Manhattan-style construction.

We now calculate the reactive components of the model at 100 kHz:

$X_C = 1/(2\pi FC) = 1/(2\pi \times 100 \times 10^3 \times 12.4 \times 10^{-6}) = 0.128\Omega$
$X_L = 2\pi FL = 2\pi FL = 2\pi \times 100 \times 10^3 \times 35 \times 10^{-9}) = 0.022\Omega$

The impedance magnitude of the capacitor is thus

$$|Z| = \sqrt{R_S^2 + (X_L - X_C)^2} =$$
$$\sqrt{1.5^2 + (0.022 - 0.128)^2} = 1.503\Omega$$

Thus, at a frequency sufficiently high to make X_C small, yet low enough for X_L to also be small, Z is approximately equal to R_S. **Fig. 9** shows estimated |Z| over the range 100 Hz to 100 MHz and illustrates that between 10 kHz and 5 MHz, the impedance is dominated by R_S, the Equivalent Series Resistance. (**Fig. 9** is only approximate, as it assumes that L, C, and R_S remain constant. In fact, these parameters are all somewhat frequency dependent.)

Our "AC ohmmeter" can be as simple as **Fig. 3**. If the ESR dominates the impedance of the capacitor under test, a bit of simple algebra shows that the voltage V_2 is proportional to the ESR:

$$ESR = (V_2R_1R_2)/V_1R_2 - V_2(R_1 + R_2)$$

Fortunately, we won't have to use this equation; rather, we will simply calibrate the voltmeter scale in terms of ESR. The scale won't be linear, of course.

Circuit description

Our ESR meter has three main elements:

- A 100 kHz sine wave source
- An AC voltmeter (calibrated in terms of ohms of ESR)
- An LED bar graph display

U5 is a CMOS version of the popular 555 timer chip. It generates a 100 kHz, 50% duty cycle square wave. The square wave is fed through a low pass filter consisting of L1, C9, and C10. By stripping off the higher harmonics, the low pass filter converts the square wave into a reasonably good sine wave.

The 100 kHz sine wave feeds the voltage divider R16 and R18. The unknown capacitor is connected across R18, a 5.1 ohm resistor. Diodes D2 and D3 protect the instrument from damage, should the capacitor under test have some residual charge.

The maximum (open circuit) voltage applied to the capacitor under test is about 110 millivolts, peak-to-peak. By intentionally limiting the test voltage to such a low value, it is possible to test a questionable capacitor in-circuit, even if a diode or transistor junction shunts it. A silicon PN junction requires about 600 millivolts to

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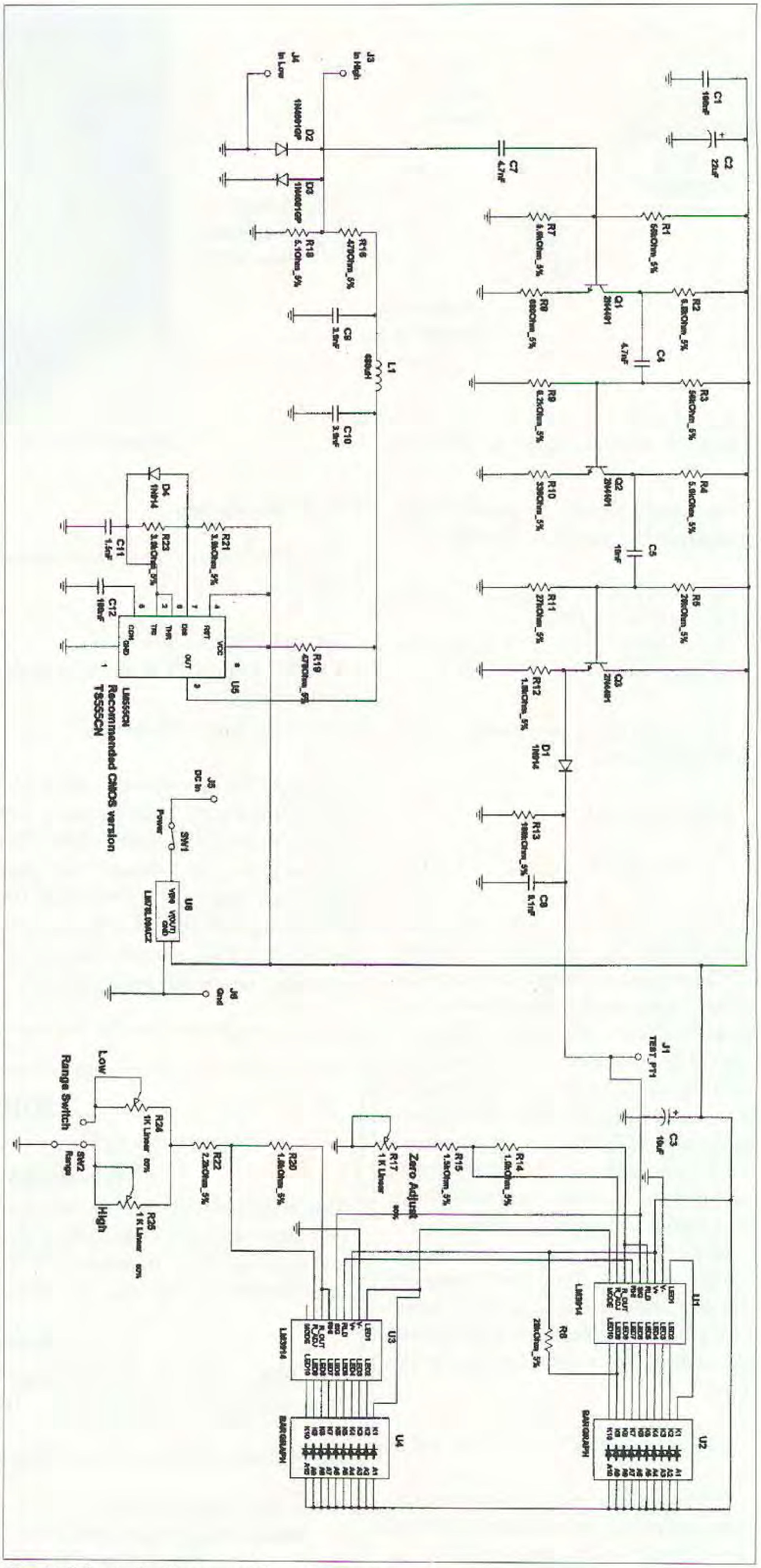

Fig. 3. Schematic diagram of the ESR meter.

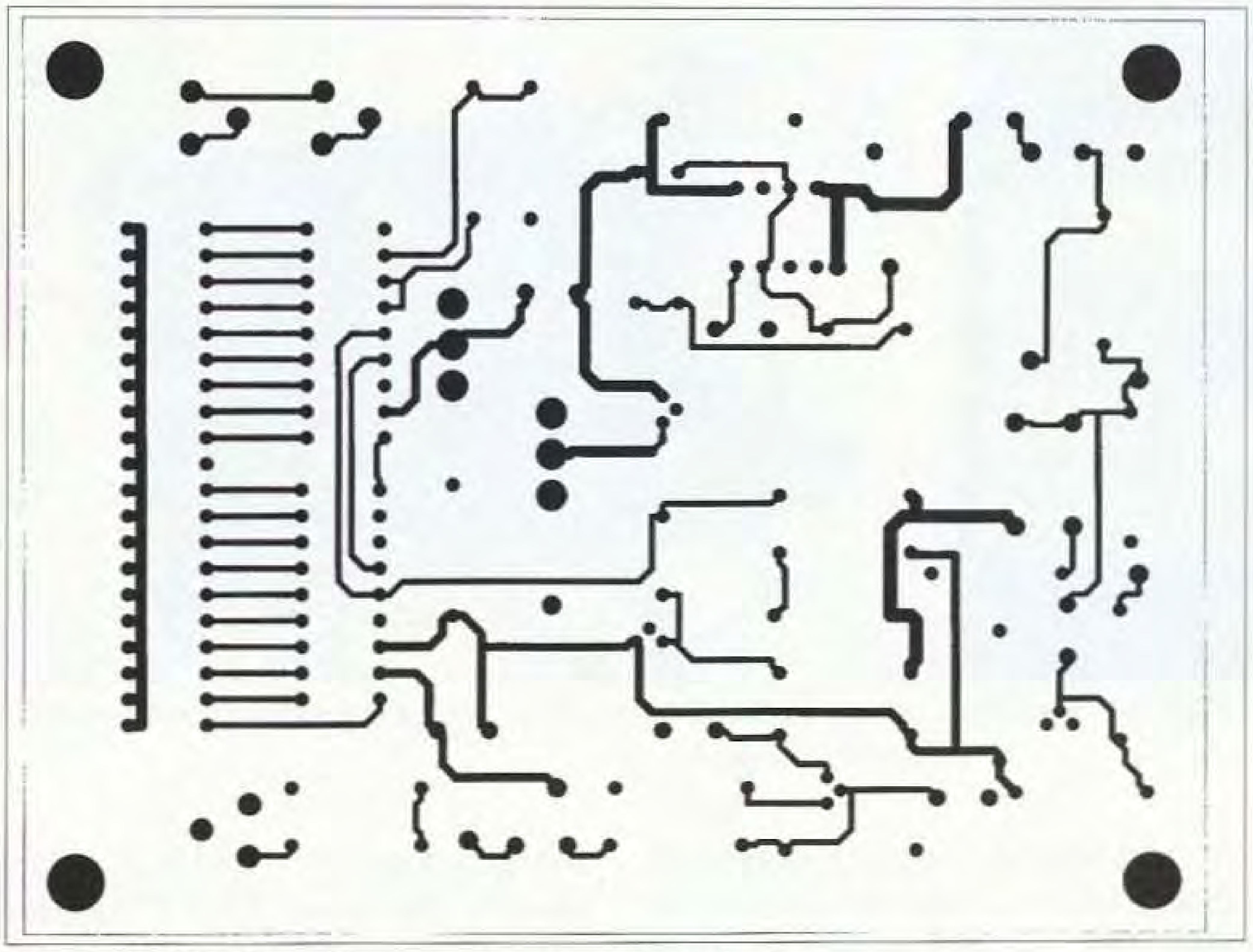

Fig. 4. 100% PC board layout — top copper (top view).

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cause significant current flow, so it looks like an open circuit to the test voltage.

Q1 and Q2 are a simple RC-coupled amplifier. The coupling capacitors (C7, C4, and C5) have been chosen to roll off frequencies below 100 kHz. The emitter resistors (R8 and R10) are intentionally not bypassed to increase stability.

The amplifier output feeds Q3, an emitter follower. D1 is forward-biased by the DC across R12, so D1, R13, and C8 act as a peak detector. The voltage at Test Point 1 ranges from 3.9 volts (short circuit across the input) to 5.5 volts

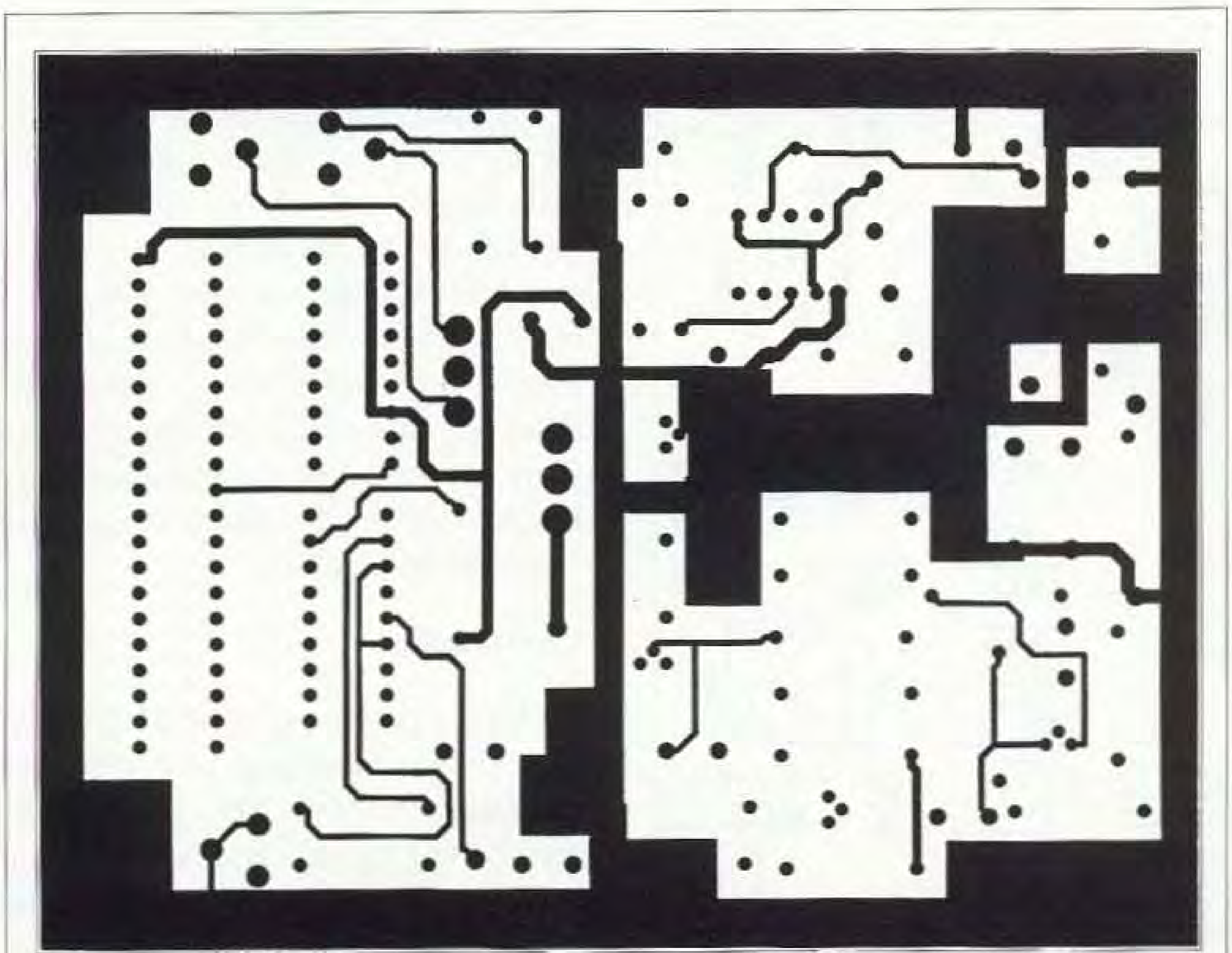

Fig. 5. 100% PC board layout — bottom copper (top view).

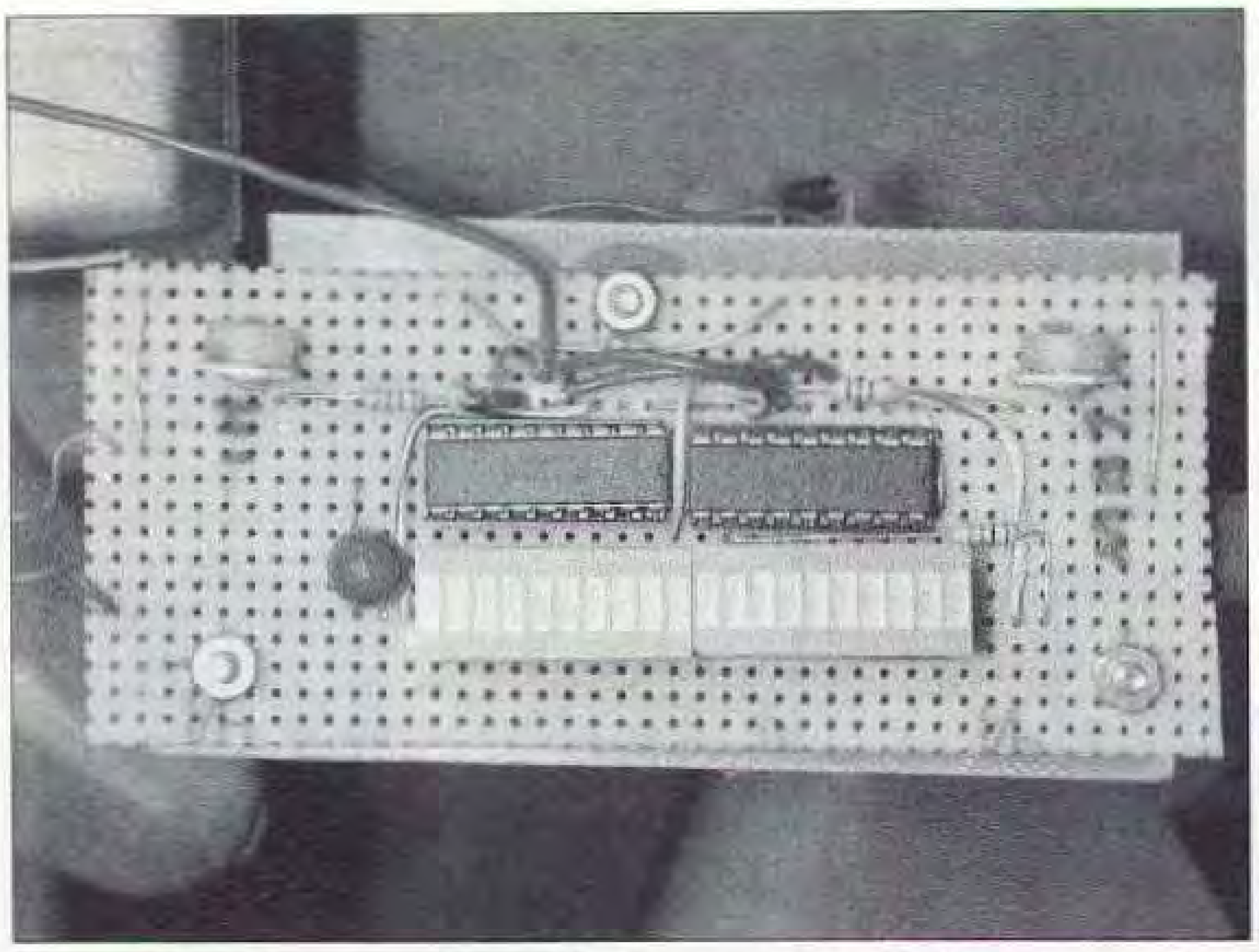

Photo C. The prototype display unit is built on standard perfboard.

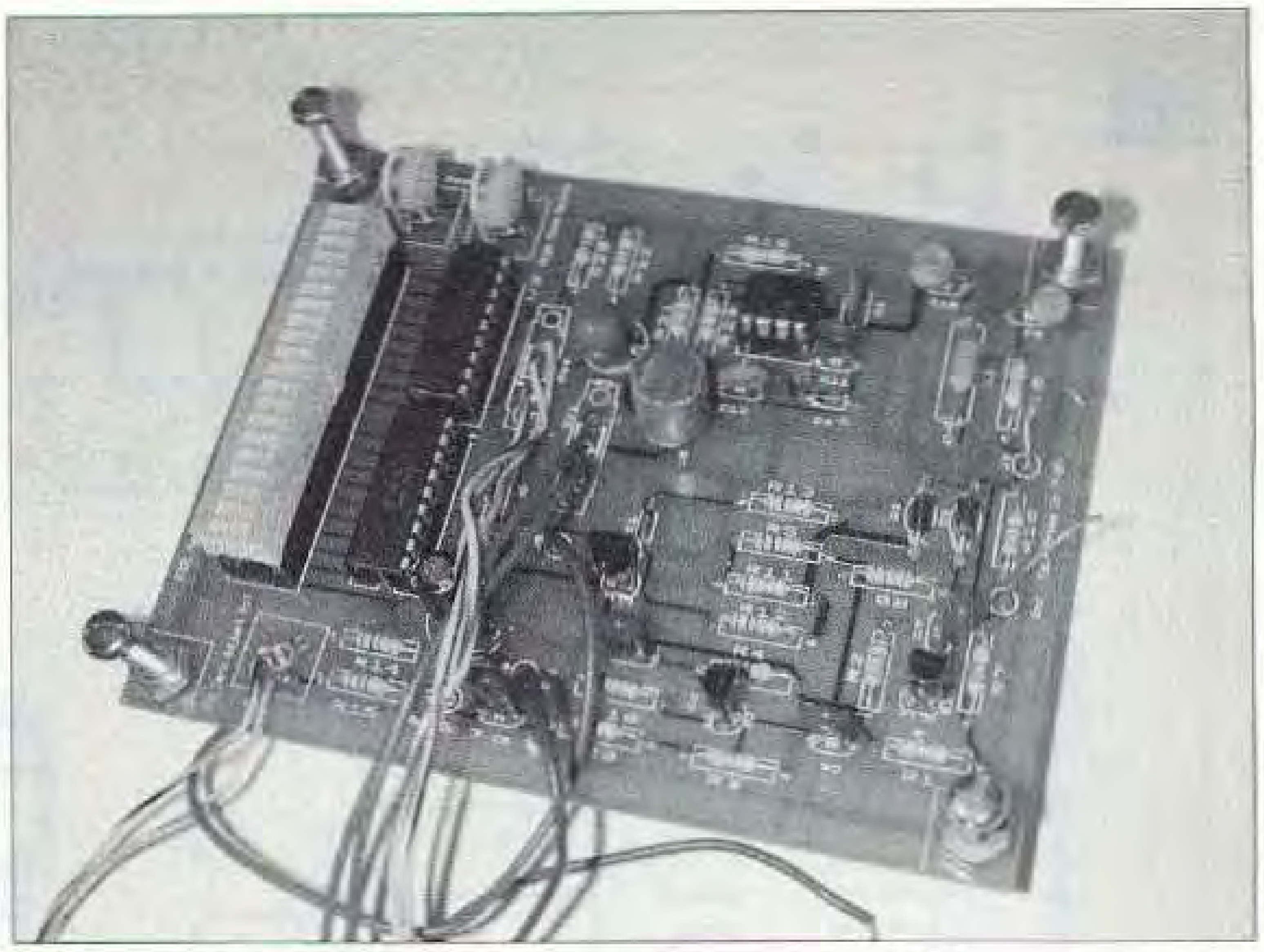

Photo D. The finished design, with a commercially made double-sided PC board.

(50 ohm resistor across the input). This voltage is applied to the signal input of the display section.

U1 through U4 form a moving dot LED bar graph to display the DC output voltage from D1. The circuit is taken directly from National Semiconductor's data sheets for the LM3914 linear bar driver. By cascading two LM3914s (U1 and U3), the voltmeter range is spread over 20 LED segments. U2 and U4 are LED bar graph displays. I used red displays because they are brighter for a given current consumption than other colors.

The LM3914s contain a voltage reference and internal voltage divider. R14, R15, and R17 adjust the voltage applied to the low end of the voltage divider chain. R17 is used to adjust the bar display "zero" setting, corresponding to the voltage output when the test terminals are short-circuited. R14 also functions as an LED display current control and is set for approximately 12.5 mA.

R20, R22, and either R24 and R25 perform the same function for the high end of the voltage divider chain. A switch permits selecting between two voltage settings. R24 and R25 are adjusted to turn on the 20th LED when a resistor corresponding to full scale (10 ohms or 50 ohms) is connected across the test terminals. R20 also functions as an LED display current control and is set for approximately 12.5 mA.

Power for the circuit is regulated by U6, a low-power 9 volt integrated regulator. DC input power should be in the range 12–14 volts, or up to 18 volts if U6 is equipped with a slip-over heatsink. I've powered the LEDs from the +9 volt regulated bus. If power consumption or regulator power dissipation is a concern, the LED drive current can be provided from a separate source of 4 volts or more.

I've used 5% carbon film resistors throughout the design because the ultimate display only shows 20 resistance steps and using the more expensive 1% metal film components isn't justified. I built two units and found the stated values were satisfactory. It's possible, however, that an accumulation of resistor tolerances might require changing R15 or R22 slightly in order to calibrate the display.

Construction

I built a prototype using 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/]. The display section used

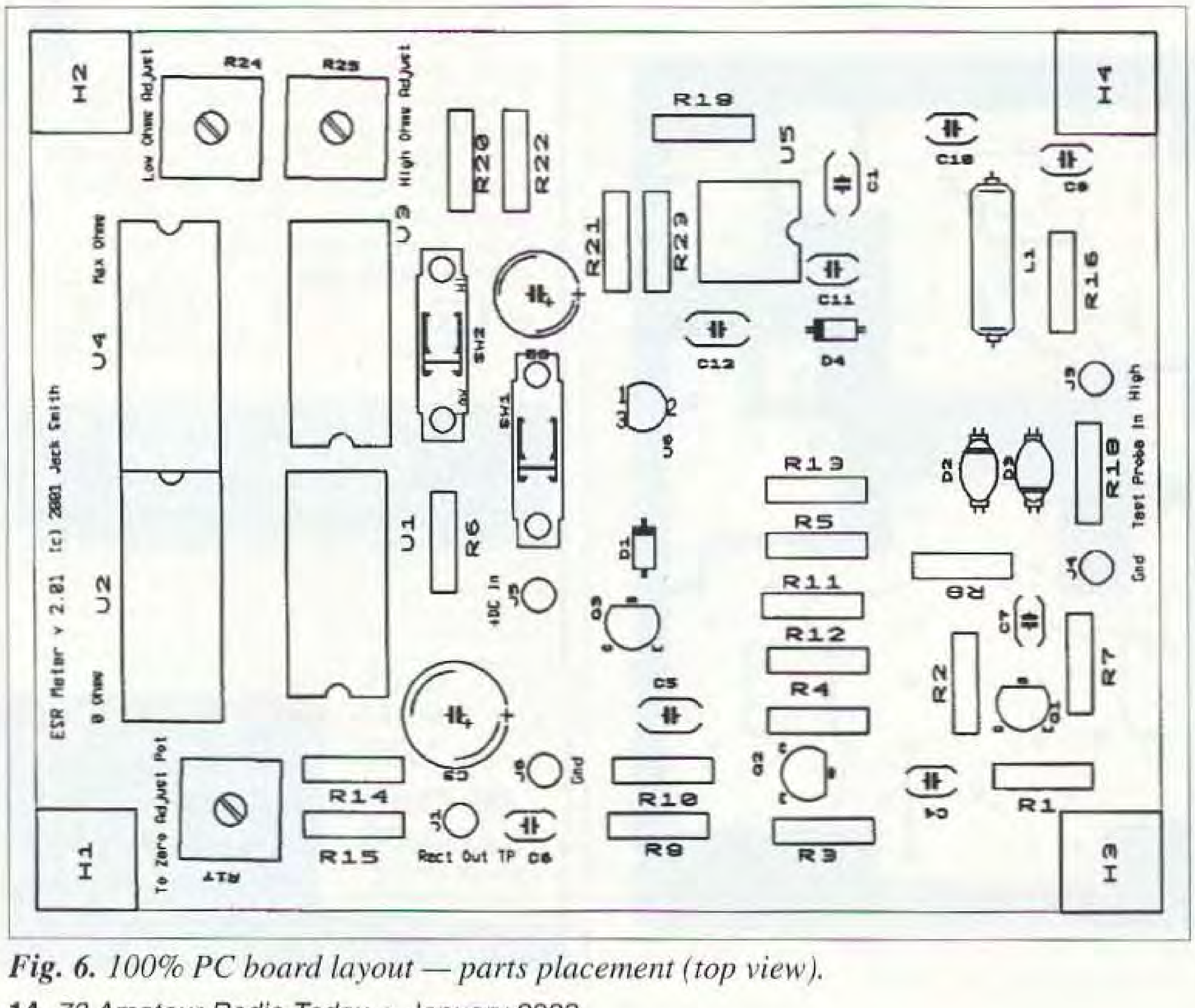

Fig. 6. 100% PC board layout — parts placement (top view).

conventional perfboard. Manhattan-style construction goes rapidly, and I built the prototype in a couple of hours. So, don't feel that a printed circuit board is necessary.

I also laid out a double-sided printed circuit board and had it fabricated by a prototype board house. I used this professional board for the completed unit.

It's always a good idea to build and debug a project in stages. The ESR meter has three logical stages that you can build and check sequentially:

The 9-volt regulator circuitry, the 555 timer and low pass filter (including R16 and R18). The output of U6 should be between 8.55 and 9.45 volts. At U5 pin 3, you should see a 100 kHz square wave, with a peak-to-peak voltage of about 8 volts. The precise frequency isn't critical, but it should be within 15% of 100 kHz. At the output of the low pass filter (junction of L1 and R16), you should see a clean 100 kHz sine wave with a peak-to-peak amplitude of approximately 10 volts. At the test lead connections (across R18), you should see a 100 kHz sine wave with a peak-to-peak amplitude of about 110 millivolts.

The amplifier and peak detector (Q1, Q2 and Q3 and D1). The following measurements are all peak-to-peak and assume the 100 kHz signal levels in the previous stage are correct. At the base of Q1, you should measure about 105 millivolts; at Q1's collector, 390 millivolts. At Q2's collector and at Q3's emitter, 3.8 volts. All should be clean 100 kHz sine wave signals. Check the DC voltage at the junction of D1, R13, and C6. With the input terminals open-circuited, you should measure about 5.5 volts. With the input terminals short-circuited, this

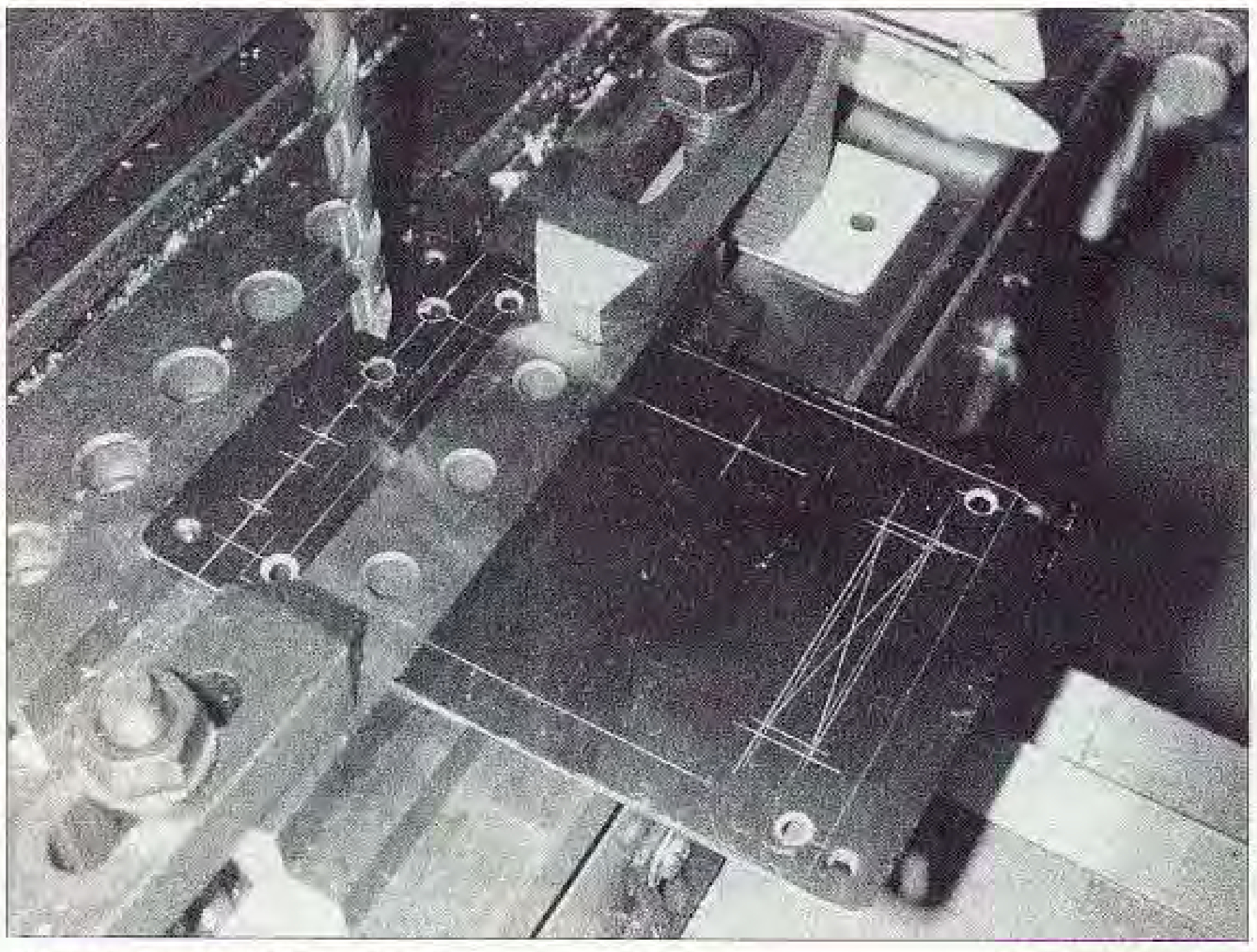

Photo E. Drilling the front panel.

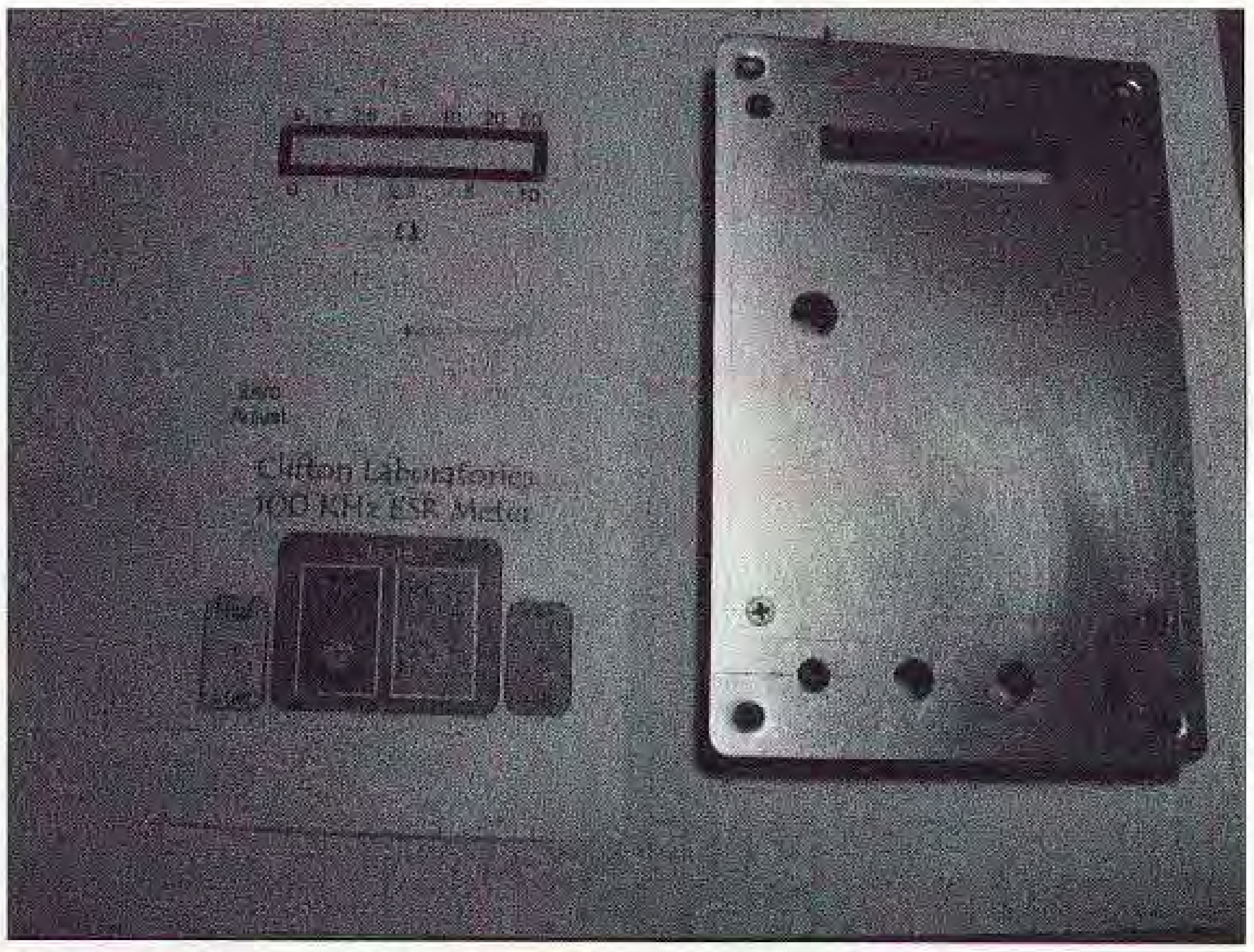

Photo F. The completed front panel and appliqué.

voltage should drop to 3.7 volts. These values are not overly critical, but you should see a good 1.75 to 2 volts swing between open-circuited and short-circuited input conditions.

LED display. With the input terminals short-circuited, you should be able to adjust the "zero adjustment" pot, R17, so that the first LED segment is illuminated. Temporarily connect a 10 ohm resistor across the input terminals. With the range switch, SW2, in low position, you should be able to adjust R24 so that the last LED is illuminated. Remove the 10 ohm resistor, connect a 51 ohm resistor across the input terminals, and place the range switch to the high position. You should be able to adjust R25 so that the last LED is illuminated. You may see a slight degree of interaction between the zero adjustment pot and R24 or R25.

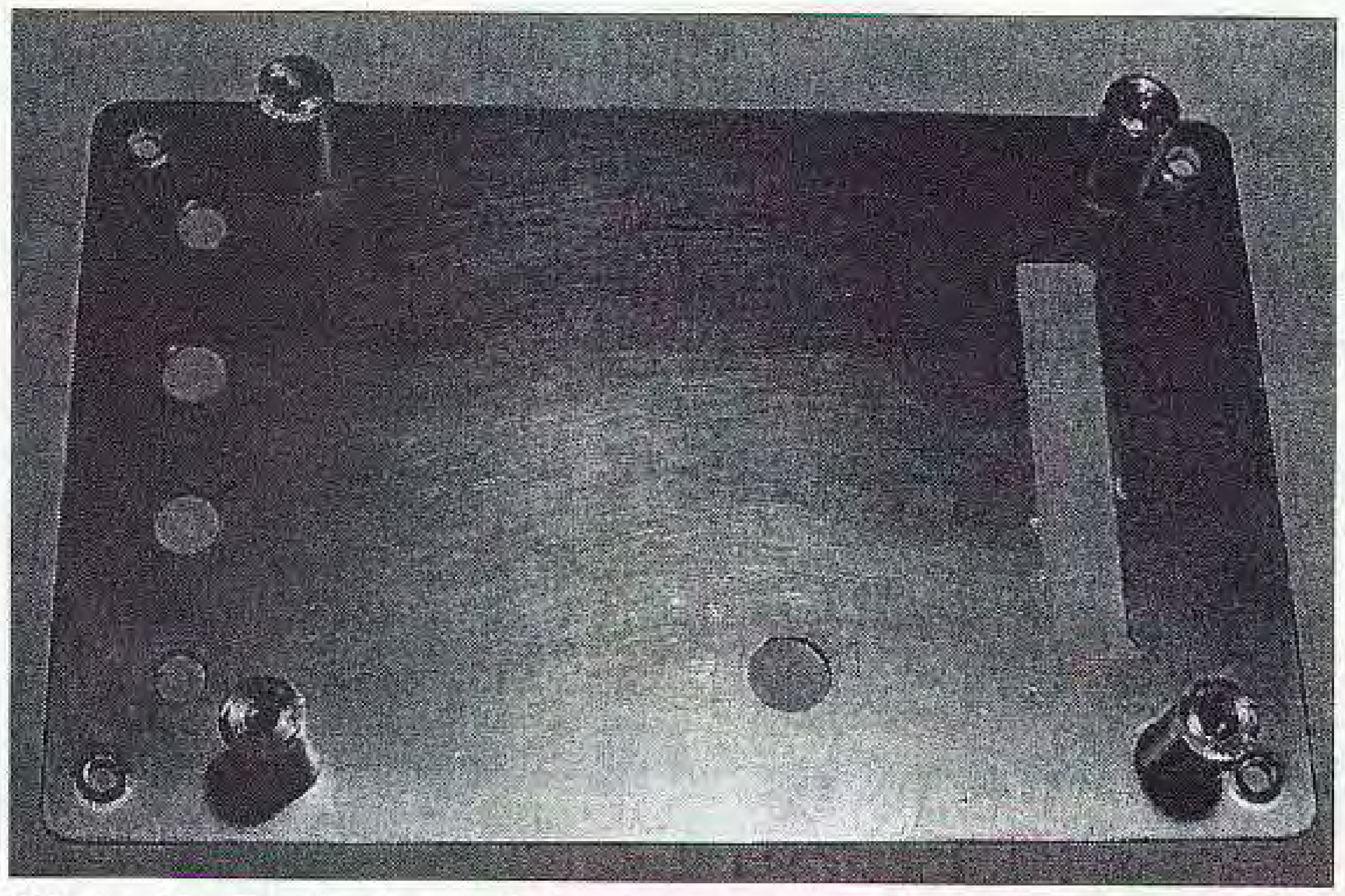

Photo G. Back view of the front panel showing the mounting spacers installed.

Calibration

To calibrate the display, first verify the zero adjustment and that R24 and R25 have been accurately set as described earlier. With the range switch in low position, connect a 1 ohm resistor across the input terminals and note which LED is illuminated. Repeat with 2.7 and 5.1 ohm resistors. Switch to the high range and repeat with 1, 2.7, 5, 10, and 20 ohm resistors. The spacing will not be linear. You should use short leads when connecting the calibration resistors.

Mechanical

I designed the printed circuit board layout to fit a Radio Shack 270-1806 plastic box, 6"x4"x2". This box is a tight fit and requires the zero pot to be squeezed between the board and the front panel, but it permits a compact package.

I milled a slot 2 inches long and 3/8 of an inch wide for the LED display. I also milled a 2-1/2 inch x 3/4 inch piece of 1/8-inch-thick red Lucite plastic to fit flush into the slot. (The Lucite lens resembles a mesa when done; a 2" x 3/8" rectangular section sticks up 0.040" from the body of the plastic.) I attached the plastic lens to the aluminum panel with a couple drops of super glue. Although a milling machine makes these tasks easy, you can accomplish the same with an electric drill and file.

I also made four custom-length spacers from 3/8-inch-diameter aluminum round stock and attached these to the front panel with countersunk 4-40 x 3/8-inch Phillips flat head screws. For my board, choice of IC sockets, and LED displays, the spacers were 0.680 of an inch long. I drilled and tapped the spacers for 4-40 threads. The aluminum cover plate is only 0.038 of an inch thick, so part of the tapered screw head appears on the inside of the front panel. Hence, you should countersink the spacer as well — otherwise the spacer will not be tight against the panel.

It's important that the heads of the screws be flush with the front panel if you intend to use a panel appliqué. It will be impossible to retighten the screws without destroying the appliqué once it is in place, so I used Loctite thread locker to prevent loosening.

I laid out the front panel appliqué using Visio Technical for Windows, but any drawing program would work. When you lay out the appliqué, place the calibration numbers to coincide with the spacing you recorded during calibration. I then printed the appliqué on an inkjet printer, and laminated it with a thin, flexible, self-adhesive transparent plastic sheet. After cutting

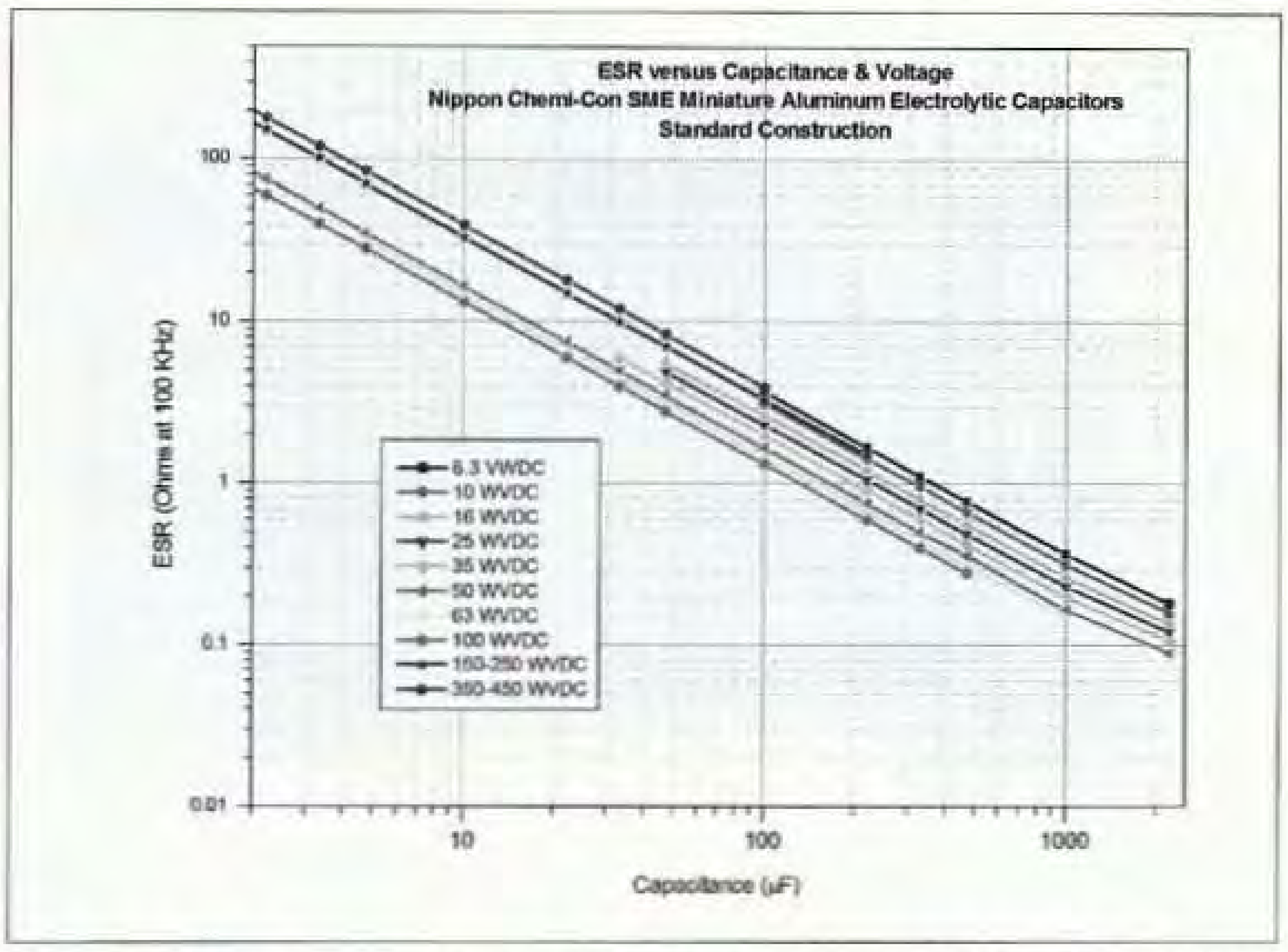

Fig. 7. ESR vs. capacitance & voltage: Nippon Chemi-Con SME miniature aluminum electrolytic capacitors, standard construction.

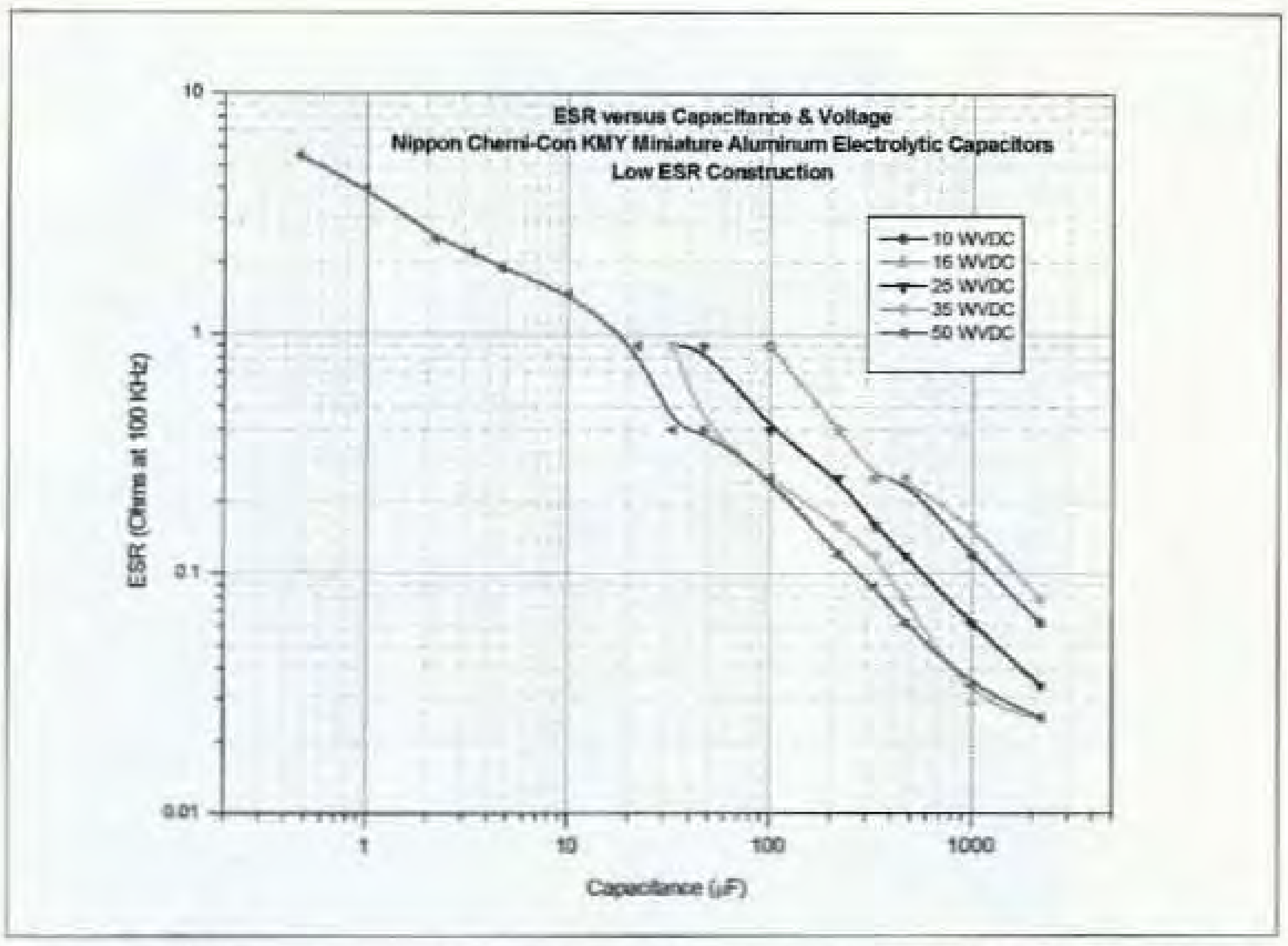

Fig. 8. ESR vs. capacitance & voltage: Nippon Chemi-Con KMY miniature electrolytic capacitors, low ESR construction.

out the LED window, I then attached the appliqué to the aluminum front panel with 3M artist's spray adhesive.

I had to do three panels before I got it close to right, so you can benefit from my mistakes:

- It's difficult to get the LED slot exactly right in the aluminum panel, so cut it a bit oversize and add a thick black mask to the appliqué. Cut the opening of the appliqué slot to match the LED size.
- Use special inkjet paper and use the high quality setting on your printer.
- A full-size zero adjustment potentiometer doesn't clear the PC board by much and requires bending some components out of the way. A miniature pot is a good idea.
- Give the Loctite enough time to set up before attaching the appliqué. I didn't, and you can see a blue circle where one screw leaked onto the backside of the appliqué.
- The front panel is only 0.038 of an inch thick, so it requires attention to prevent the countersink from going right through the panel.
- Precisely aligning the appliqué takes a bit of time. Accordingly, use an adhesive that allows sliding the appliqué over the panel. Contact cement is not a good idea!
- In general, remember the old carpenter's maxim: Measure twice, cut once.

Although I originally thought I would run the ESR meter from a 12-volt wall-wart power supply, I changed my mind and decided to make it battery-powered. I epoxied two 9-volt battery holders to the plastic case to provide 18 volts in series connection. A pair of fresh alkaline batteries will give about 10–12 hours running time. Using a 78L09 with 18 volts input and a current draw of 50 mA places it at

Photo H. Board mounted to the front panel and battery holders.

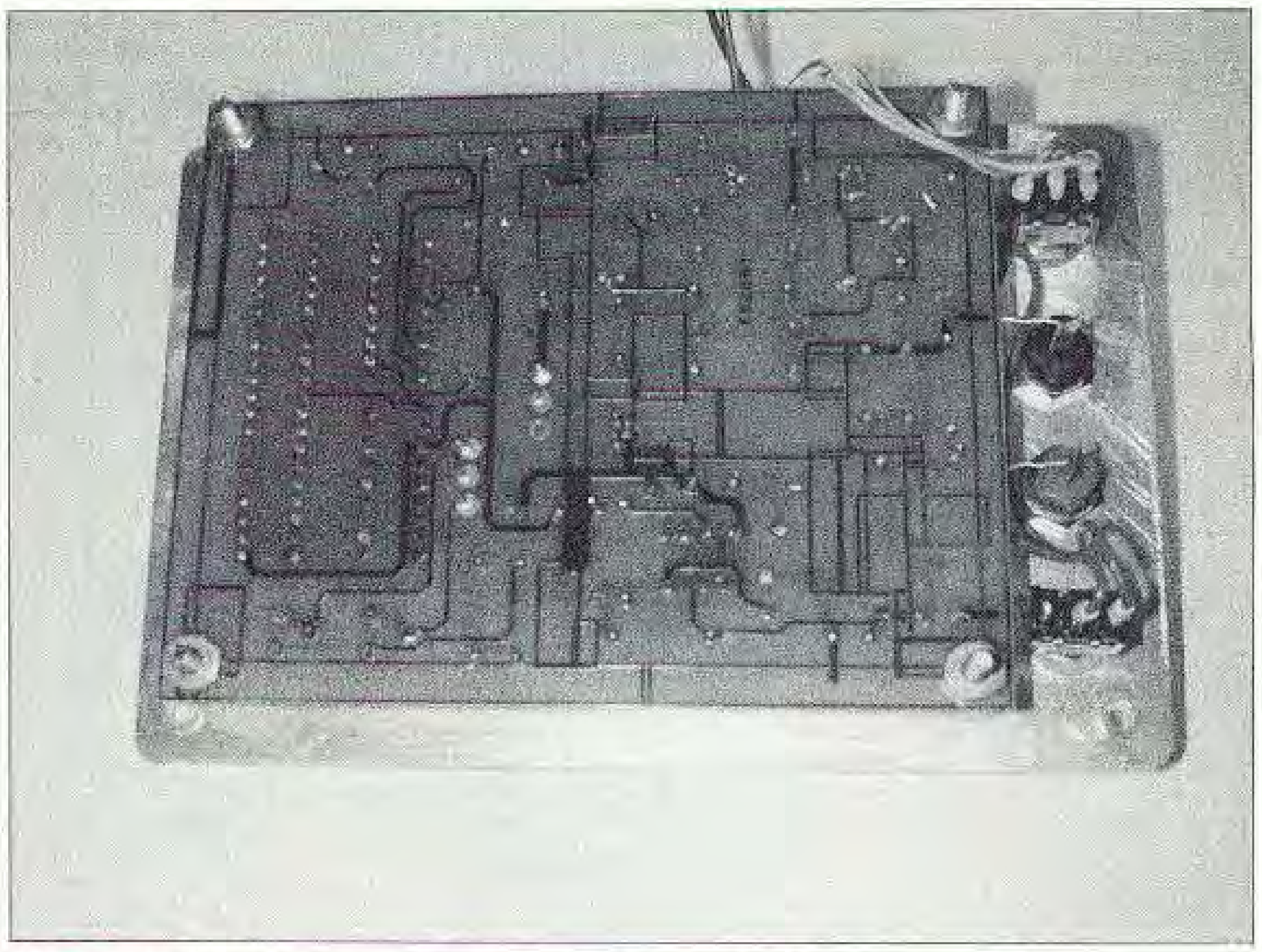

Photo I. Back view of PC board mounted on the panel.

the edge of its dissipation specifications. Hence, I made a heatsink out of a piece of 3/8-inch-diameter aluminum rod and slipped it over the 78L09.

How to use the ESR meter

It isn't usually necessary to remove a capacitor from its circuit before testing. Just put the test leads across the capacitor and read the ESR. Of course, first remove power from the equipment and allow time to discharge the capacitors. If you inadvertently attempt to measure a charged capacitor, diodes D2 and D3 will limit damage to the instrument.

Remember that long test leads, or coiled test leads, add inductance and will add some apparent ESR.

In general, the higher the voltage rating, the lower the ESR for the same capacitance. The larger the capacitance value, the lower the ESR. Tantalum capacitors have much lower ESR than an equivalent aluminum electrolytic. In addition, special low-ESR capacitors are made for switching power supplies and can have an ESR of a few milliohms.

I've plotted 100 kHz ESR data for two types of leaded aluminum electrolytic capacitors manufactured by Nippon Chemi-Con. These are only guides, however, and the best comparison will be a known good capacitor of similar value and voltage rating by the same manufacturer.

A defective electrolytic will display an ESR of several times that of a good unit.

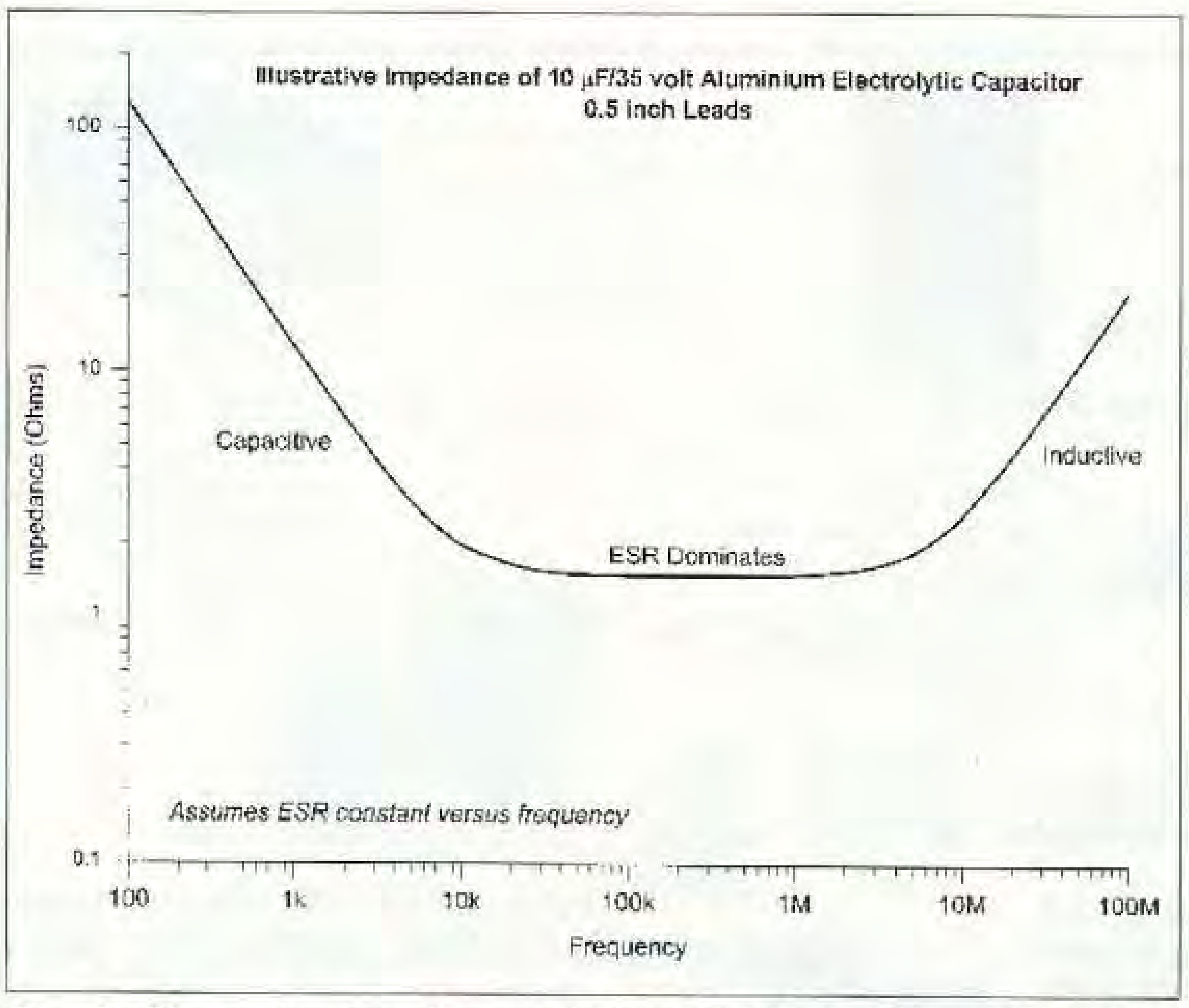

Fig. 9. Illustrative impedance of 10 µF/35 V aluminum electrolytic capacitors, 0.5-in. leads.

References

1. Kemet Electronics has several technical notes available at its Web site [http://www.kemet.com]. Of particular interest are: *What is a Capacitor?* F-2856E; *Tantalum Leaded Performance Characteristics* (09/01 edition).

2. A data sheet for the LM3914 LED graph display chip can be found at National Semiconductor's Web site [http://www.national.com/ds/LM/LM3914.pdf].

3. Many capacitor manufacturers provide detailed ESR data. See, for example, Cornell Dubilier Electronics [http://www.cornell-dubilier.com/]. Nippon Chemi-Con's electrolytic capacitor catalog is available at [http://www.chemi-con.co.jp/pdf/catalog/ALUMINUM/E/all/al-1001d-e-all-010730.pdf]. AVX Corporation's ESR data for tantalum capacitors can be found at [http://www.avxcorp.com/docs/masterpubs/tantlead.pdf].