

Secrets of Transmission Lines

Part 1: Intro and dummy load project.

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Considered as a group, radio hams are a fairly inquisitive bunch, interested in a variety of things. There are a large number of subgroups within the fraternity. Some are interested in the competitive aspects and fight for the DXCC awards, and others are avid testers. Some are simply rag-chewers who like to get together with cronies on a net and discuss nearly any topic. Some are tinkers who have to try the newest in slow scan or live TV or whatever. A few are hardware developers who build new and different equipment.

One thing is a bit surprising. Considering the technical nature of the hobby, the percentage of electrical engineers is relatively small. Ham radio attracts people from all walks of life. We all have to pass theory tests to obtain our licenses, but for most this consists of buying a "question and answer" study book aimed at a particular library or pool of questions. It can be argued that this approach does not necessarily impart a fundamental knowledge of the topics.

This series is intended for those who would like to go a little further down the technical road. The object and style of the writing is aimed at imparting a

fundamental understanding of transmission lines, impedance matching, and the Smith chart without necessarily using a lot of high powered mathematics. Each topic will be portrayed with easily repeated physical experiments to be performed with stuff to be found around most ham shacks. In some cases, computer-generated art will be used to illustrate the point. The intent is to promote fundamental understanding rather than mathematical rigor.

Contents of the series

The series will be broken down into the following blocks:

1. Review of DC fundamentals.
2. Review of AC fundamentals.
3. Fundamentals of transmission lines.
4. AC steady state transmission lines.
5. The Smith chart.
6. Impedance matching.

The review of DC and AC fundamentals is included because some grasp of these topics is essential to any understanding of the operation of transmission lines and the subject of impedance matching. Wherever possible, a physically visualizable example, experiment, or illustration is presented.

While we have noted that high-powered math is avoided, some math is necessary, and some knowledge of high-school-level trigonometry and algebra is helpful. Most of the experiments intended to illustrate the point can be performed with readily available hardware items, a multimeter, a two meter handheld transmitter, some junk box parts, and some spare coax cable. A calculator with trigonometric functions is helpful but not mandatory.

Let's see how we can get started on this venture.

DC fundamentals

In this section, we shall consider only continuous direct currents such as one might obtain from a flashlight battery and solid wires and resistors. Turn on and turn off are not considered. As a beginning, and for our purposes here, the most significant part of understanding DC circuits is described by Ohm's law, named after George Simon Ohm. In words, it states that the current flowing in a circuit is proportional to the voltage forcing the current divided by the circuit resistance.

For a physical analogy, consider the illustration in **Fig. 1(a)**. We have a

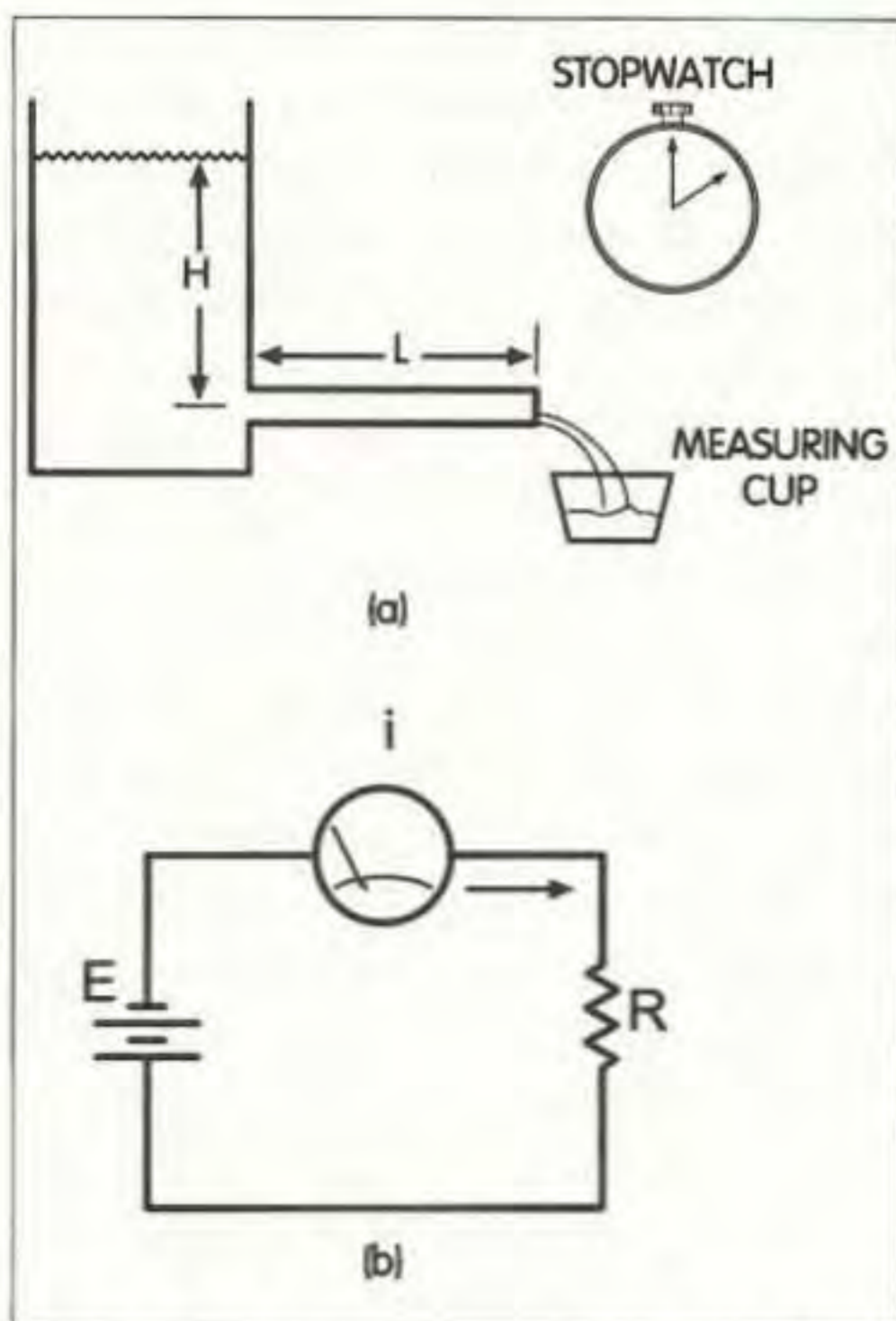


Fig. 1. (a) Ohm's law analogy. (b) Ohm's law in a circuit.

$$(1-1) \frac{E}{R} = i$$

$$(1-2) \frac{\text{volts}}{\text{ohms}} = \text{amperes}$$

container filled with water, a soda straw attached to let the water out, and a container to catch the water. The height of the water above the soda straw (H) is analogous to the battery voltage (E) in Fig. 1(b). The length of the soda straw (L) is analogous to the resistance (R) in the electrical circuit. With the measuring cup and the stopwatch we can measure the time it takes to fill the cup, thus giving us the water

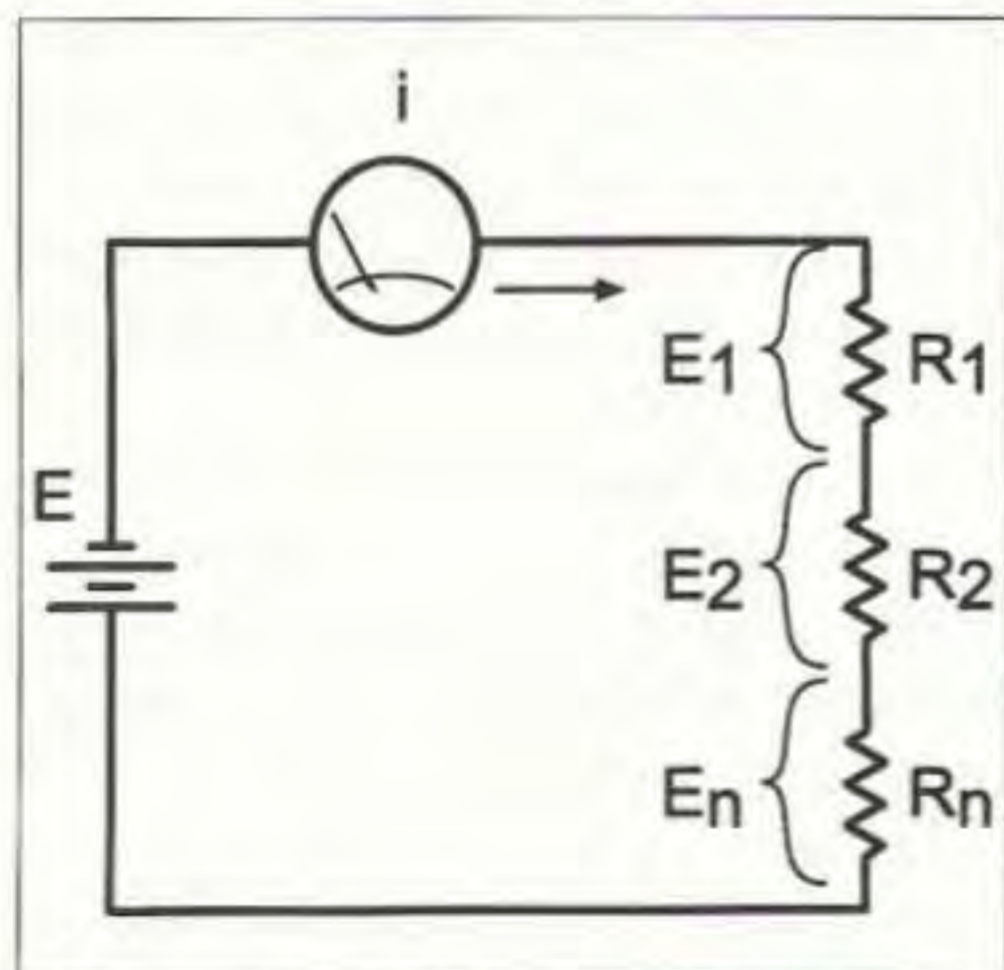


Fig. 2. Series circuits.

$$(1-3) E = E_1 + E_2 + \dots + E_n$$

$$(1-4) E = iR_1 + iR_2 + \dots + iR_n$$

$$(1-5) \frac{E}{R_1 + R_2 + \dots + R_n} = i$$

flow in gallons per minute (or cubic centimeters per second), which is more or less analogous to a measurement by the ammeter in the electrical circuit. If we shorten the soda straw to half the original length, the flow will double. Similarly, if we halve the resistance in ohms, the current will double. We don't want to carry this analogy too far, because there are differences between the way water flows through a pipe and electricity flows in a wire, but as far as it goes, the analogy is satisfactory.

Power

To understand the quantity power, we must differentiate it from the physical concept of work. Work is defined mechanically as the product of force and distance. Power is defined as the time rate of doing work. If you lift a 5 pound weight two feet, you have done $5 \times 2 = 10$ foot pounds of work. To calculate power, we must know the time it took to do that work.

When James Watt started selling steam engines to mine owners for pumping water out of mines, he had to come up with some way of describing

the work the machine would do. He found that the Welch ponies walking on a circular track driving the pumping machine could average 550 foot pounds per second, so this value was adopted for the "horsepower." How do we relate this to electrical work?

In Fig. 1, the analogy for the ampere was chosen to represent a flow rate

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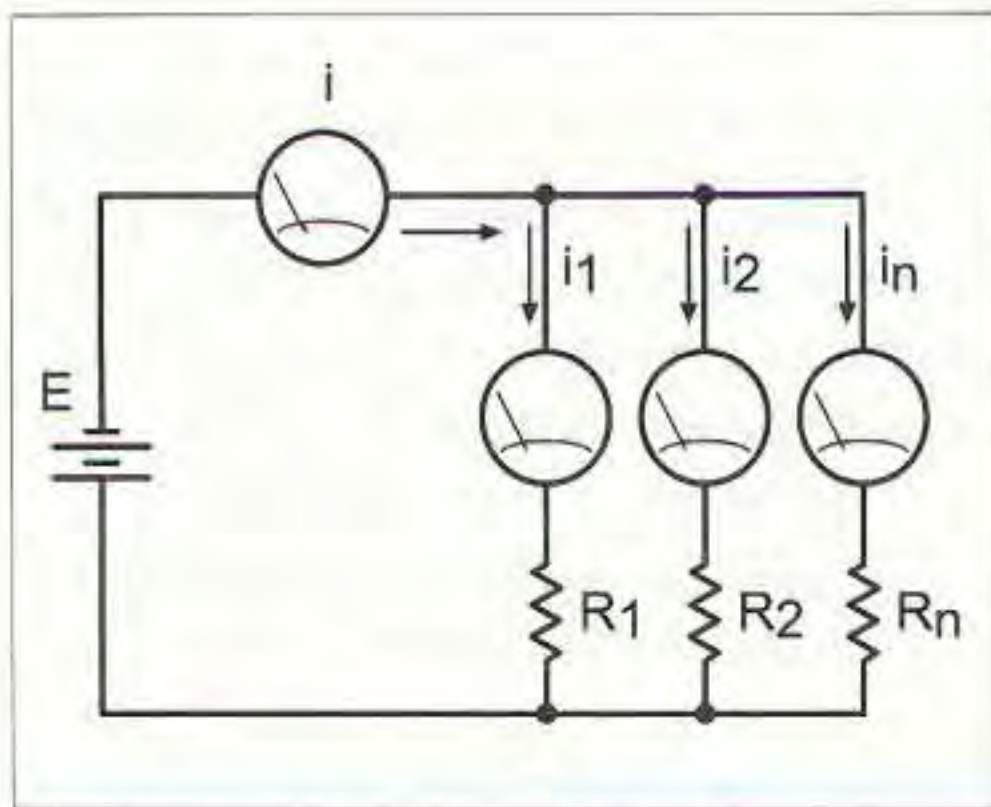


Fig. 3. Parallel or shunt circuits.

$$(1-6) i = i_1 + i_2 + \dots + i_n$$

$$(1-7) i_1 = \frac{E}{R_1} \quad i_2 = \frac{E}{R_2} \quad i_n = \frac{E}{R_n}$$

$$(1-8) \text{ Now let } G_n = \frac{1}{R_n}$$

$$(1-9) \text{ Then, } i = EG_1 + EG_2 + \dots + EG_n$$

$$(1-10) i = E(G_1 + G_2 + \dots + G_n)$$

versus time. The ampere is actually a time rate unit. An ampere is defined as an electric flow rate of one coulomb per second, which corresponds to 6.25×10^{18} electrons per second. A fantastically large number! The product of the force in volts times flow in coulombs per second is power. Thus force in volts times current in amperes is watts. 746 watts equal one horsepower.

Substitution for E or I from Ohm's law also gives useful relationships for power.

$$P(\text{watts}) = E \times i = i^2 \times R = E^2 / R$$

Depending upon the situation, one of these may be more useful than others.

Kirchhoff's law

Kirchhoff's law states that the algebraic sum of the currents at a junction is zero; in other words, the number of

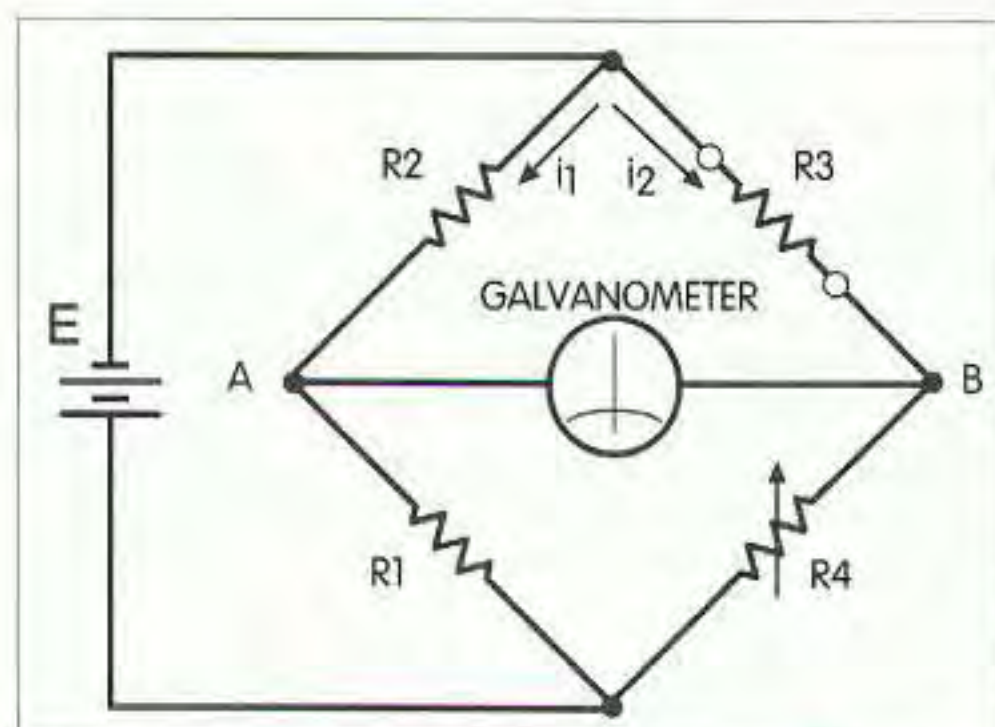


Fig. 4. The Wheatstone bridge. If $R_1 = R_2$ and $R_3 = R_4$, voltage $A = B$ and no current flows in galvanometer. Also true if $R_1/R_2 = R_3/R_4$.

electrons leaving the junction must equal the number entering it.

This is fairly easy to visualize. Suppose that we have the intersection of three streets, each ending at the intersection. If one of the streets is one way inbound and the other two are one way outbound, then the sum of the cars on the two outbound streets must equal the number of cars on the inbound street. If it were less, cars would accumulate at the junction, and if it were more we would have to create new cars at the junction.

Combining loads

When there is more than one resistance in a circuit, the values must be combined in some fashion to solve the circuit. In Fig. 2, we see a series-connected circuit consisting of resistances $R_1, R_2 \dots$ to R_n . In this circuit, the current i passes through all of the resistors. In this case, the sum of the voltage drops across the resistors would equal the battery voltage, and it is possible to simply add up the resistances and divide the battery voltage by the sum.

With the parallel or shunt circuit, we see that the input voltage E is present across all of the resistors and we must add the currents to satisfy Kirchhoff's law (see Eqn 1-6). Now the individual currents are given by the equations in 1-7. If we make the substitution of Eqn 1-8, we can rewrite Eqn 1-6 as Eqn 1-9, and, factoring out the E , we obtain Eqn 1-10.

The substitution of Eqn 1-8 translates from resistance into conductance. The units of G are in conductance given in either mho in older texts or siemens in newer texts. A resistance of 1 ohm is equal to a conductance of one siemens. A resistance of 10 ohms would be equivalent to a conductance of 0.1 siemens. When working with parallel or current combining circuits, it is more convenient to work in conductance.

In terms of conductance in mho:

$$P(\text{watts}) = E^2 \times G = i^2 / G$$

The Wheatstone bridge

The Wheatstone bridge is a very practical circuit that finds use in many places and is particularly helpful in

impedance matching instrumentation. It is shown here mainly because it represents a basic balanced circuit representative of many RF and transmission line measuring systems. It may be seen that if $R_1 = R_2$, point A is at a potential equal to $E/2$. If $R_3 = R_4$, the same is true for point B and no current will flow in the galvanometer (which is simply a very sensitive zero center ammeter). Voltages A and B will also equal the ratio between R_1 and R_2 , which equals the ratio between R_3 and R_4 . In some transmission line instruments $R_1 = R_2 = R_3 = 50$ ohms. In this case, the bridge will null when the transmission line, substituted for R_4 , is 50 ohms. This gets a tad ahead of the text, but it represents an important case in which the VSWR is 1.0:1.

A practical example

For a practical example, we will look at the design and construction of a dummy load or dummy antenna which we shall use later in the program. This is something you should have around the ham shack anyway. Since the resistors are going to be paralleled, we will work in conductance.

To begin with, we would like to have the unit handle the output of a conventional transceiver. With a nominal 100 watt transceiver, a 50 watt load is usually adequate for most measurements, since the transceiver is usually not capable of long-term key-down output in excess of 50 watts average. We can get a rating like this by paralleling about 25 resistors with 2 watt ratings. Note that an RF dummy load cannot be built using wirewound resistors—even so-called non-inductive ones. Carbon composition or metal film types are suitable to 30 or 50 MHz.

The illustration of Fig. 5 shows the general construction. A "cordwood"-type construction is used. Two pieces of 1/16-inch printed circuit board, preferably the fiberglass type, are cut and drilled with a regular drill plan on 0.5-inch centers. The boards may be stacked, foil side out, and drilled simultaneously. The selected resistors are a little less than 3/16 of an inch in diameter, so there is plenty of air space between them. This is important for cooling.

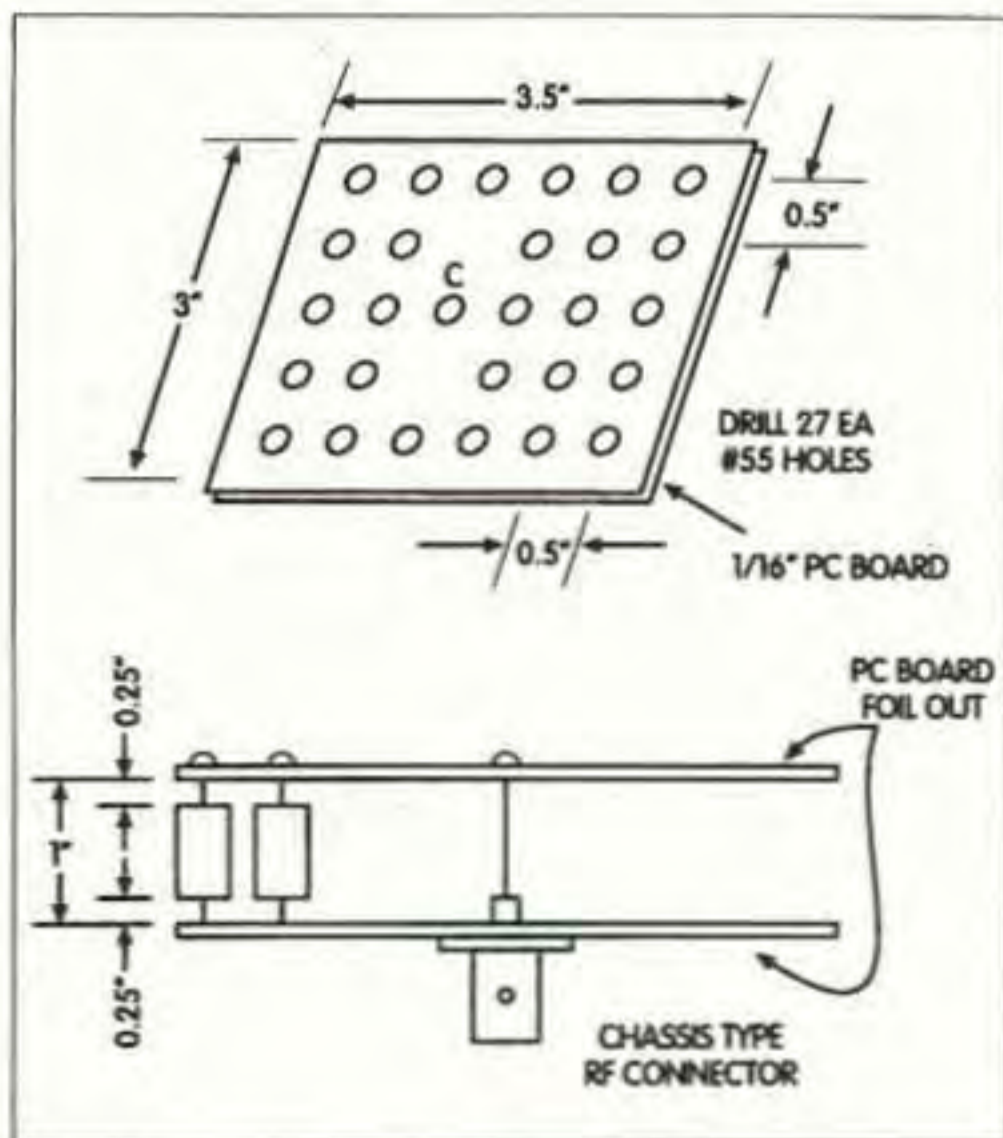


Fig. 5. Dummy load project. Resistors are 2 watt metal oxide 5%, 1200 Ω nominal, Tech America #900-0820.

After the small holes are drilled, enlarge the hole marked C in the drawing on one plate only to accept the chassis-type connector you intend to use. A BNC is shown, but you could just as easily use a UHF or type N. Make sure that a 50 ohm connector is used. Mount the connector and solder a lead in its center conductor about 1.25 inches long. You will note that 27 holes are called for and one is occupied by the center conductor.

The target resistance for the dummy load is 50 ohms or 0.02 mho. With nominal 1200 ohm resistors at 5% tolerance, the actual resistance of any resistor could lie between 1140 ohms and 1260 ohms, or between 8.77^{-4} mho and 7.94^{-4} mho. Dividing 0.02 by these numbers tells us that we need between 22.8 and 25.2 resistors respectively. Unless a check with a good digital ohmmeter shows that they are running consistently low in resistance, I would load 25 resistors into the unit.

Load all of the resistors onto the board with the connector. Hold the board with the connector side down. Next, clip the upper end of each resistor lead about a half inch above the resistor end. Clamp the upper board one inch above the connector carrying board. You may have to make some spacers for this. Next, steer the leads one at a time through the appropriate holes in the upper board. Working from the center out, slide the resistors in one at a time. When they have the

resistor body 1/4 inch below the underside of the top board, solder the lead in place. Clip off the excess lead protruding from the top. Avoid soldering any leads on the bottom board until all resistors are soldered on the top board.

After soldering the last resistor on the top board, turn the assembly over and solder each resistor on the board with the input fitting. Clip the leads after soldering.

You now have a relatively sturdy "cordwood" assembly. Measure the resistance across the input connector. If it is less than 50 ohms, you can correct it by clipping one or more resistors. Suppose that the resistance measures 48 ohms or 0.0208 mho. At 1200 ohms, each resistor represents 8.33^{-4} mho, so clipping out a single resistor should bring the conductance to 0.01967 mho or 50.08 ohms.

On the other hand, if the resistance is too high, say 51 ohms, you can add another resistor in one of the vacant holes.

Actually, the 51 ohms would probably be acceptable. However, let's examine what would be required to correct it.

51 ohms = 0.0196 mho, so 0.004 mho would bring the unit to 0.02 mho. However, let's be careful here. For 50 watts dissipated in 0.02 mho, the voltage is :

$$P = E^2 \times G$$

$$50/0.02 = E^2$$

$$E = 50 \text{ V}$$

and in the 0.004 mho correcting resistor:

$$P = 50 \times 50 \times 0.004 = 10 \text{ watts}$$

For a safe rating, you would like to make up the 0.004 mho with 5 each 2 watt resistors, so each should have a conductance of $0.004/5 = 0.0008$ mho. You would need 5 each 1250 ohm resistors to make up the error.

Conclusion

The next section will deal with alternating current fundamentals, where we will look at some of the differences between AC and DC. 73

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