

# Lab Notes

Prepared by the ARRL Laboratory Staff

## Capacitor Basics

If you've ever looked inside a piece of electronic gear, you've probably seen a lot of capacitors. Modern capacitors (often just called "caps"; they were "condensers" to old timers) are produced in a bewildering array of shapes, sizes and characteristics. Once again, ARRL Lab Engineer Mike Gruber, W1DG, starts us on the road to understanding.

**Q:** I recently uncovered my grandmother's old kitchen radio in her attic. It's a classic and no longer works. There appear to be several bad capacitors but I can't find replacements. I assume I can substitute modern types for the old ones, but I'm not sure which to use. Help!

**A:** You are correct! Capacitor technology has evolved over the years. Some older styles are no longer made, and many new ones have appeared. In fact, there are now so many kinds of capacitors that even experts occasionally admit to confusion. Fortunately, you'll probably never encounter many of the specialized and exotic capacitors now available. They are rare in consumer or amateur equipment.

It's seldom difficult to find modern substitutes when repairing older equipment, especially in noncritical circuits like your heirloom broadcast radio. Often, several types will work equally well. You need a little knowledge, but it goes a long way when selecting substitute capacitors.

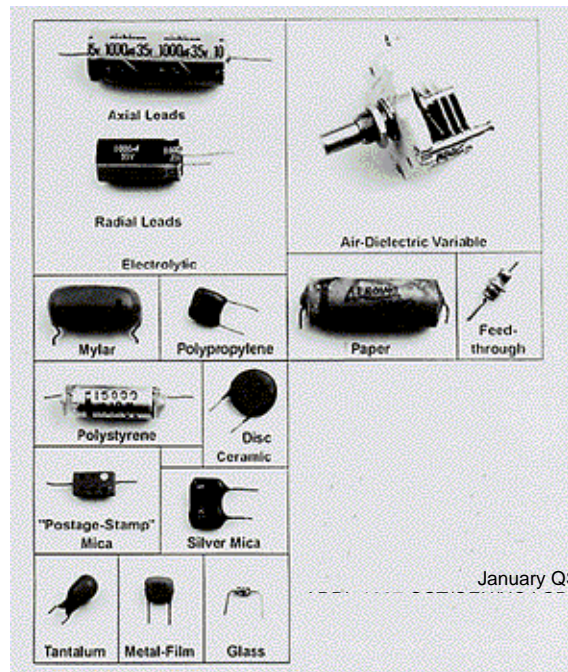
**Q:** Would you define a capacitor and describe its characteristics?

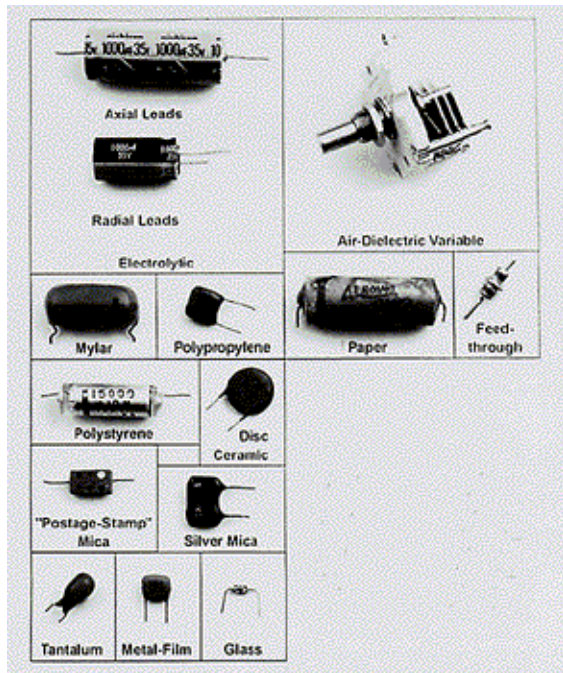
**A:** Put simply, a capacitor is a pair of conductors (or *plates*) separated by an insulator (or *dielectric*). A capacitor stores energy as an electrostatic field between the plates. We call a capacitor's ability to store that energy *capacitance*. The basic unit of capacitance is the farad (F). Common capacitor values range from microfarads ( $\mu\text{F}$ ,  $10^{-6}$  F), through nanofarads (nF,  $10^{-9}$  F) and down to picofarads (pF,  $10^{-12}$  F). The area of the plates, the distance between them and a characteristic of the dielectric (known as the dielectric constant) all determine a capacitor's capacitance.

Capacitors vary in many ways. The dielectric defines much of a capacitor's behavior, so we often describe capacitors by the names of their dielectrics, such as ceramic, mica or electrolytic. You'll find vast differences in such things as capacitance for a given size, leakage (the conductivity of the dielectric), capacitance variation with frequency, voltage and current ratings, variations with temperature and voltage-polarity requirements.

**Q:** What is the difference between axial and radial leads? Are they interchangeable?

**A:** See **Figure 1**. Axial leads extend from the component ends; they lie on a common line, or *axis*. Both radial leads extend from one end or side of a component parallel to each other. We'll refer to the figure as we discuss specific capacitor types.





**Figure 1—Examples of some capacitor packages. Other packages are possible, and sizes vary. Most leads have been trimmed to save space. The aluminum electrolytics at the upper left show the difference between radial and axial leads. Tantalum capacitors (lower left) are also electrolytic.**

For many applications—especially in point-to-point wiring—radial and axial-lead capacitors are interchangeable. Generally, it's easier to install a replacement that has leads like the original. While lead length is seldom critical at lower frequencies, it is important at VHF and UHF. Even in audio circuits, however, bypass capacitors may carry UHF harmonics to ground. So, it's best to keep lead lengths as short as possible, to avoid unwanted feedback paths that ruin performance.

**Q:** What should I consider when selecting a capacitor for a particular application?

**A:** First, you must observe the capacitor voltage ratings. Ordinary voltmeters measure the effective (RMS) value of ac voltages or dc voltages that vary or pulse rapidly. For sine waves, you can multiply the RMS value by 1.414 to calculate the peak voltage. For electrolytic capacitors, select a working-voltage rating that safely exceeds (30% or so) the circuit voltage. Choose other capacitors with voltage ratings that are twice the circuit voltage. Capacitance tolerance, acceptable leakage current, frequency range and even thermal characteristics can be factors in some applications.

**Q:** What voltage rating do I need for RF filter capacitors placed across the ac power lines?

**A:** Use only capacitors specifically rated for ac lines, such as the Panasonic X-Y series of metallized-film capacitors. Older ac and dc-rated capacitors are not safe for use on power lines because line transients often reach 10 times the normal line voltage.

**Q:** Can I normally substitute capacitors of a higher voltage rating?

**A:** Yes, within reason. Use electrolytics near their rated working voltages, but you can safely use capacitors that don't rely on electrolysis at voltages much below their ratings.

**Q:** You mentioned current—do you mean capacitors have a current rating?

**A:** Well, it's not a concern in high-impedance circuitry, but it is more of a factor in low-voltage, high-current designs. Some circuits, such as switching power supplies, require capacitors to handle large currents.

Equivalent series resistance (ESR) is a key capacitor parameter. ESR is the characteristic that produces heat in any capacitor. The familiar  $I^2R$  power formula becomes  $I^2ESR$ , where ESR varies with frequency. So, ripple-current flow, common in filter capacitors, produces heat. Old capacitors often dry and fail as ESR increases, increasing the heat, which further dries the capacitor. This is a truly destructive mechanism, especially in old paper or wax capacitors. Any nonhermetic capacitor with a liquid electrolyte will eventually dry out.

**Q:** Let's talk specifics. What are the pros and cons of different capacitor families? Are any families interchangeable?

**A:** Let's first consider three broad classes of capacitors, then take a closer look at specific examples of the more common types you'll likely encounter in amateur and consumer electronics.

1. *Low-loss and good stability*—These capacitors have dielectrics of ceramic, mica, glass, and low-loss plastics such as polypropylene or polystyrene.

2. *Medium loss and medium stability*—These capacitors have high working voltage ratings. Their dielectrics include paper, plastic-film and high-K ceramics.

3. *Maximum capacitance per unit volume*—These are electrolytic capacitors, normally either aluminum or tantalum.

Here now are some of the capacitors you may encounter in consumer and ham electronic gear:

**Ceramic**—The disc is a common package for ceramic capacitors, but monolithic, glass-encapsulation and feedthrough packages are also available. Ceramics also come in axial-lead packages that resemble film resistors. Such capacitors consist of two thin sheets of metal (silver, nickel, etc) separated by a dielectric of titanium dioxide or similar ceramic material.

Designers have long used ceramic capacitors for RF tuning and bypass applications, in part due to their low series inductance. Ceramic capacitors with wire leads are useful at frequencies ranging from dc to the low VHF region. A temperature range of  $-55$  to  $+125^{\circ}\text{C}$  is typical, with working-voltage ratings up to several kilovolts. Ceramics are available with both positive and negative temperature coefficients.

**Mica**—This is one of the earliest dielectric materials used for capacitors. Mica offers high dielectric strength, low dielectric loss and exceptional stability. They came in a variety of shapes. The two most-common packages are the postage stamp and dipped (with radial leads). The postage-stamp package was common for RF tuning, coupling and bypassing. Only dipped silver micas are commonly available today. Other mica capacitor styles have been replaced by ceramic or precision plastic-film capacitors.

Mica capacitors are ideal for high-voltage and RF applications. They are also a good choice for precision circuitry, such as filters. Dipped micas are useful from dc to lower VHF. Their typical operating temperature range is  $-55$  to  $+125^{\circ}\text{C}$ . Tolerances may be as narrow as 0.5%, but 1 and 2% tolerances are typical.

**Plastic film**—These capacitors are relatively inexpensive and provide capacitances up to a few microfarads at voltage ratings up to several hundred volts. Depending on packaging and construction, they are useful from dc to the gigahertz range.

The dielectric properties of plastics depend on their molecular structure—both polar and nonpolar molecules are possible. Polar molecules generally have greater dielectric constants than nonpolar, but their dielectric constant and losses vary with frequency. Conversely, nonpolar plastics have lesser dielectric constants, which do not vary with frequency. Two basic classes of plastic-film capacitors are therefore possible:

*Polyester* films, such as polyethylene, mylar and polycarbonate, are polar dielectrics with electrical characteristics that vary with frequency.

*Polystyrene and polypropylene* are nonpolar dielectrics. Metallized polypropylene capacitors are an excellent choice for timing applications, because of their stability and low leakage currents.

**Paper**—The dielectrics of these capacitors are paper usually impregnated with oil or wax. You'll find them in vintage gear as the capacitor-of-choice for audio coupling and RF/IF amplifier-bypassing applications. Plastic-film capacitors have replaced paper units in most circuits, but you may still find paper units in dc and line-frequency applications because of their relatively high inductance.

**Aluminum Electrolytic**—The dielectric of an electrolytic capacitor forms by electrolysis when a circuit applies a voltage of *appropriate polarity*. Electrolytics offer great capacitance for their size, so we use them in high-capacitance applications, such as power-supply filters, interstage coupling and to bypass low frequencies. Generally, it is not practical to replace an electrolytic capacitor with another type because of the high capacitance values electrolytics provide.

Because of the polarity required to form the dielectric, these capacitors have their leads marked + and -. Applying a voltage of the incorrect polarity can permanently damage the capacitor.

Electrolytics are useful at frequencies from dc to AF. A typical temperature range is  $-40$  to  $+85^{\circ}\text{C}$ . Computer-grade and high-ripple electrolytic capacitors are available for applications that pass large alternating currents. Special bipolar electrolytics can tolerate polarity reversal or ac across the capacitor.

**Tantalum**—These electrolytic capacitors use a tantalum anode. They are polarized and designed to work in relatively low-voltage circuits. Tantalum capacitors tend to be expensive, but they are compact, permit little dc leakage and offer high capacitance. They are also a bit more tolerant of reverse polarity than are aluminum electrolytics.

**Q:** The tuning (air-dielectric variable) capacitor is falling apart. Can I get a replacement?

**A:** Your chances of finding an exact replacement are slim. Look for a replacement at hamfests and flea markets. Many hams buy a second radio and disassemble it for parts to repair the first. Tuning capacitors are like vacuum tubes: They still have applications, but there is too little demand to support many suppliers. The *TIS Find* software that accompanies *The ARRL Handbook* lists a few dozen suppliers. [1]

I hope this answers some of your questions about capacitors. For more information, look in *The ARRL Handbook*. It covers capacitors in several contexts; use the index to find them.

Thanks to Dave Latchum, WA1JEX, for his contributions to this column

<sup>1</sup>*The ARRL Handbook* (Newington: ARRL 1996), The Parts Suppliers List is in the References Chapter.