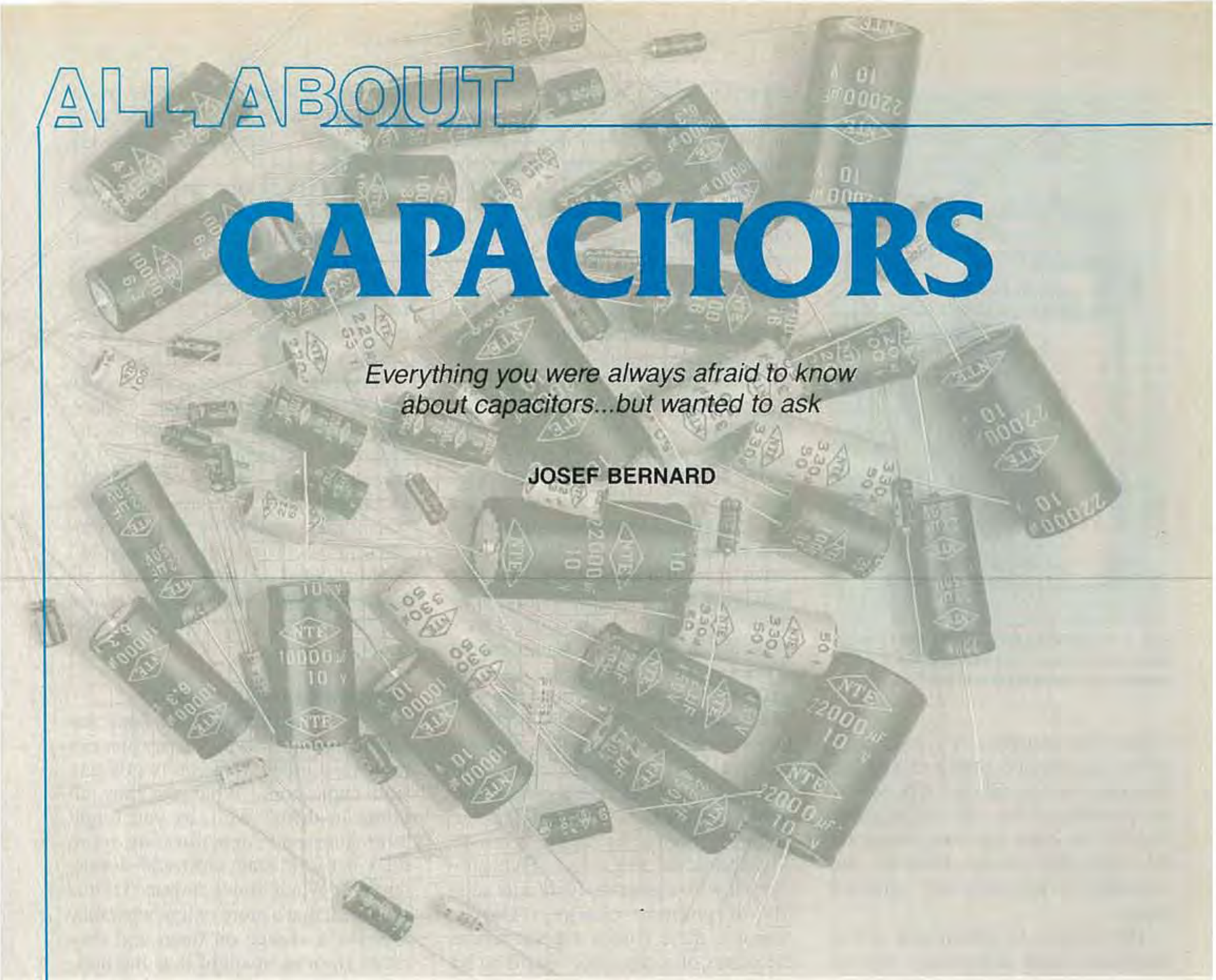
ALL ABOUT CAPACITORS



Everything you were always afraid to know about capacitors...but wanted to ask

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ASIDE FROM THE OCCASIONAL HUMAN body or lightning-struck tree that acted as an inadvertent resistor, capacitors were probably the first electronic components. When electricity was discovered and its mysteries were first being explored back in the mid-1700's, capacitors were the means used to store the mysterious new force.

Of course, they weren't called capacitors then. They were called *Leyden jars* (see Fig. 1). A popular diversion at parties of the time was to charge up a Leyden jar, form a ring of people by holding hands (the circuit), and then discharge the jar through the ring. Talk about getting a glow on!

A Leyden jar (named for the city of Leyden in Holland) was a glass container lined with, and covered on the outside with, metal foil. (The first Leyden jar probably had only one plate, a foil lining on the inside. It would have been able to hold something of a charge, but not much. The addition of the second exterior electrode provided a "vessel" for the positive charge that complemented the negative one on the inner electrode.) When the inner foil was charged up (loaded with electrons), the glass prevented them from traveling to the outer foil, and a voltage differential was established. Ignoring the question of leakage, the jar would then hold that electric charge until the charges on the inner and outer foils were equalized—perhaps through a ring of merrymakers or in the form of miniature lightning—a spark—jumping between two pointed electrodes. That was the first capacitor.

We have progressed somewhat since those days, both in the ways we seek our thrills, and in our uses for capacitors and the ways in which we construct them.

How capacitors work

A capacitor (it used to be referred to as a condenser because it seemed to condense, or concentrate electricity) is an apparently simple device. Two plates of metal separated by an insulator, which, when found in a capacitor, is known as a dielectric. You charge up one of the plates with electrons (or create a deficiency of electrons), and the dielectric keeps them from traveling to the other plate, which becomes oppositely charged with respect to the first. The opposite charges attract one another (they would mutually neutralize themselves if the dielectric were not there to keep them apart) and form a stable system.

What actually happens is a little more complicated than that. The dielectric material plays more of a role than just keeping the two plates of the capacitor separated and preventing the charge from migrating from one to the other. For it is the dielectric itself, that actually determines how much of a charge a capacitor can hold. The dielectric material itself can become

FIG. 1—LEYDEN JARS, the earliest capacitors, found their first use outside the laboratory as ice-breakers at parties.

electrically charged. A sort of tidal effect takes place within it and the electrons on one side are repelled by the electrons on the adjacent negative plate of the capacitor, while those on the other side of the dielectric are attracted by the positively charged plate.

The degree to which that effect manifests itself determines what is known as the dielectric constant, abbreviated as K, of the insulating material. The dielectric constant is a number expressing how much the capacitance of a device increases when that particular material is used instead of just separating the plates of the capacitor with a vacuum, whose dielectric constant is expressed as unity, or one. Table 1 shows the dielectric constants of some common materials.

TABLE 1
DIELECTRIC CONSTANTS (K) OF VARIOUS MATERIALS

Material	K
Air (vacuum)	1
Paraffin	2-3
Rubber	2-3
Polyethylene	2-3
Paper	2-4
Oil	3-5
Mica	4-8
Porcelain	5-7
Glass	6-9
Titanium dioxide	14-110
Various titanates	15-12,000

There are three ways in which the capacitance of a device can be increased. The first is merely by increasing the size of the plates so there is room for more electrons. More important, increasing the size of the plates increases the amount of surface area in contact with the dielectric. In today's microminiature circuits, however, that is not an ideal solution, nor has it ever been. Size and materials are always a consideration.

The second method involves bringing the oppositely charged plates closer together. One way of doing that is to make the plates and the dielectric material as thin as possible. As their proximity increases, the mutually attractive force on them becomes greater as the inverse of the square of the distance separating them. That is, halving the distance between the plates increases the attraction by a factor of four; quartering it increases it sixteenfold. The increased attraction means that more electrons can be held in place. (It should be noted that one of the electrodes of a capacitor is usually connected to ground. That provides it with a practically infinite supply of positive charge.) Unfortunately, there comes a point where the plates of a capacitor would be so close together that the electrons would jump the gap; that would destroy the dielectric in the process, and neutralize any charge that was on the plates.

The third method of increasing capacitance involves using materials with high dielectric constants. Those materials, as we have seen, can by themselves stabilize the charge on the electrodes of a capacitor, and the greater the dielectric constant of a material, the more of a charge can be stored by device in which it is used. It is the improved dielectric materials that have contributed largely to the increase in the capacitance-to-size ratio of today's capacitors.

Capacitance, the ability of a capacitor to store a charge, is measured in farads, a unit named in honor of electrical pioneer Michael Faraday. (Never use the term "capacity" when speaking of capacitors; it is not interchangeable with the term "capacitance.") A farad is defined as one coulomb of electricity applied at a potential of one volt. It is no trivial unit, since a coulomb contains 6.25 $\times 10^{18}$ (6.25 thousand million billion!) electrons.

Most applications do not require anything close to a farad of capacitance, which is fortunate because until recently it was impossible to make anything near a 1-farad capacitor in a reasonable size (see Fig. 2). Today, even Radio Shack sells 0.1-farad capacitors for just a few dollars.

However, most capacitors are much smaller in value than that. Capacitance is commonly measured in microfarads (millionths of a farad) or picofarads (trillionths of a farad). Picofarads, which are millionths of a microfarad, used to be called micromicrofarads. The term "microfarad" is abbreviated μF, and picofarad, pF. Capacitors with values in that range are sufficiently large for most electronic circuits.

How are capacitors used?

Pick up any circuit board, open any power supply, look inside any piece of radio equipment, and you're going to find capacitors. What are they all doing in there? Well, as you might have guessed, capacitors are more than just solid-state electrical storage devices. When direct current (DC) is involved, that's more or less what they are. Put a charge on them and they retain it, or as much of it as the inevitable leakage will allow. As such, their usefulness in DC circuits is somewhat limited. But in AC circuits, where the magnitude and the polarity of the voltage is constantly changing, the roles that capacitors play are enormously varied.

Capacitors block DC; once they are fully charged, no current flows into or

"Hold it! I said I needed a two micro*farad capacitor!"*

FIG. 2—THIS CARTOON was funny a few short years ago, but it has been made obsolete by today's improved technology.

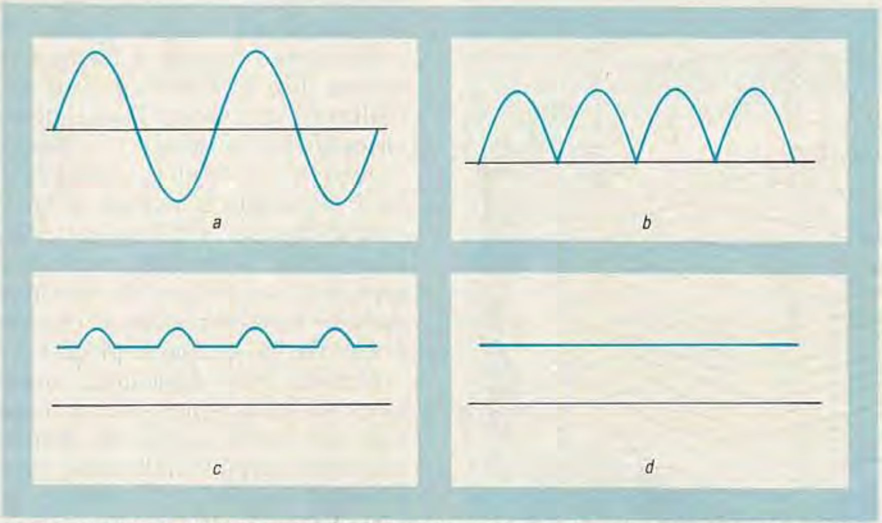

FIG. 3—ORIGINAL (*a*) AND RECTIFIED (*b*) AC waveforms. A large capacitor in the power-supply circuit smooths out the waveform, but still leaves a ripple component (*c*). Smaller-value capacitors bypass that ripple to ground, leaving pure DC (*d*).

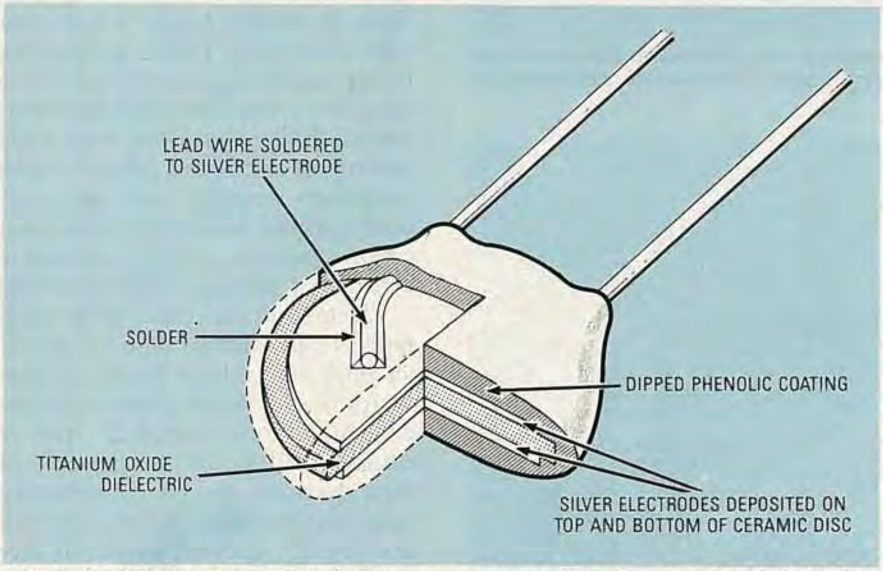

FIG. 4—CERAMIC DISC CAPACITORS are very simple. Two plates are separated by a titanium dioxide dielectric, and the entire assemblage is protected with a phenolic coating.

out of the capacitor. However, capacitors do pass AC. That is because as the charge on one electrode of the device varies, the charge on the other electrode (even if it does not change) also varies with respect to the first. The system is no longer stable. A varying electric potential is developed across the capacitor and current flows through it.

That ability of capacitors to block DC while passing AC makes them invaluable in places where only one or the other is desired. Digital logic circuits, when they switch from one state to another (say from logic-high to logic-low), frequently generate transients or spikes on the power-supply lines. If not cared for, those transients would influence the operation of the logic circuits and generate unpredictable results. For that reason, for every few IC's on a board, the power-supply lines are bypassed to ground through despiking capacitors. Those capacitors see the switching transients as a form of AC (which they are) and conduct them to ground. The normal supply voltage, being constant DC, is unaffected by their presence.

In a power-supply circuit, when alternating current is rectified, the result is not immediately pure DC. Rather, it is an alternating voltage having a single polarity. Figure 3-*a* shows an AC waveform, and Fig. 3-*b* shows the same waveform after being rectified. The large capacitors, commonly found in power-supply circuits, act as surge tanks. That is, as the voltage applied to them changes upward, they begin to charge. Then, as the applied voltage begins to decrease, they lose some of their electrons to the supply line. Figure 3-*c* shows the rectified AC waveform *after* being applied to the large capacitor.

However, there is still an AC component left in the output voltage that cannot be compensated for completely by the large capacitors. That component, called ripple, is a remnant of the original AC voltage (Fig. 3-*c*). To remove it, smaller capacitors are used to convey the electrons making up the difference between the value of the ripple voltage and that of the mostly DC output voltage to ground. The result (Fig. 3-*d*) is pure DC.

In many circuits where AC and DC are mixed, it is often desirable to pass one while blocking the other. Such a situation might exist between the stages of an audio amplifier. In order to pass the output of the first stage to the input of the second, without also passing along the high DC collector voltage from the first stage, a coupling capacitor between the two stages is used. It blocks the unwanted DC while passing the AC. Capacitors can also be used to keep the DC component of a signal, and get rid of the AC one. That is done by passing the AC component to ground.

Another place where capacitors play an extremely important role is in timing circuits. The timers involved may be considered long-interval or short-interval ones. Long-interval timers are the type found in clock circuits and other applications where some sort of time-measuring capability, or the generation of a signal used for timing, is involved. Short-interval timing circuits are the sort that generate high-frequency signals such as those used in radio and television transmission, or in microwave devices.

Because capacitors do not charge instantaneously, and because it always requires the same amount of time to charge or discharge a given capacitor to a given state, the charging time can be taken advantage of. By charging or discharging a capacitor through a resistor, or perhaps an inductor, a *time constant* can be established. That time constant can be related to the pulses of a timing circuit, a resonant frequency, etc.

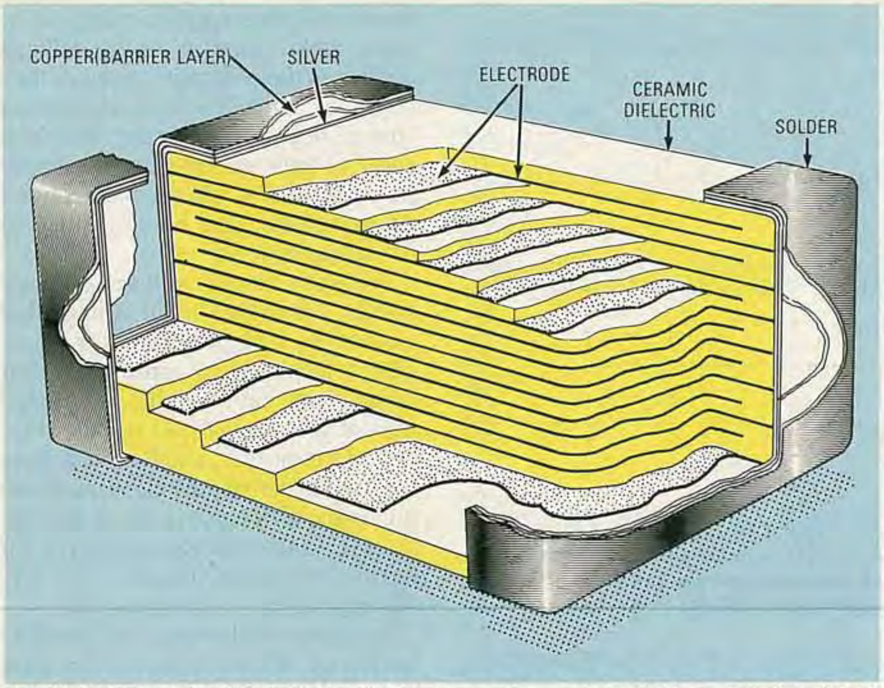

FIG. 5—PRINTED-CIRCUIT CERAMIC-CHIP capacitors use a multi-layer construction to enlarge the electrode surface area. Conductive ink is used to print electrodes directly on the substrate.

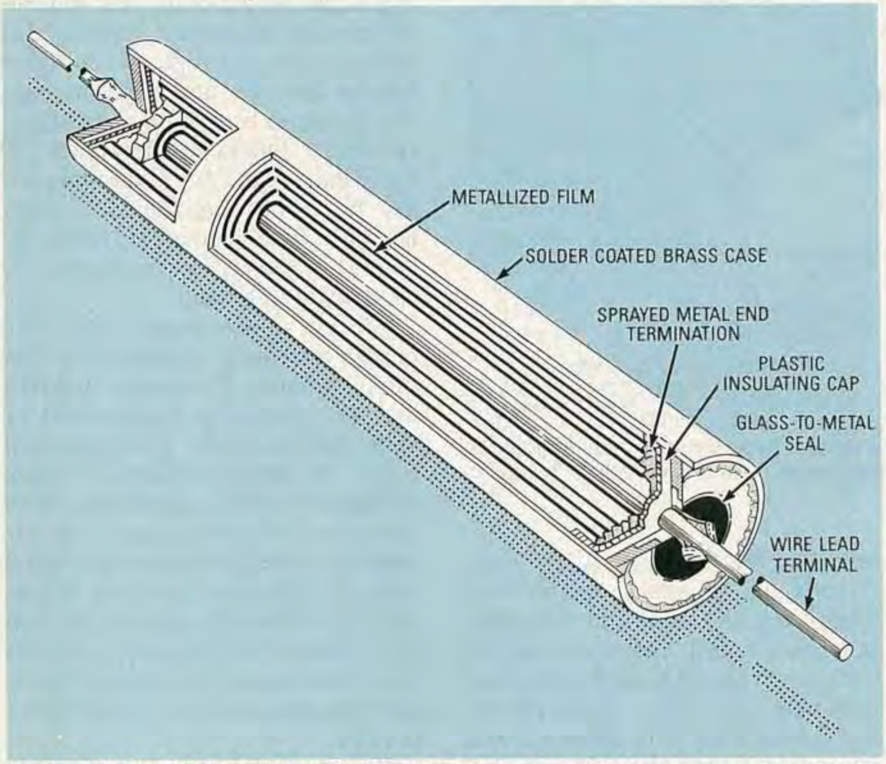

FIG. 6—TUBULAR ELECTROLYTIC CAPACITOR uses a rolled-up electrode to maximize anode surface area. The outer shell of the capacitor, which is in contact with the electrolyte, serves as the cathode.

Capacitor construction

The variety of capacitors, if not infinite, is certainly large enough to be astonishing. Excluding those capacitors used in very specialized applications, there are still enough different types to keep you counting all night. When it comes right down to it, though, there are just a few types of capacitors commonly used in electronic circuits.

Ceramic capacitors are typically represented by the ubiquitous ceramic disc capacitor and its recent offspring, the multi-layer ceramic chip capacitor. An ordinary disk capacitor, as shown in Fig. 4, is little more than two very thin sheets of metal separated by a dielectric—usually a form of titanium dioxide—and encased in a "lollipop" of ceramic. That relatively unsophisticated design is adequate enough to provide up to several thousand picofarads at ratings of up to several kilovolts. (The voltage rating is important; If too high a voltage is applied to a capacitor, the electrode material may be punctured or, even worse, the device may explode.)

Ceramic chip capacitors, sometimes known as printed-circuit capacitors, are similar in principle, but are frequently supplied in leadless form, intended for surface mounting. To achieve their small size with a reasonable degree of capacitance, the electrodes are stacked like a multi-layer club sandwich, as shown in Fig. 5. That, in effect, makes a capacitor with many sets of plates, and by electrically connecting alternate plates, a capacitor with a large electrode area is formed. Rather than using a metal foil to form the electrodes, printed-circuit capacitors actually have the electrodes printed in a metallic ink on a ceramic dielectric, having a dielectric constant of between 2000 and 6000.

Electrolytic capacitors offer much higher capacitances than ceramics, although their voltage ratings are generally lower. While their dielectric constants rarely exceed 25, that is compensated for by the thinness of their electrodes and the consequently large surface area available for electron storage. They are frequently recognizable by their cylindrical (tubular) form, although in the past ten or fifteen years, teardrop-shaped dipped tantalum electrolytics have become increasingly common.

Aluminum electrolytics are probably the most widely used type today, and their construction illustrates how electrolytics differ from other types of capacitors. While the capacitors we discussed earlier use two similar plates, electrolytic capacitors actually have only one plate in the traditional sense. That plate is made of a very thin sheet of aluminum. The other "plate" consists of a conducting electrolyte (hence the term "electrolytic") applied to a material such as plastic film or (in the early days) paper. Early electrolytes were liquids, but less-messy paste electrolytes rapidly took over for the most part. The two elements of the capacitor are

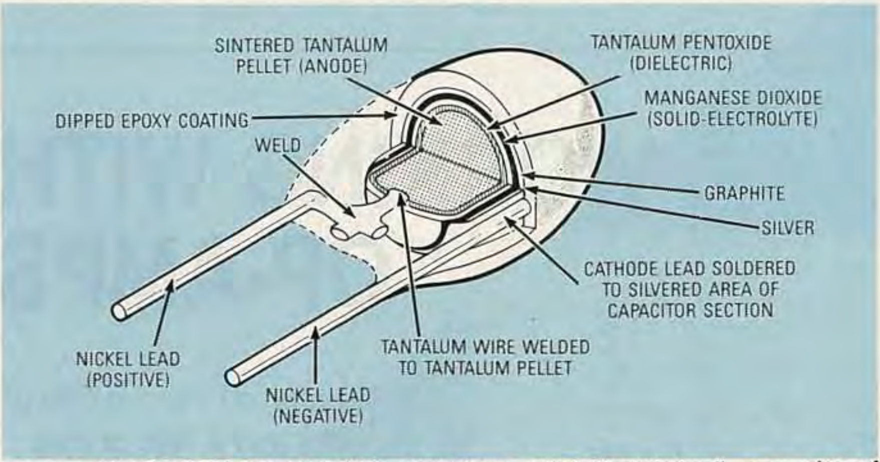

FIG. 7—TANTALUM ELECTROLYTICS, sometimes called "tantalytics," use a slug of sintered tantalum powder with a manganese dioxide electrolyte.

insulated from one another by a layer of oxide—aluminum oxide in this case—formed on the surface of the aluminum electrode. Figure 6 shows a "jelly roll" tubular electrolytic capacitor. To increase the surface area of the plates (and consequent contact with the electrolyte), the two plates are frequently roughened by an etching process.

Tantalum electrolytics, which may be cylindrical or teardrop shaped, use the same principle of a single metallic electrode in conjunction with an electrolyte. However, rather than being a sheet of metal, the electrode is actually a slug of extremely porous tantalum powder (see Fig. 7). The surface of the power grains is anodized to produce tantalum oxide, the insulator. The tantalum slug is impregnated with a liquid electrolyte containing manganese nitrate. The electrolyte solution is absorbed by the porous slug and the liquid is then evaporated, leaving manganese dioxide (formed during the evaporation process) throughout the slug to act as electrolyte. Tantalum capacitors are known for their long-term stability and low leakage. They are also very small in size. Their popularity, however, seems to fluctuate according to the price and availability of tantalum. When it is in short supply, aluminum electrolytics are frequently fallen back upon, but usually tantalums are preferred because of their highly desirable characteristics.

Electrolytic capacitors differ from non-electrolytic devices in that they are polarized. That is, because of the process used to form the insulating oxide, the metallic electrode is always positive with respect to the electrolyte, and must be connected to a positive voltage. Connecting the positive lead or terminal of an electrolytic capacitor to a negative voltage would quickly, and rather violently destroy it. Because of that, electrolytics are suitable for use only with DC (or at least where the potential does not change from positive to negative).

Most types of capacitors can be destroyed by over- or reverse-voltage situations where holes may be blasted in the plates or the dielectric material. However, electrolytics—although not the tantalum sort—have the unusual ability to heal themselves, at least where the degree of damage is relatively minor (a destroyed capacitor will never work).

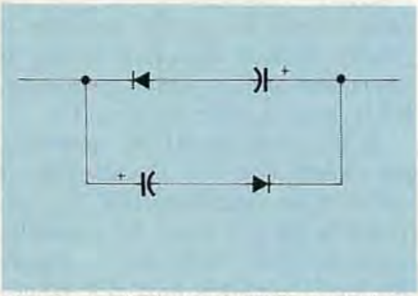

FIG. 8—A NON-POLARIZED electrolytic capacitor can be made by hand if you can't find the value that you need.

Occasionally you will find reference to non-polarized electrolytic capacitors. They are constructed by connecting two ordinary electrolytics back-to-back, frequently using series diodes to prevent reverse-current flow (see Fig. 8). Non-polarized electrolytics are frequently found in audio applications such as in crossover networks. **R-E**