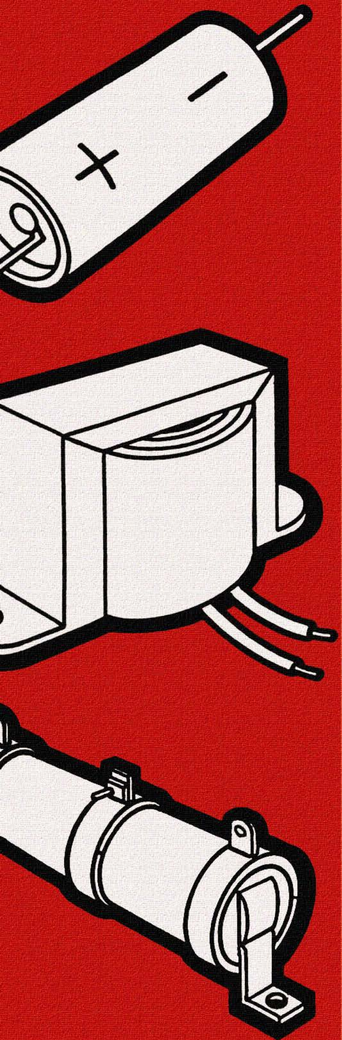
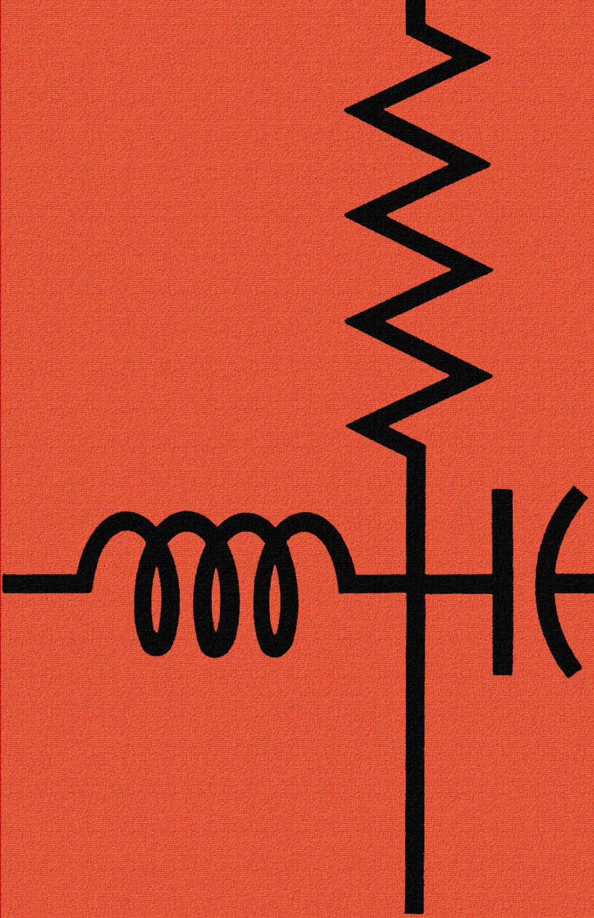
No. 227

R-L-C COMPONENTS HANDBOOK

by DAVID MARK





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Preface

The subject of this book is one which receives only token acknowledgment in texts on basic electricity and electronics. Such books go into details about the various circuits and equipment arrangements which can be made from resistors, capacitors, inductors, and transformers; however, when the reader comes to use these components in building a unit of equipment or test apparatus, he too often is confused by the large array of component types available from supply houses. When he refers to the manufacturers' catalogs, he finds that to make distinctions between the various types requires knowledge of the practical meaning of many different definitions specifications, and special features.

It is the purpose of this book to inform the reader about the various factors of importance in selecting a resistor, capacitor, inductor, or transformer and to acquaint him with the various types of available components and their special features. No attempt is made to review material already ably explained in the many excellent books on the subject of basic electricity and electronics. Instead, this book is intended to be used as a components handbook in conjunction with those texts. The book contains numerous tables and descriptions of the components that are commercially available. The miniaturized components used in transistor-type equipment are included in these surveys, and they receive special consideration when unusual features are involved.

The author offers his grateful acknowledgment to the many dozens of manufacturers who contributed technical information and illustrations for use in this book.

DAVID MARK

Stamford, Connecticut
September, 1959

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Chapter 1

Characteristics of Resistance

RESISTANCE

All substances are made up of combinations of various atoms. This is theory; but this assumption, and others associated with it, have been essential to the progress made in electricity and electronics. Details of this theory may be found in many textbooks dealing with electricity and electronics. Only the highlights relating specifically to the concept of resistance will be considered here.

All atoms consist of a core or *nucleus* around which rotate one or more *electrons*. Each electron contains (or consists of) one unit of negative charge. The nucleus contains electrically neutral particles, together with others (*protons*), each of which contains a unit of positive charge. If the atom is not subjected to any electrical or chemical action, the number of electrons rotating about the nucleus is exactly equal to the number of unit positive charges in the nucleus. The arrangement of orbits in which the electrons rotate around the nucleus in various layers or "shells" is characteristic of the element—copper, silver, gold, uranium, etc. There are approximately 100 basically different types of arrangements known at present, and these correspond to the different elements. All electrical and chemical actions affect only the outer electrons of the atom.

Insulators and conductors. If a source of voltage is connected across an object so that one end is positive while the other is negative, some outer electrons of the atoms in the object will be repelled away from the negative end and attracted toward the positive end. The number of outer electrons which are affected in this manner is determined by how strongly the outer electrons are attracted to the nucleus. The weaker this bond, the greater will be the number of outer electrons that join the flow to the positive terminal. Materials such as glass, plastics, rubber, and baked clays exhibit strong bonds between the nuclei and outer electrons and are known as *insulators*. These permit only a very small number of electrons to break away from their atoms to enter the current flow. If the outer electron bond is weak, as in copper, silver, aluminum, and other metals, a large number of electrons join the flow to the positive terminal. Such materials are known as *conductors*.

Resistivity. The opposition which any specific substance offers to the free flow of electrons is known as its *resistivity* and is measured in *ohms*, as defined by the familiar Ohm's law. Resistivity may be expressed as the number of ohms of opposition offered by a cube of material which measures one centimeter on all sides. This unit is known as the *ohm-centimeter*. In the English system of measurement the *ohm-inch* is used. When the material is in the form of wire, resistivity is expressed as the number of ohms of opposition offered by a wire 1 foot long and 1 mil (0.001 inch) in diameter. This unit is known as the *ohm per mil foot*. The resistivity of various materials is listed in engineering handbooks and tables of physical constants. Values for a few common examples are listed here:

TABLE 1-1

Material	Resistivity at 0° C* (Microhm-cm†)
Aluminum	2.6
Carbon (graphite)	800-1300
Chromium	2.6
Copper	1.6
German silver	33.1
Gold	2.2
Iron (pure)	8.9
Iron (tempered steel)	45.7
Lead	19.8
Platinum	9.8
Silver	1.4

*In most branches of engineering, as well as in the theoretical sciences, temperature is expressed in degrees Centigrade (°C). The freezing point of water is 32° Fahrenheit (°F) or 0°C. The boiling point of water is 212°F or 100°C. The following relationship can be used to convert temperature from one scale to the other: degrees F = 9/5 degrees C + 32.

†*Note:* 1 microhm 0.000001 ohm.

The reciprocal of resistivity (1 divided by the resistivity) is known as *conductivity*. The unit of measurement of this characteristic is the *mho*, a reverse spelling of the term *ohm*.

Total resistance. When a substance is formed into a rod or wire, the major interest is not in its resistivity but in the *total resistance*. This quantity is the total number of ohms of opposition offered to current flow between its ends. Total resistance may be calculated from the relationship:

$$\text{Total resistance (ohms)} = \frac{\text{resistivity} \times \text{length}}{\text{area of cross section}}.$$

A rod or length of wire has a total resistance of 1 ohm if 1 ampere of current flows through it when 1 volt of electromotive force is applied to its ends.

RESISTORS

In electrical and electronic equipment it is often required to use electrical resistance to limit current flow in various circuits, to form voltage dividers, to establish required voltages at the different elements of a vacuum tube, and to form the great variety of special arrangements considered in textbooks concerning electricity and electronics. In all of these applications the designer requires specific quantities of total resistance for insertion into the various circuits. The components which contain these known values of total resistance are known as *resistors*. There is a wide variety of resistors available, but they may be divided into the broad groups of *fixed, adjustable,* and *variable* resistors. These groups will be introduced here, and details concerning the many commercial types will be given in Chap. 2.

Fixed resistors. A fixed resistor has its total resistance determined during the manufacturing process, and there are no provisions for changing this value. The user orders the total resistance required from a broad selection of standardized values, and other values are available on special order. Of a variety of fixed resistor types available, the composition and wirewound resistors shown in Fig. 1-1 (A) and (B) respectively are two types commonly found in present-day equipment. The construction details shown in Fig. 1-1 will be described in Chap. 2. Wirewound resistors are also available with connections, called *taps,* made to any desired part of the resistance element, as shown in Fig. 1-1 (C).

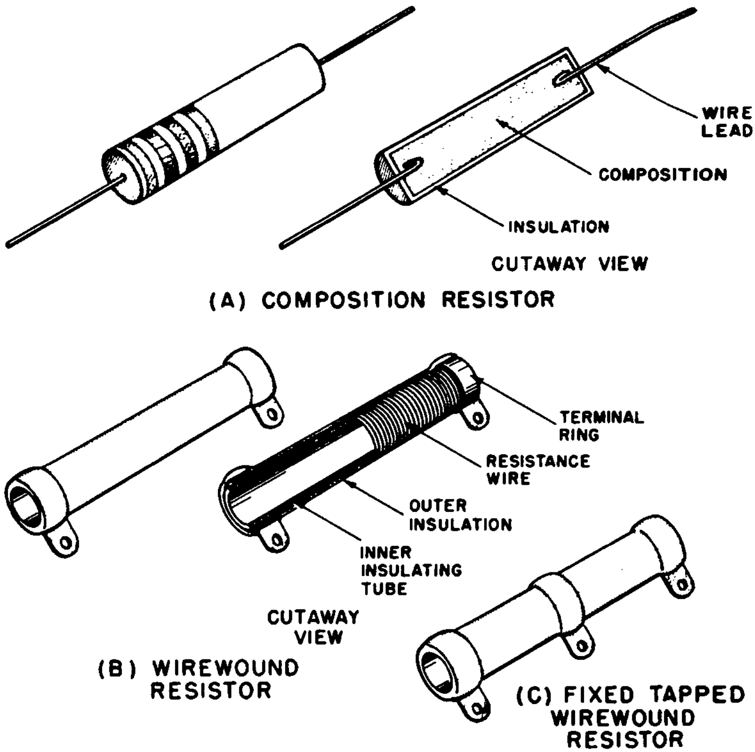


Fig. 1-1. Fixed resistors, appearance and construction. (A) Composition resistor. (B) Wirewound resistor. (C) Tapped wirewound resistor.

Adjustable resistors. Adjustable resistors, as shown in Fig. 1-2, are generally merely specialized forms of wirewound fixed resistors. The difference is that the wire of the resistance element is at least partly exposed, and a movable clamp-type terminal is supplied to make contact with the element at any desired point along its exposed sections. Moving the terminal changes the resistance between either of the end terminals and the clamp terminal. This adjustment is not intended for continuous use, since it is mechanically inconvenient and time consuming. Adjustable resistors are intended for use in applications where they are set to the required value by the equipment manufacturer, and further adjustment by the user is generally unnecessary.

Variable resistors. An example of a variable resistor is shown in Fig. 1-3 (A), and the simplified internal construction appears in

Fig. 1-3 (B) and (C). This type has its resistance element inside the circular container, and a movable terminal is also contained within. The movable terminal is easily shifted to any desired part of the resistance element simply by turning the shaft coming out of the container. Variable resistors are intended for use in applications where the equipment user has frequent requirement for adjusting the resistance, as in tone, volume, focus, and brightness controls. Variable resistors are made with either composition or wirewound resistance elements, and all considerations to be mentioned in connection with fixed resistors having those types of elements also apply to variable resistors.

CONSIDERATIONS AFFECTING RESISTOR SELECTION

An equipment designer cannot order resistors simply on the basis of the total resistance values he obtains from his calculations. It is in the nature of resistors that they cannot be manufactured on a production-line basis at the exact total resistance values

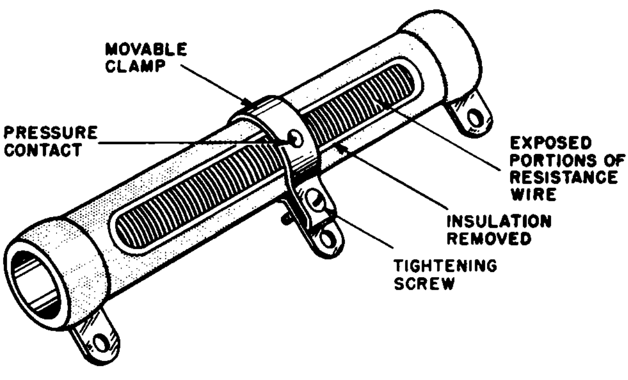


Fig. 1-2. Adjustable resistor.

desired. They can, however, be made within certain specified limits of a desired value. Thus a resistor is usually marked with its total nominal or "rated" resistance value, together with a symbol indicating the manufacturing *tolerance*. The tolerance is usually indicated in terms of the percentage by which the resistor may be higher or lower in value than that indicated by its nominal-resistance markings. In addition, the values supplied by the manu-

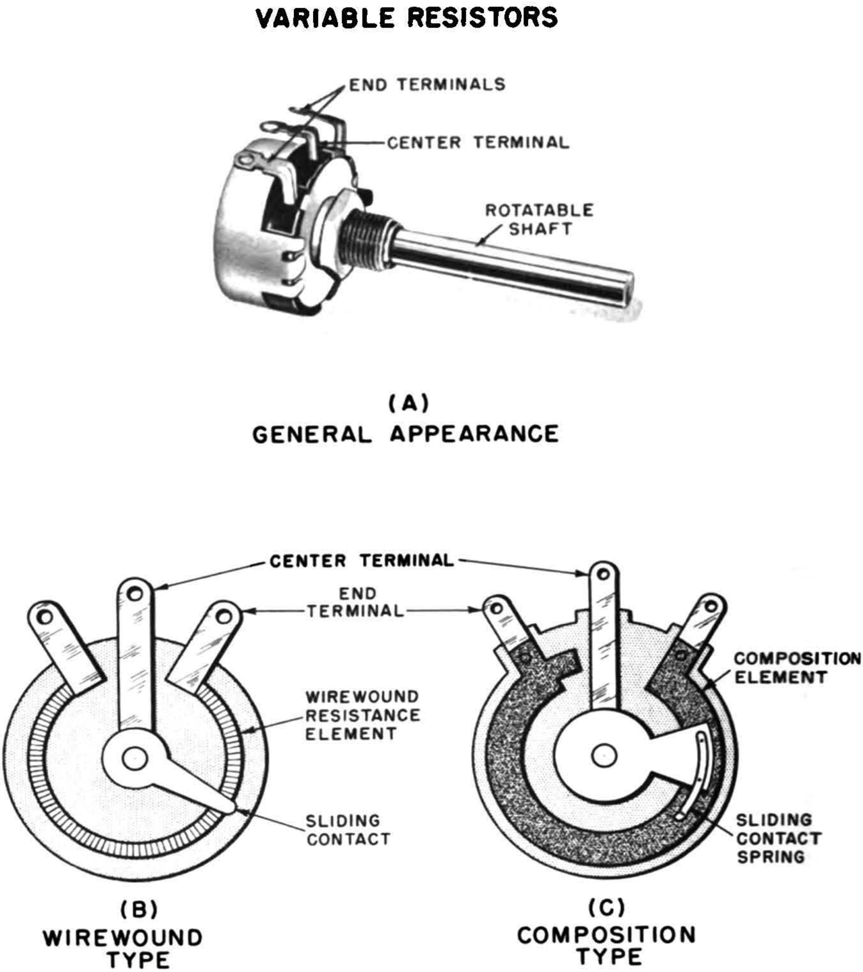


Fig. 1-3. Variable resistors. (A) General appearance. ***Courtesy Clarostat Mfg. Co., Inc.*** **(B) Simplified construction, wirewound type. (C) Simplified construction, composition type.**

facturer are not completely stable, since the total resistance changes with age, temperature, humidity, amplitude of applied voltage, and various other conditions.

While certain resistor designs eliminate most of these undesirable effects, their cost is considerably higher than those designs where little or no attempt is made to prevent variations of the total resistance value. The equipment designer must evaluate the special features and cost of each type and manufacture against the particular requirements of each specific application. In some types of circuits the least expensive resistors perform in a most satisfactory manner, but in other applications even the most highly corrected and expensive types fail to meet some requirements.

Thus the equipment designer, builder, or experimenter must be well acquainted with the considerations involved and with the special features of each resistor type to meet the requirements of each application in the most economical manner. The following paragraphs review the major considerations affecting resistor selection.

POWER DISSIPATION

When a voltage is connected across a resistor, electrons flow from the negative to the positive terminal. Since the resistance opposes the flow of electrons, the electromotive force is expended against opposition. Work is done and electric power is expended within the body of the resistor. The result is the generation of heat.

The only way for the heat to be dissipated from the body of the resistor is by conduction through the leads, by convection to the air, and by radiation to the surroundings. Because of the small diameter of the lead wires, little heat can be dissipated in this manner. The heat which can be dissipated by convection and radiation is related to both the temperature and surface area of the object. For equal heat loss the total surface area may be decreased as the temperature increases. Also, if the surface area is insufficient to dissipate the heat generated within, the temperature will rise to the level required to lose that heat, and the resistance element may be burned out in the process.

Either the construction of the resistor must be designed to withstand extremely high temperatures, or the resistor surface area must be made large enough to dissipate sufficient heat to keep the temperature down to safe limits. A combination of both of these methods is used by resistor manufacturers.

For any given total resistance value, the amount of current flow, and consequently the heat generated, is dependent upon the voltage applied across the resistor. This voltage, of course, will depend upon the circuit in which the resistor is to be used. Consequently, manufacturers generally make each standard total

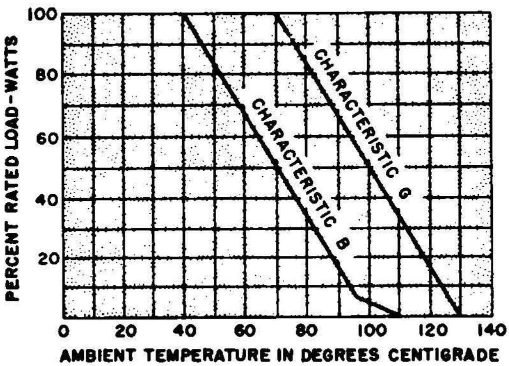


Fig. 1-4. Derating curves for composition resistors. Characteristic B designed for operation below 40° C. Characteristic G designed for operation below 75° C.

resistance value available in resistors of a number of different power ratings. In any particular application the power to be expended in a resistor may be calculated from the voltage applied across it and/or from the current flowing through it, according to any of the following relationships:

$$\text{Power (watts)} = \text{volts} \times \text{amperes}$$

$$\text{Power (watts)} = (\text{amperes})^2 \times \text{resistance (ohms)}$$

$$\text{Power (watts)} = \frac{(\text{volts})^2}{\text{resistance (ohms)}}.$$

The result of this power calculation is not necessarily equal to the actual resistor power rating. First, there are only a limited number of standard power ratings available for any particular total resistance and type of construction. Second, the manufacturer's power rating is usually based on a condition in which the resistor is mounted in free air at a temperature of 40°C (104°F). When the resistor is to be mounted in an enclosed space in which air circulation is restricted or in which the operating temperature will be above 40°C, a resistor with a power rating higher than the value indicated by the preceding formulas must be chosen. To choose the proper substitute, it is necessary to *derate* a standard power rating. This means assigning a lower power rating to the substitute resistor.

The method of assigning a lower power rating is by a *derating curve* (Fig. 1-4). Such curves are sometimes supplied by the resistor manufacturer and are almost always supplied by military standards agencies as a specification for the use of resistors in military equipment. According to the curves shown, which are for composition resistors, a resistor with the characteristic code B (designed for operation below 40°C), and nominally rated at 1 watt, may be operated at 1 watt if the temperature of its immediate surroundings remains below 40°C. If the temperature of these surroundings is at 65°C, the resistor must not be used to dissipate more than 0.5 watt, and at 100°C the maximum power rating that can be used is 0.05 watt. Thus, if a designer requires a composition resistor that will dissipate 1 watt at 65°C, he must order a 2-watt resistor. The 20-watt size required to dissipate 1 watt at 100°C is not available in composition resistors, so a wirewound type with its own derating curves will have to be investigated. A derating curve for resistors with the characteristic code G (designed for operation below 75°C) is also shown in Fig. 1-4.

TEMPERATURE EFFECTS

Closely associated with power-dissipation considerations are the effects of temperature upon total resistance. Power-dissipation considerations are concerned mainly with preventing the temperature rise from destroying the resistor. But also to be considered is the fact that temperature increase causes greater agitation of the individual atoms or united groups of atoms (molecules) in a material, thereby restricting the path through which the electron current can pass. In most cases this causes an increase in resistance, although in some unique cases there is a decrease in resistance.

This is important because the total resistance value required for proper circuit operation may be allowed to differ by particular amounts which are determined by the specific application. In some cases the total resistance may be 20% high or low without any undesired effect on circuit operation. In other applications, a change of more than 1% cannot be tolerated. Temperature effect must be considered.

Resistors intended for precision applications often have a *temperature coefficient* value supplied by the manufacturer. This value defines the expected percentage of resistance change per degree of temperature difference from a specified temperature:

$$\frac{\text{Resistance at test temperature} - \text{resistance at 25°C}}{\text{Resistance at 25°C} \times \text{temperature change}} \times 100$$

$$= \text{temperature coefficient.}$$

The magnitude of this resistance change can be seen from Table 1-2. The table shows for two types of insulated composition resistors the maximum permitted percentage resistance change for temperature variations above and below a reference temperature of 25°C (77°F).

TABLE 1-2*

	Maximum percentage resistance change			
	At −55°C		At +105°C	
Resistance at 25°C	Type E	Type F	Type E	Type F
1000 ohms and below	±13	±65	±10	±5
Above 1000 ohms to 10,000 ohms	±20	±10	±12	±6
Above 10,000 ohms to 0.1 megohm	±25	±13	±15	±7.5
Above 0.1 megohm to 1 megohm	±40	±20	±20	±10
Above 1 megohm to 10 megohms	±52	±26	±36	±18
Above 10 megohms to 100 megohms	±70	±35	±44	±22

When composition resistors are soldered into the equipment, the heat transmitted through the attaching leads may cause a resistance change of as much as 3% for the ¼-watt size and 1% for the 1-watt size. Approximately half the resistance change disappears after cooling, but the remainder is generally permanent. Thus, ordinary composition resistors may be selected for a total resistance accuracy of about ±1%, but this accuracy may well be lost in the soldering process unless special techniques or special tools are used to prevent the resistor body from being heated. If a pair of heavy pliers is used to grasp the lead between the body and the end being soldered, most of the heat will flow into the pliers rather than into the resistor body. If accuracies of ±1% or better must be maintained, the most certain method is to use the temperature-stabilized types which will be considered in Chap. 2. With these types the effect of soldering are reduced to 1/10 or less than the change found in ordinary composition resistors.

VOLTAGE EFFECTS

Due for consideration under voltage effects are voltage coefficient and voltage ratings such as insulation strength, short-term overload, and maximum overload voltage.

Voltage coefficient. In the case of low resistances, large currents flow for relatively low applied voltages, and the maximum voltage

*Adapted from MIL-R-11.

that can be applied is determined by the resistor power rating. However, in the case of composition resistors with high resistance values, a separate voltage effect takes place: resistance decreases with increasing applied voltage. For composition resistors of 1000 ohms or more the percentage decrease of resistance per applied volt can be determined from the relationship:

$$\text{Voltage coefficient} = 100\,\frac{R_1 - R_2}{R_2} \times \frac{1}{E_1 - E_2},$$

where E_1 equals the rated continuous voltage, E_2 equals 0.1 times the rated continuous working voltage, R_1 equals the resistance at rated continuous working voltage, and R_2 equals resistance at 0.1 times the rated continuous working voltage.

For ¼- and ½-watt composition resistors the voltage coefficient should not be above 0.035% per volt; for those with power ratings above ½ watt, the coefficient should not be more than 0.02% per volt.

Resistance tends to decrease with increasing applied voltage because conduction takes place only through two or more carbon particles in contact with each other. Since the contact resistance of each such point is an inverse function of the voltage, the total resistance decreases with voltage. Conduction in a metal wire takes place because of a flow of free electrons between an extremely large number of atoms. Consequently, wirewound resistors have negligible voltage coefficients.

Voltage ratings. Besides considerations of voltage coefficient and maximum current, the maximum voltage that can be applied across a resistor is limited by the danger of voltage breakdown (arcing) along the length of the resistor body or through the insulation to a conductor (usually ground) in contact with the resistor body. Resistor manufacturers and government agencies often assign voltage ratings to resistors. Resistor users should be familiar with these ratings and with the general factors governing their use.

The resistance rating and power rating of a resistor are factors used to determine the maximum d-c or rms, a-c *continuous working voltage* that may be connected across a resistor. The relationship used to determine this rating for composition resistors is:

$$E_w = \sqrt{PR}\ ,$$

where E_w equals the continuous working voltage, P equals the power rating, and R equals the resistance rating.

Regardless of the results of this calculation, there is a *maximum continuous working voltage* which may be applied to these resistors. The *maximum short-term overload* that may be applied across a composition resistor for periods of less than 5 seconds is generally 2.5 times the maximum continuous working voltage but in no case should exceed the value shown in Table 1-3. The *insulation strength* of resistors is that voltage which may be applied across a resistor and a conductor (usually ground) in close contact with its surface. Such voltage should never exceed twice the maximum continuous working voltage, unless the resistor is specifically designed for higher insulation strength.

TABLE 1-3*

Resistor power rating (watts)	Maximum continuous working voltage (volts dc or rms ac)	Maximum short-term overload (volts dc or rms ac)
¼	250	400
½	350	700
1	500	1000
2	500	1000

HUMIDITY AND AGING EFFECTS

Humidity. When standard resistors are exposed to constant conditions of high humidity such as tropical climates, there may be a resistance increase of as much as 7 to 10%. In temperate climates this effect may be only as great as from 2 to 4%. Prevention of moisture effects is accomplished by impregnating the structure with moisture-proof waxes, varnishes, plastics, or ceramics, or by sealing them in casings made of these materials. In such cases the maximum resistance change due to humidity may be kept to below 1%.

Aging. Even under stable temperature and humidity conditions, a resistor is subject to aging effects. When manufactured, it is subjected to mechanical and temperature effects which cause internal stresses in the body of the resistor. As time passes, these stresses are relieved by expansions, contractions, and warping.

*Adapted from MIL-R-11.

Minute changes in the internal structure result, and small changes in resistance take place. After several months, resistance changes of 2 to 3% may occur. Special constructions are available which reduce aging effects to 0.5% or less.

One test for aging effects is the *load-life* test. In this test, a resistor is placed in a space maintained at 40°C, and sufficient direct current is passed through it to maintain a specified percentage of the resistor's rated power load. After 1000 hours in these conditions, the resistance change is measured. The results of such tests differ widely among the various resistor constructions, and only a manufacturer's specification of percentage change provides any useful information.

FREQUENCY EFFECTS

All resistors exhibit an effect in which the resistance for dc (R_0) differs from the resistance for high-frequency current (R_f). All resistors contain small amounts of capacitance and inductance in addition to resistance. At frequencies below 1 mc, the capacitance behaves essentially as though a small capacitor were connected between the two resistor ends. At higher frequencies it exhibits more the effect of being distributed along the length of the resistor. The inductance always has the effect of being connected in series with the resistor.

As will be indicated in Chaps. 4 to 6 of this book, inductance and capacitance have different and complex effects when combined in series- and parallel-circuit arrangements. Depending upon the type of circuit arrangement and upon the specific quantities of inductance and capacitance contained therein, the effects sometimes add and sometimes cancel, to aid or retard the flow of electric current at different frequencies.

As a net result of these *C* and *L* factors, wirewound resistors show an increase in resistance as frequency increases. Roughly speaking, the high-frequency resistance rises to 1.1 times the d-c resistance at frequencies of about 2 mc and shows an increasingly rapid rate of increase at higher frequencies. When special noninductive windings are used, the resistance rise can be kept below 10% for frequencies up to 20 mc or a little higher. In fact, the winding can even be designed so as to cause a resistance decrease with frequency rise.

In the case of composition resistors, the effective resistance decreases as the frequency rises. The higher the total resistance value, the lower is the frequency at which a noticeable change takes place. As an approximate example, a ½-watt, 1-megohm composition resistor has an effective resistance of about 750,000 ohms at 0.25 mc and an effective resistance of about 500,000 ohms at 1 mc. There is a relationship which can be used to predict the frequency characteristics of a composition resistor very roughly. According to this relationship for a given type of construction, the ratio R_f/R_0 is a constant in all cases in which the products of R_0 and f are equal. For example, in comparison with the previous example, a 100,000-ohm resistor has an effective resistance of 75,000 ohms at 2.5 mc and an effective resistance of 50,000 ohms at 10 mc.* This relationship becomes increasingly incorrect at frequencies above 100 mc.

*The following calculations demonstrate this relationship:

1-megohm resistor at 250,000 cps:

$R_0 \times f = 250{,}000{,}000{,}000$

$R_f/R_0 = 0.75$

100,000-ohm-resistor at 2.5 mc:

$R_0 \times f = 250{,}000{,}000{,}000$

$R_f/R_0 = 0.75$

1-megohm resistor at 1 mc:

$R_0 \times f = 1{,}000{,}000{,}000{,}000$

$R_f/R_0 = 0.5$

100,000-ohm resistor at 10 mc:

$R_0 \times f = 1{,}000{,}000{,}000{,}000$

$R_f/R_0 = 0.5$

Chapter 2

Commercial Resistors

FIXED COMPOSITION RESISTORS

Construction. In this type of resistor the resistance element consists of a very finely powdered conducting material, such as graphite or carbon, mixed with a powdered insulating material, such as silicon or talc stone, together with a plastic binding material. These materials are pressed into the form of a rod with a wire lead imbedded part way into each end. This conducting core is covered with a layer of Bakelite with good insulating and moisture-resisting properties. The final construction, identified by the general appearance as previously shown in Fig. 1-1 (A), is known as an *insulated composition resistor* with *axial leads.*

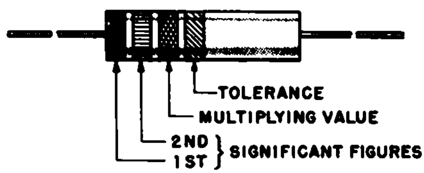
Another type of construction, which is rarely found in present-day equipment is the *uninsulated composition resistor,* sometimes known as the carbon resistor. The conducting element is made in the same manner, but the connecting leads are wound around the ends and are known as *radial leads.* No insulating material except paint is used on the body, and insulation is obtained by mounting the resistor so that it cannot come into contact with any other uninsulated components.

For any given power rating, all resistors have the same body size, regardless of the total resistance value. The total resistance is not adjusted by changing the length or diameter of the conducting rod, but rather by changing the resistivity by the adjustment of the proportions of the conducting and insulating materials.

Advantages and disadvantages. Advantages of composition resistors are small size, low cost, good frequency-response characteristics, and available resistance values ranging from 10 ohms to 22 megohms. They are available with resistance tolerances of 20, 10, and 5% and with wattage ratings of ¼, ½, 1, and 2 watts.

Disadvantages are that composition resistors are subject to aging effects and have high voltage and temperature coefficients. In addition, tolerances of less than 5% are not available except at substantially increased cost, and such lower tolerances are difficult to maintain during the normal use of the resistor.

Color codes. A single standard color code has been adopted by the United States Armed Forces and the Electronic Industries Association (EIA), formerly the Radio, Electronics, and Television Manufacturers' Association (RETMA), for the purpose of identifying the resistance characteristics of fixed composition resistors of the axial-lead type. The details of this color code are shown in



COLOR	SIGNIFICANT FIGURE	MULTIPLYING VALUE	TOLERANCE (%)
BLACK	0	1	± -
BROWN	1	10	± 1
RED	2	100	± 2
ORANGE	3	1,000	± 3
YELLOW	4	10,000	± 4
GREEN	5	100,000	± 5
BLUE	6	1,000,000	± 6
VIOLET	7	10,000,000	± 7
GREY	8	100,000,000	± 8
WHITE	9	1,000,000,000	± 9
GOLD	-	0.1	± 5
SILVER	-	0.01	± 10
NO COLOR	-	-	± 20

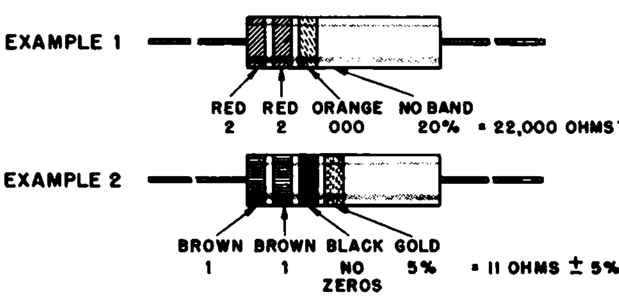
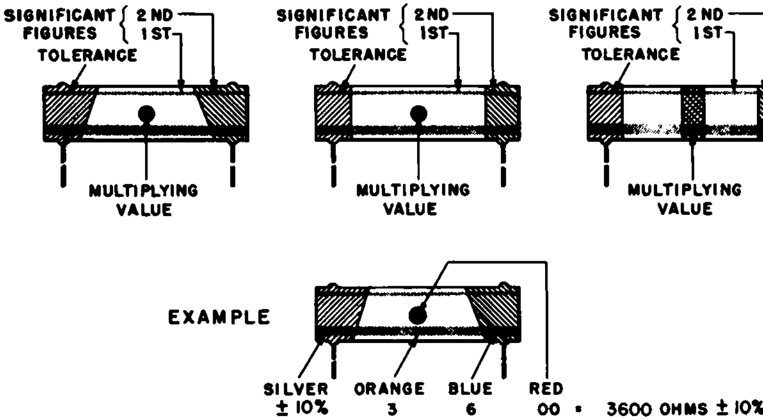


Fig. 2-1. Axial-lead composition resistor color code and examples.



COLOR	SIGNIFICANT FIGURE	MULTIPLYING VALUE	TOLERANCE (%)
BLACK	0	1	± -
BROWN	1	10	± 1
RED	2	100	± 2
ORANGE	3	1,000	± 3
YELLOW	4	10,000	± 4
GREEN	5	100,000	± 5
BLUE	6	1,000,000	± 6
VIOLET	7	10,000,000	± 7
GREY	8	100,000,000	± 8
WHITE	9	1,000,000,000	± 9
GOLD	-	0.1	± 5
SILVER	-	0.01	± 10
NO COLOR	-	-	± 20

Fig. 2-2. Radial-lead composition resistor color code and example.

Fig. 2-1, together with examples of its use. The color code for the radial-lead types of construction, and an example of its use, is shown in Fig. 2-2.

Standard values. If resistors were made available in all possible resistance values, it would be impractical to maintain a stock of spares for repair purposes. To limit the total number of resistance values required to maintain a complete supply of spares, the Armed Forces and EIA have adopted a standard list of preferred resistance values. These values are shown in tabular form in Table 2-1. Tolerances of ±20, ±10, and ±5% are available in a full range from 10 ohms to 22 megohms. The values available at each tolerance rating are sufficient for all applications in which such a tolerance is suitable. Although special values are available on

TABLE 2-1
EIA Standards for Fixed Composition Resistors.
Preferred Values of Resistance (ohms).

±20%	±10%	±5%	±20%	±10%	±5%
10	10	10	1000	1000	1000
		11			1100
	12	12		1200	1200
		13			1300
15	15	15	1500	1500	1500
		16			1600
	18	18		1800	1800
		20			2000
22	22	22	2200	2200	2200
		24			2400
	27	27		2700	2700
		30			3000
33	33	33	3300	3300	3300
		36			3600
	39	39		3900	3900
		43			4300
47	47	47	4700	4700	4700
		51			5100
	56	56		5600	5600
		62			6200
68	68	68	6800	6800	6800
		75			7500
	82	82		8200	8200
		91			9100
100	100	100	10000	10000	10000
		110			11000
	120	120		12000	12000
		130			13000
150	150	150	15000	15000	15000
		160			16000
	180	180		18000	18000
		200			20000
220	220	220	22000	22000	22000
		240			24000
	270	270		27000	27000
		300			30000
330	330	330	33000	33000	33000
		360			36000
	390	390		39000	39000
		430			43000
470	470	470	47000	47000	47000
		510			51000
	560	560		56000	56000
		620			62000
680	680	680	68000	68000	68000
		750			75000
	820	820		82000	82000
		910			91000

(Cont'd.)

TABLE 2-1 (Cont'd.)

±20%	±10%	±5%	±20%	±10%	±5%
100000	100000	100000			1.6 Meg
		110000		1.8 Meg	1.8 Meg
	120000	120000			2.0 Meg
		130000	2.2 Meg	2.2 Meg	2.2 Meg
150000	150000	150000			2.4 Meg
		160000		2.7 Meg	2.7 Meg
	180000	180000			3.0 Meg
		200000	3.3 Meg	3.3 Meg	3.3 Meg
220000	220000	220000			3.6 Meg
		240000		3.9 Meg	3.9 Meg
	270000	270000			4.3 Meg
		300000	4.7 Meg	4.7 Meg	4.7 Meg
330000	330000	330000			5.1 Meg
		360000		5.6 Meg	5.6 Meg
	390000	390000			6.2 Meg
		430000	6.8 Meg	6.8 Meg	6.8 Meg
470000	470000	470000			7.5 Meg
		510000		8.2 Meg	8.2 Meg
	560000	560000			9.1 Meg
		620000	10.0 Meg	10.0 Meg	10.0 Meg
680000	680000	680000			11.0 Meg
		750000		12.0 Meg	12.0 Meg
	820000	820000			13.0 Meg
		910000	15.0 Meg	15.0 Meg	15.0 Meg
1.0 Meg	1.0 Meg	1.0 Meg			16.0 Meg
		1.1 Meg		18.0 Meg	18.0 Meg
	1.2 Meg	1.2 Meg			20.0 Meg
		1.3 Meg	22.0 Meg	22.0 Meg	22.0 Meg
1.5 Meg	1.5 Meg	1.5 Meg			

special order (and at increased cost), such special values would usually have closer tolerance requirements, so that precision resistors, to be considered shortly, would be used instead.

Standard body sizes. Just as the use of standard resistance values simplifies the maintenance of spare parts, the acceptance of standard body sizes assures that new resistors will take up the same physical space in the equipment as the parts they replace.

Standard body sizes have been adopted for use in American military equipment, and similar sizes are also used in commercial equipment. Typical sizes are listed in Table 2-2. Note that this does not mean that all fixed composition resistors of the same wattage rating have the same size. Some manufacturers make the standard wattage ratings with a significantly smaller body size. These small sizes generally perform as well as the larger ones and are very useful in miniaturized equipment.

TABLE 2-2
Standard Body Sizes for Insulated Composition Resistors

Wattage rating	Maximum body diameter *(inches)*	Maximum body length *(inches)*
1/4	3/32	13/32
1/2	1/8	13/32
1	1/4	23/32
2	1/4	1 1/4

WIREWOUND RESISTORS, POWER TYPE

Construction. The general construction of wirewound resistors consists of a metal alloy wire wound around a solid or hollow core made of insulating material. See Fig. 1-1 (B). In power resistors the design emphasis is placed upon maximum power dissipation rather than resistance accuracy. This end is achieved by means of constructions which will withstand high operating temperatures and thus dissipate maximum heat without damage.

The usual construction method employed is to wind a single layer of resistance wire on a rod or tube of ceramic material. Metal rings with provisions for attaching terminals are crimped around the ends of the ceramic core, and the ends of the windings are connected to these rings. The windings and end rings are next coated with a ceramic paste which is then baked. Coatings which harden without baking are also used. The coating provides electrical insulation, holds the windings in place, and prevents mechanical and moisture damage. In addition, the ceramic coating is a good heat conductor, transmitting heat readily from the resistance wire to the surrounding air. The resistance value and wattage rating, plus any other identification, is printed directly on the coating. Color coding is not used.

Types of windings. In most power resistors the resistance wire is wound in a single layer. When it is required to obtain higher values of resistance without increase in size, the wire may be wound in several layers to obtain a greater length in approximately the same volume. When this is done, special precautions must be taken to obtain high-temperature-proof insulation between the layers.

Because wirewound resistors are constructed in the form of a coil of wire, they have inductance and distributed capacitance which may cause undesirable frequency response characteristics in the region of 1 to 5 mc. Over a half-dozen special types of windings have been designed to reduce these effects. Most of these special windings are designed upon the principle of winding the wire so that current flow in adjacent turns is in opposite directions. Some of these windings reduce inductive and capacitive effects sufficiently to make them negligible at frequencies of 20 mc or higher.

The type of winding used by the resistor manufacturer is usually of little interest to the equipment designer. It is the manufacturer's data concerning the frequency-response characteristics of the resistor that is important. Power-resistor windings are generally classified as being either of the inductive or noninductive type. The large majority of power resistors available are of the inductive type—in which no attempt is made to correct the frequency-response characteristics.

Tolerances. Power resistors are generally supplied in tolerances of 10%. For resistances of more than 50 ohms it is not unusual to be able to obtain tolerances of 5% at little or no extra cost. A number of types are available with tolerances as close at 1%, and some very special types are available with even smaller tolerances. Obtaining tolerances of less than 1% presents special problems, because high temperatures cause resistance changes which cannot be predicted with great accuracy. In addition, wire, such as nichrome, which will withstand high temperatures, has a large temperature coefficient which precludes close tolerances. Alloys, such as constantan, which have a low temperature coefficient must be operated at lower temperatures and cannot dissipate the same power in the same physical space. Precision constructions will be considered after a review of the characteristics of the major types of power resistors.

Special types and features. Manufacturers of wirewound resistors have available a variety of types. Figure 2-3 shows some of the more popular models that are in general use. The most common type is the cylindrical unit previously described. Those with power ratings of 5 or 10 watts generally have radial end lugs with stiff wires attached, and mounting is accomplished by means of those leads. Larger units have radial end lugs and are frequently supplied with end brackets for mounting. Manufacturers sometimes have a small selection of cylindrical resistors with one or more fixed intermediate taps, but these are generally made to order, since the placement of the taps depends upon the design of the specific equipment. Most manufacturers have available cylindrical resistors

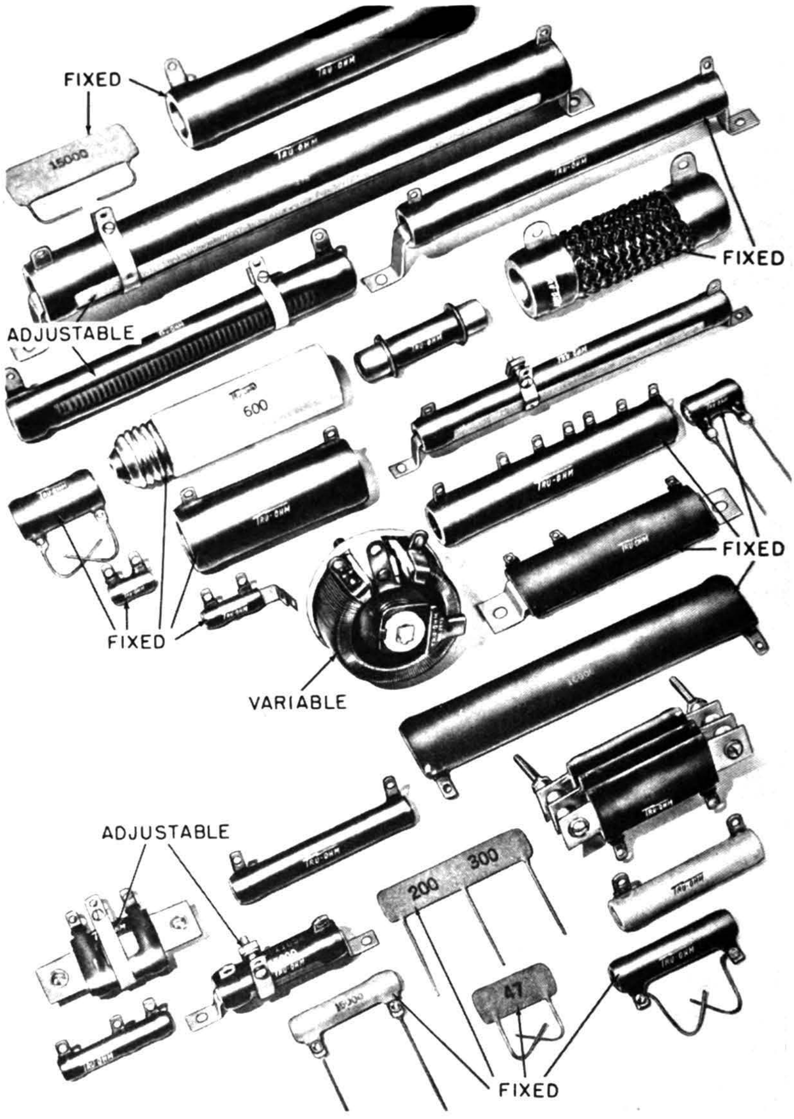


Fig. 2-3. Popular types of wirewound resistor—fixed, adjustable, and variable.
Courtesy Tru-Ohm Prod., Div. of Model Engineering & Mfg., Inc.

with no outer layer of insulation on one side. These are adjustable resistors, and the clamp-type tap can be set to the desired place by the equipment manufacturer. Extra clamps are available so that the user may attach any reasonable number of taps at the desired places.

Cylindrical units designed for compact size and high power dissipation are made with the resistance wire in the form of a flat strip which is wound with the narrow edge in contact with the core. This leaves the wire in the form of a raised, but insulated, strip which dissipates heat more easily. Cylindrical types are also available with tubular end terminals called *ferrules*. This type is intended for mounting by means of clamps which grasp the terminals. Other cylindrical types are available with screw-thread terminals similar to those used on light bulbs, and these are mounted in threaded sockets. Still other types are encased in a housing with end pins so that the resistor can be mounted in a tube socket. Most of these special terminal types are made from stock components but are generally obtainable only on special order.

When a number of power resistors are used in one piece of equipment, the oval, stack-mounting type is convenient. Each resistor is supplied with a mounting standoff at each end, and any desired number of units can be attached together, flat side to flat side. Flat power resistors are also available. These are wound on flat strips of ceramic or insulated metal, and are covered with "high-temperature insulation." This type is sold as a low-cost resistor for use at extremely high temperatures.

Types and Sizes. Table 2-3 lists the major physical characteristics of wirewound resistors of the power type.

WIREWOUND RESISTORS, PRECISION TYPE

Basic construction. In wirewound resistors of the precision type, tolerances of less than $\pm 1\%$ are considered to be of greater importance than efficient heat dissipation. Resistance wire with a low temperature coefficient is used, and the construction is designed to maintain its close resistance tolerances under operating conditions. Special types succeed in maintaining these desirable characteristics while also maintaining efficient power dissipation. Ceramic coatings are generally eliminated, protective coatings of lacquers, plastics, and other organic materials being used instead. The latter coatings offer the required mechanical support and protection while supplying good moisture-proofing. Since these materials do not require curing at high temperatures, they supply the required

TABLE 2-3
Commercial Fixed Wirewound Resistors

	Axial-Lead Type
Description:	Identical in appearance to axial-lead composition resistors. First color-code band is extra wide
Wattages:	½, 1, 2
Tolerances:	5%, 10%
Body size range:	½ watt—⅝ in. long, 3/16 in. diam.; 2 watt—1¾ in. long, ⅜ in. diam.
Resistance range:	½ watt—0.24 to 820 ohms; 2 watt—1.0 to 8200 ohms
	Power Type—Cylindrical Body
Description:	Ceramic tubular core, enamel or cement coating
Wattages:	3, 5, 10, 20, 50, 100, 200
Tolerances:	10% below 50 ohms; 5% above 50 ohms
Body size range:	3 watt—9/16 in. long, ¼ in. diam.; 200 watt—10½ in. long, 1⅛ in. diam.
Resistance range:	3 watt—1 to 1000 ohms; 200 watt—25 to 100,000 ohms
	High-Power Type—Cylindrical Body
Description:	Same as power type. Edgewound resistance element gives ribbed appearance
Wattages:	Over 20 power ratings from 90 watts to 1500 watts
Tolerances:	10% standard; closer on special order
Body size range:	90 watts—4 in. long, 9/16 in. diam.; 1500 watts—20 in. long, 2½ in. diam.
Resistance range:	90 watt—0.04 to 3.0 ohms; 1500 watt—1.0 to 70.0 ohms

protection, while the elimination of such heat treatment prevents resistance changes in the winding.

Although precision resistors have been made in the form of a coil wound on a flat strip of insulation, coils with plug-in bases, coils wound on flexible cores, and units consisting of a number of separate coils connected in series, the encased spool types with radial or axial terminals or leads, as shown in Fig. 2-4, are about the only types associated with precision resistors today. In this construction, the resistance wire is wound upon a spool of ceramic or plastic insulating material, the ends of the wire are connected to the terminals, and the coil is coated or impregnated with insulation.

Aside from obvious differences in the types of terminals and mounting provisions which will be considered later, one characteristic which is not obvious to the eye is the type of winding used to improve the frequency-response characteristics of the resistor. The standard winding in which the wire is wound like thread on a spool is known as the *continuous* or *inductive* winding. Special windings designed to minimize inductive and distributed capacitance effects are known as *noninductive* windings. The important factor is the manufacturer's actual frequency-response specifications for the resistors he can supply, regardless of the special kind of winding used.

Precision wirewound resistors are often made to order rather than carried in stock. In ordering such resistors, the purchaser selects the general body and mounting style required, total re-

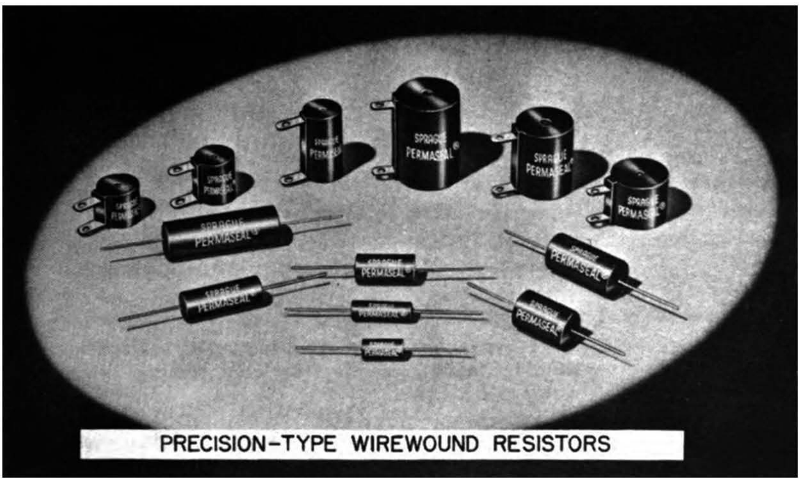


Fig. 2-4. Wirewound resistors, precision type. ***Courtesy Sprague Electric Co.***

sistance, tolerance, humidity-protection characteristics, and any other special requirements. Then the manufacturer quotes a price for meeting the straightforward requirements.

Types. Table 2-4 indicates the outstanding features of the various types of precision wirewound resistors available.

MISCELLANEOUS FIXED RESISTORS

Carbon-film resistors. Carbon-film resistors are made by depositing a thin layer of carbon on a ceramic rod or tube. The thickness of the film is varied to give the desired total resistance, and the thickness range in general use is between 0.00001 and 0.00000001 inch. Terminals are made by coating the ends with graphite or conductive paint or by plating the ends with metal. Resistances up to several thousand ohms can be obtained by control of film thickness. Higher resistance values are obtained by cutting a continuous spiral through the film over the full length of the tube. The remaining carbon is thus in the form of a band wound around a ceramic core. Controlling the width of this spiral provides a means of obtaining the desired total resistance. High-quality commercial types are coated with resin over which is placed a baked-on, moisture-resistant coating. Hermetically sealed types have an outer ceramic shell to seal out moisture and air and to give additional mechanical protection.

TABLE 2-4
Precision Wirewound Resistors

	Stock Types
Description:	Spool-type, enameled wire, noninductive winding, axial solder lugs or leads
Wattages:	0.15, 0.50, 1.0
Tolerance:	1%
Temperature coefficient:	0.0025% per deg. C from 20° to 100°C
Body size range:	0.15 watt—9/32 × 13/32 in.; 1 watt—7/8 × 15/16 in.
Resistance range:	0.15 watt—10 to 100,000 ohms; 0.50 watt—0.1 ohm to 1 megohm; 1 watt—1.5 megohms to 2.5 megohms
	To-Order Types
Description:	Spool type, enameled wire, inductive or noninductive windings, axial solder lugs or leads, ceramic cores, moisture-proof coatings
Wattages:	0.10, 0.25, 0.50, 1.0, 2.0
Tolerances:	1%, 0.5%, 0.25%, 0.1%, 0.05%, 0.01%
Temperature coefficient:	4 parts per million per deg. C
Body size range:	0.10 watt—1/4 × 1/4 in.; 2.0 watt—3/4 × 2 1/8 in.
Resistance range:	0.10 watt—10 to 70,000 ohms; 2.0 watt—0.1 ohm to 15 megohms

Advantages of carbon-film resistors are that they have negligible voltage coefficient, very low temperature coefficient, and excellent frequency-response characteristics up to 30 mc. They represent a good compromise between composition resistors and precision wirewounds. Resistors of 200 ohms have a temperature coefficient of about -0.025% resistance charge per deg. C. For resistors of 10 megohms this change is in the order of -0.05%. A ¼-watt, 1% resistor has a body about 1 inch long and ¼ inch in diameter. The resistor may be operated at 1 watt, but the tolerance then widens to 5%. A ½-watt, 1% resistor is about 2 inches long and ¼ inch in diameter and may be operated at 2 watts with 5% accuracy.

As this book goes into publication, new manufacturing techniques make available carbon-film resistors with a 1% tolerance in power ratings of ½, 1, and 2 watts and with resistances from 25 ohms to 30 megohms. The approximate body sizes for these power ratings are ¾ by 3/16, 1 by 5/16, and 2 by 5/16 inches respectively.

Boron-carbon resistors. Boron-carbon resistors are made in the same general manner as the carbon-film type and are available in similar resistance, power, and tolerance ratings. Their advantage is an even lower temperature coefficient. At a resistance of 200 ohms, the temperature coefficient is one-third that of carbon film, and at 1 megohm the coefficient is one-half that of carbon film.

Metal-film resistors. Metal-film resistors have the same general construction as carbon-film resistors except that the film consists of metal or metal alloy. Through the use of suitable alloys, temperature coefficients lower than those for carbon or boron-carbon can be obtained. Available power and tolerance ratings are equivalent to those for carbon-film types, and resistance values from 1 ohm to 1 megohm can be obtained.

High-voltage, high-power resistors. Use of the techniques for forming a spiral of resistance material on a ceramic tube has led to the development of resistors with good stability at high resistance values. Since materials with low resistivity can be made into resistors with long conduction-path length, high voltage can be applied, while low voltage per unit length is maintained. Resistors with a 2-watt, 5000-volt peak rating are available from 2500 ohms to 250 megohms in a body size of 1¾-inches long by 5/16 inch in diameter. Resistors with a 90-watt, 100,000-volt peak rating are available from 1 megohm to 20,000 megohms in a body size of 20 inches long by 2 inches in diameter. Tolerances of 5, 10, and 15% are available.

VARIABLE RESISTORS

CONSTRUCTION

Basic components. The basic components of the most widely used types of variable resistors were shown in Chap. 1, Fig. 1-3. Although the shapes and sizes of the various parts may vary with the wattage rating and with the particular production techniques of the various manufacturers, the general arrangement is nearly always the same. The only fundamental differences are in the types of resistance elements used. Figure 1-3 (B) shows construction with a wirewound resistance element, and (C) shows the same with a composition element. Both constructions consist of a base, a resistance element with a terminal at each end, a sliding contact arm connected to the center terminal, a rotatable shaft fastened to the contact arm, a threaded bushing, and a cover. The shaft can be turned so that the contact arm can be set to any desired portion of the resistance element. With different settings of the shaft, there are different resistances between either end terminal and the contact-arm terminal. The details of construction vary with the variable resistor wattage ratings. Those with ratings lower than 2 watts generally are adaptable to the mounting of a supplementary switch or additional variable resistors, as will be considered later. As is the case with fixed resistors, there are a limited number of different wattage ratings available for variable resistors. The most common ratings are 0.2, 0.25, 0.5, 2, 4, 7, 25, 50, 150, and 300 watts.

Composition element. There are two basic forms of composition elements. In one type the material used is similar to that employed in fixed composition resistors. This material is pressed to the required shape and mounted upon the base or is pressed into a shaped depression in the base. The total resistance is controlled by varying the proportions of the mixture components, as in the case of fixed composition resistors. In the other type a base of insulating material is made to the required size and shape and is coated with composition of the formulation and thickness required to give the desired total resistance.

Wirewound element. There are three basic types of wirewound elements. One type, generally used in variable resistors with power ratings below 5 watts, consists of a flat strip of insulating material with resistance wire wound around it in a single layer, with spaces between the turns. After winding, the form is bent to the required shape and attached to the base. In the second type the wire is wound around a ceramic form of the final shape desired. In this type, a ceramic protective coating is generally used instead of a metal cover, and this construction is usually found only in variable resistors with power ratings above 25 watts. In the third type, the wire is wound on a flat metal strip, usually aluminum, with a layer of flexible insulation, such as asbestos, between the wire and the strip. This element is then bent to shape and mounted upon a thick metal base. Only a thin layer of heat-resistant insulation is used, so that heat from the resistance wire is easily conducted away. This construction is usually found only in variable resistors with power ratings above 100 watts.

Types. Table 2-5 presents a survey of the outstanding characteristics of available composition and wirewound resistors.

Terminology. There are a number of basic terms which are commonly applied to variable resistors. These are illustrated in Fig. 2-5 and described in the following paragraphs.

All of the descriptive terms which are applied to variable resistors are based on the viewpoint of looking straight into the rotatable shaft, as shown in Fig. 2-7. The *left terminal* is defined as the terminal on the left, and the *right terminal* is the one on the right in this frame of reference. When the rotatable shaft is

TABLE 2-5
Variable Resistors

	Composition
Description:	See text. Design details vary with individual manufacturers
Wattages:	0.20, 0.25, 0.5
Body size:	0.20 watt—5/8 in. diam. × 1/2 in. thick; 300 watt—6 in. diam. × 2 3/8 in. thick
Total resistance range:	0.20 watt—1000 ohms to 2.5 megohms; 0.50 watts—500 ohms to 10 megohms
	Wirewound
Description:	See text. Design details vary with individual manufacturers
Wattages:	2, 4, 7, 25, 50, 150, 300
Body size:	2 watt—1 1/16 in. diam. × 7/16 in. thick; 300 watt—6 in. diam. × 2 3/8 in. thick
Total resistance range:	2 watt—6 to 15,000 ohms; 300 watt—1 to 2500 ohms

turned completely counterclockwise, the contact arm is at the closest possible point to the left terminal, and the resistance between the contact (center) terminal and left terminal is essentially zero. When the rotatable shaft is turned completely clockwise, the contact arm is in the closest possible position to the right terminal, and the resistance between the right and center terminals is essentially zero.

The *total mechanical rotation* is the complete angular rotation through which the shaft can be turned between its fully clockwise and fully counterclockwise positions. A protrusion in the base,

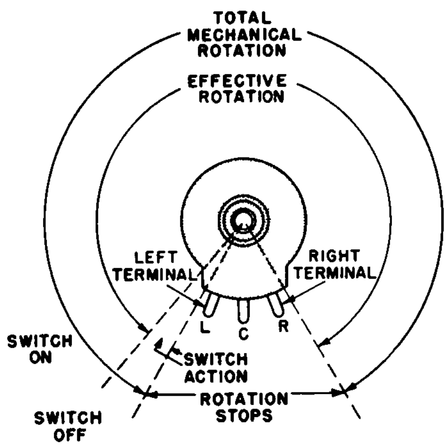


Fig. 2-5. Variable resistor terminology.

called a *stop,* prevents the contact arm from being turned past the determined limit of rotation. The *effective rotation* may be defined as the total angular rotation of the shaft which is effective in producing a change in resistance between the center terminal and either the left or right terminal.

In standard variable resistors, the effective rotation is essentially identical to the total mechanical rotation and is usually in the region of 310°. If the variable resistor has a switch mounted on it, as is commonly the case for volume controls in radios and television sets, the total mechanical rotation is increased about 20° without increasing the effective rotation. When the shaft is turned completely counterclockwise, the switch contacts are open, and the resistance between the center and left terminals is essentially zero. As the shaft is turned clockwise, this resistance remains at zero while the switch mechanism is going into operation. At approximately 20° of clockwise rotation the resistance is still zero and the switch contacts snap closed. This is the point at which effective rotation begins, since any further clockwise rotation causes an increase in resistance between the two terminals.

MOUNTING PROVISIONS

Types. There are two types of mounting provisions in common use with variable resistors. Most small variable resistors, usually those below 150 watts in power rating, have what is known as the *single-hole mounting.* The encased resistor is mounted by means of its threaded bushing through a single hole in a panel or bracket as shown in Fig. 2-6 (A). The standard thread used for this purpose is 3/8-32 NEF-2. The other type of mounting is known as the *three-hole mounting* and is generally used with variable resistors over 150 watts in power rating. In this type, shown in Fig. 2-6 (B), the shaft goes through the center hole of the case, but there is no threaded bushing. Fastening is accomplished by means of screws through two side holes. The screws are threaded into holes tapped into the resistor base and tightened. Many variable resistors have a *nonturn* device, which is a pin or tab projecting from the base. A hole is drilled into the panel or bracket, and the projection in the base enters the hole. This arrangement prevents the resistor case from turning when torque is applied to the shaft at either extreme of its mechanical rotation.

Shaft types. A wide variety of shaft types has been developed to suit the various ways used to turn the shaft, by knob or other device. The types of shafts and accessories in most common use are shown in Figs. 2-7 through 2-9.

In military equipment there are three standard types of shafts. Simplest of these is the *round* shaft shown in Fig. 2-7 (A). A knob is attached to the end of this shaft by means of a setscrew which bites into the surface. The disadvantage of this method is that the knob may slip when the shaft is forced against either limit of its mechanical rotation. The *flatted* shaft, shown in Fig. 2-7 (B), eliminates knob slip, since the setscrew protrudes down through the wall of the knob. The relationship between the positions of the flat and the contact arm of the variable resistor is standardized as shown in (B). In certain applications, the adjustment of a variable resistor is intended for use by the equipment manufacturer and by service technicians rather than by the equipment operator.

Well-known examples of this are the variable resistors located at the rear of a television set. In such cases, a *slotted shaft,* as shown in Fig. 2-7 (C), is used. No knob is attached to the end of the shaft, a screwdriver being used instead. The relationship between the slot and contact arm positions is as shown in Fig. 2-7 (C).

Variable resistors supplied for commercial equipment frequently are equipped with the types of shafts just described. However, there is a broad selection of special flats, slots and serrations available. Their purpose is to permit rapid attachment of knobs

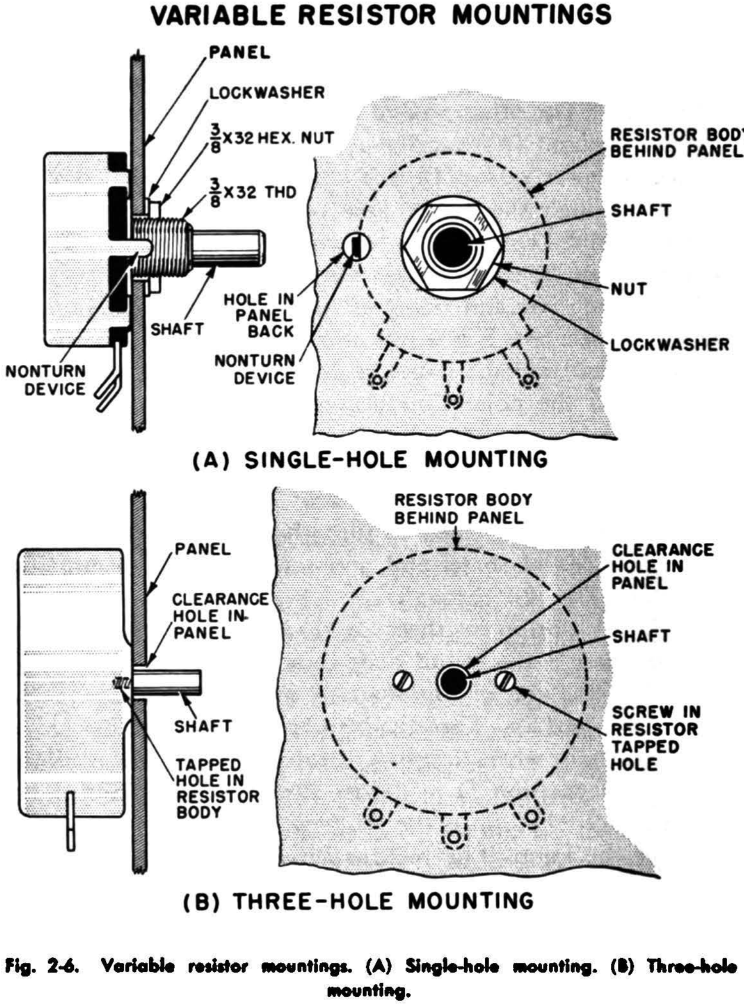


Fig. 2-6. Variable resistor mountings. (A) Single-hole mounting. (B) Three-hole mounting.

by mass-production techniques. Instead of being attached by means of setscrews, knobs for commercial equipment often are merely pressed onto the shaft and are held in place by means of springs and friction devices in the knob which grasp the special surface.

A special type of variable resistor which is very useful for repair work is the *attachable shaft* type, one example of which is shown in Fig. 2-8, together with an assortment of available shafts.

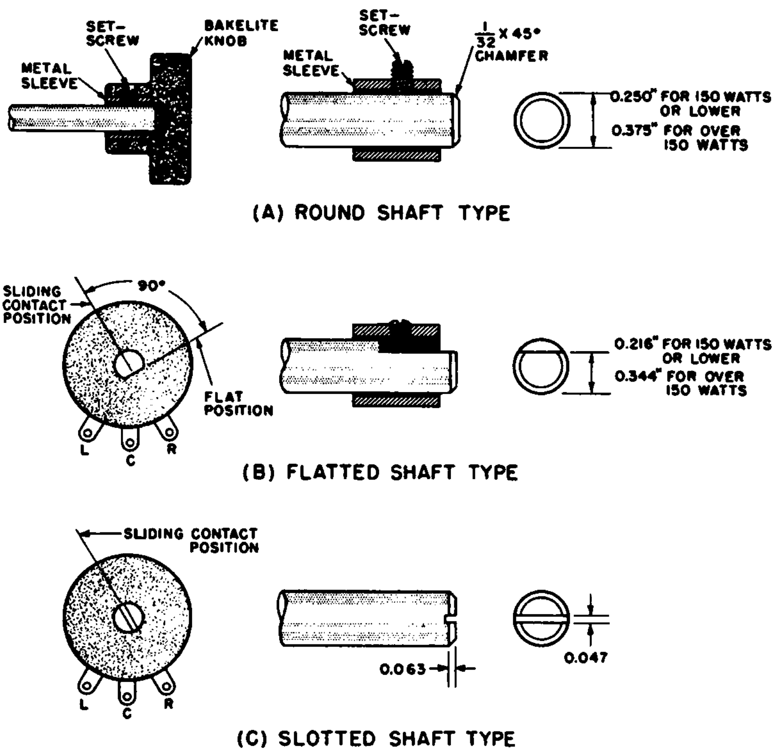


Fig. 2-7. Military standard shaft types. (A) Round. (B) Flatted. (C) Slotted.

This resistor has a short shaft provided with a deep slot into which the selected attachable shaft can be inserted. The added shaft is held to the resistor shaft by means of a split washer which clamps into a groove common to both shafts. In another type, the end of the added shaft has a knurled section which is forced into a hole in the resistor shaft, and friction holds the two together.

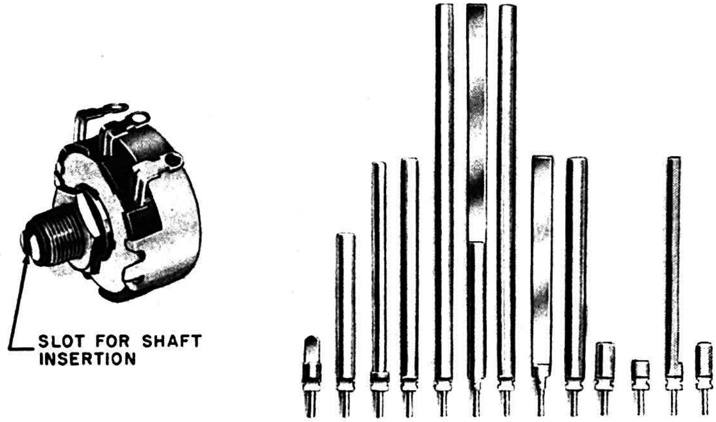


Fig. 2-8. Commercial variable resistor shaft types. (A) One technique of coupling selected shaft. (B) A selection of available shafts. *Courtesy Clarostat Mfg. Co., Inc.*

Another variable resistor arrangement which is often found is the tandem unit shown in Fig. 2-9 (A), this unit containing three variable resistors. In this arrangement a simple shaft can be used to control the sliding contact of two or more variable resistors and a switch. If independent control of two functions is required, the concentric shaft type, shown in Fig. 2-9 (B), is used. The latter type is used in combination controls, such as the volume-contrast control on TV sets, used when there is limited panel space for controls. Both the tandem and the concentric shaft types are available on order from manufacturers. The various components of these units are also available separately, so that repairmen can conveniently construct replacements for damaged units.

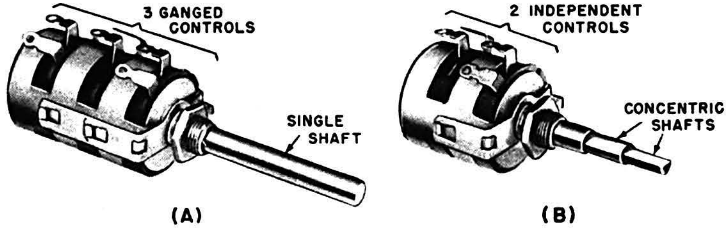


Fig. 2-9. Multiple variable resistor units. (A) Three variables controlled by single shaft. (B) Two independent variables with concentric shafts. *Courtesy Clarostat Mfg. Co., Inc.*

CIRCUIT CONNECTIONS

Variable resistors of either the composition or wirewound type are connected into electrical or electronic circuits in either the rheostat or potentiometer arrangement.

Rheostat connections. In the *rheostat* arrangement shown in Fig. 2-10 (A), one terminal of the resistance element and the terminal of the movable contact arm are connected into the circuit.

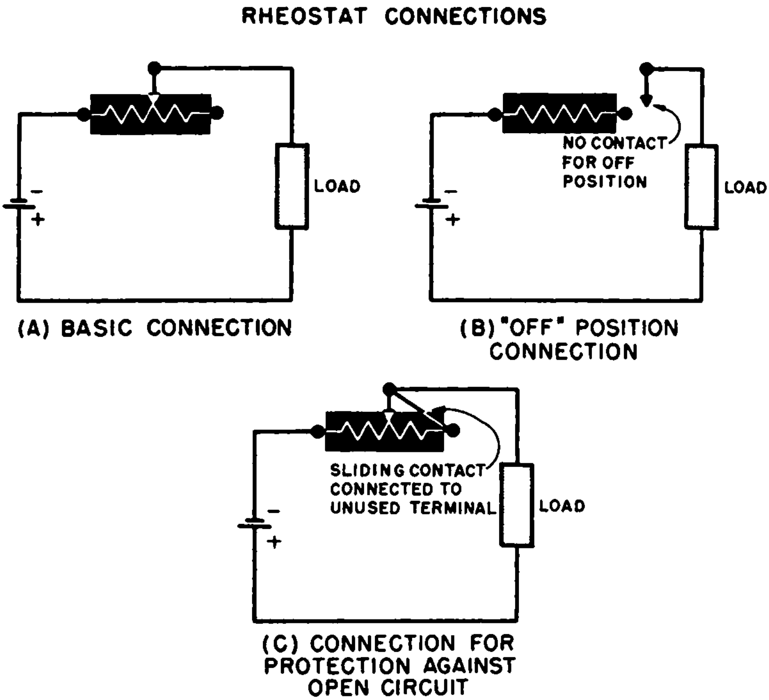


Fig. 2-10. (A) Rheostat connection. (B) Rheostat with "off" position. (C) Connection for unused terminal.

By moving the contact arm, the resistance between the two terminals can be varied from zero to the maximum value of the resistance element. Depending upon which terminal of the resistance element is used, the resistance in the circuit can be made to increase or decrease as the shaft is rotated clockwise. Since only two of the terminals are used, one of the terminals of the resistance element can be eliminated completely. In some cases the contact arm can be turned past the end of the resistance element, as shown in Fig. 2-10 (B), so that there is an "off" position in which there is no connection between the two wired contacts. With three terminals it is common practice to connect the unused terminal to the contact arm, as shown in Fig. 2-10 (C). This provides protection against a condition of infinite resistance (open circuit), should the contact arm fail to maintain proper pressure against the resistance element. Instead the total resistance of the element enters the circuit the moment the contact fails.

Potentiometer connections. In the *potentiometer* circuit arrangement the three terminals are connected as shown in Fig. 2-11.

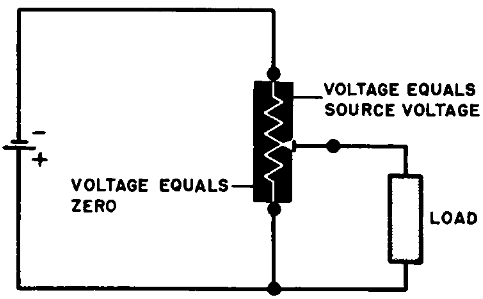


Fig. 2-11. Potentiometer connection.

A source of a-c or d-c voltage is connected across the two ends of the resistance element. The output, or load, is connected across the terminal of the contact arm and one end terminal. Turning the shaft changes the amount of resistance between the contact arm and each of the end terminals so that the output voltage can be varied from zero to the full value applied across the two outside terminals.

RESISTANCE TAPERS

Untapered resistors. If the resistance element is constructed in a uniform manner, the resistance between either end terminal and the center terminal will vary as shown in curve A, Fig. 2-12 (A), as the shaft is turned. The result is that essentially 25% of the total resistance will exist between these terminals when the contact arm is turned 25% of its effective rotation from the end terminal. When the rotation is 50 and 75%, the resistance between the end

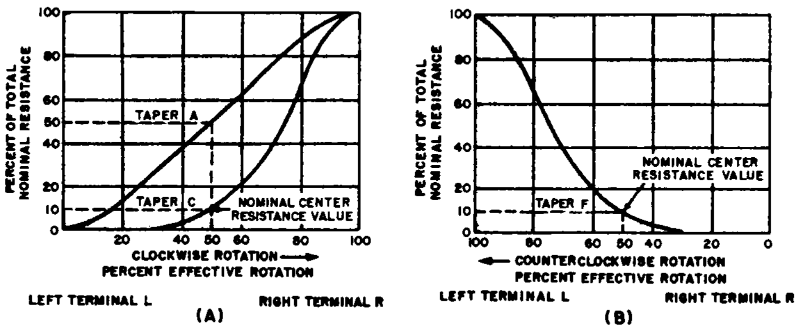


Fig. 2-12. Variable composition resistor tapers. (A) Clockwise tapers A and C. (B) Counterclockwise taper.

and center terminals will be 50 and 75%, respectively, of the total. Thus the resistance variation is uniform with the degree of rotation, and the plot of resistance against rotation is essentially a straight line. This type of resistor is known as an *untapered* or *linear* resistor. Although the term is not technically correct, this arrangement is frequently known as a *linear* taper or *A* taper.

Tapered resistors. In certain applications it is not required that resistance vary in a linear manner as the shaft is turned. Instead it is more important that the effect being controlled (such as the loudness of sound from a loudspeaker, the speed of a motor, or the brightness of a bulb) be proportional to the degree of shaft rotation. In such cases the desired result can be obtained by providing for a resistance change which is not proportional to the degree of shaft rotation. Such a resistor is known as a *tapered resistor*.

There are a number of tapers available from different manufacturers, but the most commonly used types are the *clockwise* and *counterclockwise* tapers. The clockwise taper for composition resistors is shown in curve C of Fig. 2-12 (A). When the resistance is measured between terminals *L* and *C*, the resistance varies as shown. During the first 30% of clockwise rotation, the resistance between the two terminals shows an imperceptible rise above zero. At about 50% of clockwise rotation the resistance between the two terminals is approximately 10% of its total value. Further clockwise rotation causes a very rapid increase to the total value. In military specifications this resistance variation is known as a *C* taper, and a commercial name sometimes used is the *left-hand* taper.

The counterclockwise taper for composition resistors is shown in Fig. 2-12 (B). In military specifications this type is known as an *F* taper, and commercially it is often known as the *right-hand* taper. When the resistance is measured between the right and center terminals and the contact arm is turned counterclockwise, there is

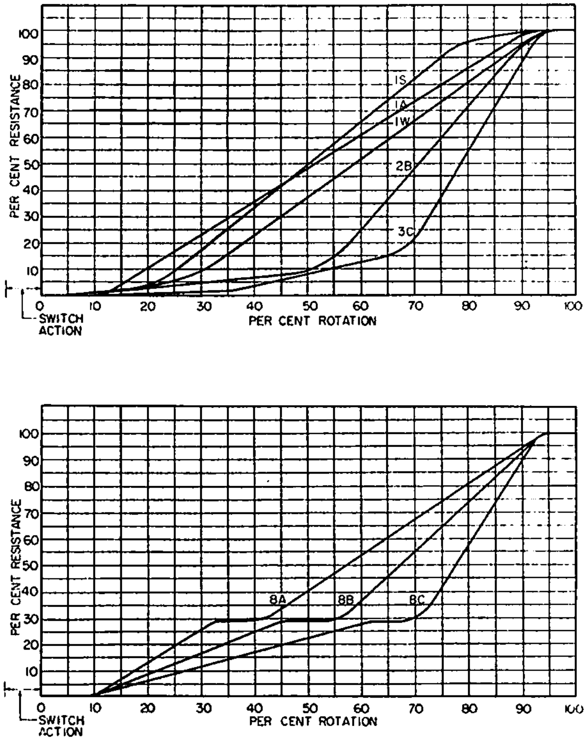


Fig. 2-13. Commercial variable composition resistor taper charts. ***Courtesy Stackpole Carbon Co.***

no significant resistance rise above zero for the first 30% of rotation. At 50% rotation the resistance is at 10% of its total value. Further rotation causes a rapid increase to the total value. Examples of commercial variable resistor taper charts are shown in Fig. 2-13.

In molded composition resistors the taper can be produced by varying the proportions of the conductive and nonconductive materials at various portions of the resistance element. The same effect can also be obtained by using a uniform mixture and varying its thickness or width along the length of the resistance element. In wirewound variable resistors, the untapered type is made by using uniform wire and uniform turn spacing along the length of the resistance element. A wirewound resistance taper can be produced by changing the turn spacing, by changing the characteristics of the resistance wire, or both. In wirewound resistors the resistance variation is not as smooth as in the composition type, as shown by the typical examples of the wirewound *A*, *C*, and *F* types in Fig. 2-14.

SPECIAL-PURPOSE RESISTORS

THERMISTORS

Thermistors are thermally sensitive resistors. While most materials increase in resistance with rising temperature, the resistance of a thermistor drops sharply. The resistance drop is in the order of 4% for every degree Centigrade rise in temperature. For this reason, thermistors are useful in applications involving temperature measurement and control.

When an electric current is passed through a thermistor, its temperature will rise. The speed and extent of the temperature

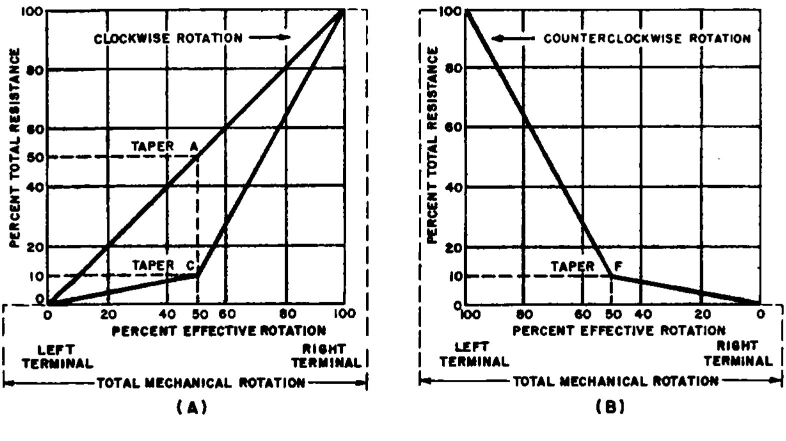


Fig. 2-14. Charts of variable wirewound resistor tapers. (A) Clockwise tapers. (B) Counterclockwise tapers.

rise depend upon the magnitudes of the current and resistance, plus the thermal mass of the thermistor and the heat dissipation facilities provided. Since a decrease in resistance accompanies the temperature rise, these various characteristics make it possible to use thermistors in voltage, current, and power control circuits and in time-delay devices. If a thermistor conducting an electric current is placed in a stream of liquid or gas, or in a container, the rate of heat dissipation is determined by the composition

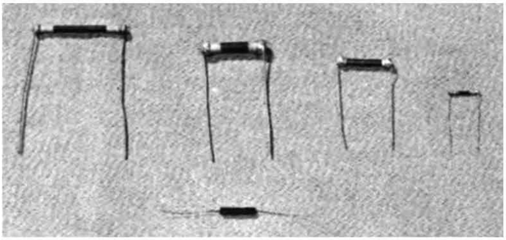


Fig. 2-15. Rod-type thermistor in various sizes. Those above are radial parallel types with wrapped soldered leads; below is an axial type with a platinum fired-in lead. *Courtesy General Electric Co.*

and flow rate of the surrounding medium. Changes in the composition or flow rate change the temperature of the thermistor and cause significant variations in the electric current. These current variations can be calibrated to indicate the composition, flow rate, pressure, or level of the medium in which the thermistor is placed.

Thermistors are made of a mixture of semiconductor oxides; mainly the oxides of nickel, manganese, and cobalt. The proportions of these materials are varied to produce the desired characteristics. During manufacture the mixture is combined with a binding material and formed into rods, discs, washers, or beads. Heating in an oven produces a finished material which has the appearance of a ceramic. Leads or terminals are bonded in place.

Bead thermistors are generally available with a glass coating or encased in a glass envelope. The bead length and diameter may be as small as 0.01 and 0.005 inch, respectively and as large as 0.5 and 0.2 inch, respectively. Available resistances at 25°C cover the range from 1000 ohms to above 10 megohms.

Disc thermistors are available in diameters ranging from 0.2 to 0.6 inch. Washer-shaped units generally have a diameter of 0.75 inch. Both types are available in thicknesses ranging from 0.05 to 0.5 inch. Available resistances at 25°C cover the range from 10 to 1000 ohms. Thermistors of these types can be stacked together to make various series and parallel arrangements, and their form makes them convenient for mounting.

Rod-type thermistors (see Fig. 2-15) are used when high resistances are required. Lengths and diameters range from 0.25 and 0.05 inch, respectively, to 2 and 0.1 inch, respectively. Resistance values range from 1000 ohms to 100,000 ohms.

VARISTORS

Varistors are resistors which exhibit a significant change of resistance with applied voltage. There are two types of varistors. One type exhibits a large change of resistance when there is a change in the polarity of the applied voltage. Units of this type are commonly known as "solid-state" rectifiers and include units such as selenium and copper-oxide rectifiers and silicon and ger-

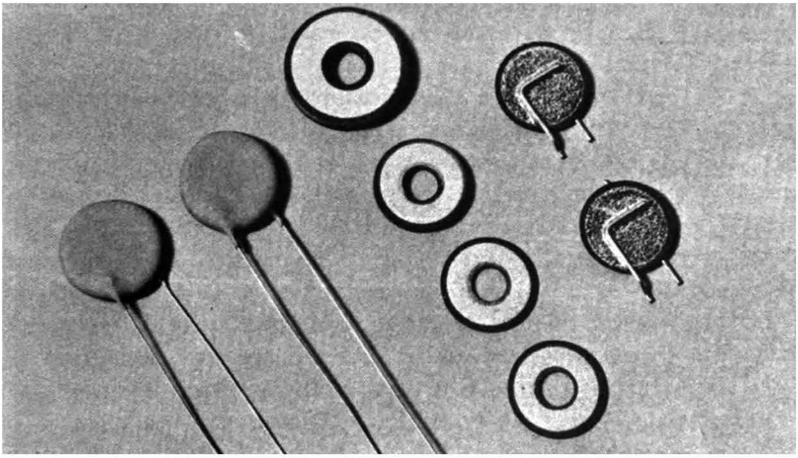


Fig. 2-16. Washer-and disc-type varistors. Courtesy Victory Engineering Corp.

manium diodes. Such devices are amply described in specialized text books, and their characteristics are so widely different from units commonly known as resistors that they will not be considered here.

The second type of varistor exhibits a resistance which changes with the applied voltage. In the case of ordinary resistors the relationship between voltage, current, and resistance follows Ohm's law. In the case of a varistor the relationship is:

$$R = \frac{E^n}{I} \,.$$

The value of n is a constant which depends upon the varistor manufacturing process. Units with n values in the range of from 3 to 5 are commonly available, and some manufacturers produce varistors with n values in the range of from 2 to 7. Because of the unusual characteristics of varistors, an increase in the applied voltage causes an increase in current which is significantly higher than in the case of a standard resistor. Variable resistance characteristics of this type make varistors uniquely suited for use as voltage and current regulators.

Essentially the same process is used in the manufacture of most commercial varistors. Silicon carbide particles are mixed with purified clay and water. The mix is pressed into washers, discs or rods; and these units are placed in a high-temperature furnace. After the firing process, metal electrodes are sprayed on, and connecting leads or terminals are attached. A coating of waterproofing compound is added.

Discs and washers are the varistor shapes commonly available (see Fig. 2-16). Diameters generally range from 0.5 to 1.0 inch, and thicknesses range from 0.025 to 0.2 inch. Four significant ratings are used to describe the functional characteristics of a varistor. Power ratings generally available range from 1 to 10 watts. Values of n are generally in the range of from 3 to 5. Recommended current ranges for a varistor may be as low as 0.05 to 10 ma or as high as from 20 to 500 ma. Because of the change of resistance with voltage, no resistance rating is listed. Instead, a voltage is listed for a specified current. Typical voltage/current ratings may be as low as 1 volt at 1 ma or as high as 50 volts at 1 ma.

Chapter 3

Characteristics of Capacitance

CAPACITANCE

Basic characteristics. When two metal plates are placed close together, as shown in Fig. 3-1 (A), the combination exhibits certain electrical effects which are known as *capacitance*. The outstanding characteristic of the combination is that it opposes any change in voltage across its plates.

This characteristic may be broken down into three effects which are closely related. First, a measurable time elapses before the two plates acquire the voltage difference of a voltage source connected across them. Second, the two plates maintain this acquired voltage difference for some time after the voltage source is disconnected. If there were no leakage conduction through such media as the air or other insulating material separating the plates, and if there were no other path of electrical conduction between the plates, the acquired voltage difference would be maintained indefinitely after the source of emf is disconnected. Third, if the two plates are connected together through a resistance, there is a measurable time delay before the voltage difference between them drops to zero.

These effects of capacitance are due to the fact that similar electric charges repel each other, and unlike electric charges attract each other. Before any voltage is connected across the plates of a capacitor, all of the atoms in both plates are electrically neutral. That is, they contain an equal number of protons and electrons. When the voltage source is connected across the plates, the negative terminal forces additional electrons onto the plate to which it is connected, and that plate becomes negatively charged. The positive voltage terminal attracts electrons away from the plate to which it is connected and leaves that plate positively charged.

The charges on the two plates are equal but of opposite polarity. Thereafter, since electrons repel each other, the electrons on the negative plate oppose the action of the voltage source in forcing more electrons toward that plate. And, since protons attract electrons, the protons on the positive plate oppose the action of the voltage source in attracting electrons from that plate.

Although opposition is offered to the charging effects of the voltage source, the voltage across the two plates eventually becomes equal to that of the source; and at that time no further charging effect takes place. However, the positive and negative charges on

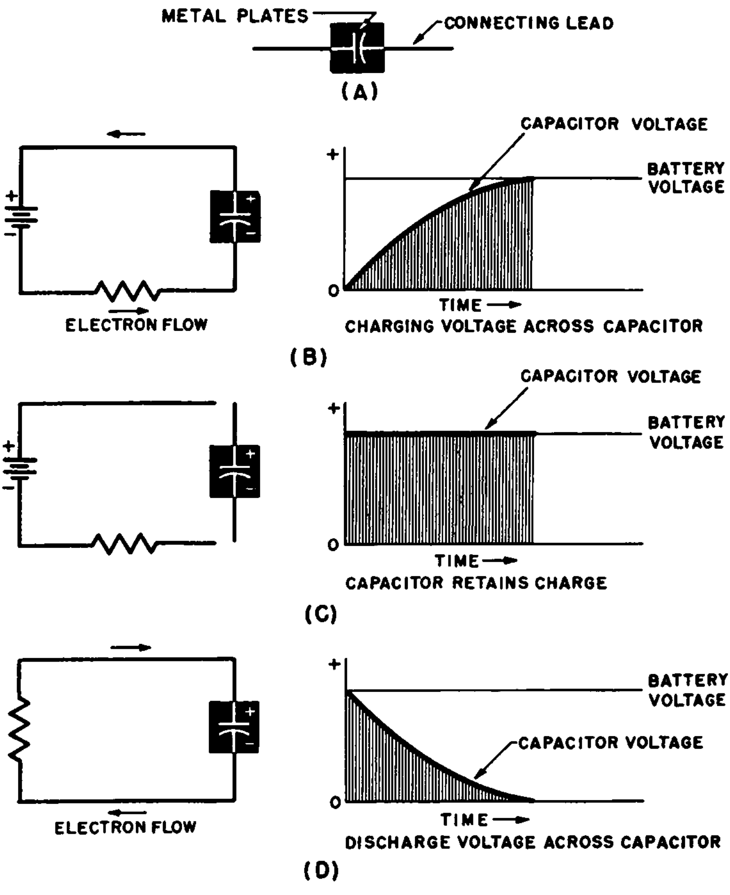


Fig. 3-1. Capacitor characteristics. (A) Basic form. (B) Delay in capacitor charge. (C) Capacitor retains charge. (D) Delay in capacitor discharge.

the two plates attract each other through the space between the plates, setting up a strong electrostatic field between the plates. Since work is expended in charging the capacitor, that work appears in the form of potential energy stored in the capacitor. This potential energy is released in the form of current flow when a circuit is connected across the plates.

Capacitive reactance. When the voltage source connected across the capacitor is a d-c source, current flows through the connecting wires only during the time the capacitor is charging. If a source of a-c voltage is connected across the capacitor, the charge on each plate continually increases, decreases, and reverses its polarity. The result is that an a-c current continuously flows through the connecting wires. The charging and discharging of the capacitor plates offers opposition to the flow of current in the circuit, and this opposition is known as *capacitive reactance.*

The charge that can be stored in a capacitor increases as the area of the plates is increased, as the distance between the plates is decreased, and as materials of better insulating quality are placed between the plates. Details concerning these relationships will be considered shortly. Capacitive reactance is infinitely large when a d-c voltage source is connected across the plates, and this reactance decreases as either or both the capacitance of the capacitor and the frequency of the applied voltage are increased.

In electrical and electronic applications there is frequent need for a unit in which any particular desired amount of capacitance is lumped into the form of a single unit which is convenient to use. Such a unit is called a *capacitor* or a *condenser.* Although *capacitance* is the preferred term applied to the electrical effects exhibited by a capacitor, the term *capacity* is in popular usage.

BASIC FACTORS DETERMINING CAPACITANCE

Basic construction. The basic form of a simple capacitor is shown in Fig. 3-2. It consists of two metal plates, with attached terminals or leads, and the two plates are separated by an insulating material or "*dielectric.*" The dielectric material commonly may be treated paper, mica, oil, ceramic, air, compressed gas, or a vacuum. The total capacitance of any particular construction is basically determined by the type of dielectric material used, the area of the plates, and the distance between the plates—although there are other important factors which will be considered later.

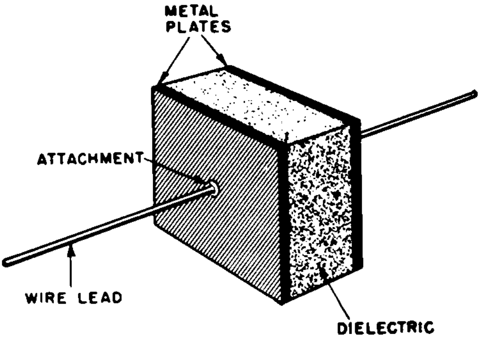


Fig. 3-2. Basic capacitor construction.

Dielectric constant. Capacitance increases as the area of the plates is increased, as the distance between the plates is decreased, and as insulating materials of higher dielectric constant are used. The term *dielectric constant* is defined on the basis of a comparison between two capacitors of identical plate area and plate separation, with the material in question separating the plates of one capacitor, air separating the plates of the other capacitor. Dielectric constant is thus defined as the ratio between the two total capacities. Since mica has a dielectric constant of about 7, a mica capacitor has 7 times the total capacitance of an identical capacitor with air as the dielectric material. The dielectric constants of several common materials are listed in Table 3-1.

TABLE 3-1

Material	Dielectric constant
Crown glass	2.5
Plate glass	7-9
Mica (U.S. clear)	6.6-8.6
Kraft paper, dry	3.5
Paraffin	2.2
Mineral oil	2.2
Fused quartz	4.5
Unglazed porcelain	6-7

The basic relationship between these various factors and the total capacitance is:

$$C = \frac{KA}{4\pi d},$$

where K is the dielectric constant, A is the area of one of two identical plates, and d is the distance between the plates.

The term "dielectric constant" is somewhat of a misnomer, since it is not a true constant. K varies with temperature and with the frequency and amplitude of the voltage applied across it.

CAPACITOR TYPES

In electrical and electronic equipment, it is very often necessary to use capacitors for coupling the signal between amplifier stages, bypassing the signal away from various vacuum-tube elements, decoupling stages, filtering ripple from power supplies, forming complex signal filter networks, and forming tuned circuits for r-f oscillators and amplifiers. In these various applications the equipment designer has a choice of three broad groups of capacitor types: *fixed, adjustable,* and *variable.* These will be introduced here, and details concerning the wide variety of commercial types will be discussed in Chap. 4.

Fixed capacitors. A fixed capacitor has its total capacitance determined at the time of manufacture, and there are no provisions for changing this predetermined value. The designer selects the total capacitance and other required characteristics from a wide selection of types and values. Figure 3-3, (A) through (D), shows the paper tubular, mica, electrolytic, and ceramic types. These are the most common types, but there are a number of other special types which will also be considered in Chap. 4.

Adjustable capacitors. There are applications, such as certain types of tuned circuits, in which the exact value of capacitance required in the circuit cannot be predicted or controlled with the required accuracy. In such applications, it is helpful to have available a capacitor which can be adjusted to the exact required value when the equipment is aligned after assembly. Adjustment by the equipment user is unnecessary, although a later adjustment may have to be made by a service technician during equipment servicing. Since the capacitor does not require frequent resetting, no special pains are taken to make this adjustment particularly convenient, and the range of adjustment is generally quite small.

Four common types of adjustable capacitors are shown in Fig. 3-4. Part (A) shows a type with mica dielectric, the total capacitance of which can be changed by compressing or expanding the distance between the plates. Fig. 3-4 (B) shows a type with

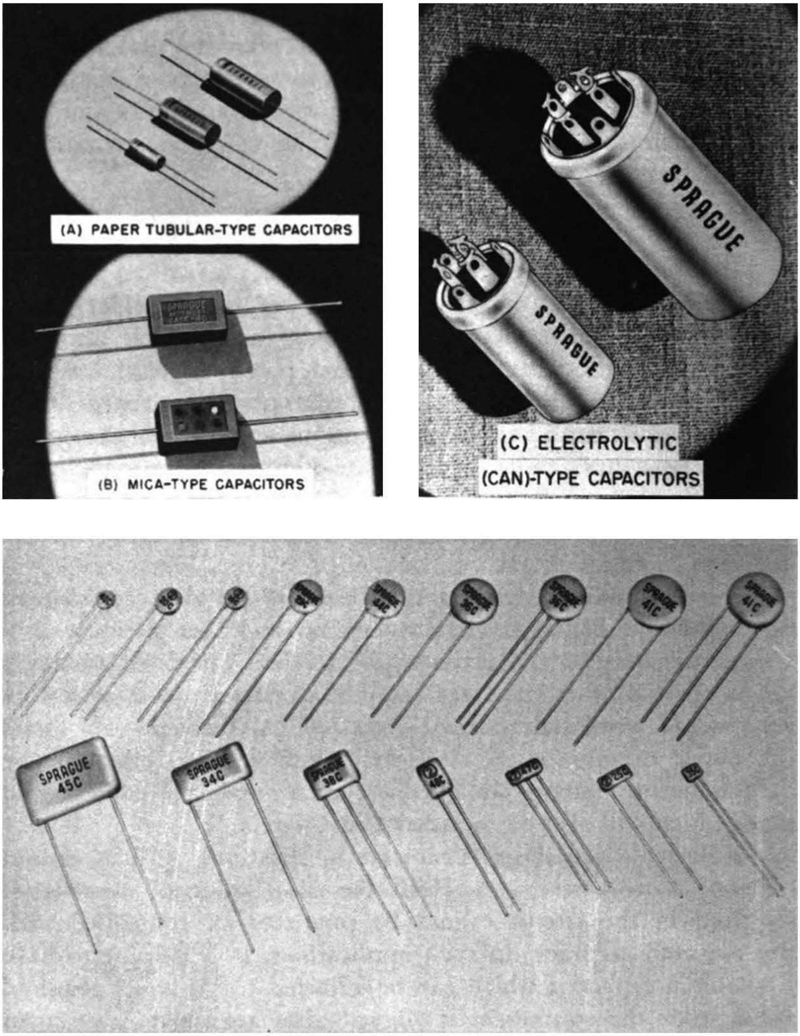


Fig. 3-3. Common types of fixed capacitors. (A) Paper tubulars. (B) Mica. (C) Electrolytic. (D) Ceramic. ***Courtesy Sprague Electric Co.***

ceramic dielectric, the total capacitance of which can be changed by rotating a movable semicircular plate with respect to a fixed plate of similar shape. Rotating the plate affects the total opposing area between the plates and thus adjusts the total capacitance. Figure 3-4 (C) shows a type with air dielectric, which is adjusted

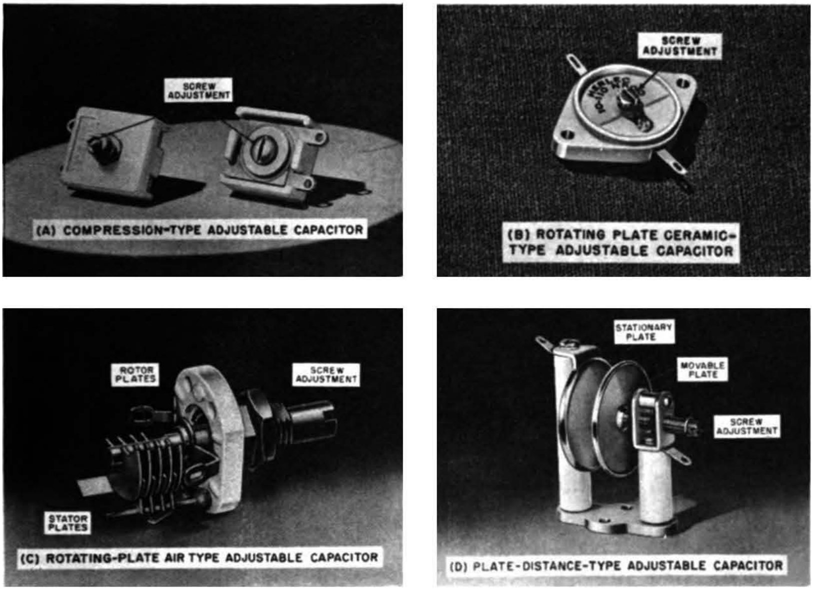


Fig. 3-4. Adjustable capacitors. (A) Compression type. *Courtesy Electro Motive Mfg. Co., Inc.* (B) Rotating-plate ceramic type. *Courtesy Sprague Electric Co.* (C) Rotating-plate air type. (D) Adjustable-plate distance type. *Courtesy Hammarlund Mfg. Co., Inc.*

by rotating the metal plates. Part (D) shows a type with air dielectric which is adjusted by changing the distance between the plates. Details of these and other adjustable capacitors will be considered in the next chapter.

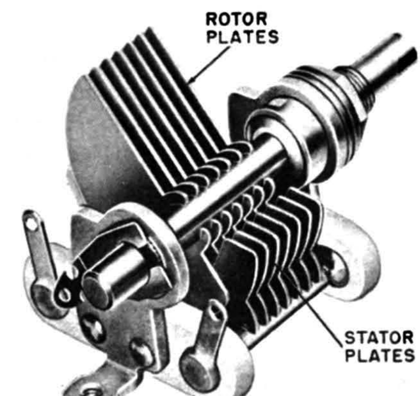


Fig. 3-5. Variable capacitor. *Courtesy Hammarlund Mfg. Co., Inc.*

Variable capacitors. In a number of applications the equipment operator must tune his equipment by changing capacitance over a fairly wide range. Figure 3-5 shows one type of variable capacitor which is commonly used for this purpose in most home radio receivers. Total capacitance is changed by varying a set of movable plates which intermesh with—but do not contact—a set of fixed plates. Because such rotation changes the total opposing area between the fixed and movable plates, the total capacitance is changed. Care is taken in the design and manufacture of these capacitors to secure ease and smoothness of rotation along with an accurately predictable variation throughout the full range of rotation. Details of different types of variable capacitors will be considered in Chap. 4.

CAPACITOR CHARGE AND ENERGY

Charge. The capacitance of a capacitor is basically determined, as mentioned previously, by the area of the plates, the distance between the plates, and the dielectric material used. The number of excess electrons that can be held upon the negatively charged plate of any given capacitor depends upon the capacitance and the applied voltage according to the relationship:

$$Q = CE \ ,$$

where Q equals the charge expressed in coulombs, the quantity C equals the capacitance expressed in farads, and E equals the applied voltage.

One farad of capacitance is that amount of capacitance which will accumulate one coulomb* of charge when the applied voltage is equal to one volt. Capacitors normally found in electronic equipment generally range in capacitance from 1 micromicrofarad (1 $\mu\mu$f) to 1000 microfarads (1000 μf). Thus few capacitors found in commercial equipment have a capacitance of more than a few thousandths of a farad.

Energy. Since the voltage source must expend energy while it is forcing electrons to accumulate on the plates of a capacitor, work is done according to the relationship:

*A *coulomb* is defined as the unit of electrical charge which results from the accumulation of 6,300,000,000,000,000,000 (or 6.3×10^{18}) excess electrons.

$$\text{Work (joules)} = \frac{\text{Capacitance (farads)} \times \text{voltage}^2}{2} .$$

Since power is defined as the time rate of doing work, the average power expended in charging the capacitor is expressed by the relationship:

$$\text{Power (watts)} = \frac{CV^2}{2T \text{ (sec)}} .$$

When an a-c voltage is applied across the capacitor, the power expended is indicated by:

$$P = CV_p^2F ,$$

where the power P is expressed in watts, the frequency F in cps, and V_p indicates the peak applied voltage.

CONSIDERATIONS AFFECTING CAPACITOR SELECTION

In the preceding discussion it was mentioned that other factors besides plate area, plate separation, and dielectric material affect total capacitance. These factors include frequency, temperature, and age. Other factors affecting the application of any particular capacitor construction are the "strength," d-c leakage, power factor, polarization, and absorption characteristics of the dielectric material. Because of these various characteristics, capacitance cannot be regarded as a constant determined only by construction but as a quantity which is affected to a significant extent by the particular application.

As is the case with resistors, an equipment designer cannot select a capacitor simply on the basis of the total capacitance he requires. Capacitors, like resistors, cannot be manufactured to the exact total capacitance values required and are generally supplied with an indication of the tolerance to which they have been made. In addition, the factors mentioned in the previous paragraph also affect capacitor application. Thus the equipment designer must determine what capacitance effects will take place in each specific application. He must decide which of these effects are undesirable and must be compensated for and which effects are unimportant to the specific application. After such considerations are made, he has a basis for selecting the lowest-cost capacitor having acceptable characteristics. The paragraphs which follow review the major considerations affecting capacitor selection, and Chap. 4 reviews the types and features of commercially available capacitors.

Dielectric strength. The ability of the capacitor dielectric to resist breakdown when voltage is applied across it is known as *dielectric strength.* This quality is usually expressed in terms of kilovolts per centimeter, or in volts per mil, of dielectric thickness.

Dielectric strength is not a quantity that is simply determined from the type of material and its thickness. There are temperature, resistance, and frequency effects which also must be considered. Dielectric strength usually decreases with temperature rise, since the resistance of most capacitor dielectric materials decreases with temperature rise. Dielectric strength is not uniform throughout the structure of a typical piece of dielectric material. Localized variations in the composition and structure of the material result in regions of low resistance. Current leakage is then concentrated in these sections, which results in localized heating and a greater tendency to break down. Because of these effects, testing the ability of a capacitor to resist breakdown requires both a brief application of high voltage and a long period of low-voltage application. In addition, a measurement is made of the steady current that flows when a constant direct voltage is applied across the capacitor, and this is known as *direct leakage current.*

These effects are not the only ones involved in checking capacitors. Dielectric strength also generally decreases with increasing frequency of the applied voltage and with age. Capacitor selection requires a careful consideration of those of the mentioned factors which are appropriate to the specific application.

The higher the strength of the dielectric used, the smaller is the distance needed between the plates to resist breakdown at any particular operating voltage. Thus, when materials with high dielectric strengths are used, greater capacitance can be obtained in a given capacitor size. The effects of this will be seen in the next chapter in comparing the physical sizes of different types of capacitors of the same total capacitance.

Dielectric absorption. When a capacitor is connected across a d-c source, there is a surge of current as a charge builds up. Following that is a small, steadier current flow which slowly decreases. This additional current flow does not add to the charge on the plates, but it is absorbed by the dielectric. This *dielectric absorption* produces a strain in the dielectric material known as *dielectric polarization,* and represents additional energy stored in the capacitor.

If the capacitor leads are touched together, the electrons from the negative plate quickly flow through the leads to the positive plate, thus apparently reducing the charge to zero. In the case of a large capacitor, such a large current flow may take place that a spark may be seen at the point where the leads touch, and a loud snapping sound may be heard. If the leads are separated and touched together again a few second later, an additional but weaker current flow may be heard and seen. This second discharge represents the energy that was absorbed by the dielectric and which has gradually been released in the form of additional charge on the plates. In the case of a capacitor with a large amount of solid dielectric, the dielectric absorption may be so large that several additional secondary discharges may be obtained.

Capacitors which exhibit relatively large amounts of dielectric absorption tend, more than other capacitors, to accumulate less and less charge as the frequency of the applied voltage is increased. At radio frequencies, and at those slightly below, the rapid reversals of the dielectric polarization cause heating of the dielectric and represent considerable power loss in the capacitor.

CAPACITOR LOSSES

Power losses in a capacitor are due to dielectric losses and leakage. The effect of these losses can be evaluated by consideration of the phase difference and power factor.

Dielectric losses and leakage are defined with respect to what is termed the *geometric capacitance.* A capacitor will accumulate greater charge when applied voltage is at a low frequency than when it is at a higher frequency. Thus, the capacitance of a practical capacitor decreases with increasing frequency, and its capacitance at infinite frequency is called its *geometric capacitance.* Though not completely correct, the term *useful capacitance* presents a more descriptive concept and may be used instead. If the capacitor had a perfect dielectric material, its capacitance would remain the same at all frequencies; its useful capacitance would then be equal to the capacitance at the lowest frequency.

Figure 3-6 (A) shows the equivalent circuit of a capacitor with both dielectric absorption and d-c leakage. In the diagram C_1 represents the useful capacitance, with the d-c leakage resistance

R_1 connected in parallel, and with the dielectric absorption indicated by the combination of R_2 and C_2 also connected in parallel with the useful capacitance. The equivalent circuit shown in Fig. 3-6 (A) is commonly resolved to the form of a capacitor with

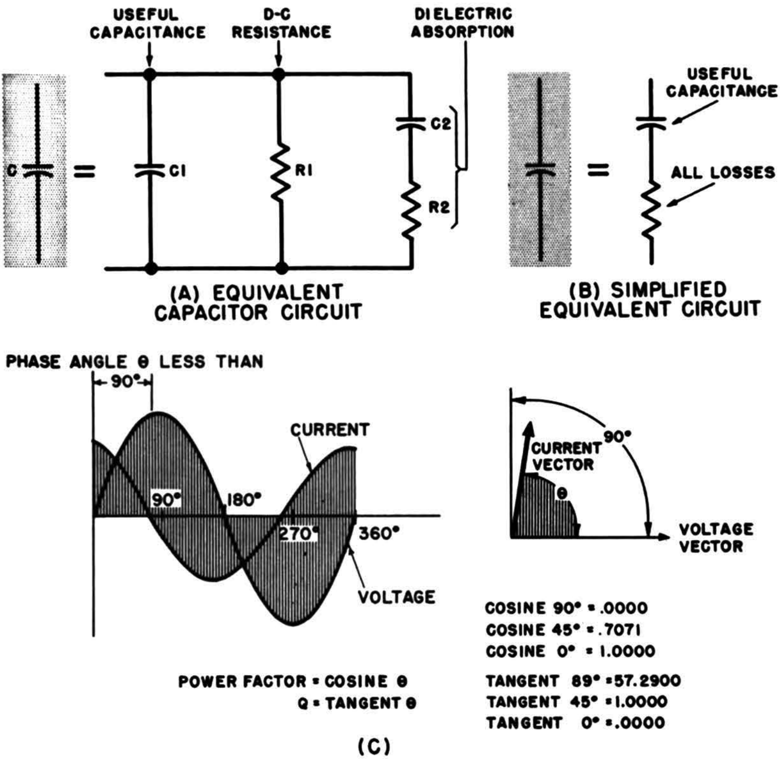


Fig. 3-6. Basic capacitor characteristics. (A) Equivalent circuit. (B) Simplified equivalent circuit. (C) Power factor and Q.

a series fixed resistor, which represents all losses, as shown in Fig. 3-6 (B).

The characteristics of phase angle are covered in texts on basic electricity and electronics and will be reviewed here only very briefly to define capacitor power factor. When an a-c voltage is applied across a capacitor, the current through the capacitor leads the voltage by an angle θ shown in Fig. 3-6 (C), which is called the *phase angle* and which may approach but never exceed 90°.

The *power factor* is equal to the cosine of the phase angle as shown by the equation:

$$\text{Power factor} = \cos\theta \ .$$

The voltage across the capacitor E and the a-c flow through the capacitor I together with the power factor can be used to define the power loss in the insulating material:

$$\text{Power loss} = EI\cos\theta \ .$$

The power factor is a term which takes into account all of the power losses in a capacitor. Most of the phase difference with respect to the ideal value of 90° is due to dielectric absorption. D-c leakage through the dielectric, represented by R_1 in Fig. 3-6(A), does add to the phase angle but, for a good capacitor, is not significant at high frequencies. If the total power loss in watts is measured, the power factor can be expressed in terms of a percentage by the relationship:

$$\text{Cos}\,\theta\ (\text{percent}) = \frac{W \times 10^6}{2\pi fCE^2} ,$$

where W equals the power loss in watts, f equals the frequency of the applied voltage in cps, E equals the rms voltage applied, and C equals the capacitance expressed in μf.

There is a factor called Q which can be used as a quantitative figure of merit for comparisons of various capacitors. Q is defined with respect to the current and voltage vector diagram shown in Fig. 3-6 (C). Q is equal to the tangent of the angle between the voltage and current vectors at any particular specified frequency. Q can be expressed by the formula:

$$Q = \frac{1}{R \times 2\pi FC} ,$$

where R equals the equivalent series resistance (symbolizing losses) in ohms, F equals the frequency in cps, and C equals the capacitance expressed in farads.

The figure of capacitor merit, Q, is referenced to the equivalent series resistance of the capacitor.

Chapter 4

Commercial Capacitors

FIXED CAPACITORS

PAPER CAPACITORS

Basic construction. The simplest and most widely used form of paper capacitor consists of two strips of metal foil rolled up with strips of paper which have been impregnated with an insulating material. Impregnating materials commonly include various types of oils, waxes, and plastics. The type used determines the voltage, temperature, and insulation resistance characteristics of the capacitor. When the capacitor is to be used at high working voltages, several layers of insulating paper are used. Details of the most common construction are shown in Fig. 4-1 (A).

After the foil and paper strips are rolled up, the protruding ends of the foil are crimped over so that the individual layers of each strip are in electrical contact with each other. A lead is attached to each end, and an outer cover of insulating material is added. The cover is marked with the capacitance and working voltage as shown in Fig. 4-1 (B), and a black ring is usually printed around one end to mark the terminal which is connected to the outermost layer of foil. In low-cost capacitors the outer covering consists of heavy paper saturated with wax. In more expensive types the outer layer consists of a hard plastic material, which enables the capacitor to be used at higher temperatures without danger of melting. In paper capacitors the total capacitance is predetermined by the thickness and dielectric constant of the paper and the total area of the foil plates.

Types. The basic capacitor construction just described is used in low-voltage applications throughout the audio-frequency range and for the lower radio frequencies. It is known as the *noninductive* construction. Since the various turns in each of the plates are all connected, no part of either plate extends for any distance beyond the terminal, and inductance effects are negligible.

There is another type of construction which can be manufactured at lower cost. In this type, shown in Fig. 4-1 (C), the foil

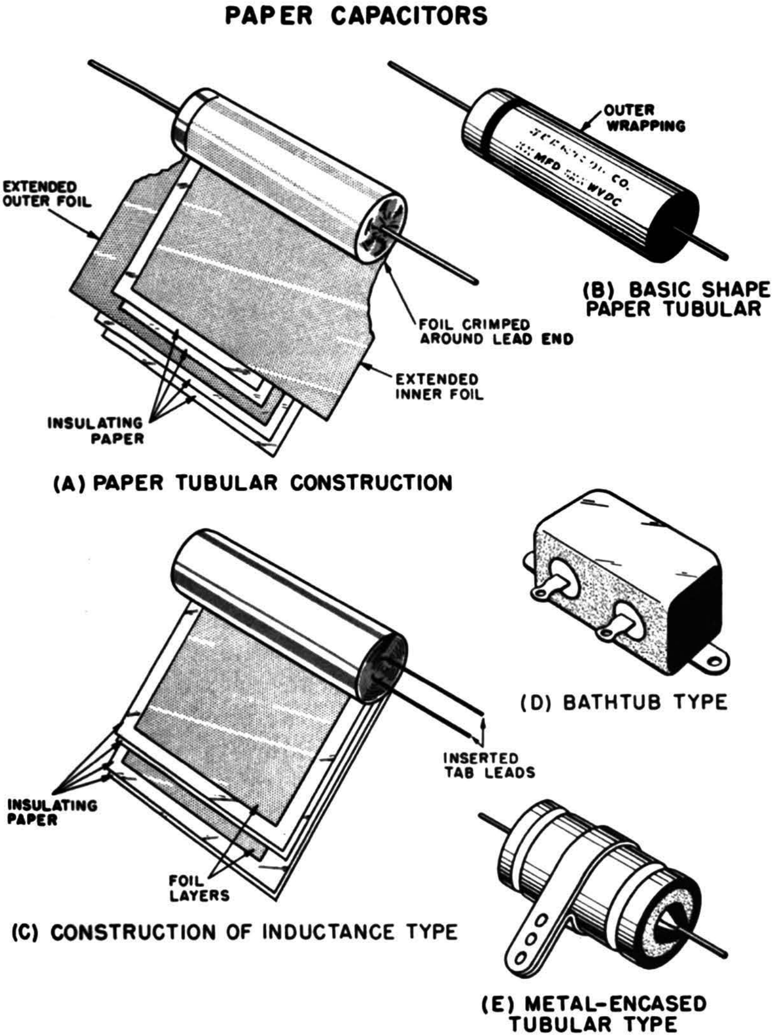
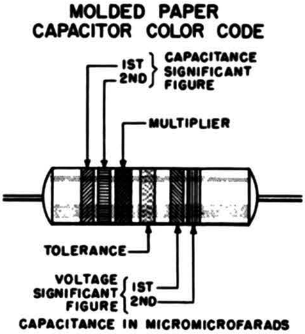


Fig. 4-1. Paper capacitors. (A) Basic construction. (B) Markings. (C) Construction of inductive type. (D) Bathtub type. (E) Metal-encased tubular.

is narrower than the insulating paper layer, and the terminal is connected to only one small part of the foil. Thus a considerable length of each foil strip extends away from the terminal, and inductance and resistance effects take place. Since the two foils are coiled about each other, the inductance effect is increased. This capacitor construction is known as the *inductive type*. Since inductance effects cause increasingly high inefficiency with rising



COLOR	SIGNIFICANT FIGURE	MULTIPLYING VALUE	TOLERANCE ±%
BLACK	0	1	20
BROWN	1	10	-
RED	2	100	-
ORANGE	3	1,000	30
YELLOW	4	10,000	40
GREEN	5	100,000	5
BLUE	6	1,000,000	-
VIOLET	7	-	-
GREY	8	-	
WHITE	9	-	10
GOLD	-	0.1	-

(F)

Fig. 4-1 (F). Color code for small paper tubulars.

frequency, this type of construction is restricted to applications at sub-audio- and low audio-frequencies.

In another paper capacitor, known as the *metalized* type, aluminum is deposited upon the paper in layers which are a small fraction of a millionth of an inch in thickness. Because of the extreme thinness of the plate, the capacitor has *self-healing* characteristics when voltage breakdown takes place through the dielectric. A spark through the paper usually destroys the thin plates for a small distance around the sparkover region, and no further breakdown can take place through the insulation at that particular point. Due to this self-healing characteristic, a single layer of paper can be used between the plates for voltages up to 200. This saving in insulation thickness and foil thickness results in an overall capacitor size which is well below one-half that of conventional foil capacitors. At higher operating voltages several layers of paper must be used between the plates, and some of the size advantage is lost. In some metalized constructions, plastic film is used instead of paper.

When paper capacitors are required to have a capacitance of over 1 μf, their physical size generally becomes too large for convenient mounting. Under such conditions, the capacitor is placed in a metal case which is filled with insulating material and then hermetically sealed. Units of this type are shown in Fig. 4-1 (D) and are known as *potted* or *bathtub* capacitors. Special brackets, or screws through holes in tabs on the base, or clamps provide secure mounting. Metal-encased construction, see Fig. 4-1 (E), is used for units of smaller capacitance when a heavy-duty unit is required for use under conditions of high temperature, high surge voltage, excessive moisture, and severe mechanical vibration.

When paper tubular capacitors are too small for convenient letter symbols to be used to indicate the various ratings, a color code, as shown in Fig. 4-1 (F), is used.

Commercial types. A survey of the various types of commercial paper capacitors is shown in Table 4-1 and the accompanying illustrations. Included in the table are typical sizes and operating characteristics. Note that voltage ratings are generally in terms of d-c working voltage. While d-c working voltage ratings are based on dielectric strength, a-c ratings require consideration of frequency and power factor, since these determine the amount of heating which takes place within the body of the capacitor. In most electronic-equipment applications, paper capacitors are used in filter circuits, bypass circuits, and as signal coupling devices. In these situations, the a-c component is only a very small part of the applied d-c voltage, and there is generally no heating problem caused by the a-c component. If the capacitor is to be used in circuits where there is a high a-c component, such as in power-supply resonant-filter networks, tests should be performed to ensure that the specified maximum operating temperature is not exceeded. A very rough rule of thumb is that the a-c voltage should not exceed 15% of the d-c rating for frequencies between 100 cps and 60 cps. At frequencies in the region of 10,000 cps the a-c voltage should not exceed 1% of the d-c rating.

MICA CAPACITORS

Basic construction. The basic construction of a mica capacitor is shown in Fig. 4-2 (A). It consists of a number of flat strips of metal foil separated by similarly shaped strips of mica. The foil strips serve as the capacitor plates, and the mica acts as the dielectric. Alternate plates are connected together. An electrode is attached to each set of plates, and a terminal or lead wire is

TABLE 4-1
Paper Capacitors

Microminiature

Description:	Tubular microminiature, metalized-paper construction
Working voltages dc:	200, 400, 600
Capacitance range:	200 volts—0.005 to 0.10 μf; 600 volt—0.0005 to 0.0068 μf
Body size range:	200 volt, min. cap.—7/16 × 3/16 in.; 600 volt, max. cap.—9/16 × 1/4 in.

Subminiature

Description:	Tubular subminiature, metalized-paper construction, metal encased, operates up to 125° C
Working voltages dc:	200, 400, 600
Capacitance range:	200 volt—0.10 to 6.0 μf; 600 volt—0.01 to 1.0 μf
Body size range:	200 volt, min. cap.—1 3/16 × 5/16 in.; 600 volt, max. cap.—1 13/16 × 1 in.

Standard Tubular

Description:	Standard tubular, cardboard wrapping, wax-coated, treated-paper dielectric
Working voltages dc:	200, 400, 600, 1000, 1600
Capacitance range:	200 volt—0.0001 to 1.0 μf; 1600 volt—0.0001 to 0.05 μf
Body size range:	200 volt, min. cap.—1 1/8 × 3/8 in.; 1600 volts, max. cap.—2 1/8 × 15/16 in.

Molded Tubular

Description:	Standard-type tubular construction molded in Bakelite jacket. Larger sizes oil impregnated.
Working voltages dc:	400, 600, 1000
Capacitance range:	400 volt—0.001 to 1.0 μf; 1000 volt—0.001 to 0.068 μf
Body size:	400 volt, min. cap.—1 × 5/16 in.; 1000 volt, max. cap.—1 7/8 × 5/8 in.

Bathtub Case

Description:	Oil-impregnated paper capacitor encased in rectangular metal case with rounded corners. One, two, and three capacitors in common case available in most voltage ranges.
Working voltages dc:	100, 200, 400, 600, 1000
Capacitance range:	100 volt—1.0 to 4.0 μf; 1000 volt—0.05 to 1.0 μf
Body size range:	100 volt, min. cap.—1 13/16 × 1 × 7/8 in.; 1000 volt, max. cap.—2 × 2 × 1 1/8 in.

Small Rectangular Case

Description:	Oil-impregnated paper capacitor encased in rectangular metal case with square corners. One, two, and three capacitors in common case available in most voltage ranges.

(Cont'd.)

TABLE 4-1 (Cont'd.)

Working voltages dc:	400, 600, 1000, 1500
Capacitance range:	400 volt—0.1 to 1.0 μf; 1500 volt—0.01-0.01 to 0.05-0.05 μf
Body size range:	400 volt, min. cap.—1 5/16 × 5/8 × 1 1/16 in.; 1500 volt, max. cap.—1 5/16 × 5/8 × 2 in.
	Large Rectangular Case
Description:	Oil-impregnated paper capacitor encased in rectangular metal case with square corners. Single capacitors only.
Working voltages dc:	600, 1000; 1500; 2000; 2500; 3000; 4000; 5000; 6000; 7500; 10,000; 12,500
Capacitance range:	600 volt—0.25 μf; 2500 volt—0.1 μf to 2.0 μf
Body size range:	600 volt, min. cap.—1 13/16 × 1/16 ×1 5/8 in.; 12,500 volt, max. cap.—13 1/2 × 5 1/8 × 13 3/4 in.

connected to each electrode. Then the entire construction is encased in a container of plastic insulating material. In manufacture the total capacitance can be increased by enlarging the area of the individual plates, by increasing the number of plates, by using thinner mica strips to decrease the distance between the plates, or by a combination of all three methods.

The accuracy with which the total capacitance can be predetermined in the manufacturing process depends upon the precision with which the plates can be cut to the desired area and the accuracy with which the mica can be split to the required thickness. In actual practice, the mica and foil plates can be cut to size with an accuracy of 0.001 inch, and it is not unusual for the mica plates to be split with accuracy into layers of 0.0005-inch thickness.

An alternate construction is that of the "silvered" mica capacitor. In this construction very thin layers of silver are deposited directly upon one side of the mica, and the plates are stacked together so that alternate layers of silver are separated by alternate layers of mica. The result is the equivalent of the foil construction. This method enables closer manufacturing tolerances to be met, since precision masking techniques permit the area of the deposited plate to be determined with greater accuracy and greater uniformity than in the cut-foil construction. In addition, the thickness of the completed capacitor is less, due to the thinness of the deposited plate.

MICA CAPACITORS

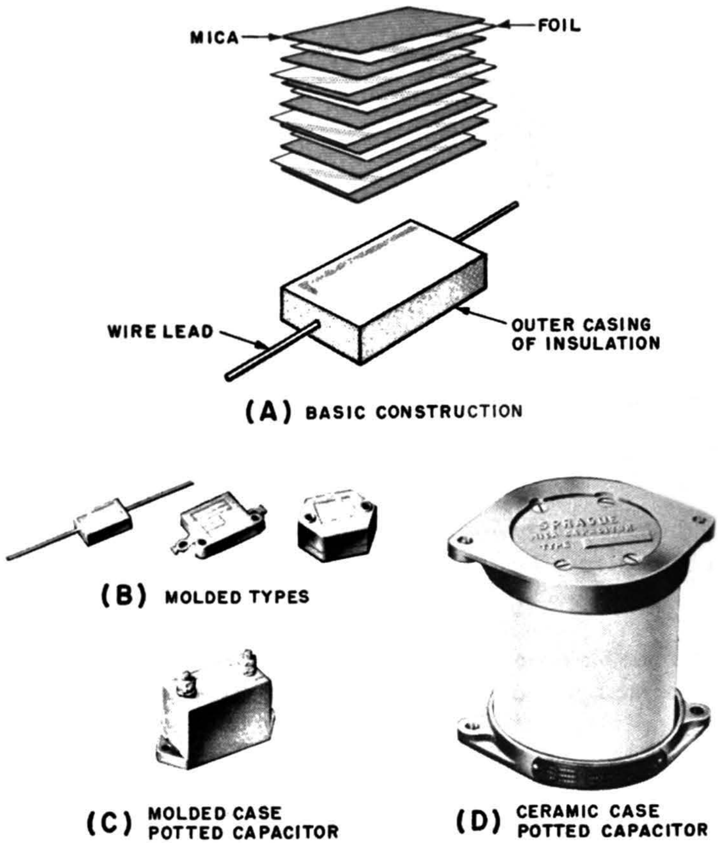


Fig. 4-2. Mica capacitors. (A) Basic construction. (B) Molded types. (C) Molded case potted capacitor. (D) Ceramic case potted capacitor. *Courtesy Sprague Electric Co.*

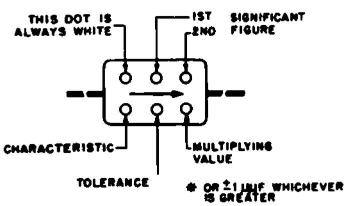
Characteristics. The construction of mica capacitors results in unusually good permanency of physical dimensions. In addition, the electrical and physical characteristics have great stability throughout the entire temperature range normally found in electronic equipment. Voltages as high as 5000 fail to break down a layer of quality mica only 0.001 inch thick. Mica exhibits high insulation resistance and high *Q*, making it suitable for capacitor applications involving high a-c currents and high frequencies.

There are three basic types of mica capacitors which are commercially available. *Molded capacitors,* Fig. 4-2 (B), are those in which the stack of plates and dielectric are molded directly into the case material. When the stack is surrounded by insulating material contained within a molded case, the construction is known as a *molded-case potted capacitor*. See Fig. 4-2 (C). The third construction is almost identical to the second except that the outer case is made of ceramic material. This type is known as a *ceramic-case potted capacitor*, Fig. 4-2 (D). When the case design of these various types does not permit stamping the various capacitor ratings on the outside, a color code, as shown in Fig. 4-3 (A), is used. Interest

E I A COLOR CODE
(FORMERLY RETMA)

CAPACITANCE IN MICROMICROFARADS

COLOR	CAPACITANCE: SIGNIFICANT FIGURE	CAPACITANCE: MULTIPLIER	* TOLERANCE ± %	CHARACTERISTIC
BLACK	0	1	20 (M)	A
BROWN	1	10	1 (F)	B
RED	2	100	2 (G)	C
ORANGE	3	1,000	3 (H)	D
YELLOW	4	10,000	-	E
GREEN	5	-	5 (J)	F
BLUE	6	-	-	-
VIOLET	7	-	-	-
GRAY	8	-	-	-
WHITE	9	-	-	-
GOLD	-	0.1	5 (J)	-
SILVER	-	.01	10 (K)	-



* OR ±1 μμF WHICHEVER IS GREATER

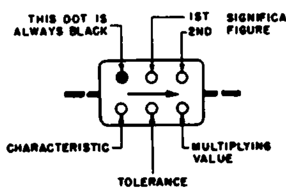
LETTER DESIGNATION FOR CHARACTERISTIC

CHARACTERISTIC	TEMP. COEFF. PARTS PER MILLION PER °C	CAPACITANCE DRIFT (MAXIMUM)
A	± 1000	(5% OF NOM. CAP. + 1) μμF
B	± 500	(3% OF NOM. CAP. + 1) μμF
C	± 200	(0.5% OF NOM. CAP. + 0.5) μμF
D	± 100	(0.3% OF NOM. CAP. + 0.1) μμF
E	+ 100 TO - 20	(0.1% OF NOM CAP. + 0.1) μμF

MIL-C-5A COLOR CODE

CAPACITANCE IN MICROMICROFARADS

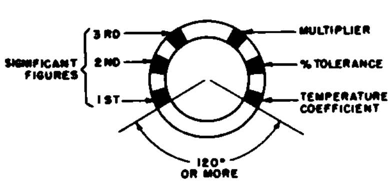
COLOR	CAPACITANCE: SIGNIFICANT FIGURE	CAPACITANCE: MULTIPLIER	* TOLERANCE ± %	CHARACTERISTIC
BLACK	0	1	20 (M)	-
BROWN	1	10	-	B
RED	2	100	2 (G)	C
ORANGE	3	1,000	-	D
YELLOW	4	10,000	-	E
GREEN	5	-	-	F
BLUE	6	-	-	-
VIOLET	7	-	-	-
GRAY	8	-	-	-
WHITE	9	-	-	-
GOLD	-	0.1	5 (J)	-
SILVER	-	-	10 (K)	-

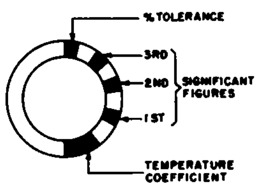


LETTER DESIGNATION FOR CHARACTERISTIC

CHARACTERISTIC	TEMP. COEFF. PARTS PER MILLION PER °C	CAPACITANCE DRIFT (MAXIMUM)
B	NOT SPECIFIED	NOT SPECIFIED
C	-200 TO +200	± 0.5 PERCENT
D	-100 TO +100	± 0.3 PERCENT
E	-20 TO +100	- 0.1 PERCENT + 0.1 μμF
F	0 TO +70	± 0.05 PERCENT + .1 μμF

(A)





(B)

Fig. 4-3. Mica capacitor color codes. (A) Rectangular mica. Courtesy *Electro Motive Mfg. Co., Inc.* (B) Button mica.

in miniaturization has led to the development of a small mica capacitor shaped in the form of a button. Two methods of color coding this type are shown in Fig. 4-3 (B). Characteristics of typical commercial mica capacitors are shown in Table 4-2.

TABLE 4-2
Mica Capacitors

	Small Molded
Description:	Small rectangular molded case, foil or silvered mica construction, wire leads, mounted by wire leads. Wide range of capacitance values in identical body size
Working voltages dc:	300, 500, 1500, 2000, 3000
Capacitance range:	300 volt—0.007 to 0.01 μf; 500 volt—0.00001 to 0.006 μf
Body size range:	300 volt—53/64 × 53/64 × 11/32 in.; largest 500 volt—53/64 × 53/64 × 11/32 in.; 3000 volt—1 × 5/8 × 11/32 in.
	Ear Mounting
Description:	Molded phenolic case, rectangular shape with phenolic mounting ears, solder terminals. Wide range of capacitance values in identical body size
Working voltages dc:	600, 1200, 2500
Capacitance range:	600 volt—0.00005 to 0.03 μf; 2500 volt—0.00005 to 0.005 μf
Body size range:	600 volt—1 5/8 × 1 1/3 × 23/64 in.; largest 2500 volt—1 5/8 × 1 1/8 × 29/64 in.
	Semihexagonal
Description:	Molded phenolic case, semihexagonal shape; ends have tubular metal inserts, threaded or unthreaded, which serve as terminals. Wide range of capacitance values in identical body size
Working voltages dc:	600, 1200, 2500
Capacitance range:	600 volt—0.033 to 0.047 μf; 2500 volt—0.000022 to 0.015 μf
Body size range:	600 volt, min. cap.—1 25/32 × 1 11/32 × 15/32 in.; 2500 volt, max. cap.—1 25/32 × 1 11/32 × 3/4 in.
	Potted Molded Case
Description:	Mica stack potted in low-loss phenolic case. Case is rectangular with phenolic mounting ears and threaded terminals with two nuts. Only two body sizes
Working voltages peak a-c:	250, 500, 1000, 1500, 2000, 3000, 5000
Capacitance range:	250 volt—0.047 to 0.1 μf; 5000 volt—0.000047 to 0.0024 μf
R-f current range:	250 volt, max. cap.—11 amp at 3 mc; 5000 volt, max. cap.—8.2 amp at 3 mc
Body size range:	Small, 2 1/16 × 1 17/32 × 61/64 in.; large, 2 5/16 × 1 27/32 × 1 17/64 in.

(Cont'd.)

TABLE 4-2 (Cont'd.)

	Potted Ceramic Case
Description:	Mica stack potted in glazed ceramic cylinder with cast aluminum end bell terminals. Designed for transmitter applications. Wide range of capacitance values in four standard body sizes
Working voltages peak a-c:	1000; 1500; 2000; 3000; 4000; 5000; 6000; 8000; 10,000; 12,000; 15,000; 20,000; 25,000; 30,000
Capacitance range:	1000-volt—0.075 to 0.1 μf; 30,000 volt—0.0001 to 0.001 μf
R-f current range:	1000-volt, max. cap.—18 amp at 3 mc; 30,000 volt, max. cap.—18 amp at 3 mc
Body size range:	Small, 2½ in. long × 2 13/16 in. diam.; large, 5¾ in. long by 5 in. diam.

ELECTROLYTIC CAPACITORS

When capacitances of more than 1 μf are required, the size and cost of a suitable paper capacitor becomes prohibitive for all but very special applications. Electrolytic capacitors are used in such cases, since they provide capacitances to several thousand microfarads at reasonable size and cost. Electrolytic capacitors are generally suitable only for circuits in which a d-c voltage is applied across them. Special types are available for use in applications in which d-c voltage of changing polarity may be applied. Other special types may be used in a-c applications, such as motor starting, in which a-c voltage is applied intermittently. Although electrolytic capacitors are available in a large variety of sizes, shapes, and special ratings, there are only two basic types of construction used —the obsolete *wet* and the present-day *dry* types. The principles of operation of both these types are practically identical.

Basic construction. The basic construction of a wet electrolytic capacitor is shown in Fig. 4-4 (A), and the construction of the dry type is shown in Fig. 4-4 (B). The *anode* (positive plate) is a rolled strip of aluminum foil or cotton gauze sprayed with aluminum. The dielectric material is a layer of aluminum oxide formed upon the surface of the anode. The thickness of the oxide layer is only a few hundred thousandths of an inch, and the dielectric constant of this oxide is approximately 10. In the wet construction the rolled anode with its oxide layer is immersed in a liquid electrolyte. In the dry construction the anode is rolled together with a similar but uncoated negative plate, and the electrolyte is either a very thick liquid or a paste. In the most common present-day constructions, a gauze or paper layer is saturated with liquid electrolyte, and this semisolid electrolyte is placed between the two metal plates. A vent is used in the container of the wet type to allow gas bubbles to escape, and most dry types have a closed vent which opens if excessive gas pressure develops in the sealed container. The electrolyte is in very close contact with both the oxide layer and the container, and the electrolyte serves the function of the negative plate (*cathode*) of the capacitor. The aluminum

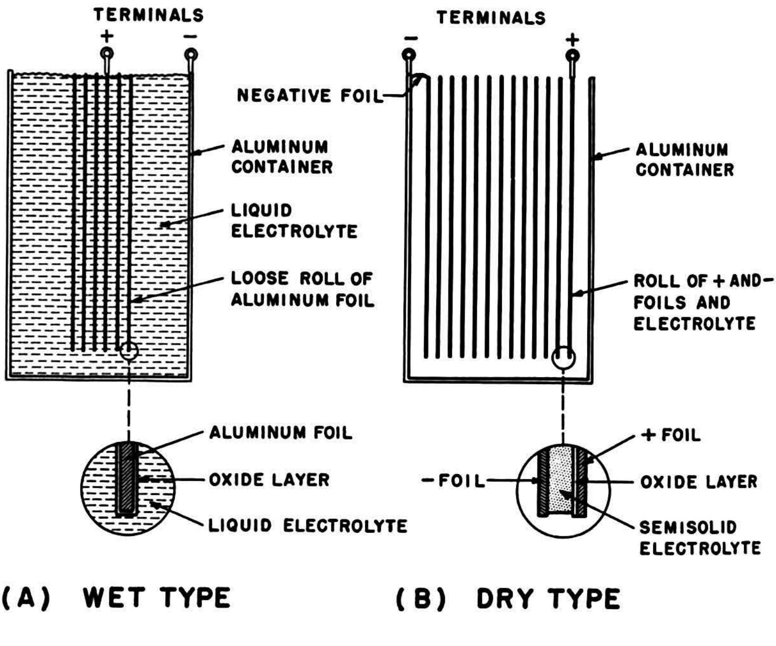


Fig. 4-4. Electrolytic capacitors, simplified construction. (A) Wet type. (B) Dry type.

container of the wet type serves as the negative terminal and provides an electrical contact between the electrolyte and outside circuits. This same purpose is served by the negative plate of the dry type.

Since the dielectric material, the oxide layer, is extremely thin and has a high dielectric constant, the construction yields an extremely high capacitance. When the oxide layer is formed on plain aluminum foil, the effective area of the anode plate is the actual area of the aluminum surface. If the surface of the foil is etched by chemical treatment or if the plate is made of cotton gauze sprayed with aluminum, a vast quantity of tiny holes are formed in the surface, and the effective area of the anode is greatly increased — hence a much higher capacitance in the same space. Because the construction of an electrolytic capacitor makes it difficult to control the thickness of the dielectric and the total area of the anode plate, fairly loose tolerances of total capacitance are allowed by military specifications. In general, an electrolytic capacitor is acceptable if its actual capacitance is no less than 90% or more than 250% of its rated value.

The construction of an electrolytic capacitor makes it quite economical to place several anode plates inside a single casing. Thus a common case with a single negative terminal and the same electrolyte material serves for all the anode plates in the unit. Each anode has its own positive terminal. Commercial units are commonly available with two and three anodes at the same or different total capacitance and voltage ratings.

CHARACTERISTICS

Voltage characteristics. Within the rated operating temperature range the *d-c working voltage* rating of an electrolytic capacitor is that d-c voltage which can be applied continuously across its terminals without breakdown. The *peak working voltage* rating represents the sum of the d-c working voltage and peak a-c voltage that may be applied continuously across the terminals. A *surge voltage* rating is often given; this represents the maximum d-c voltage that may be applied for a short period. Typical relationships between d-c working voltage and surge voltage are shown in Table 4-3.

D-c leakage current. Commercial and military specifications establish the maximum leakage current that may flow through an electrolytic capacitor after the d-c working voltage has been applied. This leakage current is usually limited to either below 10 ma or below that given by the formula listed below—whichever is smaller:

$$\text{Maximum leakage current} = KC + 0.3 \ ,$$

where C is the capacitance as rated in μf and K is a constant as given in Table 4-4.

TABLE 4-3

Working voltage (dc)	Surge voltage (dc)
15	20
25	40
50	75
100	150
150	200
200	250
250	300
300	350
350	400
400	450
450	500

Equivalent series resistance. Leakage current, in itself, does not clearly indicate the power loss resulting from the use of a particular electrolytic capacitor. A knowledge of the equivalent series resistance is also required. The equivalent series resistance in an electrolytic capacitor is an expression of the total effect of electrolyte resistance, the contact resistance between the various materials, and the dielectric resistance. The power losses of an electrolytic capacitor are expressed as the equivalent series resistance multiplied by the square of the leakage current. Military specifications for electrolytic capacitors provide a maximum permissible value for equivalent series resistance and thus effectively establish a limit to acceptable power loss. The relationship used is put in a form which makes it applicable to all capacitance values. According to this relationship, the product of the equivalent series resistance and the capacitance (in microfarads) shall not exceed the P value shown in Table 4-5. Measurements of series resistance should be made with a polarized capacitance bridge at a frequency of 120 cps.

Commercial types. The various types, sizes, and other characteristics of commercial electrolytics are indicated in Table 4-6.

Nonpolarized electrolytics. In the electrolytic capacitors described above, permanent damage results if the polarity of the

TABLE 4-4

Working voltage (dc)	K
15 - 100	0.01
101 - 250	0.02
251 - 350	0.025
351 - 450	0.04

TABLE 4-5

Working voltage (dc)	P (Rated capacitance × equivalent series resistance)
15	600
25	500
50	400
100	330
150	300
200	250
250	230
300	210
350 - 450	200

applied voltage is ever reversed, even if that reversal is only for a few seconds. In addition, the a-c component in the applied voltage must always be low with respect to the d-c component so that the anode is never driven negative with respect to the cathode. Certain other types of electrolytic capacitors are available for applications where the d-c polarity may shift or a-c voltage is applied. In such capacitors, the negative plate is replaced with another anode plate.

The most common application for these is in connection with capacitor-start a-c motors. In this type of service, a-c voltage is applied across the capacitor for about ½ second or less. Once the motor is started, the capacitor is switched out of the circuit by a speed-controlled switch within the motor itself. Such capacitors

TABLE 4-6
Electrolytic Capacitors—Aluminum Foil Type

	Midget Axial-Lead Tubulars
Description:	Aluminum container with waxed cardboard outer wrapping. Axial insulated or bare wire leads. Dual section types in common case are available. Mounted by leads or body clamp
Working voltages dc:	6, 12, 15, 25, 50, 150, 250, 350, 450, 475, 500
Capacitance range:	6 volt—50 to 2000 μf; 500 volt—8 to 20 μf
Body size range:	6 volt, min. cap.—1⅛ in. long × ⅜ in. diam.; 500 volt, max. cap.—2⅛ in. long × 1 in. diam.; dual-section 40 + 40 μf at 450 wv dc—3⅞ in. long × 1 in. diam.
Temperature range:	85°C, max. operating temperature for 6 to 450 wv dc sizes; 65°C, max. operating temperature 475 to 500 wv dc

(Cont'd.)

TABLE 4-6 (Cont'd.)

	Axial-Lead Tubulars
Description:	Same as midget type, except that all have flexible insulated leads and all are mounted by body clamps. Dual- and triple-section types available
Working voltages dc:	150, 250, 350, 450
Capacitance range:	150 volt—10 + 10 to 50 + 50 μf dual section; 450 volt—10 + 10 to 40 + 40 μf dual section
Body size range:	150 volt, min. cap.—2⅜ in. long × 11/16 in. diam.; 450 volt, max. cap.—3⅝ in. long × 1⅜ in. diam.
Temperature range:	65°C, max. operating temperature
	Screw-Down Type
Description:	Tubular aluminum case with threaded neck at one end. Neck fits through chassis hole and is held by ¾-16 or ⅞-16 nut. Color-coded flexible leads extend from neck. Color code marked on case. Case insulated from capacitor. Single, dual, and triple sections available
Working voltages dc:	450 (525-volt surge), 475 (600-volt surge), 600 (800-volt surge)
Capacitance range:	450 volt—4 to 40 μf, 16 + 16 μf dual, 8 + 8 + 8 triple; 600 volt—4 to 16 μf
Body size range:	450 volt, min. cap.—2 7/16 in. long × 1⅜ in. diam.; 600 volt, max. cap.—4 7/16 in. long × 1½ in. diam.
	Twist-Prong Type
Description:	Tubular aluminum case with 3 or 4 mounting prongs at one end. Prongs fit through metal or Bakelite mounting plate and are twisted to hold capacitor. Solder lug terminals located between mounting prongs serve as common negative terminal. Single to quadruple sections available in wide assortment of capacitance and voltage combinations
Working voltages dc:	6, 10, 15, 25, 150, 200, 250, 300, 350, 400, 450, 475, 500
Capacitance range:	6 volt, single section, max. cap.—2000 μf; 500 volt, single section, max. cap.—15 μf; 450 volt, quadruple section, max. cap.—40 + 20 + 10 + 10 μf
Body size range:	6 volt, single section, max. cap.—2 in. long × 1⅜ in. diam.; 500 volt, single section, max. cap.—2 in. long × 1 in. diam.; 450 volt, quadruple section, max. cap.—2 in. long × 1⅜ in. diam.

are available in capacitance ratings of from 50 to 500 μf and are intended for use with 60-cycle, 110-volt motors. Since the capacitor is heated by the a-c voltage during each start, these types should not be used in applications where the motor is required to start more often than once every three or four minutes.

Very small a-c motors, rated at 25 to 50 volts at 0.01 horsepower or less, require that the capacitor be connected across the a-c voltage for the entire time the motor is operating. Electrolytic capacitors are available in sizes from 10 to 75 μf for continuous duty in such applications.

Tantalum electrolytics. The operation and basic construction of tantalum electrolytics are similar to aluminum electrolytics. A typical example is shown in Fig. 4-5. The major difference is that tantalum is used for the anode plate material and tantalum oxide

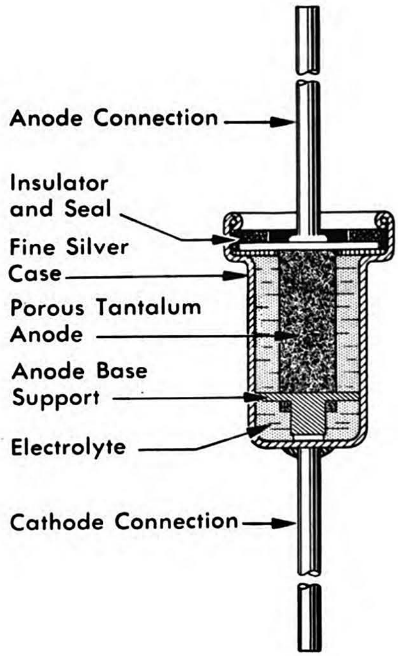


Fig. 4-5. Construction of tantalum electrolytic capacitor. ***Courtesy Fansteel Metallurgical Corp.***

serves as the dielectric. The anode may take the form of a porous plug, a curved or flat plate, or a network of wires. Until recently the higher cost of tantalum as compared to aluminum electrolytics has restricted their use. The reason has been the cost of the basic materials and the special construction required because of the corrosive action of the electrolyte.

Basic advantages of tantalum electrolytics have been that tantalum oxide has a higher dielectric constant and a lower leakage current than aluminum oxide. The need for subminiature electrolytics for use in transistor applications and the need for electrolytics that will maintain their performance at high temperatures have both led to the commercial development of the tantalum construction. This, in turn, is leading to the widespread use of tantalum electrolytics in special applications, in spite of appreciably higher cost as compared to aluminum electrolytics.

Present-day tantalum electrolytics are of two general types: One type is extremely small and is intended for use in applications involving subminiature circuitry. They maintain their characteristics at operating temperatures from −55°C up to +85°C and have leakage currents of less than 0.1 ma/volt/μf. Special variations with silver outer cases have even lower leakage currents. Subminiature tantalum electrolytics are generally available with axial leads. Typical dimensions and ratings are shown in Table 4-7.

The second type of tantalum electrolytic is designed for use under wide extremes of operating temperature range (−55°C to +200°C) and under conditions where resistance to corrosion and mechanical shock are required. This type is generally constructed with a steel outer case with hermetic sealing and with terminals instead of wire leads for making electrical connections. Typical dimensions and ratings are shown in Table 4-8.

CERAMIC CAPACITORS

Fixed ceramic capacitors are available in a wide variety of sizes and shapes, and various special types are available for special

TABLE 4-7
Tantalum Electrolytics—Subminiature Type

Description:	Tubular metal-case units with radial or axial leads. Case insulated or uninsulated. Construction details, sizes, and ratings differ with manufacturers. Nonpolarized types available
Working voltages dc:	About two dozen working voltages from 0.5 volt to 150 volts
Capacitance range:	0.5 volt—4 to 60 μf; 150 volt—0.5 to 36 μf
Body size range:	0.5 volt, min. cap.—5/32 in. long × 5/64 in. diam.; 0.5 volt, max. cap.—½ in. long × ⅛ in. diam.; 150 volt, min. cap. —11/16 in. long × 3/16 in. diam.; 150 volt, max. cap.—2¾ in. long × ⅜ in. diam.
Operating temperature range:	— 55° C to + 85° C

TABLE 4-8
Tantalum Electrolytics—Heavy-Duty Type

Description:	Tubular or rectangular metal-case units. Case insulated. Construction details, sizes, and ratings differ with manufacturers. Nonpolarized types available
Working voltages dc:	About two dozen working voltages from 10 volts to 600 volts
Capacitance range:	10 volt—120 to 240 μf; 600 volt—3.5 to 7 μf
Body size range:	10 volt, min. cap.—approx. 7/8 × 7/8 × 1/2 in.; 600 volt, max. cap.—approx. 7/8 × 7/8 × 4 in.
Operating temperature range:	Extreme operating temperature range available— — 55°C to + 200°C

purposes. Fixed ceramic capacitors are frequently used in vhf and uhf applications and are particularly useful in applications which require extremely high working voltage and low or precisely known temperature coefficient.

Basic construction. Although ceramic capacitors are available in a number of basic shapes, including the tubular, adjustable-tubular, stand-off, feed-through, disc, adjustable-disc, and high-voltage types shown in Fig. 4-6, they all have the same basic construction. Even in many of the newer shapes, including collar-button, pin-head, shirt-stud, and metal-cup shapes, the construction is basically the same. This basic construction, shown in Fig. 4-7, consists of a ceramic disc or tube with silver or copper plates deposited on the opposite faces of the ceramic material. In the manufacturing process, electrodes are attached to the plates, leads or terminals are fastened to the electrodes, and a moisture-proof coating of plastic or ceramic is added.

Effects of ceramic used. As is the case with all capacitors, the total capacitance of a ceramic capacitor is determined by the area of the plates, the distance between the plates, and the dielectric constant of the ceramic dielectric material. The type of ceramic material used determines the special characteristics of the capacitor. Steatite ceramics have a dielectric constant (K) in the region of 6, magnesium titanate has a K in the region of 16, and barium titanate has a K of approximately 1200. When the dielectric constant is below 500, the ceramic material is considered to be of the low-K type. If the K is above 500, the dielectric material is considered to be of the high-K type. Use of low-K ceramics results in a capacitor which has good stability with regard to temperature

BASIC TYPES OF CERAMIC CAPACITORS

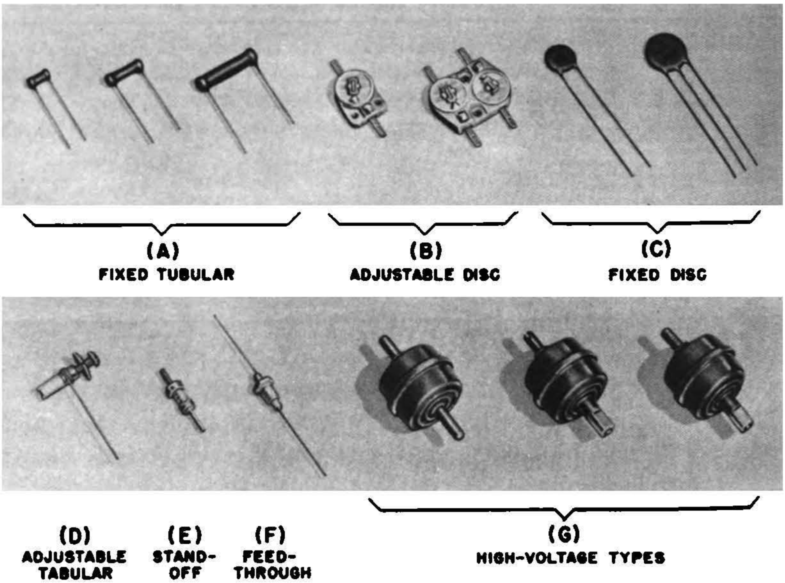


Fig. 4-6. Basic types of ceramic capacitors. (A) Fixed tubular. (B) Adjustable disc. (C) Fixed disc. (D) Adjustable tubular. (E) Stand-off. (F) Feed-through. (G) High Voltage. *Courtesy P. R. Mallory & Co., Inc.*

and voltage changes. Although use of high-*K* ceramics results in greater capacitance without a size increase, there is a loss in the stability of the capacitance with regard to voltage and temperature changes.

Characteristics. According to the type of dielectric used, ceramic capacitors may be divided into three main types with several additional specialized types. The first is a general-purpose type generally intended for the replacement of mica and paper capacitors in bypassing and coupling applications. Such replacement is often desirable since ceramic capacitors have lower losses for vhf and uhf signals and higher insulation resistance than capacitors with paper or mica dielectrics. These capacitors are commercially available in capacitances from 10 to 5000 $\mu\mu$f and in tolerances of $\pm 20\%$. Details concerning the temperature coefficient are not stated for this type.

The second type has a precisely specified temperature coefficient. Most commercially available varieties have negative temperature coefficients of 470 or 750 parts/million/deg.C. These are particularly useful as compensating capacitors in tuned circuits which have a positive temperature coefficient and tend to change frequency during warmup. The compensating capacitor decreases its capacitance with rising temperature, and a decrease in temperature causes a capacitance rise—thus helping to correct the frequency drift in the tuned circuit.

I-f transformers and other precision circuits often require a constant capacitance which is not affected by a temperature change. In such applications the third type of ceramic capacitor is useful,

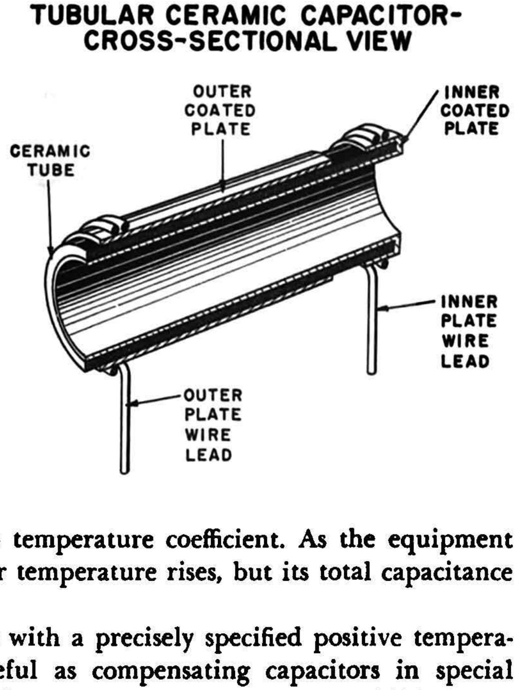


Fig. 4-7. Tubular ceramic capacitor, simplified construcstruction diagram.

since these have a zero temperature coefficient. As the equipment warms up, the capacitor temperature rises, but its total capacitance remains unchanged.

Ceramic capacitors with a precisely specified positive temperature coefficient are useful as compensating capacitors in special applications in which the other circuit components exhibit lowering values of capacitance as the temperature rises. This type is used in special-purpose equipment and is generally available only on special order from the manufacturer. Another special type of ceramic capacitor includes those in which an extremely high dielectric strength is important, rather than close capacitance tolerances. These are used as power-supply filter capacitors in TV systems and are designed to have a capacitance in the order of 500 $\mu\mu$f at a working voltage of 20,000 volts dc.

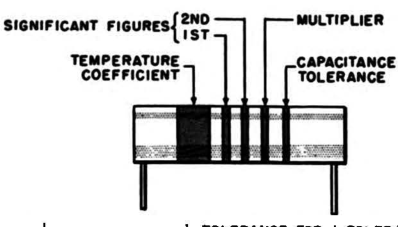
Color code. The total capacitance and other special characteristics of a ceramic capacitor are frequently stamped on the body. However, a color code is sometimes used, details of which are shown in Fig. 4-8.

Stamped types often have a code to indicate the temperature coefficient. There are two symbols in common use, and these indicate the possibilities of other variations. A marking of NPO (or a black band or dot) indicates a negative-positive-zero characteristic; that is, the temperature coefficient remains essentially zero over a wide range of temperatures (usually from −20°C to +85°C). A marking of N470 or N750 (blue or violet marks) indicates that the capacitor has a negative temperature coefficient equal to 470 or 750 part/million/deg. C, respectively.

Commercial types. Table 4-9 summarizes the commonly available ceramic capacitors and their most outstanding characteristics.

VARIABLE AND ADJUSTABLE CAPACITORS

The difference between variable and adjustable capacitors is similar to that between variable and adjustable resistors. When the capacitor adjustment must be made available to the equipment



COLOR	SIGNIFICANT FIGURE	MULTIPLIER	TOLERANCE FOR NOMINAL CAPACITANCES GREATER THAN 10 μμF IN PERCENT	TOLERANCE FOR NOMINAL CAPACITANCES OF 10 μμF OR SMALLER IN μμF	TEMP. COEFF. PARTS PER MILLION PER °C
BLACK	0	1	20	2.0	−0
BROWN	1	10	1	-	−30
RED	2	100	2	-	−80
ORANGE	3	1,000	-	-	−150
YELLOW	4	-	-	-	−220
GREEN	5	-	5	0.5	−330
BLUE	6	-	-	-	−470
VIOLET	7	-	-	-	−750
GRAY	8	0.01	-	0.25	+30
WHITE	9	0.1	10	1.0	+120 TO −750
GOLD	-	-	-	-	-

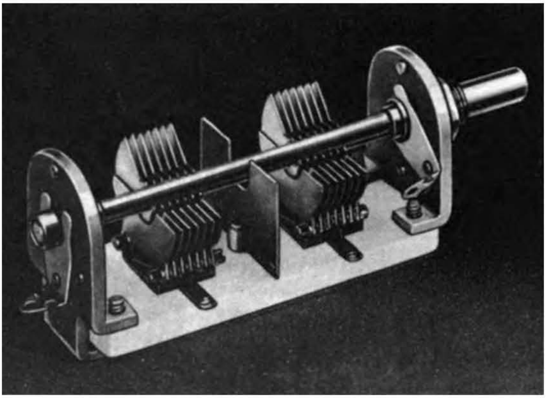
Fig. 4-8. Ceramic capacitor color code.

TABLE 4-9
Ceramic Capacitors

	Disc Type
Description:	Thin circular discs with insulating coat. Parallel wire leads. Single-, dual-, and triple-section types
Temperature coefficients:	Available with unspecified (general purpose), zero, and negative (−750 ppm/°C) temperature coefficients. High-*K* types available
Working voltages dc:	500 volts (1000-volt test) for most types; 1000-volt and 3000-volt types available
Capacitance range:	General-purpose type—5.0 $\mu\mu$f to 0.02 μf; zero temp. coef. type—10 $\mu\mu$f to 270 $\mu\mu$f; negative temp. coef. type—10 $\mu\mu$f to 330 $\mu\mu$f; high-*K* type—10 $\mu\mu$f to 0.03 μf.
Body size:	Smallest size—3/8 in. diam. × 5/32 in. thick; largest size—29/32 in. diam. × 13/64 in. thick
	Tubular Type
Description:	Ceramic tubes with phenolic coating and radial leads
Temperature coefficients:	Unspecified, zero, and negative (− 750 ppm/°C) temperature coefficients
Working voltages dc:	600 volts for most types
Capacitance range:	General purpose type—10 $\mu\mu$f to 0.005 μf; zero temp. type—0.75 $\mu\mu$f to 175 μf; negative temp. coef. type—5.0 $\mu\mu$f to 100 $\mu\mu$f
Body size:	Smallest size—1/4 in. diam. × 1/2 in. long; largest size—7/10 in. diam. × 1 3/16 in. long
	Doorknob Type
Description:	Ceramic elements in low-loss plastic cases. Cylindrical shape with wide variety of terminal types. Designed mainly for high wattage filter applications in television sets
Ratings:	500 $\mu\mu$f at 20,000 and 30,000 wv dc
Body size range:	20,000 volt—1 in. diam. × 1 in. long; 30,000 volt—1 5/16 in. diam. × 1 1/4 in. long

operators, as in tuning a radio receiver, a variable capacitor is used. On the other hand, if the capacitor adjustment is intended for use by the equipment manufacturer or service technician, as in adjusting the frequency of i-f transformers, an adjustable capacitor is installed. The major difference between the two types is the degree of convenience provided for making the capacitor adjustment.

Variable capacitors. A typical variable capacitor is shown in Fig. 4-9. A shaft, frequently mounted in ball bearings to provide smooth turning action, is provided for making the capacitor adjust-



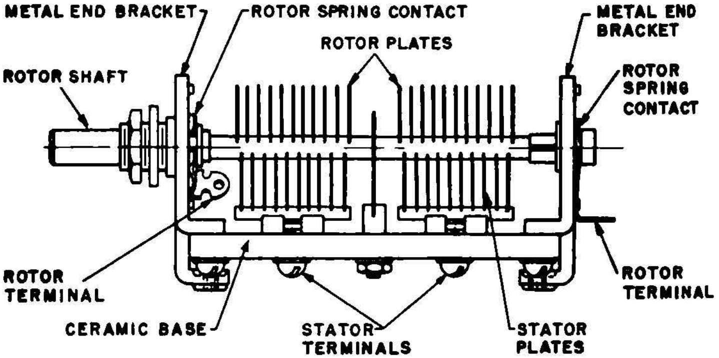


Fig. 4-9. Variable capacitor construction. *Courtesy Hammarlund Mfg. Co., Inc.*

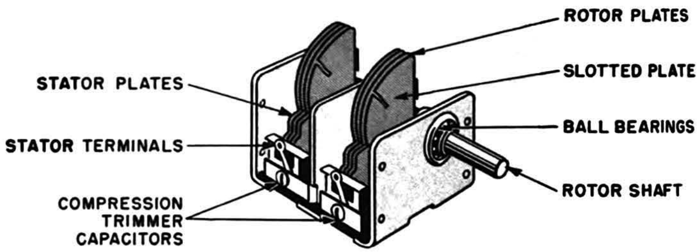
ment. The capacitor is generally mounted so that the shaft protrudes through the front panel of the equipment. A knob is attached to the end of the shaft to permit ease of turning. A pointer and dial are often added to permit the operator to estimate the required adjustment. Frequently a special drive and pointer arrangement is attached to the shaft, as on the more expensive home radios and communications receivers, so that very fine capacitor adjustments can be made with great ease and accuracy.

Adjustable capacitors. Typical adjustable capacitors are shown in Fig. 3-4. In these types the major design stress is laid upon compact and economical construction rather than ease of adjustment. The design generally provides for adjustment by means of a screwdriver, and the accuracy of the adjustment depends upon the skill and understanding of the technician rather than special attachments.

VARIABLE CAPACITORS

Basic construction. As in all capacitors the capacitance of variable or adjustable capacitors is determined by the area of the plates, the spacing between the plates, and the type of dielectric material used. The total capacitance may be varied by changing any of these factors. Although changing the dielectric presents major problems, it is a simple matter to vary the plate area or the distance between plates.

Figure 4-9 shows a typical construction for a variable capacitor. One set of plates is mounted upon a base of insulating material which is fastened between metal end brackets. These plates are electrically connected together by a strip of metal, but there is no electrical connection between them and the metal end brackets. The plates are fixed in position and are known as *stator* plates. Another set of plates is mounted upon the metal shaft of the capacitor and is connected together electrically through that shaft. When the shaft is turned, these plates rotate with the shaft and are therefore known as *rotor* plates. Although the rotor plates are electrically connected to the metal end brackets of the capacitor through the bearings, the lubricant in the bearings prevents a zero-resistance path to the frame. Separate terminals, therefore, are usually provided for making electrical connections to the rotor and stator plates. Contact between the rotor and its terminal is generally provided by one or more springs which press on the rotor shaft. The construction which has been described is intended for use in transmitter applications, where high voltages are applied across the rotor and stator terminals, or in instrument applications, where minimum dielectric losses are required. A more economical construction is used in radio broadcast-band receivers. In this construction (see Fig. 4-10) a one-piece metal frame takes the place of the end brackets and base. The stator plates are mounted on the frame by strips of Bakelite or similar insulation. Springs are used to make a low-resistance path between the rotor and the frame. Since the frame is fastened to the equipment chassis or



BASIC GANGED CAPACITOR CONSTRUCTION-GROUNDED STATOR

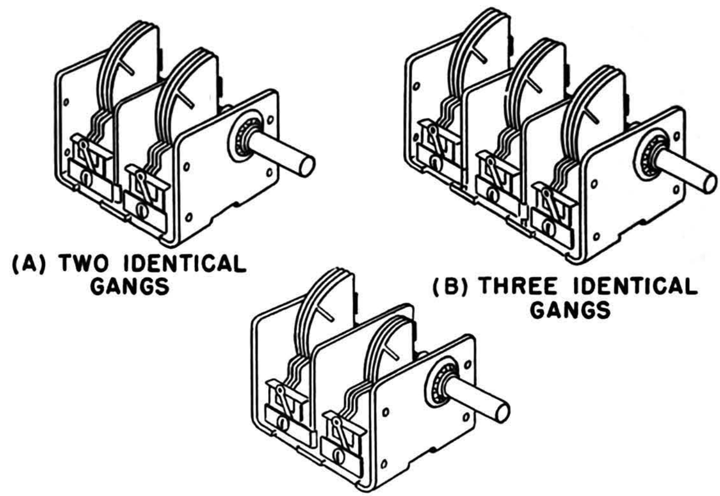


Fig. 4-10. Grounded stator construction. (A) Two identical gangs. (B) Three identical gangs. (C) Two different gangs. *After Insuline Corp. of America.*

front panel, connections to the rotor do not require a separate terminal but are made simply by circuit connections to the chassis.

Since the metal plates and framework expand as the temperature increases, the capacitance changes with temperature. Although this change may be corrected by a slight adjustment of the shaft, this is sometimes undesirable. Capacitance changes of this type may be minimized by using Invar metal, which has a very low coefficient of expansion, for the metal parts of the capacitor. Aluminum, plated brass, and even plated steel are the more commonly used metals in capacitors for commercial equipment.

Range of adjustment. When the shaft of a variable capacitor is turned so that the rotor plates are completely intermeshed with the stator plates, the opposed areas of the two sets of plates are at maximum, and the capacitance is at maximum. The total capacitance may be reduced by turning the shaft so that the rotor plates are only partly intermeshed with the stator plates. Since only the intermeshed areas are effective, the total capacitance is thus reduced. When the shaft is turned so that the rotor plates are completely out of mesh with the stator plates, the capacitance is at a minimum but not at zero. This is because there is a small residual capacitance; the ends of the rotor and stator plates are still close together and have the effect of plates of small area. In addition, there is a small amount of capacitance due to the proximity of the rotor plates and terminal to the metal frame of the capacitor. Because both the maximum and minimum capacitance are of interest to the equipment designer, manufacturers of variable capacitors usually list both these values in their specifications. Although the maximum value of the capacitance can be increased by including more stator and rotor plates in the construction and by increasing the areas of those plates, there is also an increase in the minimum capacitance.

Ganged capacitors. In a number of applications, such as radio receivers, several variable capacitors are required, and all must be adjusted each time the equipment is tuned. Instead of providing separate variable capacitors, each with its own tuning shaft, the various capacitors are usually mounted together in the *ganged* construction shown in Fig. 4-10. Turning the shaft varies all sets of rotor plates simultaneously. Ganged capacitors are commonly available with two, three, and even four sections, and, as required by the application, the individual sections may have almost identical or completely different maximum and minimum capacitances.

Trimmers. Capacitor manufacturers cannot supply variable capacitors which are absolutely identical. Consequently the equipment engineer must include in his circuit additional adjustable capacitors (or inductors) to provide a means for adjusting the circuit capacitance to exactly that required by the application.

A trimmer is a small adjustable capacitor which is attached to the frame of the variable capacitor. In a ganged capacitor each section is frequently supplied with a trimmer, which usually consists of a small number of flexible metal plates separated by thin sheets of mica. A screw adjustment provides a means for applying pressure to the plates so that the distance between them may be decreased and the capacitance increased.

One set of trimmer plates is connected to the main rotor plates, and the other is connected to the stator plates. Thus the capacitance of the trimmer is added to that of the main capacitor. Since the maximum capacitance of the trimmer is only a few times greater than the minimum value of the main capacitor, adjusting the trimmer has a negligible effect on the maximum capacitance of the entire unit. However, adjusting the trimmer provides an effective method for increasing the absolute minimum value of the variable capacitor to any convenient minimum capacitance which is within the adjustment range of the trimmer.

Slotted plates. In some applications it is desirable to be able to adjust the capacitance of a variable capacitor at several points over the entire tuning range. These adjustments are made possible by the *slotted plate* construction. In this arrangement, the two outer rotor plates are made with several slots. The portions of the plates between the slots can be pressed inward to increase the capacitance or bent outward to decrease the capacitance. The amount of bending should be kept small enough so that the bent section does not touch the frame or stator plates at any point throughout the rotation of the shaft. Since several slots are provided, different sections of the rotor plate may be bent inward or outward in any desired combination, and a wide range of small adjustments can be obtained over the entire range of shaft rotation.

Plate shape. Different applications require different percentages of capacitance change per degree of shaft rotation. The desired variation can be obtained by shaping either or both the rotor and stator plates. While there are an indefinite number of possibilities, the three types shown in Fig. 4-11 are the most common. Part (A) shows a capacitor with semicircular rotor and stator plates. The capacitance variation of this type is such that equal changes in shaft rotation cause equal changes in capacitance. Thus there is a linear relationship between shaft rotation and capacitance, and this type of plate shape is known as the *straight-line-capacitance* (SLC) type.

In frequency meters and in special types of radio receivers, it is desirable to mark the capacitor tuning dial directly in terms of frequency. It is also highly desirable to have the frequency scale evenly spaced across the dial so that equal amounts of shaft rotation represent equal frequency changes. The plate shape which

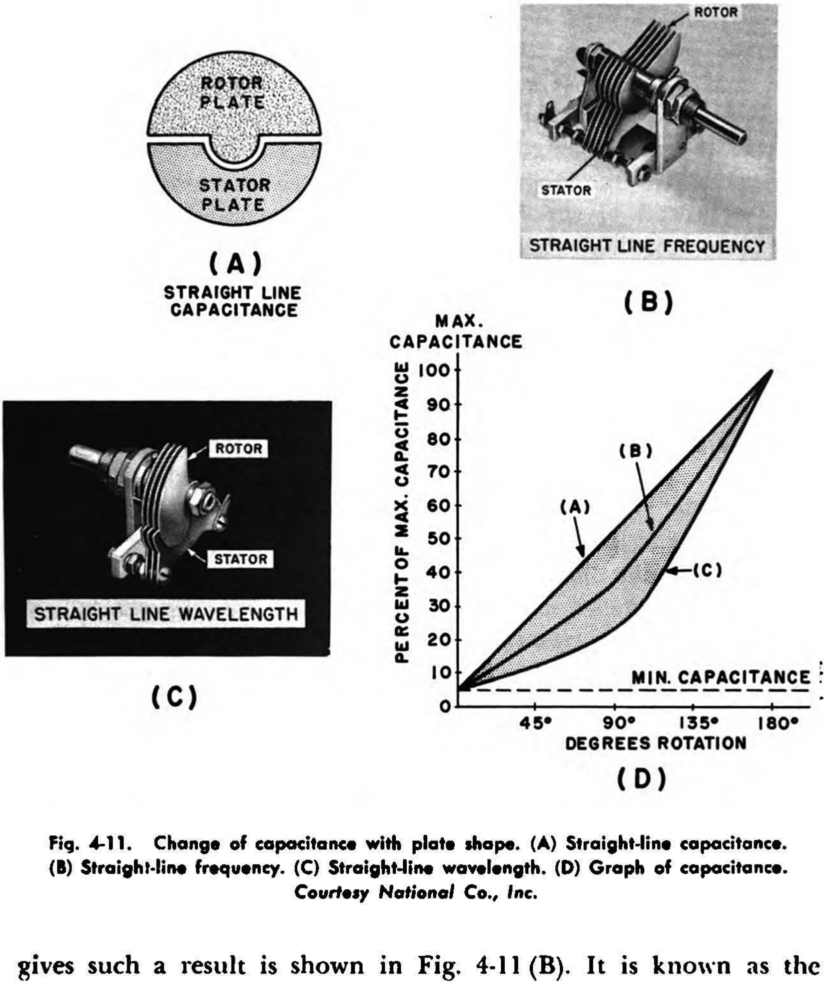


Fig. 4-11. Change of capacitance with plate shape. (A) Straight-line capacitance. (B) Straight-line frequency. (C) Straight-line wavelength. (D) Graph of capacitance. *Courtesy National Co., Inc.*

gives such a result is shown in Fig. 4-11 (B). It is known as the *straight-line-frequency* (SLF) type. It can be seen that at 90° rotation the frequency is half way between minimum and maximum, but the capacitance is at approximately 25% of its maximum value.

In wavemeters and other special devices the capacitor dial is marked in terms of wavelength, and it is desirable to have this wavelength scale vary in a linear manner with respect to shaft rotation. Figure 4-11 (C) shows the capacitor plate shape which gives this result. This is known as the *straight-line-wavelength* type. At 90° rotation the wavelength is midway between its two extremes, but the capacitance is at approximately 40% of its maximum value.

Capacitors used in home broadcast receivers generally have a shape which is a compromise between the shapes shown in Fig. 4-11 (B) and (C). This type has roughly a straight-line-frequency characteristic when it is near maximum capacitance and a straight-line-wavelength characteristic in the minimum capacity region. The result is that the frequency calibrations at the low-frequency end of the band (maximum capacitance) have wide and even spacing, while the frequency calibrations at the high-frequency end of the band have a fairly even but narrower spacing.

Power factor. The power factor of variable air capacitors is very low. It is not equal to zero even though air as a dielectric has a power factor of zero. The basic reasons for this are that the insulating material which holds the rotor and stator plates in position does have dielectric losses and that the resistance of the springs and the various electrical and mechanical connections between the plates is not equal to zero. The combined effect of these is that at frequencies below 1000 kc the power factor steadily decreases as the rotor plates are turned so as to increase capacitance. At higher frequencies the power factor decreases to a minimum value as the capacitance is increased to about 10 to 30% of maximum, and then it increases steadily as the capacitance is increased to maximum.

Voltage breakdown characteristics. The voltage breakdown characteristics of variable capacitors are determined by the spacing between the plates; if compact design is important, the thickness of the plates also must be considered. At normal atmospheric pressure, a 0.01-inch air spacing between plates will withstand approximately 1500 volts dc without sparkover. However at 50,000 feet altitude, the same plate spacing will exhibit sparkover if 400 volts dc is applied. From this example it can be seen that there is no problem of voltage breakdown in radio receiver variable capacitors designed to operate at sea level. In transmitter applications where higher voltages are applied, air gaps of 0.02, 0.03, and 0.07 inch are successfully used to withstand voltages of 800, 1200, and 1700.

For aircraft applications, and particularly for aircraft transmitters operating at high frequency, note that air has a lower dielectric strength at reduced pressure. In addition, sharp edges cause concentrated voltage gradients in the electric field around the plate and cause ionization of the air in that region, which results in localized voltage breakdowns. These appear as a faint bluish glow known as *corona*. Corona represents a power loss even at line-voltage frequencies; and the effect, along with its power loss, increases with frequency.

Since aircraft equipment requires that minimum space be used at maximum efficiency, capacitors designed for such applications cannot be safeguarded against breakdown effects simply by increasing the air gap. Gaps must be kept small to reduce plate size, and corona effects must be eliminated by rounding all edges to prevent concentrated voltage gradients. Reducing voltage gradients also involves selecting special ratios between plate thickness and air gap. While it has been found that best results are obtained when the air gap is between two and three times the plate thickness, this is not sufficient basis for selecting capacitors for such applications. Prime consideration should be given to the manufacturers specifications for the voltage, frequency, and altitude at which his various models will operate without breakdown.

Temperature coefficient. Since all the materials used in variable capacitor construction expand as their temperature increases, plate size and spacing also change with temperature, resulting in a change of capacitance. These capacitance changes cannot be predicted with accuracy since they depend upon the exact mechanical construction of each capacitor design. The matter is further complicated by the fact that the plates may warp slightly due to twisting by uneven frame expansion and by the fact that there is also a change in the dielectric constant of the insulating material used in the construction. As a result the temperature coefficient for any particular design may be either positive or negative, and it may be anywhere in the range of from +175 to −75 parts/million/deg.C. Careful design and production control can produce variable capacitors with zero temperature coefficient or an accurately controlled positive or negative temperature coefficient. Such types are expensive, and in most applications satisfactory results are more economically obtained by the addition to the circuit of a temperature-compensating ceramic capacitor.

Commercial types. Variable air capacitors are available in literally dozens of construction types. Although there are miniature, medium and large types, these are variations in name only. The minimum plate area, number of plates, and air spacing are limited by the required capacitance and voltage rating, as has been described previously. The smallest capacitors in common use have three pairs of plates with a capacity range of from 3 to 15 $\mu\mu$f and an overall length of about 1⅛ inches.

Types in common use in superheterodyne receivers have two gangs. The gang for the oscillator section has about 17 to 20 plates with a range of from 8 to 170 $\mu\mu$f. The gang for the r-f section has from 25-30 plates with a capacitance range of from 10 to 450 $\mu\mu$f. Overall body size, less shaft, is about 1½ by 1⅞ by 1¼ inches.

Heavy-duty transmitter types have air gaps as wide as 0.500 inch, up to 80 plates or more, and capacitance ranges as wide as from 50 to 1200 $\mu\mu$f. The largest sizes in common use have an overall length of 20 inches.

ADJUSTABLE CAPACITORS

Basic types. The most common types of adjustable capacitors, shown in Fig. 3-4, include the book-type capacitor, the ceramic-disc type, the circular metal-disc type, and the rotating-plate type. Additional variations include sealed metal-plate capacitors in which the dielectric is compressed gas, a vacuum, or various types of oil. These types are available as fixed, adjustable, and continuously variable capacitors.

The basic construction of the book type was described in the review of the trimmer for variable capacitors. When this type is supplied as a separate unit, the metal plates are usually mounted on a ceramic base, as shown in Fig. 3-4 (A).

The basic construction of the ceramic-disc type consists of a rectangular ceramic base and a circular disc of the same material. These two units are fitted together as shown in Fig. 3-4 (B) so that one face of both the base and the disc are in close contact, and the two units are held together by a center pivot. The faces in contact with each other are polished so that the circular disc may be turned with a minimum of friction. A semicircular silver plate is deposited upon the faces of the ceramic units which are not in contact with each other. The capacitance is adjusted by turning the circular disc so as to obtain the desired amount of overlap between the two silver plates. The principles involved are the same as those of a variable air capacitor with semicircular plates, as is shown in Fig. 3-4 (C). By selection of the type of ceramic material used, a degree of temperature compensation may be obtained.

In the circular metal-disc type of construction, see Fig. 3-4 (D), two circular metal plates are mounted in line with each other. One plate is fixed and the other is mounted on the end of a rod with a screw thread. By turning the rod, the distance between the two plates may be varied, and the capacitance is thus adjusted.

In the rotating-plate type, Fig. 3-4 (C), the construction is almost identical to that of a variable air capacitor. The principles of operation are identical, and the difference is in the type of shaft supplied. Since the adjustment is not intended for use by the equipment operator, a short shaft with a screwdriver slot is usually supplied. Sometimes there is a device supplied for locking the shaft in the selected position.

Gas, vacuum and oil types. Capacitors of the gas, vacuum, and oil types are special items sometimes used in high-power transmitters for tuning, neutralizing, and antenna coupling networks. Although these types may be either of fixed or variable construction, they are most commonly available as adjustable types. The internal construction may consist of rotor and stator plates similar to those in variable capacitors, or it may consist of discs with an adjustable spacing between them. The major difference is that the plates are mounted in a hermetically sealed container, and, instead of air, the dielectric may be compressed gas, a vacuum, or oil. The reason for such construction is that air does not have favorable dielectric strength when used with high voltages or high frequencies, as already has been considered in the review of the voltage characteristics of variable air capacitors.

When compressed gas is injected into the container, the capacitance remains essentially unchanged, but higher voltages can be applied without breakdown. Nitrogen is the gas most frequently used. At pressures of about 2000 pounds per square inch, the voltage that can be applied across the plates is about five times that of an equivalent air capacitor. Although this construction increases the cost, such cost compares favorably with that of an air capacitor with equivalent characteristics. A significant saving is also achieved in the space requirements.

In the vacuum-type capacitor, the air within the container is pumped out until a very low pressure equivalent to those found in vacuum tubes is obtained. As the air pressure is reduced inside, the remaining air is more easily ionized, and corona and sparkover occur at lower voltages. However, when a "high vacuum" is reached, there is insufficient air present for easy ionization, and the voltage rating rapidly increases. Fixed-vacuum capacitors of reasonably small size are available in a variety of capacitance and voltage ratings up to, and beyond, 200 $\mu\mu$f at 35,000 volts peak.

Vacuum capacitors of the variable type have a metal bellows or diaphragm with suitable mechanical devices for moving the bellows or diaphragm inward or outward and thus changing the distance between the plates inside. The range of adjustment is not as wide as obtainable with air variables and is generally limited to the range of about 20% of the maximum capacitance. Vacuum adjustables are available in various sizes up to the region of 400 $\mu\mu f$ with a peak voltage rating of 10,000 volts.

When a capacitor container is filled with oil, both the voltage rating and the capacitance are increased. The improvement obtained in these characteristics depends upon the dielectric strength and dielectric constant of the particular type of oil used. A capacitance increase of from three to five times is readily obtainable. The use of oil has advantages over compressed gas and vacuum dielectrics. Since there is no pressure differential between the inside and outside of the case, only simple seals are required. This makes it a relatively easy matter to use a rotatable shaft through the container without oil leakage, and the convenient rotor-stator construction can be achieved.

Chapter 5

Characteristics of Inductors and Transformers

INDUCTANCE

Basic characteristics. Inductance is a phenomenon associated with the flow of electric current through wires, particularly coils of wire. Included here will be a brief review of inductance, but the major subject of this chapter is an analysis of the practical characteristics of inductors such as chokes, transformers, and tuning coils used in electrical and electronic equipment.

The basic cause of all inductance, as shown in Fig. 5-1 (A), is the fact that a magnetic field is produced whenever electric current flows through a wire. The magnitude of the inductance increases when the wire is wound in the form of a coil [see Fig. 5-1 (B)], and a further increase may be obtained by placing a core of iron within the coil, as shown in (C). When dc flows through a coil, the well-known electromagnet is produced. When ac flows through the coil, the result is what is known as a *choke,* since it has the effect of impeding the flow of ac. If another coil of wire is placed close to the coil under discussion, as shown in Fig. 5-1 (D), an a-c voltage appears across the ends of this second coil—resulting in a *transformer.*

In an a-c circuit the effect of a coil bears some resemblance to that of resistance in a d-c circuit, but there are important differences. When ac flows through a coil, the current alternately increases to a peak, falls to zero, reverses direction, rises to a peak in this opposite direction, and then decreases to zero. The result is that the magnetic field produced increases and decreases in the same manner. Since a voltage is produced in a conductor when it is intercepted by a changing magnetic field, a new voltage is

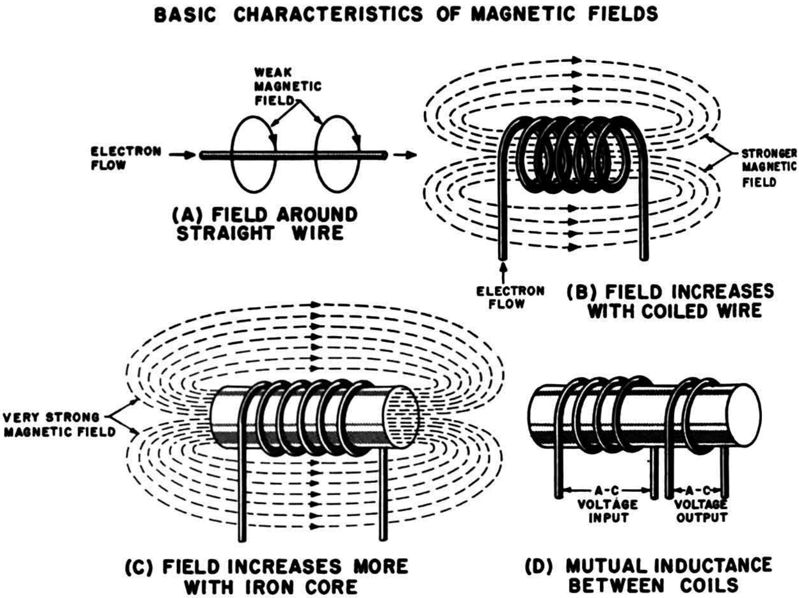


Fig. 5-1. Basic characteristics of magnetic fields. (A) Field around straight wire. (B) Field increases with coiled wire. (C) Field increases more with iron core. (D) Mutual inductance between two coils.

induced across the coil of the choke by its own moving magnetic field. This voltage, known as the "back emf," is always in such instantaneous polarity that it opposes the change in the current originally producing the magnetic field. The effect is known as *inductance*. A coil has an inductance of 1 henry if an induced voltage of 1 volt results when the current changes at a rate of 1 ampere per sec. The opposition which a coil offers to the flow of ac is known as *inductive reactance* and is measured in ohms.

Since a coil has a small amount of capacitance between its turns and since the wire forming the coil has resistance, a coil also exhibits small amounts of capacitive reactance and resistance. The combined effects of inductive reactance, capacitive reactance, and resistance is known as *impedance*. In a well-designed coil the impedance consists almost entirely of the inductive reactance.

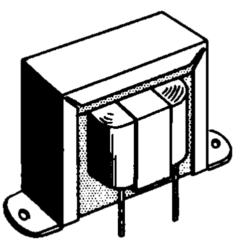
Chokes. In electrical and electronic equipment a choke consists of a single many-turn coil of wire. Depending upon the frequency of the ac expected to flow through the coil, it may have a core consisting of iron in various forms (to be considered shortly) or a core made of insulating materials which give mechanical support but have no intended magnetic effect or no core at all. Examples of these types are shown in Fig. 5-2 (A) and (B).* The purpose of a choke is to impede the flow of ac in a circuit while offering a minimum resistance to the flow of dc. In this type of application, chokes are used in a variety of power-supply filter circuits and in special filters in signal circuits. For these purposes, a choke is generally desired to have the maximum amount of inductive reactance which is compatible with size, weight, and cost requirements.

Inductive reactance can be determined from the relationship:

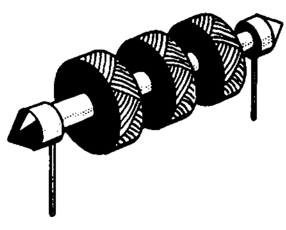
$$X_L = 2\pi f L \ ,$$

where X_L is inductive reactance expressed in ohms, f is the frequency of the input voltage expressed in cps, and L is the inductance expressed in henries.

From this relationship it can be seen that inductive reactance for dc is equal to zero and increases in proportion to the frequency



(A) IRON-CORE CHOKE



(B) INSULATING MATERIAL CORE CHOKE

Fig. 5-2. Typical chokes. (A) Iron-core type. Courtesy Standard Transformer Corp. (B) Insulating material core type.

of the applied voltage. For instance, a 1-henry choke has an inductance of just under 200 ohms at 30 cps, about 600 ohms at 100 cps, about 6000 ohms at 1000 cps, and about 6,000,000 ohms at 1 mc.

In many applications it is desired to impede the a-c component without affecting the d-c component of a given current.

*Reference to air-core chokes has been eliminated, since they are not in common use.

A resistor impedes ac and dc equally, according to the Ohm's law relationship and therefore cannot be used for this purpose. However, a choke impedes ac to a high degree, according to the inductive reactance formula, while the opposition it offers to dc is equal to the very low resistance of the wire in the coil.

Transformers. When ac flows through a coil, a magnetic field is formed which continuously expands, contracts, and reverses direction. Advantage can be taken of this effect by using it to provide inductive reactance, as in the case of the chokes mentioned previously. Another type of application can be obtained by placing one or more additional coils of wire in close contact with the first. When the magnetic field expands and contracts across these nearby coils, an a-c voltage is generated across the ends of these coils, and the result is a transformer.

Transformers find widespread use as practical devices for increasing or decreasing a-c voltages and for coupling circuits of widely different impedances. As in the case of chokes, the physical form of a transformer depends upon the frequency of the expected applied voltage. Thus, as shown in Fig. 5-2, transformers may consist of coils of wire wound on a core made of iron in various forms or on a core made of insulating materials which apply mechanical support only; or there may be no core at all.

In a well-constructed transformer, the following voltage relationship exists between the input (*primary*) winding and each of the output (*secondary*) windings:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} ,$$

where V_p and V_s are the input and output voltages respectively, and N_p and N_s are the number of turns in the input and output windings respectively. When the secondary voltage is higher than that of the primary voltage, the assembly is known as a *step-up* transformer. When the secondary voltage is lower than that of the primary, the result is a *step-down* transformer.

In such a transformer the input power and the output power are equal, as indicated by the relationship:

$$V_p \times I_p = V_s \times I_s ,$$

where V_p and V_s are the input and output voltages, respectively and I_p and I_s are the input and output currents, respectively.

Mutual inductance. In a transformer, the secondary winding is placed so that as much as desired—in most cases as much as possible—of the primary magnetic field passes through the secondary. The changes in the magnitude and direction of this primary magnetic field produce the voltage developed across the secondary winding, and thus the secondary voltage is directly proportional to the number of amperes/sec which the primary current changes. When two coils are so placed that any such coupling exists, they have what is called *mutual inductance.* If a change of 1 ampere/sec in the primary winding causes 1 volt to be developed across the secondary winding, 1 henry of mutual inductance exists in the combination of the two coils.

Leakage inductance. When a transformer is well designed, most, but not all, of the magnetic flux of the primary winding passes through the secondary winding. This effect is known as *leakage inductance.* Its result is to make the voltage across the secondary winding lower than that indicated by the turns ratio. This effect also limits the high-frequency response of the transformer, although the low-frequency response is affected by the mutual inductance.

Current flow and loading effects. The flow of ac through a coil produces a magnetic field which alternates in the same manner. The expansion and collapse of the magnetic field cause it to pass through the coil and to generate a voltage known as the *electromotive force (emf) of self-induction.* The emf of self-induction opposes the change in current flow. If a second coil is placed close to the first, as in the case of a transformer, an emf is induced in this second coil, and it is known as the *emf of mutual induction.* Thus electric energy is transferred from the primary to the secondary. Since the emf of mutual induction opposes the current flow that is producing it, the current flow in the secondary winding is in the opposite direction of that in the primary; and the magnetic field developed by the secondary is always in the opposite direction from that in the primary.

If no load is connected to the secondary, there is an open circuit in that winding and no current can flow through it. Consequently, the secondary winding cannot develop a magnetic field which opposes the magnetic field of the primary. As a result the primary magnetic field develops maximum emf of self-induction in the primary winding. There is maximum opposition to the voltage applied to the primary and only a very small current flows in the primary. When a load is connected to the secondary, current can flow in that winding. The magnetic field produced by the secondary winding opposes that of the primary.

Therefore, the emf of self-induction in the primary is reduced, and a larger current flows in that winding. The lower the load resistance connected to the secondary, the larger the current flow in the primary. A transformer, thus, is a self-regulating device which does not draw current from the primary voltage source unless current is drawn from the secondary winding. In an ideal transformer the secondary power is equal to the primary power.

CLASSIFICATION OF TRANSFORMERS AND INDUCTORS

There are a number of methods of classifying transformers and coils, or *inductors*. These methods include classifications of the type of winding employed, the type of core material used, the basic overall type of construction, and the a-c frequency at which the component will be used. Methods of classification will be considered in the review of commercial transformers and inductors in Chap. 6.

Another method of classification is that employed in the military standards for transformers and inductors. Specification MIL-T-27, which is used in procurement of transformers and inductors for the Departments of the Army, Navy, and Air Force, considers these components by grades, classes, and families. Classification by grade divides these components into grade 1—transformers and inductors most resistant to moisture—and grade 2—transformers and inductors less resistant to moisture. According to the arrangement into classes, class A includes transformers and inductors using organic insulation, class B includes those components using inherently inorganic insulation, and class C includes those using special insulation. It is in the classification of families that transformers and inductors are listed according to function. This listing, as shown in Table 5-1, gives a good survey of the applications of transformers and inductors.

CONSIDERATIONS AFFECTING INDUCTOR SELECTION

Although the basic interest in the selection of a coil or choke is its inductance (or its inductive reactance), the circuit designer cannot order such a unit simply on the basis of that quantity.

TABLE 5-1*
Family Group 01 to 07: Power Transformers and Inductors

Group No.	Description		
01 - 07:	Power Transformers and Inductors:		
01	Transformers supplying unrectified loads		
02	Transformers supplying rectified loads		
03	Transformers supplying both rectified and unrectified loads		
04	Power inductors		
05	Vibrator transformers		
06	Multiunit power transformers and inductors		
07	Continuously variable power transformers		
10 - 20:	Audio Transformers and Inductors:		
	Popular name	Dc in primary, source impedance	Dc in secondary, load impedance
10	Input	No, any	Yes or no, > 10,000
11	Input	Yes, ≤ 1000	Yes or no, > 10,000
12	Driver	Yes, > 1000	Yes, any
13	Output	Yes, > 1000	No, ≤ 10,000
14	Modulation	Yes, any	Yes, r-f tube load
15	Interstage	Yes, > 1000	No, > 10,000
16	Matching	No, any	Yes or no, ≤ 10,000
17	Matching	Yes, ≤ 1000	Yes or no, ≤ 10,000
18	Audio oscillator		
19	Multipurpose or multiple audio transformers and inductors		
20	Audio inductor		
30 - 37:	Pulse Transformers and Inductors:		
30	Input, line to grid		
31	Interstage, plate, or cathode to noncurrent-drawing grid		
32	Driver, plate or cathode to power-drawing grid or diode		
33	Output; plate, cathode, or network to line		
34	Modulation; plate, line, or network to oscillator		
35	Pulse oscillator; blocking tube		
36	Miscellaneous pulse transformers		
37	Resonant-charging inductor		

There are a number of other factors which must be considered. These include Q, or figure of merit, power factor, distributed capacitance, resistance effects and temperature coefficient, corona, core losses, and others.

*Adapted from MIL-T-27.

Figure of merit. Since the purpose of a coil is to provide the maximum economical amount of inductive reactance at a particular operating frequency, it is convenient to have a figure of merit which indicates how well a particular inductor accomplishes its function. Such a figure of merit has been established and is known as Q. For inductors, Q is expressed by the relationship:

$$Q = \frac{\text{Inductive reactance at frequency of interest}}{\text{D-c resistance}} = \frac{X_L}{R}.$$

If an inductor has a high Q, it is an indication that all the losses involved are low, and the inductor is performing its job effectively. For single layer coils, Q-values of several hundred are attainable

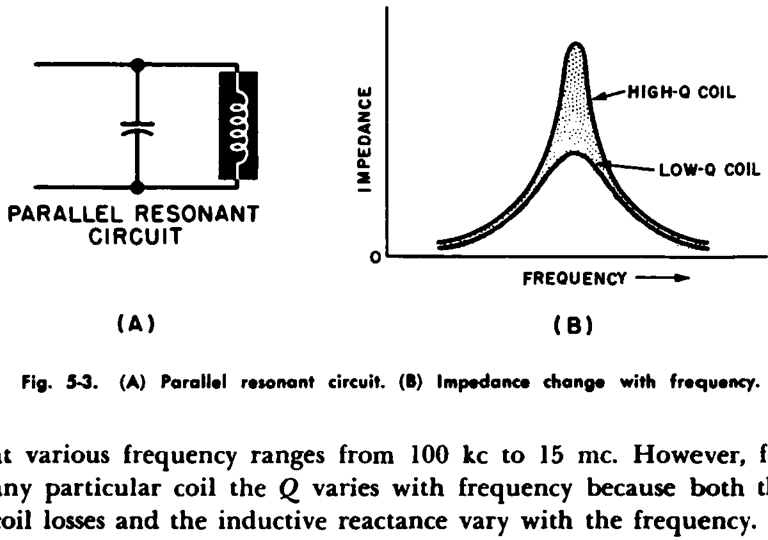


Fig. 5-3. (A) Parallel resonant circuit. (B) Impedance change with frequency.

at various frequency ranges from 100 kc to 15 mc. However, for any particular coil the Q varies with frequency because both the coil losses and the inductive reactance vary with the frequency.

The effect of Q can be seen in parallel resonant circuits, such as that shown in Fig. 5-3 (A). Such circuits are commonly used in r-f amplifiers and filter circuits. Since the coil has low reactance at low frequencies and the capacitor has low reactance at high frequencies, the circuit has a low total impedance except at the frequency where the two reactances are equal. At that particular *resonant* frequency, the two reactances combine to form a very high total impedance. The impedance increases to a peak at the resonant frequency, as shown in Fig. 5-3 (B) in which impedance is plotted against frequency for coils of different Q's. Note that with increasing coil losses, as represented by the coils of lower Q, the total impedance does not rise to as sharp a peak; and the combination is less frequency selective.

There are a number of methods of reducing losses, or increasing inductive reactance, without increasing the d-c resistance. These methods include using particular wire types and diameters at various frequency ranges, using particular types of windings and coil length-to-diameter ratios, and using special core materials. As far as the purchaser is concerned, these techniques are only of academic interest. It is the manufacturer's specifications of Q available in the various commercial types that are of interest.

As described in the previous paragraphs, many applications require amplification of a narrow band of frequencies. This is achieved by using tuned circuits containing coils with high Q. There are a number of television and fm radio applications, however, which require the amplification of a wide band of frequencies. This is sometimes accomplished by using coils with low Q, and the broadband amplification effect may be increased by tuning several low-Q amplifier stages to slightly different frequencies.

Measurement of Q. For equipment designers who wish to check specified values of Q or to check the Q of a custom-made coil, there is a type of instrument available known as a "Q Meter." Such a meter will measure values of Q with much greater accuracy than any complex and painstaking mathematical computation. The instrument contains an oscillator and a built-in capacitor. Connecting the coil to be tested to the instrument places it in a resonant circuit with the capacitor, and the output of the oscillator is connected to the resonant circuit. Contained in the instrument is a voltmeter which is connected across the capacitor. Since Q is equal to the ratio of the resonant-circuit voltage to the known oscillator voltage, the voltmeter may be calibrated directly in terms of Q.

Power factor. According to basic electrical relationships, the derivation of which will not be reviewed here, the *power factor* of a coil is shown by the familiar impedance triangle shown in Fig. 5-4. In this diagram R equals the d-c resistance of the coil, X_L equals the inductive reactance, Z equals the resulting impedance, and θ (theta) equals the angle between the vectors R and Z. According to the relationships shown in this diagram,

$$\text{Power factor} = \frac{R}{Z} = \cos\theta \ .$$

Consideration of power factor is important because it bears a very convenient relationship to Q. Q has been defined as X_L/R, which is equal to the tangent of the angle θ. In well-designed coils, Z is almost equal to X_L, since R and any distributed capacitance effects are kept to a minimum. When these conditions are met, the following relationship exists between the power factor and Q:

$$\text{Power factor} = \frac{R}{Z} = \frac{R}{X_L} = \frac{1}{Q} .$$

This is a convenient relationship in calculations dealing with parallel resonant circuits. In this type of circuit the power factor of the complete circuit is equal to the power factor of the coil plus the power factor of the capacitor.

Distributed capacitance. When any two conductors are placed in close proximity a certain amount of capacitance exists between them, according to the relationships described in Chap. 3. Thus, a small amount of capacitance exists between every two turns of

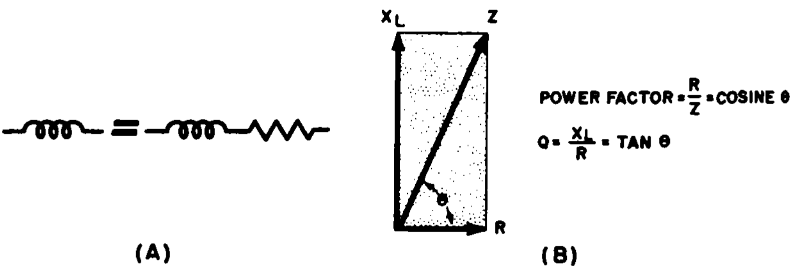


Fig. 5-4. Definition of coil power factor and Q. (A) Equivalent circuit of inductance and resistance. (B) Impedance diagram.

wire in the coil. The overall effect is that of a number of series capacitors connected in parallel at points along the entire coil as shown in Fig. 5-5, and this effect is known as *distributed capacitance*. Distributed capacitance is undesirable in chokes, since the capacitance offers a path for a-c signals around the choke, which is the very effect that a choke is intended to prevent. In addition, there are capacitor dielectric losses between adjacent turns in the coil, as defined in Chap. 3, and this represents a power loss in the coil. Since a large number of capacitors in series gives a smaller total capacitance than a small number of capacitors in series, the distributed capacitance can be reduced by designing

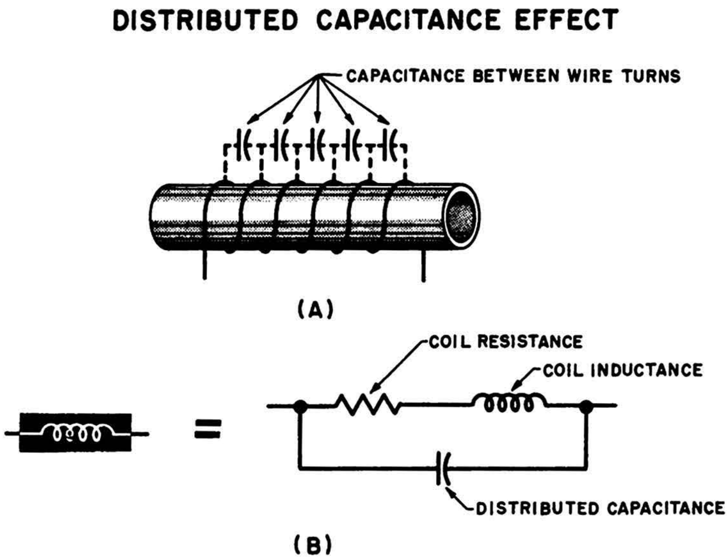


Fig. 5-5. Distributed capacitance effect. (A) Capacitance between turns. (B) Resultant effect of coil resistance and distributed capacitance.

a coil which is long with respect to its diameter. Using thinner wire, and increasing the center-to-center distance between turns, also decreases distributed capacitance.

While these techniques are successful in reducing distributed capacitance, they do not contribute toward obtaining maximum *Q*. Consequently, the intended use of the coil determines the type of compromise which must be made in coil design. If the coil is for use in a tuned circuit, the compromise is almost always in favor of maximum *Q* and minimum coil losses with little consideration for distributed capacitance. In choke applications, it is desired to reduce distributed capacitance to a minimum, and lower *Q* values are sufficient.

Resistance losses and temperature coefficient. Resistance losses lower the value of *Q*, as described previously, and also represent a power loss in the form of heat developed by current flow through the resistance of the coil wire. In addition, when high-frequency current flows through the coil, the magnetic flux generated by the individual electrons causes them to repel each other. As a result, most of the current flow occurs in a thin layer near the surface of the wire (*skin effect*), thus heightening the resistance in the path of the current and increasing the heat generated. The resistance increase due to skin effect can be decreased by using a conductor consisting of a number of twisted strands of fine insulated wire, thus offering an increased surface area for current flow. Such wire is known as "litz" wire.

Because of the heat generated by the skin-effect resistance, the temperature of the coil increases when the coil is used for high-frequency currents. This temperature increase causes a change in the inductance of the coil; thus the temperature coefficient of the coil becomes important. The major reason for a temperature coefficient of inductance is that the metal of the conducting wire (and the material of the coil form) expands when heated, thus changing the dimensions of the coil and varying the inductance. Since the wire in most coils is tightly wound around the coil form, any expansion redistributes the mechanical strains involved and produces an effect which is greater than that due solely to the expansion of the wire. Such changes in coil dimensions also affect the distance between the turns and thus affect the distributed capacitance. Heating also raises the resistance of wire, further heightening the undesirable results of skin effect. When equipment temperature stability is of primary importance, a thorough check of the various manufacturers' temperature-coefficient specifications should be made before selecting a coil.

Sparkover and corona discharge. When voltages of more than several hundred volts are applied across an inductor or exist in the windings of a transformer, it is possible for *sparkover* or *corona discharge* to take place. When the voltage is high, the electric field in the air or other insulation between adjacent coil turns or terminals may be arranged in either a uniform or nonuniform manner, depending upon the arrangement of the physical components and the insulation. Under uniform field conditions, sparkover occurs, which consists simply of current flowing through the air or other insulation. Sparkover may be eliminated by greater physical separation between the ends of the sparkover gap or by the use of better insulating materials.

When the field is not uniform, particularly at places where there are points or sharp bends in a conductor, a local electrical discharge takes place, producing a faint purplish glow around the point or sharp bend. This is corona, which can be prevented by redesigning physical components, by reducing the voltage in the region of the discharge, and by special shielding techniques. Both corona and sparkover produce considerable power loss in the coil or transformer. Corona, in addition, causes local radiation at high frequencies, resulting in radio interference. Also, corona causes ionization in the surrounding air, producing ultraviolet light and ozone, both of which tend to deteriorate dielectric materials.

Military specifications generally require a corona test for inductors and transformers which are to be used in connection with high-voltage circuits. The test consists of applying a specified a-c voltage across the winding under test. If corona is present, an oscilloscope connected to that winding will indicate a high-frequency oscillation superimposed upon the test voltage.

Miscellaneous inductor and transformer losses. There are a number of other losses which make a transformer or inductor operate at less than 100% efficiency. It was mentioned that one major loss is the power lost in heat caused by the resistance of the coil wire. Another loss is due to the fact that not all of the current resulting from the applied voltage flows through the wire of the coil, but some small amount flows through the insulation between the turns and through the core material. These are known as *dielectric losses.*

Hysteresis losses occur whenever iron or other magnetic core materials are used to increase the inductance of a coil. When the magnetic field reverses direction in these materials, the minute magnetic elements within the substance tend to maintain the orientation which was established by the previous direction of the magnetic field. Power must be expended in realigning these magnetic elements in the direction of the new field; this power loss appears as heat developed in the core.

If wires from other circuits are placed close enough to lie within the magnetic field of an unshielded coil, some of the power input to the coil is expended in developing a current flow in those conductors. Such items as mounting brackets, shields for other components, portions of the equipment chassis, insulators, and assorted hardware parts also may be placed within the magnetic field of a coil. The coil field generates localized current flows, known as *eddy currents,* within the bodies of these items. This represents another power loss to the coil. Still another type of loss occurs in coils or transformers operating at very high frequencies. At such frequencies a small coil becomes a reasonably efficient electromagnetic radiator, and appreciable amounts of power may be lost by actual radio transmission.

These various losses can be minimized through careful selection and use of the type and size of wire selected for the windings, the type and shape of the individual coils, the type of magnetic core material, etc.

MAGNETIC EFFECTS IN FERROUS CORES

The major magnetic effects in ferrous cores are magnetic induction, permeability, and hysteresis. The eddy currents are not considered to be a magnetic effect. Eddy currents are electric currents which flow in the metallic core material due to the changing

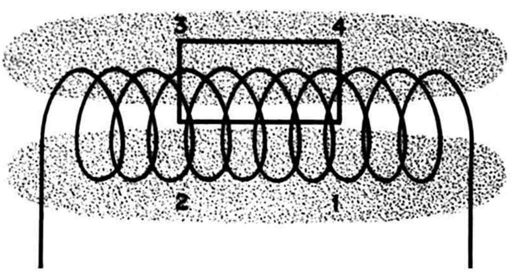


Fig. 5-6. Path of unit north pole to define *H*.

magnetic field through that material. These various effects impose important limitations on both transformers and chokes.

Magnetizing force or H. Since magnetic force is defined as the force exerted by the magnetic field on the north pole of a permanent magnet of unit strength, the intensity of the magnetic field within a coil can be described. If the intensity or *magnetizing force* of this field is designated as *H*, the work done in taking a unit north pole over the path from 1 to 2 inside the coil (see Fig. 5-6) will be *H* times the distance between 1 and 2. The work done in taking the pole around the path from 2, through 3 and 4, and back to 1 is essentially zero. It can be shown that the magnetic field intensity at the center of the coil is expressed by the relationship:

$$H = 4\pi NIA ,$$

where N equals the number of turns of wire per unit length of coil, I equals the current through the coil, and A equals the area of the cross section through the coil. Note that this relationship is true only at the center of the coil, since about half the lines of force "leak" out of the coil before they reach the ends.

Magnetic induction or B. In unmagnetized ferrous material, each molecule actually has its own magnetic lines of force. However, the completely random arrangement of these molecules results in complete cancellation, and there is no resultant overall field of magnetic lines of force. When ferrous material is shaped in the form of a core and placed inside the coil, as shown in Fig. 5-1 (C), the magnetic fields of the individual molecules are lined up with and by the field of the coil. Thus lines of force are added to the coil field, and the lines added by the magnetization of the iron are known as *lines of magnetization.* The resulting field in the core is the sum of the lines of force of the coil and the lines of magnetization of the core material. This total is known as the *lines of induction,* and the resultant effect in the core is known as the *magnetic induction* of the core material. This induction is defined as the total number of lines in a unit cross-section area in the core material and is represented by the symbol B, where

$$B = H + 4\pi I$$

and where I is known as the *intensity of magnetization* of the core material. This relationship is not very convenient to work with, since an evaluation of I requires consideration of pole strength and magnetic moment. These are difficult to evaluate with the odd-shaped cores used in most chokes and transformers. A more convenient evaluation of B is given through a consideration of magnetic *permeability.*

Permeability. Permeability may be understood from consideration of the effects which take place when the current is changed through a coil having a ferrous core. Changing the current changes the magnetizing force H, and the induction of the core (B) is measured for each value of the magnetizing force. Plotting B against H for common magnetic materials results in curves such as shown in Fig. 5-7. Note that most of the core materials represented in Fig. 5-7 exhibit an almost linear relationship between B and H for very low values of H. As H increases, B increases, first more rapidly, since lines of magnetization from the core material are added, and then less rapidly until a linear relationship is re-established. In this final stage the core is said to be *saturated,* since the only increase in B is that due to increases in H. The core is completely magnetized in this state and can contribute no additional lines of magnetization. *Permeability* or μ

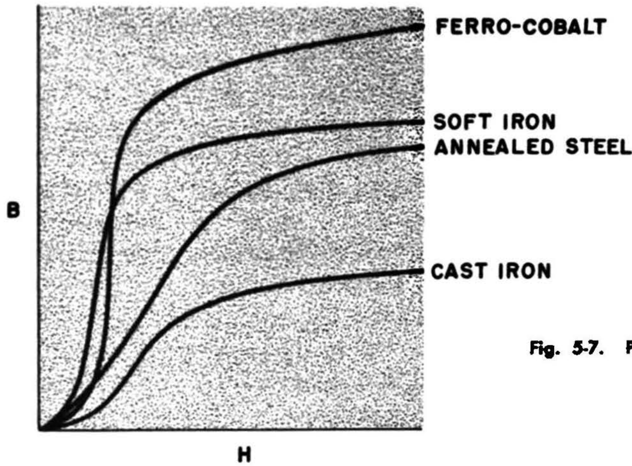


Fig. 5-7. Plot of B against H.

is defined as the ratio between B and H, and the use of this term permits the use of a new relationship:

$$B = \mu H \ .$$

It can be seen from the curves that permeability is not a constant but varies with the magnetizing force. This is a distinguishing characteristic of core materials. It can also be seen that permeability is different for different materials, with ferrocobalt having very high permeability with a high induction at saturation. In most applications high permeability is required at high induction with low hysteresis.

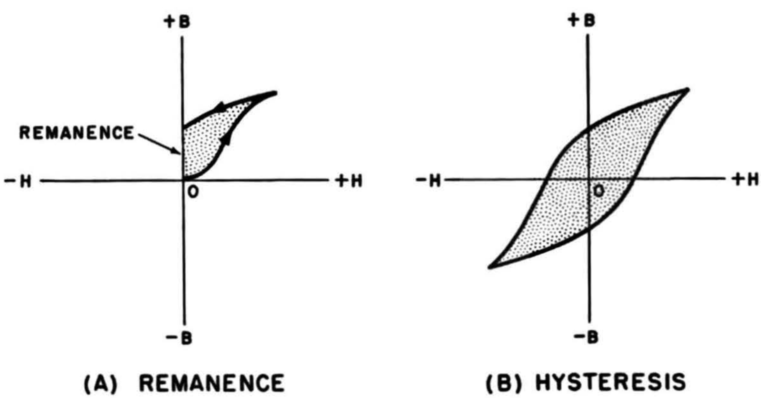


Fig. 5-8. (A) Remanence. (B) Hysteresis.

Hysteresis. When H is varied up to a maximum and then returned to O, the value of B changes as shown (typically) in Fig. 5-8 (A). Note that B does not decrease at the same rate as its initial rise. *Hysteresis* is the term used to define the lag of B behind H. Examination of the curve shows that B is not equal to zero when H is returned to zero. This residual magnetism is known as the *remanence* of the core material. For B to be returned to zero, H must be applied in the opposite direction. The H necessary to accomplish this is known as the *coercive force* of the core material. The terms remanence and coercive force are only seldom used, since they are indefinite characteristics which depend both upon the material and upon the values of H in use.

If ac is passed through the coil, the H-B relationship is (typically) as shown in Fig. 5-8 (B). Note that with a reversal of H, B also reverses in the same manner as described previously. The closed curve shown is known as a *hysteresis loop*. It can be seen from the curve that the magnetization of the molecules within the core tends to lag behind the applied field and that a definite amount of force is required to reorient the magnetic lines in the opposite direction. The area within the hysteresis loop is a measure of the energy expended in rearranging the magnetic lines of the core material, and this energy appears as heat developed in the core. It is desirable that core materials have a hysteresis loop of minimum area.

Chapter 6

Commercial Inductors and Transformers

INTRODUCTION

This chapter contains a survey of commercial inductors and transformers. The various basic commercial types will be reviewed according to their construction, fundamental applications, operating characteristics, and their outstanding physical and electrical features.

Most inductors and transformers may be classified according to certain features of construction which they share in common. Most have laminated ferrous cores, powdered ferrous cores, or air cores. In addition there are only relatively few methods of coil winding which are suitable for mass-production manufacturing, and most commercial inductors and transformers are wound according to one, or a combination, of these methods. Much duplication will be avoided by reviewing the basic core and coil types before considering specific inductors and transformers. Therefore, this topic is presented first.

After this is a survey of commercial inductors and transformers. Where applicable, these will be divided into power-line-frequency, audio-frequency, and radio-frequency types, and the individual features of each of these will be considered separately.

CORES AND WINDINGS

INDUCTOR AND TRANSFORMER CORES

Basic considerations. Commercial inductors and transformers can be divided into three main groups according to their use of core materials. It was mentioned in the previous chapter that the inductance of a coil can be increased by the use of magnetic core materials. When it is necessary to obtain maximum inductance in a minimum amount of space, ferrous cores are used whenever possible. These cores cannot be used at all frequencies, since the various losses and eddy currents increase with frequency. Eddy-current losses are the most serious, since they increase as the square of the frequency. Hysteresis losses are kept to a minimum by using materials such as silicon steels and nickel-iron or nickel-iron-copper alloys, which offer a minimum resistance to a reversal in magnetic direction of the minute magnetic components within the material.

Eddy-current losses can be minimized by dividing the material into sheets as thin as several thousandths of an inch or into small particles. The sheets or particles are electrically insulated from each other, which limits the possible paths and the length of the possible paths through which the current can flow. Eddy-current losses also can be minimized by using materials which offer high resistance to the flow of electric currents.

In spite of the existing methods for minimizing the losses involved in the use of ferrous core materials, such losses strictly limit the frequency range over which these materials can be used. Consequently, chokes and transformers designed to be used at frequencies below 20,000 cps may be constructed with magnetic core materials divided into thin layers. The layers used must be made increasingly thin as the frequency increases. The losses involved become increasingly significant above 5000 cps, and cores for use above this frequency are sometimes made of thin strips or ribbons of magnetic materials. At frequencies between 1000 and 5,000,000 cps or more, cores of compressed granular magnetic material are frequently used. At frequencies from about 0.5 to 5 mc, air cores are commonly used, and at higher frequencies air cores are almost exclusively used.

To summarize the effects of magnetic core materials, it can be stated that such cores provide three distinct advantages which are accompanied by three distinct limitations. The use of these cores may increase the inductance of a coil as much as two or three thousand times. This increase is generally automatically accompanied by an increase in Q, due to the definition of Q as outlined in the previous chapter. Since the magnetic lines necessarily follow the shape of the core, proper shaping of the core can result in confining the field so that it does not interfere with other circuits—thus cutting down on the amount of magnetic shielding required. Limitations of magnetic cores are that they

TYPICAL LAMINATED IRON-CORE INDUCTOR AND TRANSFORMER SHAPES

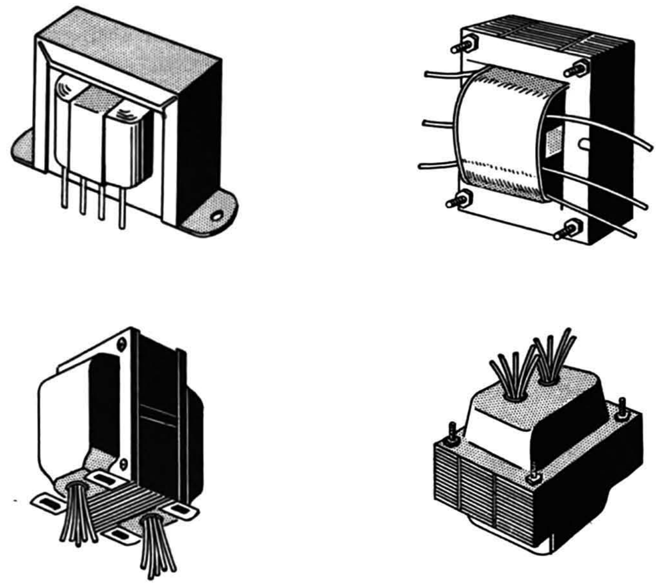


Fig. 6-1. Typical laminated iron-core inductor and transformer shapes. *After Chicago Standard Transformer Corp.*

saturate and thus restrict the gain in inductance, that they introduce hysteresis and eddy-current losses, and that their permeability is not constant for all values of current.

Laminated cores. Laminated-core types of inductors and transformers essentially consist of a core and one or more coils of wire, which are sometimes sealed in a container. Representative examples of unenclosed and encased inductors and transformers are shown in Fig. 6-1. This illustration shows the variety of transformer styles available from a single manufacturer. From outward appearances the only difference between chokes and transformers of this type is the number of leads or terminals appearing on the outside. Chokes almost always have only two leads or terminals which are unidentified by color or symbol. Transformers almost always have at least four or more leads or terminals, and these are always carefully identified by color or by stamped or engraved symbols or numbers.

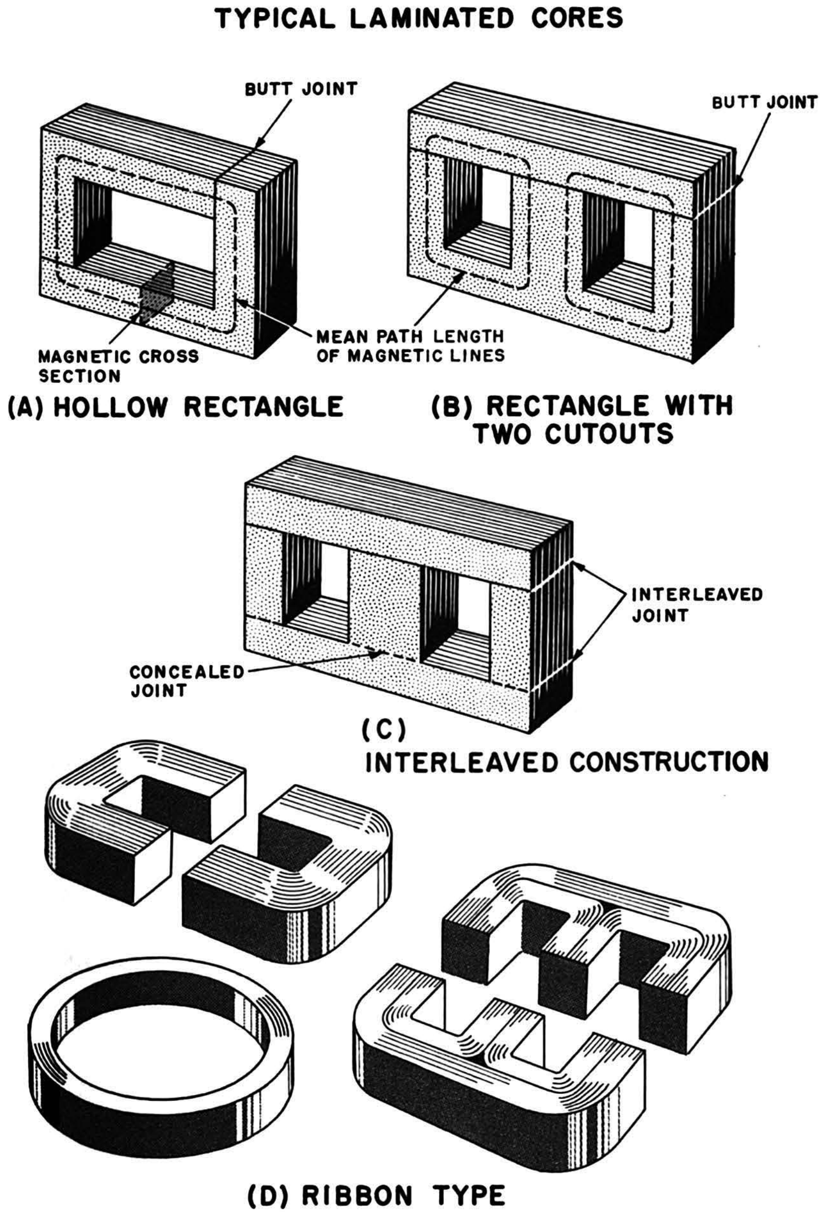


Fig. 6-2. Typical laminated cores. (A) Hollow rectangle. (B) Rectangle with two cutouts. (C) Interleaved construction. (D) Typical ribbon cores. *After Arnold Engineering Co.*

Typical laminated cores are shown in Fig. 6-2. These cores consist of a number of layers of thin sheet metal formed in the shape of a hollow rectangle or, more frequently, in the shape of a rectangle with two rectangular cutouts. Note that each lamination consists of two parts. The reason for this is that it simplifies the manufacturing process to wind the coil or coils separately, then to fit it onto one section of the core. Then the remainder of the core is assembled around the coil. The path length of the magnetic lines through the core material and the cross section of the path may be estimated from the diagram shown in Fig. 6-2 (A).

To reduce eddy-current losses, sheet metals used in inductor and transformer cores must be made thinner as the frequency of the expected current increases. At power-line-frequencies, lamination thicknesses are commonly in the range of 20 to 25 mils (thousandths of an inch). In the audio-frequency range, lamination thicknesses of 10 to 15 mils are commonly employed. At the upper end of the a-f band and for higher frequencies, the lamination thickness may range from 10 mils down to 1 mil. Since these sheets are never completely flat, and since they often are covered with various types of varnish or other materials for electrical insulation, the cross section of the magnetic material is not equal to the measured cross section of the stacked assembly. The percentage of magnetic material in the total cross section is called the *stacking factor*. For laminations of between 20 to 25 mils in thickness, the stacking factor is over 95%. For laminations of between 3 and 5 mils the stacking factor is between 70 and 80%.

A small air gap exists at the point where the two sections of the laminations join together. This gap can vary from several thousandths of an inch down to several ten-thousandths of an inch across, depending upon the care with which the ends are squared and leveled. Since this space is actually an air gap in the path of the magnetic lines through the core, the inductance of the coil can be adjusted, if desired, by varying the size of the gap. When it is desired to take advantage of this effect, as in the swinging choke, to be considered shortly, a spacer of insulating material is inserted in the gap; selecting a spacer of the desired thickness provides a convenient means of gap adjustment. When it is desired to minimize air-gap effects, the interleaved construction, shown in Fig. 6-2 (C), may be used.

The operation of a swinging choke is based upon the fact that the magnetization of the core by dc in the coil can be reduced by increasing the air gap in the core. In a swinging choke the air gap is adjusted to give maximum inductance at a point between maximum and minimum dc. Another method is to use a large gap in part of the core to provide the required inductance at maximum dc and a small air gap in another part of the core to provide about twice as much inductance for very small d-c drain.

Powdered-iron cores. Since eddy currents increase as the square of the applied frequency, cores constructed of laminated ferrous materials become unsuitable for frequencies above the audio range. To minimize eddy currents by causing further restrictions to the paths through which these currents can flow, the magnetic material is divided into small grains. The grains are mixed with insulating and binding materials and then are compressed at high pressure into the desired core shape.

Typical core shapes are shown in Fig. 6-3. This construction lowers eddy current and other core losses, and it lowers the permeability. Cores of this type permit high Q to be maintained at high frequencies. But in spite of the small size of the particles, eddy currents do still exist, and the particle size must be decreased as the frequency increases. For high audio-frequencies, particles as large as several thousandths of an inch are used, but for the vhf range particles must be as small as several millionths of an inch.

Coils employing powdered cores are generally wound in the same manner as for the air cores to be considered next. The use of the powdered core increases coil inductance by well over ten times. By employing mechanisms which permit adjusting the distance that a powdered core enters an air core, the inductance of the coil can be increased as desired. This is called *permeability* or *variable-reluctance tuning.*

Air cores. In an air-core inductor the coil is wound upon a rod or tube of insulating material. A powdered core may be inserted part way into the tube-type core to obtain permeability tuning. There are many considerations which go into the selection of the insulating material, but most of these are resolved by the coil manufacturer. The material should be strong, moisture resistant, and heat resistant. It should have a low thermal coefficient of expansion, low core losses, and be easy to shape or form. All of the materials in use are treated to obtain the most desirable properties. Common materials in use include porcelain, polystyrene, ceramics, glass, and Bakelite. Treated Bakelite is the least expensive and most commonly used material for coil forms.

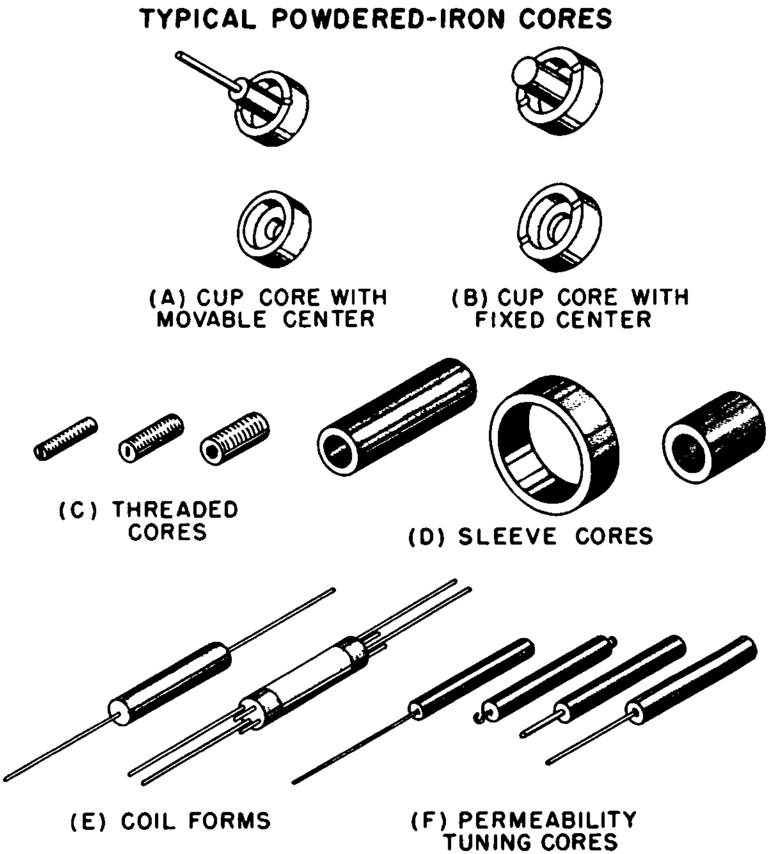


Fig. 6-3. Typical powdered-iron cores. (A) Cup core with movable center. (B) Cup core with fixed center. (C) Threaded cores. (D) Sleeve cores. (E) Coil forms. (F) Permeability tuning cores. *Courtesy Stackpole Carbon Co.*

Polystyrene is frequently used in more expensive coil forms, since it introduces extremely low power-factor losses, and has a moisture resistance second only to glass.

INDUCTOR AND TRANSFORMER WINDINGS

A great many types of windings have been developed for use in inductors and transformers. Only a few of these are suitable for commercial production, and these will be described here. After a brief discussion of the types of wire used, there will be a survey of the types of windings used with air-core and powdered-core inductors and transformers. This will be followed by a review of the types of windings used with laminated cores.

Types of wire. Solid copper wire with enamel insulation is the type most commonly used in inductors and transformers. Litz wire, mentioned in Chap. 5, is most effective in the region between 500 kc and 5 mc and has little advantage at other frequencies. If a single-layer winding is used with an air space between turns, uninsulated wire may be used. This wire may be tinned to provide ease in soldering taps to the coil, or it may be silver plated to reduce skin effect at high frequencies.

Alternate types of insulation include single or double layers of cotton, silk, or nylon, which may also be used in combination with enamel-coated wire. After the winding is completed, it is usually impregnated with varnish or other insulation. This prevents the absorption of moisture and provides some mechanical support to the winding.

Single-layer winding. The single-layer winding, shown in Fig. 6-4 (A), is the type most commonly used at frequencies from the top of the radio-broadcast band up to 200 mc or more. If the winding is made so close that the insulation of the individual turns touch, the coil has high distributed capacitance along with considerable dielectric and eddy-current losses. Because of variations in wire diameter and tightness of the winding, inductance variations up to 10% can be expected.

To provide a means of adjusting for these variations, about 10% of the total number of turns are sometimes spaced away from the rest of the winding. Adjustment is made by sliding individual turns from one winding to the other or by sliding the entire group of end turns closer to or further away from the main winding. Another method is the permeability method of tuning by inserting a powdered-iron core mounted upon a screw thread, as shown in Fig. 6-4 (B). Moving the core into the coil increases the inductance. If the initial inductance of the coil is made slightly low, moving the core into the coil will bring it to the value desired. If the initial inductance is high, a copper or brass band mounted on a core of insulating material can be used to lower the inductance to the desired value.

If the turns are wound in a spiral groove in the coil form, or if a suitable cement is used to maintain the spacing, uninsulated wire may be used. This lowers the distributed capacitance and the other losses. Fixing the winding in this manner also stabilizes the inductance with regard to temperature.

Multilayer windings. When increased inductance is required without increasing the length of the coil, additional layers of turns can be wound upon the first layer. The simplest method of

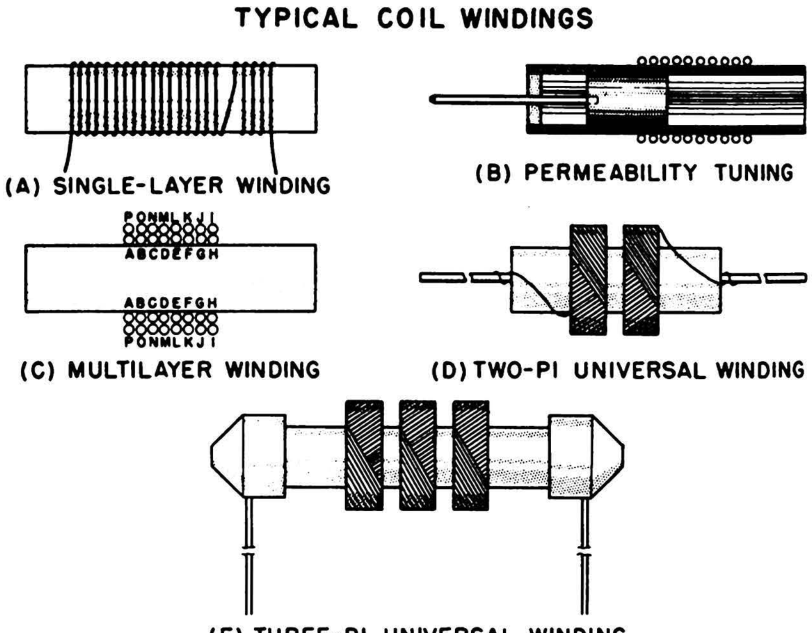


Fig. 6-4. Typical coil windings. (A) Single-layer (solenoid) winding. (B) Permeability tuning. (C) Multilayer winding. (D) Two-pi universal winding. (E) Three-pi universal winding. *Courtesy National Co., Inc.*

doing this would be to wind back and forth in the multilayer winding pattern shown in Fig. 6-4 (C). This type of winding has a high distributed capacitance, since wires with large potential differences are placed close and parallel to each other. While this effect can be tolerated at power- and audio-frequencies, the high distributed capacitance makes this type of winding unsuitable for rf.

Universal windings. The universal winding provides one method of adding more turns without obtaining the excessive distributed capacitance that is characteristic of multilayer windings. Universal windings are widely used in i-f and r-f transformers and r-f chokes. A universal coil is made by spiraling the wire back and forth during winding, and the result has an appearance similar to that shown in Fig. 6-4 (D). The crisscrossing of the wire holds the coil together without any supporting sidewalls. Distributed capacitance is low, since wires with large potential differences cross each other instead of being closely parallel.

When all the wire in the inductor is wound in a single coil of this type, the unit is known as a *single-pi inductor*. Distributed capacitance can be lowered even further by winding the wire into two or more sections, as shown in Fig. 6-4 (E). This is known as a *two-*, *three-*, or *four-pi inductor*, depending upon the number of sections used.

The inductance of a universal winding can be adjusted by the use of a powdered-iron core, as described previously. If a single-pi winding is loosely wound with only a few turns per layer, known as a *honeycomb winding*, the inductance can be increased by crushing the ends of the coil to decrease the overall length, while increasing the diameter. Or it can be decreased by crushing the circumference of the coil to decrease its diameter, while slightly increasing its length. If a multiple-pi winding is used, inductance can be increased or decreased respectively by squeezing the individual windings together or by spreading them apart. A single-pi universal winding can be made so that it is long with respect to the number of layers. The inductance of this type is most easily adjusted by permeability tuning.

The individual sections of a universal winding are manufactured in widths ranging from 1/16 to 1/2 inch. Inductance values range from several μhenries up to more than 1 henry.

Windings for laminated cores. Figure 6-5 (A) shows the basic type of coil winding used with laminated-core inductors and transformers. A rectangular fiber or paper form provides the base for the winding. The form is sized so that it will slide over the core and provide sufficient clearance at the ends when the core is assembled. Solid copper wire coated with insulation is wound upon the form, leaving a small unwound space at each end to guarantee that the core will not cut into the wire. A layer of specially treated paper is sometimes used as insulation between each layer of turns. This prevents turns with a large voltage difference from coming too close to each other—thus lowering distributed capacitance and permitting the use of only a thin layer of insulation on the wire itself. In addition, the use of paper insulating layers provides a mechanical gripping surface for the wire turns, and no special provisions are necessary to prevent the wire from slipping out of the open ends.

If the paper insulating layers are omitted, the result is known as a *random winding*. The number of turns in the same space may be increased by about one and a half times; but superior insulating material must be coated on the wire, distributed capacitance is

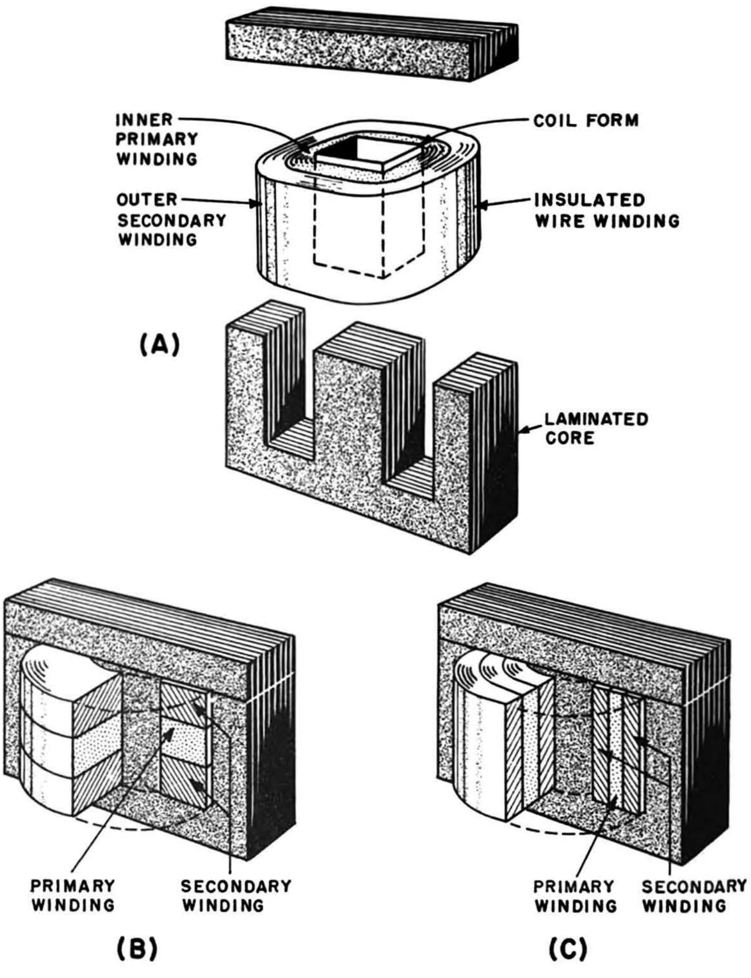


Fig. 6-5. Laminated core windings. (A) Coil on laminated core. (B) Side-by-side sectionalization. (C) Layer-by-layer sectionalization.

increased, and special holding devices must be used to prevent the turns from slipping off the ends of the form.

Either before or after assembly to the core, the coil assembly is vacuum impregnated with an insulating material which hardens after treatment. This provides additional mechanical support to the windings and prevents the absorption of moisture.

In laminated-core transformers the same basic techniques are used. The secondary winding or windings may be wound over the primary winding, with insulating layers used to separate the primary and the various secondary windings. There are special winding techniques which yield improved frequency response, balance between two identical secondary windings, and other special characteristics. These techniques include sectionalizing the primary and secondary windings either side by side or layer by layer, as shown in Fig. 6-5 (B) and (C) respectively.

A wide variety of combinations is possible. In addition, electrostatic screening may be used to prevent undesired signal pickup between the primary and the various secondary windings. This electrostatic screening may be obtained by placing wire layers which will be close to ground potential at the dividing layer between the different windings. Another method is to use grounded layers of insulated copper between the various windings.

SHIELDING

The purpose of shielding is to prevent the electrostatic and electromagnetic fields generated by a coil from interacting with other coils and other circuit components. Containers of high-conductivity metals are effective for both types of shielding. Electrostatic shielding is provided, since the container is connected to ground and shorts out stray electric fields. The conducting material in the container also generates eddy currents which oppose the magnetic field inducing those currents. Since eddy current increases with frequency, a given container provides better shielding as the frequency increases.

Aluminum shields are the most common. Copper shields are more effective due to their better conductivity, but they are more expensive. Shields of ferrous materials are sometimes used. Their usefulness stems from the fact that the stray magnetic field tends to concentrate within the magnetic material. Magnetic shields of this type are frequently supplemented by electrostatic shielding.

INDUCTORS

BASIC INDUCTOR TYPES

There are six basic types of applications for inductors in electronic equipment, and specific types of inductors are used for these purposes. Examples of typical circuits are shown in Fig. 6-6. *Filter chokes* are used in rectifier power supplies. In this application, the rectifier output is a d-c voltage which rises to a peak at a frequency usually equal to or twice that of the power line. The filter choke exhibits high reactance to the a-c component of the rectifier output, while it has a very low resistance for the d-c component. The a-c component is bypassed to ground by means of one or more capacitors (usually electrolytic) as shown in Fig. 6-6 (A), and the current that passes through the choke has only a small percentage of a-c ripple. When a very small load current is drawn through the coil, the magnetic field generated by the coil is insufficient to magnetize the core. Thus, a given choke will have a much smaller filtering effect for very low load-current drain than for its full rated load. In most power supplies the inductance of the choke is selected to have the required reactance when the normal minimum load current flows through it. If this minimum is very low, a resistor may be added in parallel with the load to increase the current. In those applications where a wide variation in the load current is expected, a *swinging choke* is used, as shown in Fig. 6-6 (B). The reactance of such a choke varies with the d-c load current through it so that the filtering effect is sufficient over the entire predicted current range. This type of choke is more economical for such applications than one which maintains essentially the same high inductance at large load currents as required for good filtering at small load currents.

Figure 6-6 (B) shows how *audio-frequency, video-frequency*, and *radio-frequency chokes* are used to connect d-c plate voltage to a tube across which a load is connected. In this example, the use of a choke permits almost full B+ voltage to be applied to the plate of the tube while providing high impedance to the signal voltage appearing at the plate. Although resistors are frequently used in such applications, a resistor causes a drop in the d-c voltage applied to the plate, thus producing less favorable operating conditions for the vacuum tube in some cases.

BASIC INDUCTOR CIRCUITS

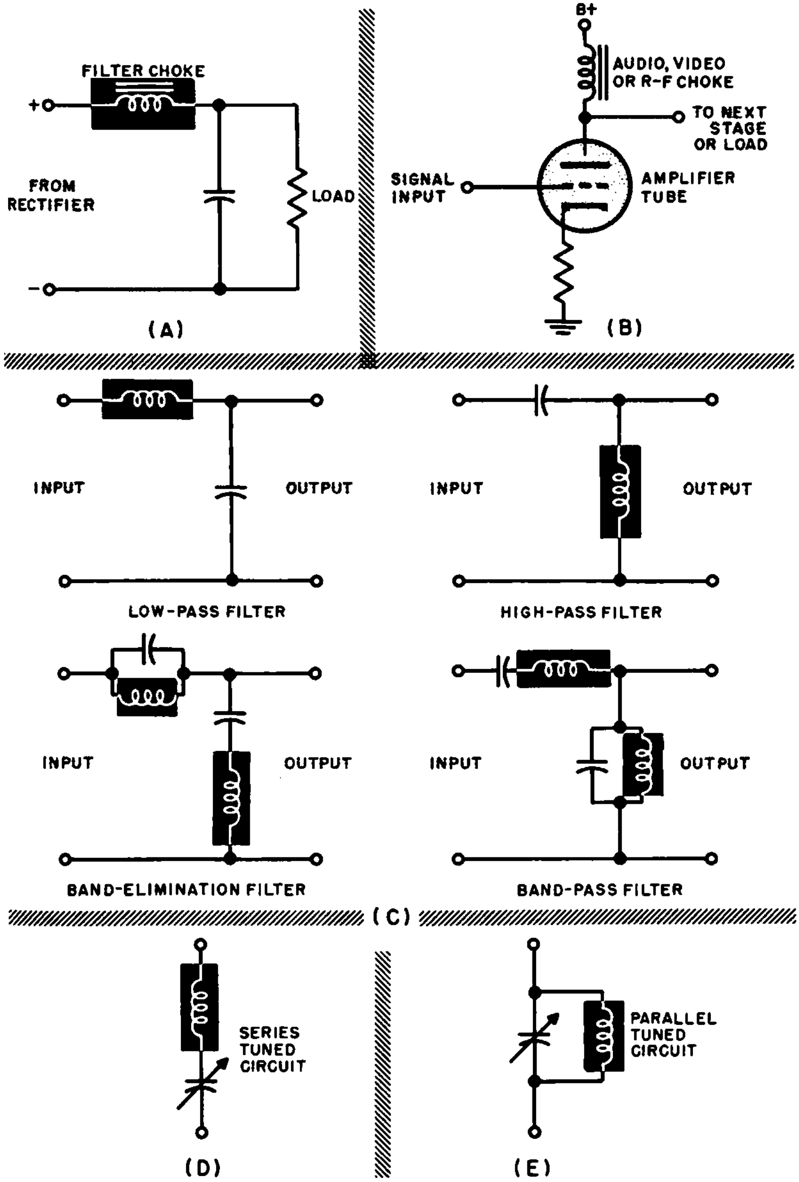


Fig. 6-6. Basic inductor circuits. (A) Filter circuit. (B) Plate-supply choke. (C) Special filter circuits. (D) Series-tuned circuit. (E) Parallel-tuned circuit.

Chokes are used in a wide variety of low-pass, high-pass, band-elimination, and bandpass filters [see Fig. 6-6 (C)] to eliminate signals of certain frequencies while allowing those at other frequencies to pass through. Analyses of these types of circuits fill many pages in texts on the subject of electronic engineering. Inductors are also connected either in series or in parallel with capacitors, as shown in Fig. 6-6 (D) and (E) in order to form *series- and parallel-resonant circuits.* These are used in receivers,

TABLE 6-1
Commercial Inductors

Power-Supply Filter Chokes and Swinging Chokes

Description: Encased or unencased iron-core units. Style and mounting varies with manufacturer.

Range of ratings—filter chokes:

henries	d-c ma	ohms d-c resistance	size	weight lbs.
20	15	900	1½ x 1½ x 3 in.	¾
6	500	75	7½ x 6 x 7 in.	24

Range of ratings—swinging chokes:

henries	d-c ma	ohms d-c resistance	size	weight lbs.
3-13	150-3	130	3¼ x 2½ x 2½ in.	2¼
4-16	500-50	75	7½ x 6 x 7 in.	24

Audio Chokes

Description: Similar in appearance to filter chokes. Ratings are generally at 200 cps.

Range of ratings:

henries	d-c ma	ohms d-c resistance	size	weight lbs.
130	5	6500	2¾ x 2¾ x 2¼ in.	1¾
16	50	600	2 x 3 x 1¾ in.	1

Video Chokes

Description: Universal coils wound on plastic forms or on shunt resistors. Powdered-iron-core types available.

Inductance range: 1 to 500 μh

Body size range: ⅜ in. long x 3/16 in. diam. to ⅞ in. long x 5/16 in. diam.

R-f Chokes

Description: Single- or multiple-pi universal coils with or without powdered cores.

Inductance range: 0.2 μh at 1000 ma to 125 mh at 75 ma. Many intermediate ratings. Average size 2 in. long x ½ in. diam.

transmitters, and other more specialized equipment to permit amplification of only the particular frequency to which the circuit is tuned.

Commercial inductors. Table 6-1 presents a survey of the outstanding features of the inductor types which have been mentioned.

TRANSFORMERS

COMMERCIAL TRANSFORMER TYPES

There are five basic uses for transformers in electronic equipment, and specific types of transformers are used for these purposes. Each type has a number of variations which also will be considered.

Power transformers are used in electronic equipment to supply high-voltage ac to rectifiers and low-voltage ac to vacuum-tube filaments. In addition, they also supply alternating voltages for other specialized purposes. While power transformers generally are not equipped with a means for adjusting the voltage obtained from the secondary windings, certain special types which do provide for such variation will also be considered.

Audio transformers usually are used in conjunction with electronic audio amplifiers and provide a means for coupling various types of inputs and outputs to and from the amplifier. In addition, they are used for other types of coupling, such as from line to loudspeaker in an intercom system. Five types of audio transformers will be reviewed.

Intermediate-frequency (i-f) and *radio-frequency* (r-f) *transformers* are used in radio and television applications to provide a frequency-selective coupling between amplifier stages. I-f transformers are adjustable in frequency, and they are almost always supplied as complete units together with tuning capacitors and shielding containers. R-f transformers are generally intended for use in tuned circuits which can be varied in frequency by the equipment operator. Because of this, the r-f transformer is generally supplied in the form of mounted coils, with or without a container, and the equipment manufacturer generally adds variable tuning capacitors and shielding as needed.

Pulse transformers are used in radar and other special applications. The input signal is generally a single half-cycle of square wave, the duration of which is frequently measured in μsec. The time interval between these input impulses may be measured in hundredths of a second or longer. The pulse transformer must step up or step down this signal as required by the application. Because of the extremely short duration of the input signal, a

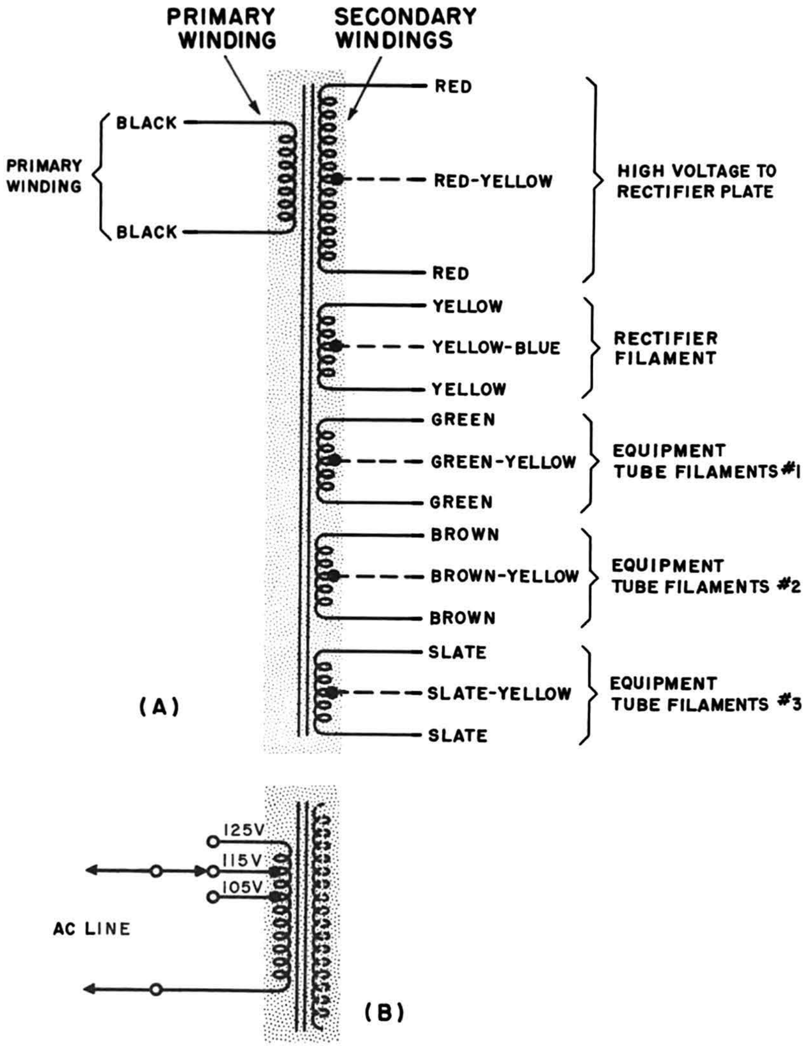


Fig. 6-7. Power transformers. (A) Color code for rectifier plate- and filament-supply transformer. (B) Transformer with tapped primary.

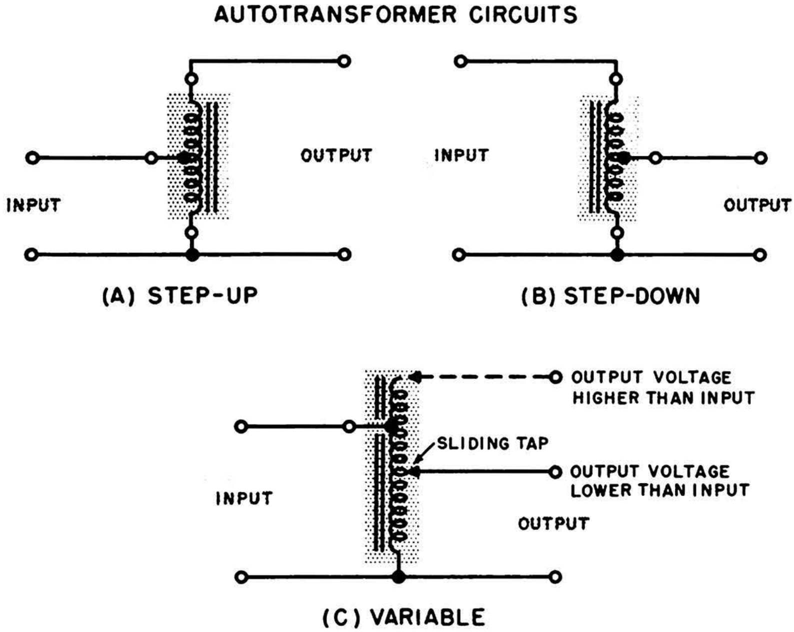


Fig. 6-8. Autotransformers. (A) Step-up. (B) Step-down. (C) Variable.

pulse transformer must have a number of special features to make the output signal an acceptable duplicate of the input signal.

In addition, there is a wide variety of specialized transformers available for use in television and special-purpose equipment. These types will be reviewed briefly without detailed consideration of the applications involved.

POWER TRANSFORMERS

Basic types. There are three basic types of power transformers in electronic equipment; schematic diagrams of these are shown in Figs. 6-7 and 6-8. *Rectifier-plate and filament-supply* transformers are the most common and have the most variations. The basic type is shown in Fig. 6-7 (A), along with the color code commonly used to identify the various leads. This type has a single primary winding and a number of secondary windings. Any of the secondary windings may or may not have a center tap, depending upon the requirements of the equipment in which it is used. Generally, one of the secondary windings steps up the power-line voltage for connection to the plates of a rectifier. When the rectifier is a vacuum tube, its filament is heated by a separate step-down winding. In addition, there is a step-down winding for heating the filaments of the various vacuum tubes in the equipment.

If it is necessary to isolate some of the vacuum-tube filaments from the others, separate step-down windings are used for the other filaments. Additional step-up or step-down windings also may be supplied as required for special purposes. Transformer manufacturers have available a wide variety of standard transformers of these types so that all usual requirements are met; additional special windings can be installed at extra cost.

The power-line voltage may be fairly stable, but it may vary from time to time. When the power-line voltage changes, the voltage outputs of all of the secondary windings also change, as determined by the turns ratios of the different windings. Certain types of equipment cannot operate properly if the secondary voltages are too high or too low by more than a small percentage. While special voltage-regulating circuits are available to compensate for such changes, the transformer itself (when furnished with the appropriate taps) can be used to correct such conditions. In such an event the transformer primary may be equipped with a number of taps as shown in Fig. 6-7 (B), and a switch can be used to connect the line voltage to the desired tap. When the equipment is set up for use, the operator measures the line voltage; then he sets the switch to the marked position which is closest to that voltage. Since the switching changes the number of turns in the primary winding, the turns ratios of the various windings are thus adjusted to obtain the desired output voltages.

An *autotransformer* has a single winding. Part of the single winding is common to both the primary and the secondary. If the transformer is of the step-up type, the secondary uses more turns than the primary, and if it is of the step-down type, there are fewer turns in the secondary. Schematic diagrams of both these types are shown in Fig. 6-8 (A) and (B) respectively. The principles of operation are identical to those previously described for transformers. A step-up transformer often may be used in step-down applications, and vice versa, by interchanging the primary and secondary connections. The advantage of the autotransformer is that it is somewhat lower in cost than a transformer with separate windings, since it is easier to construct due to the fact that less wire and less winding time are required.

A distinct disadvantage of this construction is that it does not isolate the secondary winding from the power line, and this is unsuitable in many applications.

The autotransformer can be used to distinct advantage when a particular and precise output voltage is required. For such applications, one of the secondary taps may be manufactured in the form of a sliding contact which can be moved from the outside of the transformer case. A schematic of this type is shown in Fig. 6-8 (C). By moving the sliding contact, the operator can change the turns ratio and obtain any high or low voltage that is in the range of the transformer. Transformers of this type are generally connected between the power line and the primary winding of a rectifier plate and filament supply transformer, thus permitting more precise and convenient voltage adjustment than is available by taps on the primary winding of the latter transformer.

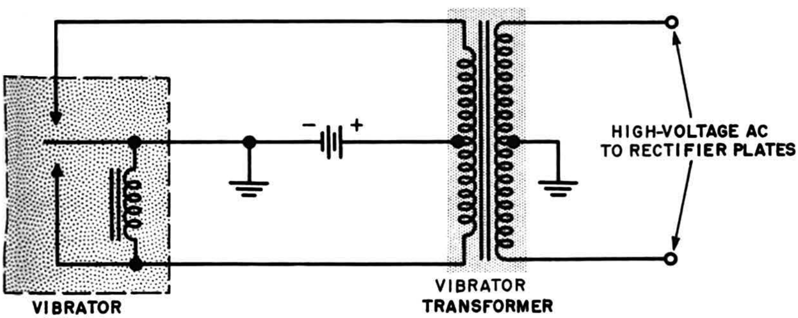


Fig. 6-9. Vibrator transformer hook-up.

This use is most common in laboratory setups, but variable autotransformers are sometimes installed in special equipment.

When high-voltage ac is required for a rectifier and the only available source of electric power is a low-voltage storage battery, a vibrator and *vibrator transformer* is sometimes used. A typical circuit is shown in Fig. 6-9, an arrangement common in automobile radios. The transformer is used only for supplying voltage to the rectifier, which is usually of the dry-metal type, and filament voltage for the vacuum tubes is obtained directly from the storage battery. In its operation the vibrator's moving contact swings back and forth and changes the battery voltage (by interruption) to the form of an a-c voltage with approximately a square-wave shape. This voltage is stepped up by the transformer. The major difference between this and previous transformers is that only one secondary winding is generally required, and a large turns ratio must be used to step up the 6- or 12-volt battery voltage to several hundred volts.

Commercial power transformers. Table 6-2 and the accompanying diagrams present the outstanding features of the power transformers which have been mentioned.

AUDIO TRANSFORMERS

Basic types. There are five basic types of audio transformers in general use. Schematic diagrams of typical applications and

TABLE 6-2
Power-Supply Transformers

Combination Rectifier Plate and Filament Supply			
Description:	Encased and unencased units with iron cores. Style and mounting varies with manufacturer. Ratings listed here are for 117 volts, 60 cps on primary.		
Range of ratings: rectifier plate	rectifier filament	other filaments	size
235-0-235 volts at 40 ma	5 volts at 2 amp	6.3 volts at 2 amp	3¼ x 3¼ x 2½ in.
1000-0-1000 volts at 300 ma	5 volts at 6 amp	6.3 volts at 5 amp	5½ x 5 x 6 in.
Filament Transformers—Single Secondary			
Description:	Same as for combination transformer. Primary is connected to a-c power line; secondary supplies filament voltage to equipment vacuum tubes.		
Secondary voltages:	2.5, 5.0, 6.3, 7.5, 10, 11, 12.6, 25.2		
Secondary current range:	2.5 volt—1.5 amp to 10 amp; 6.3 volt—1.2 amp to 20 amp; 10 volt—4 amp to 12 amp; 25.2 volt at 1 amp. max.		
Size range:	2.5 volt at 1.5 amp—1⅝ x 2⅞ x 1½ in.; 10 volt at 12 amp—5⅛ x 4⅝ x 8½ in.		
Vibrator Transformers			
Description:	Same as for combination transformer. Typical circuit is shown in Fig. 6-9. Direct voltage and current ratings are those obtained with synchronous vibrator.		
Range of ratings:			
secondary a-c volts	d-c volts at filter	dc	size
210-0-210	150	40 ma	2¼ x 2⅞ x 2⅝ in.
370-0-370	330	100 ma	3½ x 2⅞ x 2⅞ in.

color codes are shown in Fig. 6-10. All of these applications make use of the impedance-matching abilities of transformers. When a low-impedance phonograph pickup or microphone must be connected to the input grid of an amplifier, an *input transformer* is used as shown in Fig. 6-10 (A).

R-C coupling is widely used to couple the plate of an amplifier tube to the grid of the following stage, however, transformers are sometimes used for this purpose, as shown in Fig. 6-10 (B). Another useful application for interstage transformers is to connect the plate of an amplifier tube to push-pull amplifier grids in the following stage, as shown in Fig. 6-10 (C). If the grid or grids in the following stage or stages draw current, as in the case of a final audio-output stage, the transformer is known as a *driver transformer*. When the transformer couples the plate or plates of the final amplifier stage to a loudspeaker, as shown in Fig. 6-10 (C), it is commonly called an *output transformer*. In those cases in which an output transformer must be capable of matching a wide variety of speakers to a wide variety of final amplifier stages, a *universal matching* transformer (see Fig. 6-10D) is used. If the transformer is used to couple the final stage of an audio amplifier to one of the r-f amplifier stages of a transmitter, as shown in Fig. 6-10 (E), it is known as a *modulation transformer*.

Impedance effects. Impedance effects present serious limitations to transformer coupling unless special corrective measures are taken. The reason for this is that the inductive reactance of the primary and secondary windings increases with frequency. To illustrate this very quickly, consider only the inductive reactance of the primary winding. This reactance is equal to $2\pi fL$. Thus at frequencies of 100 and 1000 cps, the X_L of the primary winding is 10 times and 100 times higher respectively, than it is at 10 cps. This X_L in many applications appears as the plate-load impedance of the tube to which the primary winding is connected. As a result, unequal amplification takes place throughout the a-f range. As an example, the overall gain produced by an uncorrected transformer-coupled amplifier is about 2.5 times higher at 200 cps than at 10 cps. At about 3000 cps the gain is about 3 times higher than at 10 cps. At higher frequencies, capacitance effects become significant, and the gain drops very rapidly.

Transformer impedance matching. Impedance matching is a transformer function which finds widespread applications which have already been mentioned. In these uses the principles involved

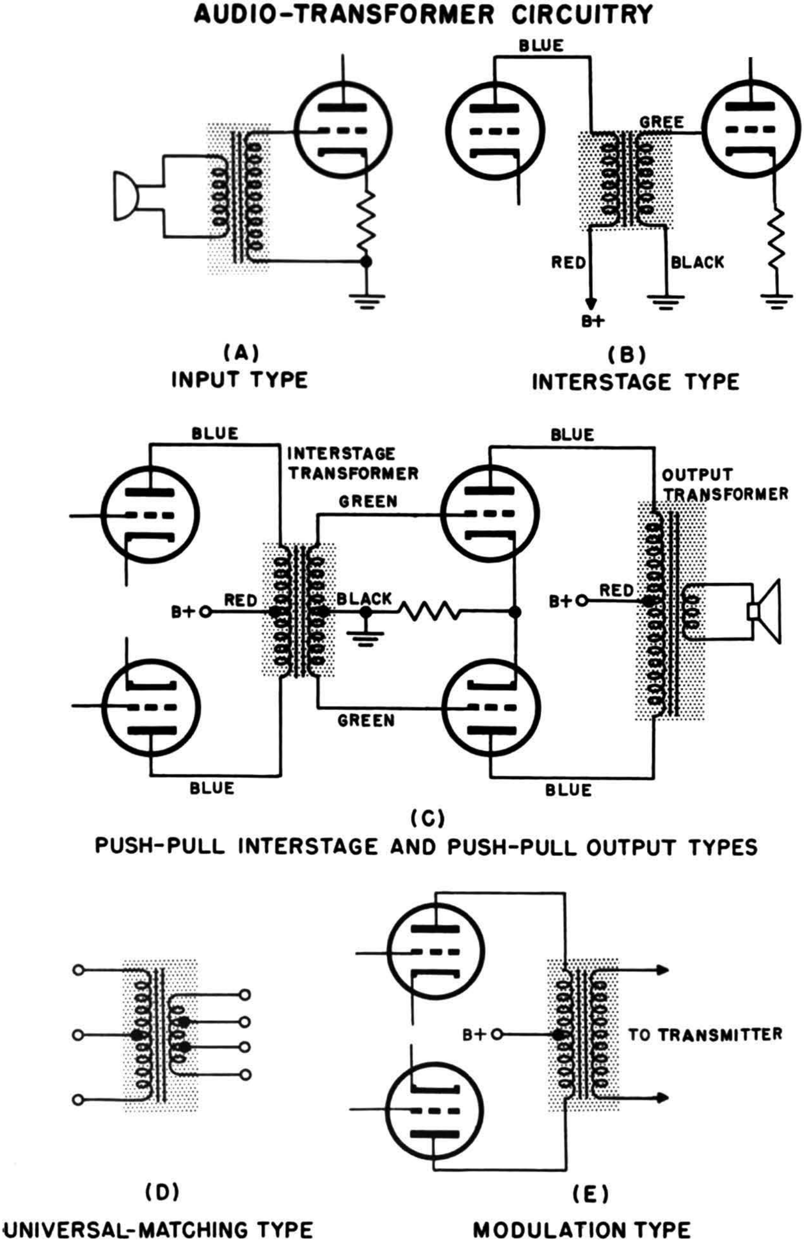


Fig. 6-10. Audio transformers. (A) Input. (B) Interstage. (C) Push-pull interstage and push-pull output. (D) Universal matching. (E) Modulation.

are always the same and are best illustrated by considering the impedance-matching characteristics of an output transformer. As was shown in Fig. 6-10 (C), an output transformer matches the high-impedance plate circuit of the final amplifier stage (several thousand ohms or a great deal more) to the low-impedance voice coil (from 2 to 16 ohms) of the speaker.

When there is no load connected across the secondary winding, there is no effect, or essentially no effect, on a load connected across the voltage source connected to the primary. If a load of resistance R_s is connected across the secondary, the load resistance R_p that is effectively applied to the primary is indicated by the relationship:

$$\frac{R_p}{R_s} = \left(\frac{N_p}{N_s}\right)^2 ,$$

where N_p and N_s represent the number of turns in the primary and secondary windings respectively. Thus the load matching characteristic of a transformer is determined by the turns ratio of the windings.

If the turns ratio is selected according to the above relationship, the voltage appearing across the primary and secondary windings is as follows:

$$\frac{R_p}{R_s} = \left(\frac{V_p}{V_s}\right)^2 ,$$

where V_p and V_s are primary and secondary voltages, respectively.

The problem of manufacturing impedance-matching transformers for electronic equipment is not an insurmountable one, since there are a limited number of applications in which this technique is used and there is a high degree of standardization in primary and secondary loads. Thus, almost all impedance matching problems encountered in practice can be resolved by a rather limited number of such transformers.

Unusual cases can be solved frequently by the use of so-called *universal-matching* transformers. These have a secondary winding with a number of taps, and sometimes the primary winding has a center tap, as shown in Fig. 6-10 (D). The transformer input can be connected across either the entire primary winding or across half of the primary winding. The transformer load can be connected across any two of the connections to the secondary winding. Consequently, a number of turns ratios are available from a single transformer. It is the number of turns actually connected in the primary and secondary circuits that determines the ratio, and the number of unconnected turns is not involved.

All of these various types of audio transformers are available as cased or uncased units. Appearance and mounting types vary with the manufacturer. Midget types are available which easily fit within a 1-inch cube and weigh less than ½ ounce. Universal output transformers are available to supply 75 watts to a speaker voice coil. These transformers measure about 5 by 4 by 4 inches and weigh about 8 pounds. Even larger output transformers are available for use with high-fidelity equipment.

Transformers for transmission lines. The audio transformers mentioned in the previous paragraphs are generally used under conditions in which the two components to be coupled together by the transformer are located no more than a few feet apart. In sound studios, theaters, intercom systems, and large hi-fi installations the use of the equipment often requires that microphones, record player pickups, amplifiers, and speakers be located tens, or even hundreds, of feet apart. If a high-impedance microphone or record player pickup is separated from its amplifier by such distances, there may be excessive noise pickup from surrounding power lines and other equipment.

Connecting low-impedance devices, such as the secondary of an output transformer to a speaker voice coil, over such distances may result in sound power loss when the resistance of the connecting wire reaches a significant fraction of the voice coil impedance. *Transmission-line arrangements* are used to make such couplings with maximum efficiency. The choice of components for these arrangements depends upon the impedances of the devices to be connected, and the signal level involved.

The distant devices are connected together by means of *line transformers* and transmission lines. Characteristic impedances of a-f transmission lines in common use are 30, 50, 250, 500, 1000, 1500, and 2000 ohms. A wide variety of line transformers, such as microphone-to-line, line-to-grid, plate-to-line, line-to-speaker, etc., are used, as appropriate to the devices to be connected. The specifications for such transformers include a statement of the impedances of the device and transmission line for which they are intended.

Commercial audio transformers. The various types of audio transformers mentioned previously are available as cased or uncased units. Appearances and mountings vary. The size and weight range from subminiature input types, which measure about 1/8 by 1/8 by 3/4 inches and weigh about 0.02 pound to standard universal output types measuring about 5 by 4 by 4 inches and weighing about 8 pounds. Even larger output transformers are available for use with high-fidelity sound equipment or amateur radio applications. Because of the many variations, a survey of these transformers does not lend itself to a simple listing. Instead, the paragraphs which follow present a descriptive review which includes the most outstanding characteristics and functional variations.

Input transformers have turns ratios ranging from approximately 1 to 10 through approximately 1 to 100. These are usually used for low-impedance devices such as speaker-type microphones, carbon microphones, and low-impedance dynamic microphones or pickups. Typical primary impedances are 4, 8, 15, 30, 50, 125, 200, 250 and 500 ohms, with and without center taps. Typical secondary impedances for line input include 50, 125, 200, 250, 300 and 500 ohms. For input to grids the secondary impedances range from about 50,000 ohms to about 1.5 megohms. Many input transformers have multiple primary and secondary taps to make them useful for a wide variety of impedance conditions. Input transformers are most commonly divided into the microphone-to-line, line-to-input-line, microphone-to-grid, pickup-to-grid, and line-to-grid types.

Interstage transformers have turns ratios generally ranging from 1 to 1 through 1 to 4. Primary impedances commonly range from 5000 to 20,000 ohms and secondary impedances from 10,000 to 200,000 ohms. Some types are available with center taps in either or both windings. Multiple-purpose types have center-tapped primaries and split secondary windings permitting a variety of step-up or step-down connections for single-ended or push-pull stages. Interstage transformers are generally of the single plate-to-single grid, single plate-to-push-pull grid, push-pull plate-to-single or push-pull grid, and push-pull plate-to-parallel grid types.

Driver transformers are interstage transformers used in high-power audio amplifiers, usually between the final and next-to-final stages. These are generally of the single plate-to-push-pull and/or push-pull plate-to-push-pull grid types. The secondary windings generally are designed to carry more current than ordinary interstage transformers. There is a type for 500-ohm line to push-pull grids, and this has a center-tapped primary. Turns ratios range from 1 to 0.75 through 5 to 1. The maximum current ratings range from 5 to 150 ma per section.

Modulation transformers are commonly divided into two groups. The plate modulation type has a center-tapped primary with impedances ranging from 5000 to 15,000 ohms and secondary impedances ranging from about 3000 to 10,000 ohms. Power ratings extend from 2.5 to 250 watts or more. The multiple-match type has tapped primary and secondary windings so that impedances of from 2000 (or less) to 20,000 ohms (or more) can be obtained in either winding. Power ratings extend from 10 to 500 watts or more.

Output transformers are of the single plate-to-voice coil, push-pull plate-to-voice coil, single and push-pull plate-to-line, line-to-voice coil, universal, hum-reducing, ultra-linear and crystal-cutter types. Primary impedances generally range from about 1500 to 30,000 ohms. (Primary impedances of the line-to-voice coil types are of the order of 250 or 500 ohms.) The most common secondary impedances for voice coil use are 2, 3.5, 4, 6, 8, 15, and 16 ohms. Power ratings extend from about 2 to 100 watts.

R-F AND I-F TRANSFORMERS AND INDUCTORS

Radio-frequency (r-f) and intermediate frequency (i-f) transformers are used to couple the various r-f and i-f stages of radio and television receivers (and transmitters). In both these types of transformers, either the primary or secondary or both windings are tuned to a particular frequency, usually by connecting a capacitor across them. In some cases the winding is tuned by its own distributed capacitance or the input capacitance of the associated tube stage.

Tuned transformers are used for this purpose because receivers are intended to amplify only a very limited band of frequencies or—in a radio transmitter—only one frequency at a particular time. Using a capacitor to form a parallel-resonant circuit with one or both windings causes a high impedance to be presented only to signals at or close to the resonant frequency. Signals at other frequencies "see" only a low impedance and are effectively shorted out.

Both r-f and i-f transformers are very similar in construction and operation. The major difference is that r-f transformers are usually used in conjunction with at least one variable capacitor or variable inductor so that they can be tuned to the desired frequency by the equipment operator. On the other hand, i-f transformers are always tuned to the same frequency. Therefore, these are supplied with adjustable capacitors or inductors which are set by the equipment manufacturer (or service technician) and require no adjustment by the equipment operator.

There are literally dozens of types of special transformers and inductors available for use in broadcast-band radio, communications receivers, f-m radio, and television, plus industrial and military electronics. The major features of all of these various types will be brought to light by a consideration of typical r-f and i-f transformers and oscillator coils used in broadcast-band receivers. The other coils and transformers mentioned have basically the same features and differ mainly in the frequency of operation and in the addition of extra windings. Manufacturers' condensed descriptions of these coils and transformers generally list only the specific characteristics that are important in the use of each part. It is common to find some, but not all, of the following characteristics listed: size, case style, weight, turns ratio, primary and secondary resistance and impedance, Q, voltage and current ratings, and special features.

Capacitance-tuned r-f transformers. The general construction of the most commonly used types of broadcast-band r-f transformers, and typical circuits, are shown in Fig. 6-11. The coils are generally wound upon forms of treated compressed paper or Bakelite, although polystyrene is often used in more expensive equipment designed to operate at higher frequencies. Adjustable powdered-iron core inserts are frequently mounted in the coil form to provide a convenient means for adjusting the coil inductance.

In broadcast-band transformers, universal and honeycomb windings are widely used to obtain the required inductance with minimum distributed capacitance. At higher frequencies, which require less inductance, the same effect can be obtained with single-layer windings. The coupling between the coils may be fixed by the transformer manufacturer, as shown in 6-11 (A), for best operation in standardized circuits. It is fairly common for the equipment manufacturer to order r-f transformers manufactured to particular specifications for best operation in specially designed circuits.

Standard r-f transformers are also available with a construction which permits the coupling between the primary and secondary windings to be adjusted as required by the equipment builder. This may be accomplished by mounting the primary winding on a circular collar which can be moved along the length of the coil form, or, as shown in Fig. 6-11 (B), by mounting the primary so that it can be moved along an insulating rod mounted at right angles to the secondary coil form. Frequently the rod angle is adjustable. R-f transformers are available with or without shield cans. The use of shield cans depends upon the proximity of other circuits in the equipment layout.

Figure 6-11 (C) shows a common circuit arrangement for using an r-f transformer to couple an antenna to an r-f amplifier tube

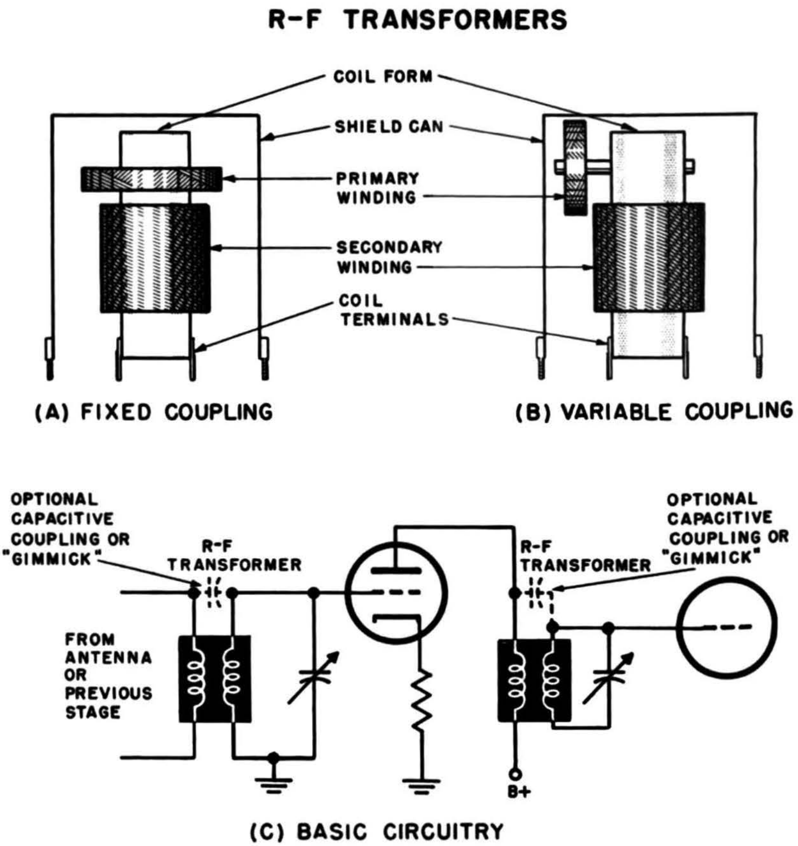


Fig. 6-11. R-f transformers. (A) Fixed coupling. (B) One type of variable coupling. (C) Basic circuits.

and a circuit for coupling two r-f amplifier tubes. Note that it is common for only one of the transformer windings, usually the secondary, to be tuned by means of a variable capacitor. Although increased gain may be obtained by using ganged capacitors to tune both windings simultaneously, this extra gain is generally considered insufficient to justify the increased cost and space requirements of the added capacitor.

Gain is more economically obtainable by means of i-f amplifiers generally included later in the same equipment. The most usual arrangement is to use a high-impedance primary winding without a variable capacitor. The stray capacitance in the primary circuit, and sometimes an added fixed capacitor, is used to resonate this winding at approximately 0.7 times the lowest frequency to be amplified.

The result of tuning the primary winding in this manner is that the overall transformer gain at the low-frequency end of the tuning range is higher than at the high-frequency end. Gain at the upper frequencies can be increased by using capacitive coupling between the windings, as shown by the dotted capacitor in Fig. 6-10 (C). Although a small capacitor can be used for this purpose, it is more convenient to connect a piece of wire to the primary and to twist it in one or more turns around the insulated secondary winding. This device is called a "capacitive winding" or, more popularly, a "gimmick," and it adds from 1 to 10 $\mu\mu$f of coupling between the two windings.

The most common type of r-f transformer for use in broadcast-band equipment can be tuned from 500 to 1700 kc when connected to a variable air capacitor with an approximate range of 15 to 400 $\mu\mu$f.

Inductance-tuned r-f transformers. In the interests of space saving and economy of manufacture, special r-f transformers are made with a powdered-iron insert which can be moved freely inside the coil form to accomplish variable permeability tuning. The iron core is connected to the receiver tuning knob (or adjustment screw) by a special mechanism which varies the position of the core inside the coil form as the knob (or screw) is turned. The position to which the core is set by the tuning knob adjusts the inductance of the coil so as to resonate it at the desired frequency with a fixed capacitor connected across the ends of the coil.

Either or both coils of the transformer may be tuned in this manner. Except for the method of tuning, the principles involved are the same as for capacity-tuned r-f transformers. Inductance-tuned transformers are generally made to order for equipment manufacturers, and, to date, there is no large selection of standardized types available, as is the case with capacity-tuned types.

Oscillator coils. All superheterodyne receivers contain an oscillator stage. Of the many oscillators which can be used, there are only two basic types of oscillator coils which meet the requirements of most types of superheterodyne oscillator circuits. The general appearance and construction of an oscillator coil unit is almost identical to that of the capacitance-tuned r-f transformers which have been described. Some oscillator coil units have two universal windings, and these are used in conjunction with pentagrid converter oscillator circuits. Another type has a single winding with a tap. Most broadcast oscillator units are designed for use in conjunction with variable air capacitors with a maximum capacitance of 365 $\mu\mu$f. With such a capacitor they can be tuned over a range of from 540 to 1600 kc.

I-f transformers. I-f transformers are constructed in very much the same manner as r-f transformers. However, the i-f transformer is always tuned to the same frequency, and no adjustment is required by the equipment operator. This means that ganged variable capacitors are unnecessary for tuning, and both windings can be set to the desired frequency either by adjustable air or mica capacitors or by means of fixed capacitors and adjustable powdered-iron inserts in the coil form. Both of these tuning methods are economical and are in widespread use. Construction details of one of the types employing adjustable air capacitors are shown in Fig. 6-12 (A). Although adjustable air capacitors are commonly used in more expensive units, compression-type mica capacitors are used in lower-cost units. Ceramic trimmers, with or without supplementary temperature compensation, are used in special-purpose units.

When permeability tuning is employed, the construction is generally the same. The variable capacitors are omitted, and fixed mica or ceramic capacitors are used instead. The upper coil is tuned by an adjustable powdered-iron core which is set to the desired position by means of a screw adjustment at the top of the coil form, while the lower coil is adjusted by means of a similar arrangement at the bottom. A typical unit of this type is shown in Fig. 6-12 (B).

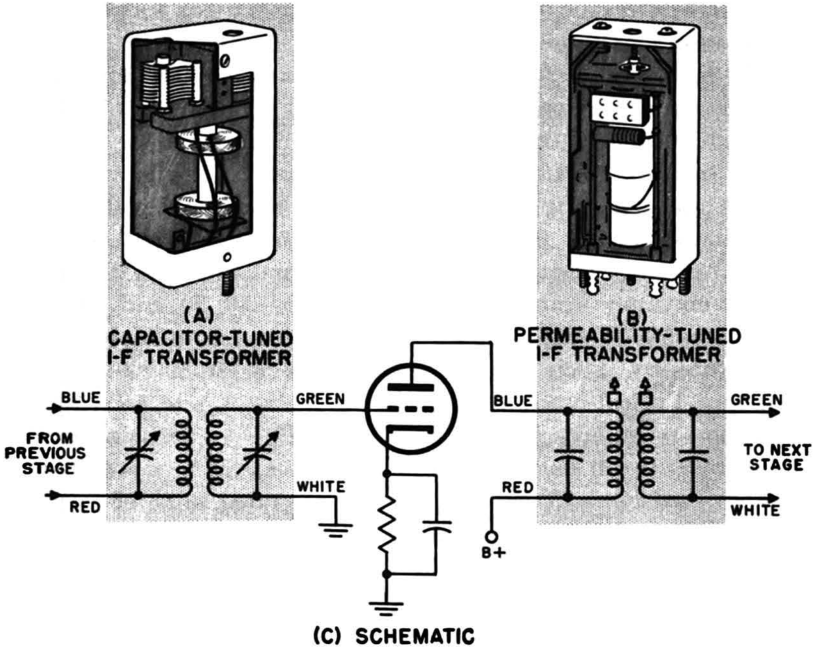


Fig. 6-12. I-f transformers. (A) Capacitor tuned. (B) Permeability tuned. (B) Basic circuits.

Figure 6-12 (C) shows a typical schematic with color coding. For illustrative purposes, the first i-f transformer is shown as capacitor tuned and the second i-f transformer is illustrated as permeability tuned.

In broadcast-band equipment, i-f transformers usually are designed for tuning to a frequency of 455 kc. Frequencies commonly used in i-f circuits of television and communications receivers are 4.5, 10.7, 21, 30 and 41 mc.

OTHER TRANSFORMER TYPES

Extensive developments in television and military and industrial electronics have led to the development of a large variety of special-purpose transformers and inductors. To make a comprehensive review of the function and special characteristics of these units would require including extensive information which is beyond the scope of this book. However, to give the reader at least a summary of the most outstanding types, the paragraphs which follow review the most important electrical specifications of the most widely used types.

Television deflection yokes contain coils for the horizontal and vertical deflection of the picture-tube electron beam. Each coil is divided into two halves for location on opposite sides of the picture-tube neck, and all four coil sections are mounted in a single unit which fits around this neck. Horizontal coil ratings range from about 8 mh, 13 ohms to 30 mh, 45 ohms; vertical coil ratings range from about 3.5 mh, 3.5 ohms to 50 mh, 65 ohms. Typical maximum scan angles include, 50, 54, 70, 90, and 110°.

Television filter chokes are intended for use in high-voltage power supplies. Their insulation ratings range from 500 to 3000 volts rms. Typical inductance ratings are about 3 henries at 50 ma (200 ohms resistance), 1 henry at 300 ma (43 ohms resistance), and 10 henries at 100 ma (225 ohms resistance). Inductance values are also listed for various percentages of the rated value of current, such as 75% and 115% off the rated ac in ma.

Television focus coils are designed for mounting in the desired position around the neck of the picture tube. D-c resistances range from about 200 to 1000 ohms, current ratings from about 75 to 200 ma.

Television high-voltage oscillator coils are intended for systems using separate high-voltage power supplies. The coil ratings extend from about 8000 volts at 350 μa to about 30,000 volts at 50 μa.

Television width coil specifications list the inductance range and resistance of each coil. Typical inductance ranges extend from 0.05 to 0.50 mh up through 1 to 10 mh. Typical resistances are 0.5 to 30 ohms. Width coils are available with automatic gain control windings of typically 2.7-7.6 mh, 19.5 ohms, or 0.16-70 mh, 1 ohm. Some types can be used as either width or linearity coils. *Linearity coil* specifications also list the inductance range of the coil, which is generally in the same order of magnitude as for width coils. Linearity coils are also available with tapped windings.

Television horizontal output transformers are commonly known as "flybacks." Their ratings range for conditions such as 50° scan with 10,500-volt second anode, 320-volt B+, 420-volt boost; and 110° scan, 21,000-volt anode, 300-volt B+, and 480-volt boost.

Television vertical blocking-oscillator transformers are available in a variety of mounting styles and with a range of turns ratios from about 1 to 0.5 through 1 to 4.2. *Horizontal blocking-oscillator transformers* typically have a turns ratio of 2 to 1 and are usually available in either open construction or in completely enclosing cases.

Television vertical deflection output transformers most frequently have turns ratios in the range of from 6 to 1 through 70 to 1. The primary impedances range from about 3000 ohms at 40 ma dc to about 30,000 ohms at 10 ma dc.

Television booster and converter transformers are usually intended for use with a plate supply rated for 120- or 150-volts ac and a d-c current of either 25 or 50 ma. The filament supply is generally 6.3 volts at from 0.5 to 1.5 amperes.

Photoflash transformers have been developed for use with photographic "strobe" lights. Their weight is generally less than 2 pounds and sometimes as low as 0.2 pound. Different models are available for different input power sources, such as: 4- or 6-volt d-c vibrator, 117 volts ac, or discharge from a charged capacitor. The output windings are intended for use in d-c circuits of about 450 to 2200 volts.

Transistor transformers are intended for use with transistors in miniature and subminiature equipment. These transformers have primary and secondary winding arrangements similar to those used for equivalent vacuum-tube circuits. Some transistor audio transformers will fit inside a ½-inch cube and others will fit into a ⅜-inch cube. Types intended for r-f and i-f amplifiers generally measure ½ by ½ by ¾ inches or smaller. Due to the characteristics of transistors, the primary and secondary impedances of the associated transformers often differ from those found in equivalent vacuum-tube circuits, for example, transistor-to-speaker transformers where typical primary impedances are 25, 50, 200, 250, and 500 ohms.

Pulse transformers and inductors, used in radar and industrial equipment, operate in conjunction with pulses ranging from about 0.10 to 100.0 μsec in duration at repetition rates from about 500 to 500,000 pps (pulses per second). The peak power handled in these circuits may be as low as millionths of a watt or higher than 10 million watts. The types of circuits used in conjunction with pulse signals are even more extensive than those found in television equipment. Because of the wide range of conditions under which pulse transformers and inductors are used, there are many basic types and many variations. Sizes range from as small as a cigarette filter to larger than heavy-duty power transformers in large TV sets.

PRINTED CIRCUITS AND COMPONENTS

A discussion of "printed" resistors, capacitors, and inductors has been reserved until this time because these units are most frequently combined, together with their associated wiring, in a single compact unit.

Printed circuits. The purpose of printed and etched circuits is to achieve complete equipment units or sections of minimum size. The most common type of "printed" circuit is actually an etched circuit. It consists of a sheet of insulating material to which a thin sheet of copper is bonded. A network of acid-resisting material is deposited over the copper by silk screening, printing or photographic techniques. An acid bath is used to etch away the unprotected copper.

The remaining copper is in the form of thin bands which duplicate the function of the wires which interconnect the components on a standard circuit board. Soldering terminals, and often tube socket terminals, are etched into the copper and have holes drilled completely through them and through the board. This permits standard circuit components and subminiature tubes or transistors to be soldered directly to the board. Truly "printed" circuits have the same form, but the copper bands are replaced with a silver-bearing, highly conductive ink which is printed or silk screened directly onto the insulating board. An etched board with mounted components is shown in Fig. 6-13.

Printed components. Although standard or miniature resistors, capacitors, and inductors are generally used in conjunction with

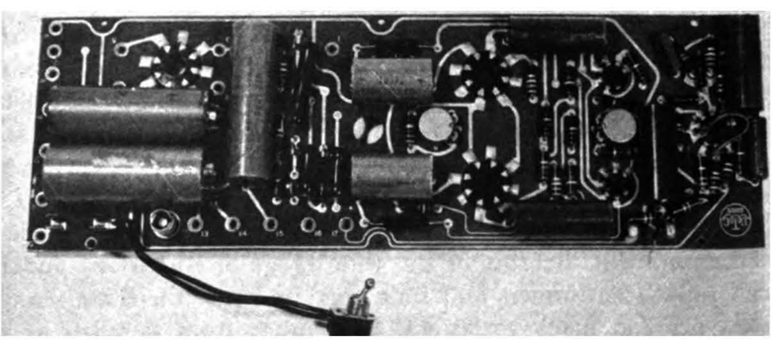


Fig. 6-13. Etched board with assembled components. *Courtesy Photocircuits Corp.*

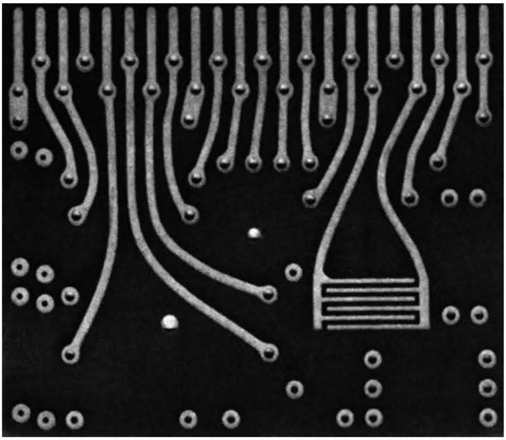


Fig. 6-14. Plug-in circuit with printed capacitor. *Courtesy Photocircuits Corp.*

printed circuits, these components are often printed directly onto the board.

Resistors are made by printing, silk screening or stenciling a straight or "zigzag" line of conductive ink between two printed terminals. The total resistance of this printed unit is determined by the length, width, and thickness of the ink line and by the conductivity of the dried ink. The ink consists of minute metal particles mixed with an insulating binder and a solvent. Once the solvent dries, the conductivity of the ink is determined by the proportions of metal and binder. It can be seen that there are four factors which affect the final total resistance and that a high degree of precise control is necessary in order to obtain the desired value. Because of the special techniques involved, few equipment manufacturers attempt to make their own printed resistors. An equipment manufacturer wishing to make use of printed resistors can order the modular units, to be considered later, or he can order to his specifications a printed circuit board from a company specializing in such services.

Coupling capacitors can be made by printing or etching techniques. Capacitors made in this manner are similar in construction to fixed air capacitors. Two parallel lines of conductive material are formed close to each other (see Fig. 6-14). The capacitance obtained depends upon the length, thickness, and width of the lines, the distance between the lines, and the dielectric constant of the combined insulation and air between them. Higher values of capacitance can be made by printing a number of parallel lines and interconnecting them to simulate the construction of a multiple-plate fixed air capacitor. Printed capacitors can also be made by forming large flat areas of conductive material on opposite faces of the insulating board.

R-f coils can be constructed by printing or etching techniques. Since even a straight line of conductive material has inductance, it is possible to increase the inductance by forming a number of

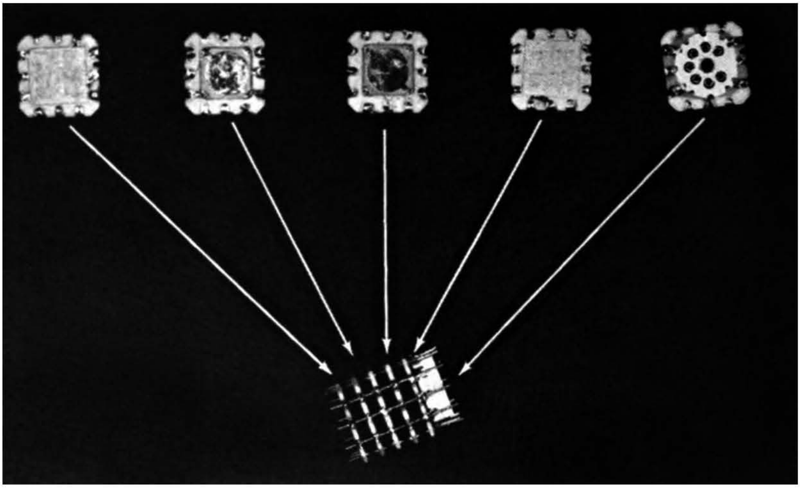


Fig. 6-15. Component parts of a module. Wafers contain tube socket, capacitors and resistors. Courtesy *National Bureau of Standards*.

parallel lines and connecting the ends to form a long zigzag path. Additional increase in total inductance can be obtained by decreasing the spacing between the lines. It is possible to make r-f transformers by meshing together two such constructions.

As in the case of printed resistors, the manufacture of printed capacitors and inductors requires a high degree of precision. The usual alternatives for the equipment manufacturer are to order standard modular units or to have printed circuit units manufactured according to his specifications.

Modular units. Modular units are constructions which contain combinations of the printed and etched components considered previously. Standard miniature resistors, capacitors, and inductors are sometimes also combined into the construction. The complete unit is encased in a jacket of insulating material, and the connecting leads or terminals protrude from the jacket. Sometimes the modular units are made in the form of flat rectangles which can be fastened together with other similar units in a "Tinkertoy" construction (see Fig. 6-15). Such assemblies can be used to make up one or more equipment stages, including sockets for miniature tubes or built-in transistors. Typical standard modular constructions that are available include cathode followers, video limiters, d-c regulators, dual cathode limiters, video amplifiers, etc.

There are relatively few complete standard modular units of the type mentioned. On the other hand, there are many basic single-package units consisting of one or more printed resistors and capacitors together with interconnections. These units when connected to a vacuum tube (or transistor) make up a complete or almost complete equipment stage. Typical stages constructed in this manner include pentode amplifiers, vertical integrators, output stages, pentode detectors, horizontal oscillators, filters, interstage coupling networks, and a wide variety of special circuit components. Sizes of these single-package units range from $\frac{1}{2} \times \frac{1}{4} \times \frac{1}{8}$ inch for a simple resistor and capacitor network to $1\frac{1}{2} \times 1 \times 3/16$ inch for a complete vertical integrator network containing eight interconnected resistors and capacitors.

BIBLIOGRAPHY

MILITARY SPECIFICATIONS

SUBJECT	TITLE	NUMBER
Resistors		
	Resistors, External Meter, Ferrule Terminal Type	JAN-R-29
	Resistors, Fixed, Composition, Insulated	MIL-R-11A
	Resistors, Fixed, Composition Film, VHF	MIL-R-10683A
	Resistors, Fixed, Film (High Stability)	MIL-R-10509A
	Resistors, Fixed, Wirewound, Accurate	MIL-R-93A
	Resistors, Fixed, Wirewound (Low Power)	JAN-R-184
	Resistors, Fixed, Wirewound, Power Type	MIL-R-26B
	Resistors, Variable, Composition	JAN-R-94
	Resistors, Variable, Wirewound (Low Operating Temperature)	JAN-R-19
	Resistors, Variable, Wirewound, Power Type	MIL-R-22A
Capacitors		
	Capacitors, Fixed, Ceramic-Dielectric (General Purpose)	MIL-C-11015A
	Capacitors, Fixed, Ceramic-Dielectric (Temperature Compensating)	JAN-C-20A
	Capacitors, Fixed, Dry-Electrolytic, Polarized	JAN-C-62
	Capacitors, Fixed, Electrolytic (A-C, Nonpolarized)	MIL-C-3871
	Capacitors, Fixed, Glass-Dielectric	MIL-C-11272A
	Capacitors, Fixed, Mica-Dielectric	MIL-C-5A
	Capacitors, Fixed, Mica-Dielectric, Button Styles	MIL-C-10950A
	Capacitors, Fixed, Paper-Dielectric, Metallic Cases	MIL-C-25A
	Capacitors, Fixed, Paper-Dielectric (Nonmetallic Cases)	MIL-C-91A
	Capacitors, Variable, Air-Dielectric (Trimmer Capacitors)	JAN-C-92
	Capacitors, Variable, Ceramic-Dielectric	JAN-C-81
Inductors and Transformers		
	Transformers and Inductors (Audio, Power & Pulse)	MIL-T-27

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