VICTOR MEELDIJK

SELECTING THE BEST RESISTOR/CAPACITOR

There's much more to selecting components for your designs and projects than meets the eye. In this article, we'll look at the various types of resistors and capacitors, and what factors you should consider when selecting which type to use.

DID YOU KNOW THAT:

Polystyrene foil capacitors may be better for timing circuits than polycabonate types?

Tantalum capacitors are not recommended for any application where current spikes are present?

A hybrid potentiometer consisting of a wirewound element and a conductive plastic track will have a life span that is 10 times greater than that of a wirewound potentiometer?

Power wirewound resistors can be operated with a body temperature of 275°C, and that some can operated at body temperatures of as high as 500°C?

From the above, it should be clear that there's a lot to know about the many different types of resistors and capacitors available. That's because each type has its own unique characteristics, and those characteristics make some types of resistors and capacitors far better for certain applications than others. Selecting the proper component for a particular application is vital in order to ensure the reliability of your design. In this article, we'll look at the various factors that you should consider when selecting resistors and capacitors for your projects.

Resistors

When selecting a resistor, consider stability, noise, power dissipation, environment, AC requirements, and resistance. Actual resistance value is a function of tolerance, voltage coefficient, temperature coefficient, and drift with time. The power rating is based upon ambient temperature and derating. Derating, which is the operation of a component at something less than 100% of its specified rating, may be necessary because of environmental conditions.

Resistor compositions include carbon, film, and wirewound for fixed resistance units, and cermet and conductive plastic for variable resistors. Figure 1 shows many of the types of resistors available.

Carbon resistors

Carbon-composition units have a resistive element that is molded from carbon powder that has been mixed with a phenolic binder to from a uniform resistive body. That device, molded with end leads, is a general purpose resistor capable of withstanding temperature and electrical transient shocks. The carbon-composition resistor is used in applications where initial tolerance need not be closer than ±5% with long term stability no better than ±20%.

For variable resistors, one problem is that the carbon element requires a high contact force to ensure that any variation in the contact resistance remains within acceptable limits. That results in high shaft-torque and poor adjustability.

Carbon elements are susceptible to moisture absorption and such moisture absorption can cause the resistance to change by as much as 20%. That resistance shift can be reversed if the device is baked at high temperatures (100°C).

Film resistors

Metal-film devices are used in applications requiring higher stability and precision than available from carbon devices. In addition, metal-film resistors should be used in applications where AC is present. Operation is satisfactory from DC to the MHz range. Metal-film units have low temperature coefficients and suffer little degradation to ambient temperatures of 125°C and higher. Film resistors can be classified according to the techniques used in their manufacture.

One such technique is vacuum deposition, which is also known as evaporated metal film. In it, a nickel-chromium alloy is superheated in a vacuum. The alloy vaporizes and is deposited on a ceramic substrate. Small quantities of contami-

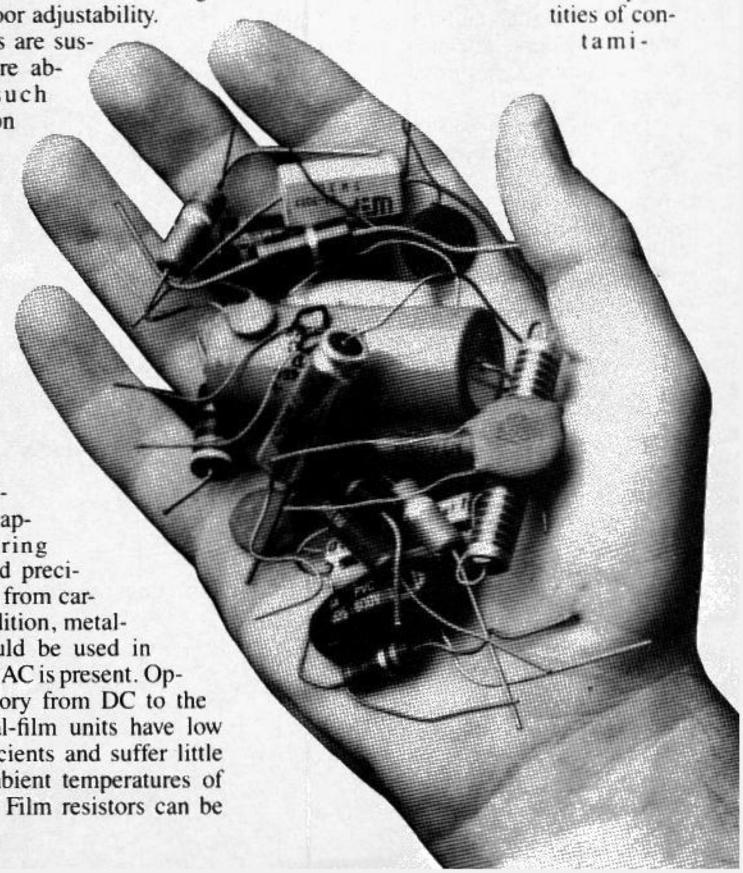

FIG. 1—THERE ARE MANY DIFFERENT resistor compositions and types. Among them are carbon, film, wirewound, cermet, and conductive plastic.

nants, called dopants, are used to control resistor characteristics such as resistance range. Those resistors are used in applications that require an extreme degree of precision.

In sputtering, a nichrome target is heated and bombarded by argon atoms. That results in metal atoms being knocked off and deposited on a substrate. Resistors manufactured using that sputtering technique are also suitable for applications that require a high degree of precision.

In metal-oxide deposition, a chemical vapor is used to deposit a tin-oxide film onto a glass substrate. That technique, which is primarily used by Corning is used to produce resistors for general-purpose, semi-precision, and precision applications.

Thin-film resistors are highly stable, have low-noise characteristics, and have a very low temperature-coefficient. They are used in digital multimeters, precision voltage-dividers, attenuators, A/D and D/A circuits, and in current-summing applications.

Typical thin-film resistors are sputtered tantalum nitride, deposited chromium cobalt, or nichrome, on a substrate. Substrates of alumina, sapphire, glass, quartz, beryllia or silicon are used.

Thin-film resistor networks are also available; those are housed in DIP's and SIP's (*S*ingle *I*nline *P*ackage).

In individual resistors, the terminals used may be either surface or wrap-around types. Wrap-around terminals wrap around the side of the substrate allowing connections to the underside. Terminals of solder, silver over nickel, platinum, or platinum gold are available. Trimming of the resistor is done either mechanically or by using a laser.

In thick-film resistors, a ceramic substrate is coated (silk screened—a mechanized stenciling process) with a glass-metal material and then fired (to cure it) at a high temperature. The glass-metal materials include nichrome, silver palladium, platinum, ruthenium, rhodium, gold and a tantalum-modified tin oxide. That film is up to 100 times thicker than evaporated or sputtered metal film (greater than .0001 inches thick) and is used in applications requiring high power density or the capability of surviving power spikes or overloads. Those units are suitable for some precision applications, but not those requiring an extremely high degree of precision.

Bulk metal resistors, made in a process that is properietary to the Vishay Corporation, metal foil is laminated to a substrate and then chemically etched to produce a conductive path. The flat element is used exclusively for high-precision applications and has tight tolerances and an excellent temperature coefficient.

TABLE 1—RESISTOR SELECTION GUIDELINES

TYPE	SPECIFICATIONS AND NOTES
Carbon composition	**Resistance range:** 2.7 ohms to 100 megohms
	Power rating: to 2 watts
	Tolerance: 5% to 20%
	Temperature coefficient: −200 to −8000 PPM/°C
	Noise: less than 6 µV/V
	Derating factors: 50% power, 80% voltage
	Notes: General purpose. Excellent transient and surge handling capabilities. RF produces capacitive effects end to end, and operation at VHF or higher frequencies reduces effective resistance due to dielectric losses. Resistance increases by 20% during storage under humid conditions.
Carbon composition potentiometer	**Resistance range:** 50 ohms to 10 megohms
	Power rating: to 5 watts
	Temperature coefficient: 1000 PPM/°C
	Derating factors: 50% power, 80% voltage
	Life expectancy: 5,000,000 rotations
	Failure mode: noise
	Notes: High shaft torque causes poor adjustability
Carbon Film	**Resistance range:** 10 ohms to 25 megohms
	Power rating: 0.1 to 10 watts
	Tolerance: 2% to 10%
	Temperature coefficient: −200 to −1000 PPM/°C
	Noise: less than 10 µV/V
	Derating factors: 50% power, 80% voltage
	Notes: General purpose, cost less than carbon-composition units
Metal film	**Resistance range:** 10 ohms to 3 megohms (high voltage types: 1 kilohm to 30 gigohms)
	Power rating: to 10 watts (high voltage types: to 6 watts)
	Tolerance: 0.1% to 2%
	Temperature coefficient: ±25 to ±175 PPM/°C
	Noise: less than 0.1 µV/V
	Life expectancy (potentiometers): 100,000 rotations
	Failure mode: resistance change or catastrophic failure
	Derating factors: 50% power, 80% voltage
	Notes: Fair degree of precision in lower value units. High stability, long life, and excellent high-frequency performance. Resistance values stable to about 100 MHz; begin to decrease beyond that frequency. Used in high-frequency tuning circuits, measuring circuits, filters, etc.
Film networks	**Resistance range:** 10 ohms to 33 megohms
	Power rating: to 0.2 watts per element, to 1.6 watts per network
	Tolerance: 0.1% to 5%
	Operating temperature range: −55 to +125°C
	Temperature coefficient: ±25 to ±300 PPM/°C
	Notes: Tracking between resistors 5 PPM/°C
Chip resistors	**Resistance range:** 1 ohm to 100 megohms
	Power rating: to 2 watts
	Tolerance: 1% to 20%
	Operating temperature range: −55 to +125°C
Power wirewound	**Resistance range:** 0.1 ohm to 180 kilohms
	Power rating: to greater than 225 watts
	Tolerance: 5% to 10%
	Temperature coefficient: less than ±260 PPM/°C
	Noise: low static, high dynamic noise levels
	Derating factors: 50% power, 80% voltage

Carbon-film resistors were introduced to perform the same basic functions as carbon-composition resistors, but at a lower price. Just like composition types, they lack the ability to withstand transient voltage spikes and have a poor temperature coefficient.

An axial-lead, carbon-film resistor is made by screening carbon based resistive inks on a ceramic rod and then firing the assembly. Alternate techniques include depositing pure carbon by cracking a hydrocarbon gas or by depositing a nickel film for resistor values of less than 10 ohms. The resistive element may also be sprayed on, applied with a transfer wheel, or dipped on.

The rod is then cut to size, leaded end caps are attached, and the unit is trimmed to a precise value. The resistor is then coated with an insulating material. Carbon-film resistors are available in the same resistance values as carbon-composition units and have a typical tolerance of ±5%.

Wirewound resistors

Wirewound resistors are used where large power dissipation is required and where AC performance is relatively unimportant. Those devices are generally satisfactory for use at frequencies up to 20kHz. They are available with various insulating/moisture preventative coatings such as vitreous enamel, cement, molded phenolic, glass sleeves, or silicone.

Vitreous enamel units have excellent moisture-resistance properties and will not burn (although they may melt) under high overload conditions since they are made from a glass type material.

Silicone, which also has excellent moisture-resistance characteristics, is an organic material and is more flammable at lower overload conditions than vitreous enamel. It will also emit gases under overload conditions leaving deposits on electrical contacts.

Cement coatings are composed of inorganic materials. Those coatings are essentially flameproof but can be made to burn if subjected to high overloads for long periods. Resistors coated with that material are also subject to changes in value with exposure to moisture.

Aluminum and water-cooled housings are also available. Those housings facilitate the transfer of heat away from the resistive element.

In wirewound resistors, three alloys are commonly used for the resistive element. They are nickel-chromium, Copper-nickel, and gold-platinum. Nickel-chromium is the most common due to its excellent temperature coefficient (less than ±5 PPM/°C) and its availability in many different diameters. Copper-nickel is the next most popular, with a temperature coefficient of ±20 PPM/°C. The gold-platinum alloy, that is actually a complex alloy of gold, platinum with small amounts of copper and silver has a high temperature coefficient of ±650 PPM/°C, but has low resistance. That resistance is 85 ohms/cmf (cmf is a circular mil foot, a hypothetical quantity equivalent to one foot of wire that is .001 inches in diameter) while nickel-chromium has a resistivity of 800 ohms/cmf. The gold-platinum alloy can also withstand harsh environments.

The ceramic core of a wirewound resistor is either beryllium oxide, which has a high cooling capability, alumina (aluminum oxide) or steatite, which has the lowest thermal conductivity of the three materials but is low cost. Figure 2 shows some steatite cores.

Wirewound resistors are most often used in voltage divider circuits, as power-supply bleeder resistors, or as series dropping resistors. Variable devices are used where voltage and current variations are expected, such as motor-speed and heater controls. Precision variable types are used in servo systems requiring precise electrical and mechanical performance.

Other resistor types

For low resistance/high current applications, edgewound ribbon type power

TABLE 1 CONTINUED

TYPE	SPECIFICATIONS AND NOTES
Precision wirewound	**Resistance range:** 0.1 ohm to 800 kilohms **Power rating:** to 15 watts **Tolerance:** .01% to 1% **Temperature coefficient:** varies with resistance **Noise:** low static, high dynamic noise levels **Life expectancy (potentiometers):** 200,000 to 1,000,000 rotations **Failure mode:** Catastrophic failure **Derating factors:** 50% power, 80% voltage **Notes:** Wirewound resistors are used in low-tolerance, high-power dissipation applications where AC performance is not critical. Power dissipation depends on heat sink or air flow around the device. When mounting on a PC board, standoffs should be used to prevent charring the board. Not suitable for use at frequencies above 50 kHz. Wirewound potentiometers do not suffer from contact resistance variations. The units can be manufactured with low temperature coefficients and tight tolerances. Applications include motor speed controls, lamp dimmers, heater controls, etc. Precision types are used in servo mechanisms.
Cermet	**Resistance range:** 50 ohms to 5 megohms **Power rating:** to 2 watts **Life expectancy (potentiometers):** 50 to 500,000 rotations **Failure mode:** noise **Derating factors:** 50% power, 80% voltage **Notes:** Very stable under humid conditions. Low temperature coefficients. Low end resistance (2 ohms). Short life expectancy. High resolution of the resistive element allows for more precise trimmer settings. Less reactance in high-frequency applications than wirewound units, and are lower in price. Cermet is also the thick film used in resistor networks and chip resistors.
Conductive plastic potentiometers	**Resistance range:** 150 ohms to 5 megohms **Power rating:** to 1 watt **Temperature coefficient:** −600 to −300 PPM/°C **Life expectancy:** 100,000 to 4,000,000 rotations **Failure mode:** Noise **Derating factors:** 50% power, 80% voltage
General purpose conductive plastic potentiometers	**Resistance range:** 1 ohm to 15 kilohms, depending on power rating **Power rating:** to 1000 watts
Precision conductive plastic potentiometer	**Resistance range:** 100 ohms to 500 kilohms **Power rating:** to 7 watts **Tolerance:** 3% **Temperature coefficients:** less than 70 PPM/°C **Life expectancy:** Greater than 2,000,000 rotations
Conductive plastic trimmers	**Resistance range:** 10 ohms to 100,000 ohms **Power rating:** to 1 watt **Notes:** Conductive plastic potentiometers have a long life expectancy and low-noise characteristics. Resistance will shift if exposed to humidity.
Hybrid potentiometers	**Resistance range:** 200 ohms to 250,000 ohms **Power rating:** to 7 watts **Tolerance:** 5% **Temperature coefficient:** less than ±100 PPM/°C **Life expectancy:** 10,000,000 rotations

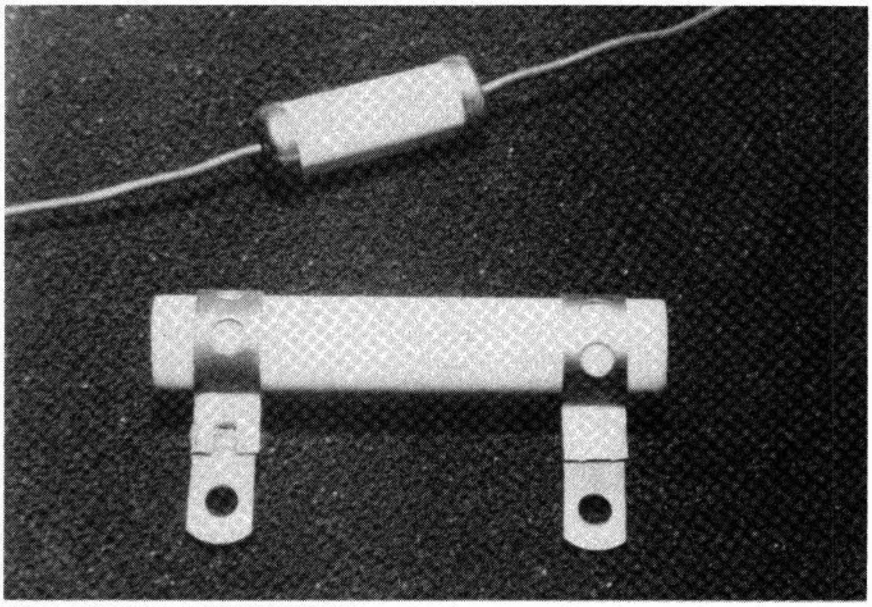

FIG. 2—**MANY WIREWOUND RESISTORS** use Steatite cores, such as the ones shown here.

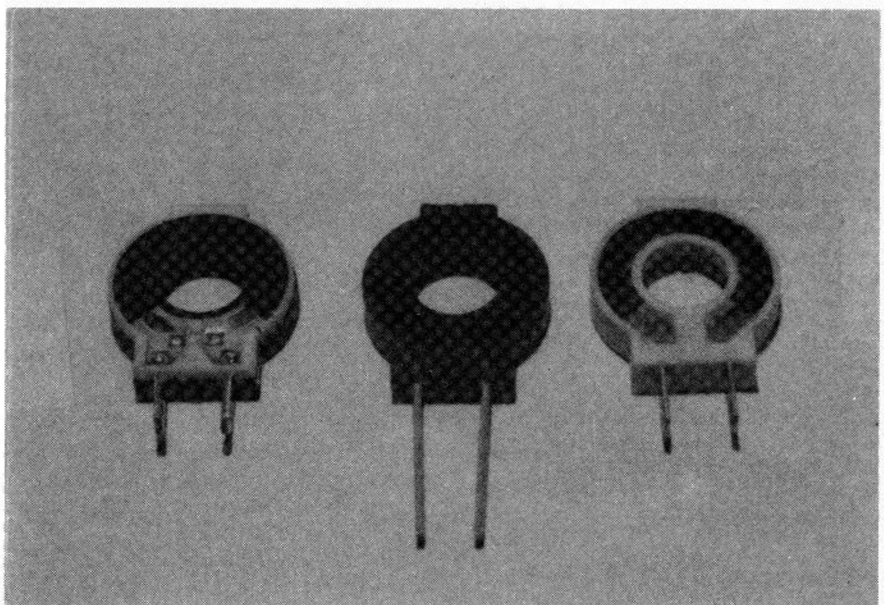

FIG. 3—**POTENTIOMETERS** can use resistive elements made of many different materials. Three such materials, shown above from left to right, are cermet, carbon, and conductive plastic.

resistors are available. Designed for power handling up to 1000 watts (at currents up to 100 amps) these devices are made up of steel ribbons wound into a coil and supported by ceramic insulators. They are generally rated for normal operation with a temperature rise of 375°C. Those units are used in power-supply testing and in motor-breaking systems. (You may have seen them underneath subway cars, especially the older trains in New York City.)

Cermet devices have a resistive element made by combining very fine particles of ceramic, or glass, with precious metals. Cermet devices are very stable under humid conditions and have low temperature coefficients of ±100 PPM/°C. Conductive-plastic or hot-molded carbon potentiometers, for example, have an average temperature coefficient of ±1000 PPM/°C. In variable resistors, however, the cermet element is abrasive and long periods of rotational cycling will wear out the wiper long before similar use would wear out the wiper in resistive-film or conductive-plastic units. Cermet potentiometers are available in low resistance values, which makes them useful in many audio applications.

Cermet is also the thick film used in resistor networks and in chip resistors.

Conductive plastic potentiometers have a resistive element consisting of a blend of resin (epoxy, polyester, phenolics, or polyamides) and a carbon powder applied to a plastic or ceramic substrate. The plastic substrate results in a better temperature coefficient due to greater compatability between the ink and the substrate. Those devices have a long rotational life and excellent contact resistance variation, or low noise. End resistance is low, two ohms maximum.

Conductive plastic units are suitable for use in applications that require a consistent temperature coefficient over a limited temperature range, such as −25°C to 75°C. Temperature coefficient values of −200 PPM/°C may be attained by special processing of the carbon material or by incorporating metal powders, or flakes, into the element. Nickel, silver, and copper are frequently used in low-resistance devices. Conductive-plastic elements, like carbon units, vary in resistance when exposed to humid conditions. Figure 3 shows cermet, carbon, and conductive plastic units.

Hybrid potentiometers are wirewound units with a conductive-plastic track deposited along the contact path of the resistive element. That results in a device that has a better resolution and a longer life, by a factor of 10, over wirewound types. Compared to conductive-plastic units, hybrid devices have a higher power handling capability, due to the wirewound element. Like wirewound units however, they have stray capacitance at higher frequencies and have high contact resistance and marginal output smoothness when drawing current through the wiper contact.

Table 1 summarizes the resistor types available, their characteristics, recommended applications, and suggested derating factor. Use of a derating factor is an effective means to decrease the failure rate of most devices since device life is stress and temperature dependent. Derating is accomplished by either decreasing part stresses such as power/voltage or current or by selecting a higher rated part. Optimum derating occurs at or below the point where an increase in stress or operating temperature results in a large increase in the device failure rate.

One note about Table 1: The values and rating shown are provided as guidelines. While they apply to the most commonly found units, it is not impossible to find units with slightly, or greatly, different specifications.

While that concludes our look at resistors, our look at component selection is far from over. In the next part of this article, we'll turn our attention to the factors that should be considered when selecting capacitors. **R-E**

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SELECTING THE BEST RESISTOR/CAPACITOR

There are a lot of factors to consider when selecting the proper capacitor for your design or project. In this article we'll look at those factors, and which of the many, many types of capacitors is right for your application.

Part 2

AS WE SAW LAST TIME, there are a lot of factors you should consider in selecting resistors for your projects and designs. As you might expect, the same holds true for capacitors. In capacitor selection, you should consider such things as operating temperature, humidity, AC ripple, and operating frequency. In addition, capacitance, as well as other capacitor specifications such as current rating, leakage current, voltage rating, and life expectancy, should be considered so that the device chosen will be appropriate for the application at hand.

Materials used in manufacturing a capacitor, as well as how those materials have been assembled, will effect capacitor specifications. As an example, capacitance is based upon electrode area and the type and thickness of the dielectric used. Varying any or all of those things will, of course, change the capacitance of the device. But that is not the only parameter that will change.

For instance, if the electrode surface area of an aluminum electrolyic capacitor is increased (to increase the unit's capacitance) through the use of finely etched electrode foils, the device will have a larger ESR (*E*quivalent *S*eries *R*esistance) than similar smooth-metal foil units. That is because the ESR depends upon the volume of the foil used.

You can also increase capacitance by using dielectrics with high dielectric (high-K) constants. But capacitors that use high-K dielectrics are not as stable (they are more sensitive to temperature and voltage variations) and generally have a higher dissipation factor than capacitors that use dielectrics with lower dielectric constants.

Capacitor package styles also should be considered. High lead inductances, common to tubular units, restrict high-frequency performance. Tubular ceramic capacitors however, are the most stable form of capacitor and, since there is no opposing electrode to provide stray capacitance pickup, almost the total capacitance is provided by the ceramic.

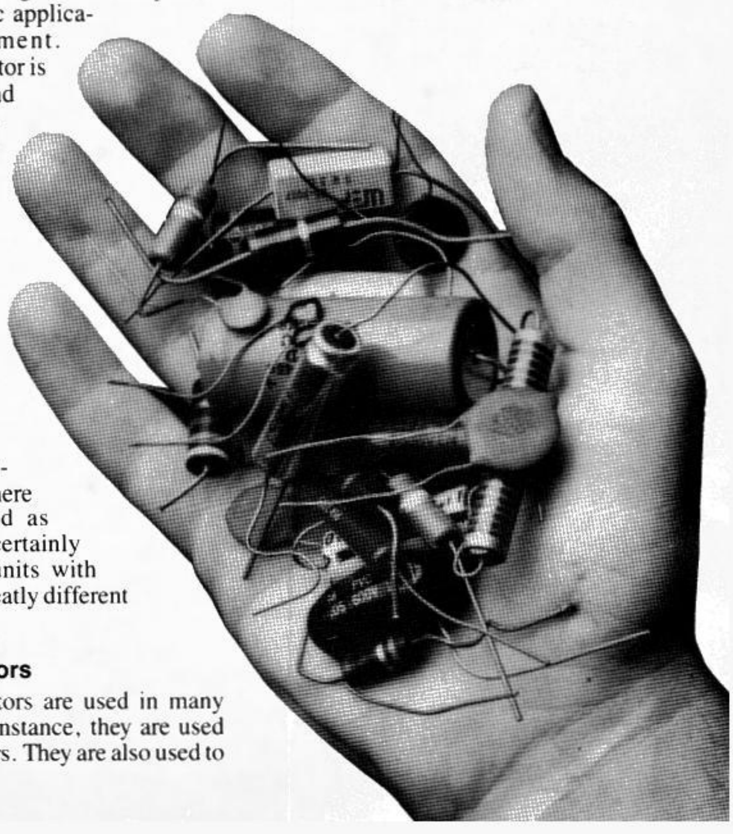
Dipped or molded radial-lead packages reduce interconnection impedances by allowing the capacitor to be mounted close to a PC board surface.

Chip capacitors have contacts, rather than leads, to even further reduce interconnection impedances. In addition, those devices are thin enough to mount beneath unsocketed IC's, thus reducing the length of a trace for a bypass capacitor. That is important in high-frequency circuitry since a PC trace can have an inductance of 10 nanohenries/inch.

Capacitors come in a variety of styles including ceramic, mica, paper, plastic, aluminum, and tantalum types.

Each type was designed for best performance in a specific application or environment. Each type of capacitor is discussed below, and the important specifications and considerations that pertain to the type of capacitor are summarized in Table 2. Table 3 is a glossary of capacitor terms and specifications.

One note about Table 2—the specifications shown there are only provided as guidelines. It is certainly possible to find units with slightly, or even greatly different specifications.



Ceramic capacitors

Ceramic capacitors are used in many applications. For instance, they are used as bypass capacitors. They are also used to compensate for temperature-caused changes in resonant frequency in tuned circuits. When used in that second application, the ceramic capacitors should be mounted close the the tuned circuit, but be shielded from any heat generating components.

The EIA has broken ceramic capacitors into categories. Class 1 capacitors are

TABLE 2—CAPACITOR SELECTION GUIDELINES

CERAMIC
Values: 1 pF to 2.2 μF
Tolerance: 10% or 20%
Voltage rating: 3.3 volts to 6 kilovolts DC
Dissipation factor: to 5%
Temperature coefficient: to 200,000 PPM/°C
For NPO's—
Tolerance: .25% to 10%
Temperature coefficient: 0 ± 30 and 0 ± 60 PPM/°C
Notes: General purpose high insulation-resistance devices used for transient decoupling of IC's and compensation of reactive changes caused by temperature variations. Applications include filtering, bypass, and non-critical coupling in high frequency circuits. Frequency sensitive (capacitance will vary with frequency) so characteristics should be measured at intended operating frequency. Should be mounted next to components being compensated, and shielded from sources of heat. Due to low voltage failure problems, should not be operated significantly under rated voltage under humid conditions. In circuit design, considerations should be given to changes in the dielectric constant caused by temperature, electric field intensity, and shelf aging.

CERAMIC CHIPS
Values: 10 pF to .18 μF
Tolerance: 5 to 20%
Temperature range: −55 to +125°C
Insulation resistance: greater than 100,000 megohms

MICA
Values: 1 pF to .1 μF
Voltage ratings: 100 to 2500 volts DC
Temperature range: −55 to +150°C
Temperature coefficient: −20 to +100 and 0 to +70 PPM/°C
Derating factor: 60% voltage (dipped case) and 40% voltage (molded case)
Mica chips—
Values: 1 to 10,000 pF
Voltage rating: to 500 volts
Notes: Used in timing, oscillator, tuned circuits, and where precise high frequency filtering is required. Capacitance and impedence limits are very stable and capacitors perform very well at frequencies of 10 kHz to 500 MHz. Devices using silver in their construction are very susceptable to silver ion migration resulting in short circuits. Failures can occur in a few hours if capacitors are exposed to DC voltage stresses, humidity, and high temperature.

GLASS
Values: .5 to 10,000 pF
Tolerance: to 5%
Voltage rating: 100 to 500 volts DC
Temperature range: −55°C to +125°C
Temperature coefficient: 0 to 140 PPM/°C
Notes: High insulation resistance, low dielectric absorption and fixed temperature coefficient. Has much higher Q than mica devices. Performs very well at high frequencies up to 500 MHz and can operate in range of 100 kHz to 1 GHz. Capable of withstanding severe environmental conditions but are susceptable to mild mechanical shocks and should be mounted accordingly.

PAPER/PLASTIC DIELECTRICS
Many dielectric and case configurations are available. Each type has its own characteristics. For example, metalized paper units have low insulation resistance and are prone to dielectric breakdown failures. Plastic types have superior moisture characteristics than paper units. Polycarbonate and Mylar types are used in applications that require minimum capacitance change with temperature, such as tuned or timing circuits.
Metalized polycarbonate and polycarbonate film—
Values: up to 50 μF
Voltage rating: to 1000 WVDC
Dissipation factor: .5% (at 25°C and 120 Hz)
Temperature range: −55 to +125°C
Derating factors: 50% voltage; 80% of rated temperature
Notes: DC blocking, filter, bypass, coupling, and transient supression applications. Close tolerance, high frequency capability (40–400 kHz) and high insulation resistance. Not suitable for sample/hold circuits, fast settling amplifiers, or filters due to dielectric absorption characteristics. Small size, medium stability, and long life expectancy under load.

Metalized polyester/polyester foil—
Values: .001 to 100 μF
Voltage rating: up to 1500 WVDC
Dissipation factor: 1% (at 25°C and 120 Hz)
Temperature range: −55 to +125°C (with 50% derating above 85°C)
Notes: See polycarbonate for typical applications. Moisture resistant and high insulation resistance. Small size, medium stability and very good load life. Capacitance will however vary widely with temperature. Foil units are generally lower cost than metalized types. Polyester film is commonly known as Mylar, which is a DuPont trademark.

Polystyrene foil—
Values: to 10 μF
Voltage rating: up to 1000 WVDC
Dissipation factor: .03% (at 25°C and 120 Hz)
Temperature range: −40 to +85°C without derating
Notes: Used in timing, integrating, and tuned circuits. High insulation resistance, and small capacitance change with temperature. Has excellent dielectric absorption characteristics. Large size with excellent stability and very good load life.

Paper/metalized paper/paper foil—
Values: to 100 μF
Voltage rating: to 5000 WVDC
Temperature range: −30°C to +100°C (derated by 30% over 75°C)
Temperature coefficient: greater than 4,500 PPM/°C
Notes: General purpose. Medium stability and very good load life. Large size; low cost. Metalized paper has paper coated with thin layer of zinc or aluminum and are smaller than metal foil units. They are, however, prone to dielectric breakdown of insulation resistance and have poor surge handling capability. Paper foil units used in high voltage/high current applications. Their dissipation factor varies with temperature. Maximum temperature is +125°C.

Polypropylene foil/metalized polypropylene—
Values: to 10 μF
Voltage rating: to 400 volts DC and 270 volts AC (foil units: 200 to 1600 volts DC and 300 to 440 volts AC)
Temperature range: −55°C to +105°C

Notes: Foil units are used in tuned circuits, integrating circuits, timing circuits, and CRT deflection circuits. Metalized units are used in DC blocking circuits. Good high frequency capability, high insulation resistance, close tolerance, high stability, and excellent dielectric absorption characteristics.

Less common types—
Polysulfone: Similar to polycarbonate and polyproplyene capacitors. Small size, high temperature range (to 150°C), suitable for high-frequency applications, and high insulation resistance. Excellent in high current and military applications. Not for sample/hold, fast settling amplifiers, or filters due to dielectric absoption characteristics. Poor history of availability.
Polyvinylidene fluoride: Considered experimental; Has high dielectric constant (about four to twelve times that of polyester devices), which results in a very small sized capacitor. Those units suffer from significant capacitance change with temperature, particulary at low temperatures.
Polyethylene terphthalate: For applications that require high reliability; high insulation resistance at high temperatures.
Metalized paper polyester/paper polyester foil: The foil unit has a slightly better dissipation factor than the metalized type. Operating temperature of −55°C to +125°C with voltage ratings of 240 to 600 (DC) available.
Paper polyproplyene: Available in voltage ratings of 400 to 800

(AC). Operating temperature from −40°C to +80°C.
Teflon/Kapton: Has a temperature range of −55°C to +250°C with a temperature coefficient of .009%/°C. Teflon's extremely low dielectric absorption makes it good for critical sample and hold circuitry. Those capacitors used in specialized applications such as oil well drilling equipment. Those capacitors are large in size since the dielectric is not available in thin gauges.
Parylene: Manufactured by Union Carbide, those capacitors are equivalent to polystyrene types in performance but are rated to +125°C, versus +85°C for polystyrene.

TANTALUM ELECTROLYTIC
Solid type—
Values: .001 to 1000 μF
Temperature range: −55°C TO +85°C (if derated, to +125°C)
Voltage rating: 6 to 120 volts DC
Tolerance: 5% TO 20%
Leakage current: varies with temperature
Derating factor: 50% voltage
Notes: Used in low-voltage DC applications such as bypass, coupling, and blocking. Not for use in RC timing circuits, triggering systems, or phase shift networks due to dielectric absorption characteristics. Also not recommended for applications subject to voltage spikes or surges. High capacitance in a small volume with excellent shelf life. Solid types not temperature sensitive and have lowest capacitance-temperature characteristic of any electrolytic unit. Dielectric absorption and high leakage currents make them unsuitable for timing circuits. Except for non-polarized units, these devices should never be exposed to DC or peak AC voltages in excess of 2% of their rated DC voltage. To prevent failures due to leakage or shorting when series connecting for higher voltages, parallel each unit with a shunt resistor.
Chip types—
Values: .068 to 100 μF
Tolerance: 5% to 20%
Voltage rating: 3 to 50 volts DC
Temperature range: −55°C to +125°C
Leakage current: varies with temperature.
Non-solid types—
Values: .5 to 1200 μF
Tolerance: −15 to +30, and 20%
Voltage rating: to 350 WVDC
Temperature range: −55°C to +85°C (if derated, to +125°C)
Leakage current: varies with temperature
Notes: Polarized foil units are used for bypassing or filtering out low-frequency pulsating DC. Allowance must be made for leakage current. Not suitable for timing or precision circuits due to wide tolerences. Large values available. Etched foil has 10 times the capacitance per unit volume as plain foil types. Peak AC and applied DC voltages should not exceed rated maximums. Usable to 200 kHz. Non-polarized foil are used in tuned low-frequency circuits, phasing low-voltage AC motors, and in servo systems. Sintered slug units are used in low-voltage power supply filtering and in DC applications. Can not withstand any reverse voltage. Leakage current lowest of all tantalum types; no appreciable leakage below 85°C. Usable to frequencies of 1 MHz.

ALUMINUM ELECTROLYTIC
Values: .68 to 220,000 μF
Tolerance: −10 to +75%
Voltage rating: up to 350 volts
Temperature range: −55°C to +85°C (if derated, to +125°C)
Dissipation factor: varies with temperature
Temperature coefficient: varies with temperature
Notes: Used in filter, coupling, and bypass applications where large capacitance values are required and capacitances above nominal can be tolerated. Sum of the applied AC peak and DC voltages should never exceed the the rated DC voltage. Aluminum electrolytics are larger than tantalum electrolytics but less expensive. Loss of capacitance, to as little as 10% of rated value, will occur as the aluminum oxide electrode electrochemically combines with the electrolyte. Oxide film deterioration also requires capacitors to be "re-formed" after storage to prevent dielectric failure. That involves application of rated voltage for a period of 30 minutes, or more, to restore initial leakage current value. Over time, dissipation factor can rise by as much as 50%. Four terminal devices are available (two leads for each connection) that offer low ESR and inductance at high frequencies. Those units were designed for use in switching power supplies.

TRIMMER CAPACITORS
Values: range from .25 to 1 pF and 1 to 120 pF.
Glass/Quartz: Low loss, high Q, and high stability for high tuning sensitivity applications. Frequency range up to 300 MHz.
Sapphire: High level of performance between 1 and 5 GHz.
Plastic: High grade units can be operated up to 2 GHz.
Ceramic: Smallest sized single turn units with maximum capacitance under 100 pF. Capacitance changes with temperature.
Air: High level of performance through UHF Band, from 300 MHz to 1 GHz.
Mica: Has wide capacitance range and relatively high current handling capability.
Vacuum/Gas: Used for high voltage applications. Values from 5 to 3000 pF, with voltage ratings from 2 to 30 kilovolts (DC).

those that have very predictable temperature vs. capacitance characteristics. One type of Class 1 ceramic capacitor is the NPO (*N*egative-*P*ositive-Zero) capacitor. That designation means that the negative and positive temperature coefficients of the device are zero and that they suffer almost (nothing is ever absolute) no change in capacitance vs. temperature. Other Class 1 capacitors have very predictable changes in capacitance with temperature. For instance, a ceramic capacitor that is specified as N750 has a negative temperature coefficient of 750 parts-per-million, per-degree-centigrade. That is, for each degree centigrade the temperature rises, the capacitance of the unit will drop 750 parts-per-million.

Class 2 capacitors are those that are non-linear. Their temperature coefficients are specified by a three letter code that specifies the low and high temperature ranges and the maximum change in capacitance from that at 25°C. Table 4 shows the EIA Class 2 code, and what the various designations mean. As an example, an X7R capacitor will vary in capacitance by no more than a factor of ±15% over the temperature range of −55°C to +125°C.

Mica capacitors

There are two types of mica capacitors. One type is a stacked foil unit consisting of alternate layers of metal foil (or deposited metal film) and sheet mica insulators. The metal foil layers are connected together with tin-lead foil strips with terminals attached by using solder coated pressure clips.

The second type of mica capacitor is the silver-mica capacitor. Those have a silver electrode material screened on the mica stampings, which are then assembled as described above. The silver-mica capacitors are very susceptible to silver-ion migration, which can occur within a few hours, when exposed to high DC-voltage stress, high humidity, and high temperature. The ion migration results in the capacitor short circuiting.

To keep internal inductance small for high-frequency use, button-style silver-mica capacitors have the anode connected through the center of the stack of mica sheets. The other terminal is formed by the case, which is connected to all points around the outer edge of the electrode. That design permits the current to fan out in a 360° pattern from the center terminal thus providing the shortest RF current path from the center terminal to the chassis.

One of the more common micas used for capacitors is Muscovite mica, which comes from India. That substance has a dielectric constant between 6.5 and 8.5, can be split into thin sheets, is non-porous, and does not readily absorb moisture.

Mica capacitors are temperature and frequency stable, have a low dissipation factor, and perform well at frequencies up to 500 MHz. Those high precision units are used in a variety of applications, including tuning circuits, oscillators, filters, and RF power circuits.

Glass capacitors

Glass capacitors are used in applications that require high stability in a hostile environment. Those devices can withstand vibration, acceleration, extreme moisture, vacuum, and high operating temperatures; they are, however, susceptible to damage from mild mechanical shocks. They have a life expectancy of 30,000 hours or greater.

Glass capacitors perform very well at high frequencies up to 500 MHz, and have a frequency range of 100 kHz to 1 GHz. Because of their characteristics, those devices are commonly used in missile and spacecraft electronics.

TABLE 4

Letter Symbol	Low Temp.	Number Symbol	High Temp.	Letter Symbol	Maximum Capacitance Change
				A	±1.0%
				B	±1.5%
Z	+10°C	2	+45°C	C	±2.2%
		4	+65°C	D	±3.3%
				E	±4.7%
Y	−30°C	5	+85°C	P	±10.0%
				R	±15.0%
		6	+105°C	S	±22.0%
X	−55°C	7	+125°C	T	±22%–33%
				U	±22%–56%
				V	±22%–82%

Paper/plastic capacitors

Paper and plastic capacitors are used in applications that require high and stable insulation resistance at high temperatures, and good capacitance over a wide temperature range. (However, an exception to that are the metalized—we'll talk about metalization in a moment—paper units, which have low insulation resistance and are prone to dielectric breakdown.) Plastic types are less affected by humid conditions than paper units since they are non-absorbent. Plastic capacitors, such as polycarbonate and polyester (Mylar) types, are generally intended for applications where minimum capacitance change with temperature is required. They are especially suited for tuned and precision-timing circuits.

In metalized capacitors, a thin film of metal is deposited directly on the paper or plastic dielectric. Doing that gives the capacitor a "self-healing" characteristic called "clearing." If there is a hole or contaminent in the dielectric of the capacitor, a short may occur, resulting from the heavy current flow in the fault area. In a metalized capacitor, that heavy current flow will melt away a very small part of the thin metal film, thus disconnecting the fault from the capacitor. These capacitors are best for analog circuits because the momentary current flow during the clearing action may result in a spurious signal and cause false triggering in digital logic circuits.

Metalized plastic devices work well in switching power-supply output filters because they have a comparatively low ESR, as well as stable temperature characteristics. When using those capacitors in such an application, however, be sure that the unit selected is rated to handle the voltage surges produced by the circuit.

TABLE 3—GLOSSARY

DC leakage—Small current that flows through or across the surface of the dielectric or insulation of the capacitor.
Dielectric—Insulating material between the plates of a capacitor.
Dielectric absorption—A property of a capacitor's dielectric such that even when the capacitor is discharged to zero, a residual charge remains stored in the dielectric.
Dissipation Factor—Important in AC applications, it is the ratio of effective series resistance (ESR) to capacitive reactance X_C, and is usually expressed as a percentage. The dissipation factor factor varies with temperature, humidity, and frequency.
Electrolyte—Current conducting solution (liquid or solid) between two electrodes or plates of a capacitor.
Equivalent series resistance (ESR)—Energy losses in the capacitor due to lead resistance, termination losses, and dissipation in the dielectric.
Insulation resistance (IR)—Measure of a capacitor's insulation quality expressed either in megohms or as a time constant, RC, in seconds. That value determines a capacitor's leakage current for a continuously applied DC voltage when a capacitor is fully charged.
Temperature coefficient—A capacitor's change in capacitance per °C. May be positive, negative, or zero and is usually expressed in parts per million per °C (PPM/°C).
Working voltage (WVDC)—The recommended maximum voltage at which a capacitor should be operated
Quality factor (Q)—A figure of merit used mostly in tuned circuit applications. It is defined as a 1/DF or X_C/ESR.

Tantalum electrolytics

Tantalum capacitors offer high capacitance in a small package size and have an excellent shelf life. Various types of tantalum electrolytic capacitors are available including solid, sintered slug, plain foil, etched foil, wet slug, and chip. Applications include low-frequency filtering, bypassing, coupling, and blocking. The solid types are not temperature sensitive and have a lower capacitance-temperature characteristic than any other electrolytic capacitor.

Applications that tantalums are not suitable for are in RC timing circuits, triggering systems, or phase-shift networks. That's because they have high "dielectric absorption" characteristics. That is, when a capacitor is discharged, the dielectric retains a residual charge. Thus, even if a capacitor that has a high dielectric absorption characteristic has been discharged to "zero," it may still be holding a considerable charge. That, as you might imagine, can cause considerable problems in timing circuits and the like.

Tantalum capacitors also are not recommended for circuits that produce spikes, surges, or pulses. If their voltage rating is exceeded by even a few volts, the device is likely to fail.

Tantalums may be polarized or non-polarized. Polarized capacitors should never be exposed to a reverse DC or peak AC voltage greater than 2% of its rated DC voltage. Non-polarized units, as their name would apply, do not suffer from that limitation. Non-polarized units are made up of two polarized units in series with their cathodes connected together.

Aluminum electrolytics

Aluminum electrolytic capacitors are generally larger than tantalums, and are less expensive. One problem with aluminums is that they will change capacitance (drift) over time. That is caused by the aluminum oxide electrodes chemically combining with the electrolyte. Because of that, capacitance can drop substantially, to 10% of rated values. Those units also have a limited shelf life due to oxide film deterioration and must be "reformed" after long periods of storage. Reforming consists of applying the capacitor's rated voltage to the unit for a period of 30 minutes. Re-forming also prevents dielectric breakdown or shorting. In addition, the dissipation factor of these devices can rise as much as 50%.

To prevent electrolyte evaporation and component cleaning problems, aluminum electrolytics sometimes have an epoxy end seal. However, without a vent, such

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RESISTOR/CAPACITOR

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capacitors may explode if exposed to reverse or overvoltage conditions.

Aluminum electrolytics are used in filtering, coupling, and bypass applications were large capacitances, and capacitance that are higher than the nominal value, can be tolerated.

Trimmer capacitors

Trimmer capacitors fall into three categories: multi-turn, single turn, and compression types. Multi-turn capacitors have either glass, quartz, sapphire, plastic, or air dielectrics, while single-turn devices use ceramic, plastic, or air dielectrics. Compression types use a mica dielectric.

Glass, quartz, or air dielectric devices are selected for applications requiring low loss, high Q, stability, and tuning sensitivity. Glass and quartz devices are used at frequencies up to 300 MHz. Air dielectrics are usable to about 1 GHz. For frequencies of 1 GHz, sapphire dielectrics offer the best performance.

Ceramic and plastic styles are less expensive, with high grade plastic dielectric devices being usable at frequencies up to 2 GHz. **R-E**