2

Passive Components

RELIABILITY

While most passive components are very reliable, reliability is just as important for the amateur as for the professional. To us, a breakdown may mean a frustrating search with inadequate instruments for the defective component. This can be especially trying when you have just built a published circuit, and it does not work. Reliable components do tend to be expensive when bought new, but may sometimes be bought at rallies if you know what to look for. The aim of this chapter is to give some guidance.

If you test components before using, you save yourself from this troubleshooting.

Components should be de-rated as much as possible. In 1889 a Swedish chemist, Arrhenius found an exponential law connecting chemical reaction speed with temperature. As most failures are caused by high temperature, reducing the temperature will greatly reduce failure rate. Some components, particularly electrolytic capacitors, do not take kindly to being frozen, so take the above advice with proper caution. Similarly, operating at a voltage or current below the maker's maximum rating favours long life.

WIRE

Copper is the conductor most often used for wire, being of low resistivity, easily worked and cheaper than silver. PVC or PTFE covered wire is most often used in equipment and for leads. Kynar covering is favoured for wire-wrap layouts. **Table 2.1** gives the characteristic of some coverings. Silicone rubber is cheaper than PTFE and can be used in high temperature locations but has not the strength of PTFE.

For inductors, the oleo enamel, cotton, regenerated cellulose and silk of yesteryear have given way to polyester-imide or similar plastics. These have better durability and come with a variety of trade names. They are capable of much higher temperature operation, and resist abrasion and chemicals to a greater degree. Either trade names or maximum temperature in degrees C are used to describe them. They are more difficult to strip, especially fine or 'Litz' wires. Commercially, molten sodium hydroxide (caustic soda) is used, leaving bright easily soldered copper, but there is a hazard, not only is the material harmful to the skin but, if wet, is liable to spit when heated. Paint stripper is a good substitute, but is liable to 'wick' with Litz wire. Be sure to clean it off.

Material	Temperature guide (maximum °C)	Remarks
PVC	70-80	Toxic fume hazard
Cross-linked PVC	105	Toxic fume hazard
Cross-linked polyolefine	150	
PTFE (Tefzel)	200	Difficult to strip
Kynar	130	Toxic fume hazard. ε_r=7*
Silicone rubber	150	Mechanically weak
Glassfibre composite	180-250	Replaces asbestos

If temperature range is critical, check with manufacturer's data.

* ε_r *is the dielectric constant.*

Table 2.1: Equipment and sleeving insulation

Metal	Resistivity at 20°C (μΩ -cm)	Temperature coefficient of resistivity per °C from 20°C (ppm/°C)	Notes
Annealed silver	1.58	4000	
Annealed pure copper	1.72	3930	
Aluminium	2.8	4000	(1)
Brass	9	1600	(1)
Soft iron	11	5500	
Cast iron	70	2000	
Stainless steel	70	1200	(1)
Tungsten	6.2	5000	
Eureka	50	40	(1, 2)
Manganin	43	±10	(3)
Nichrome	110	100	(1)

Notes:

(1) Depends on composition and purity. Values quoted are only approximate.

(2) Copper 60%, nickel 40% approx. Also known as 'Constantan', 'Ferry' and 'Advance'. High thermal EMF against copper.

(3) Copper 84%, manganese 12%, nickel 4%. Low-temperature coefficient only attained after annealing at 135°C in an inert atmosphere and a low thermal EMF against copper. Cannot be soft-soldered.

Table 2.2: Resistivity and temperature coefficient for commonly used metals

There are also polyurethane coatings, usually pink or, for identification purposes, green, purple or yellow. These can be used up to 130°C, and are self-fluxing, if a sufficiently hot iron is used. The fumes are irritating and not very good for you, especially if you are asthmatic.

Dual coatings of polyester-imide with a lower melting point plastic layer outside are made. When a coil has been wound with these, it is heated by passage of current and the outer layers fuse, forming a solid bond. Dual coatings are also found where the outer coating is made of a more expensive material than the inner.

Oleo enamel and early polyester-imide cracks with age and kinking so old wire should be viewed with suspicion. The newer synthetic coatings can resist abrasion to a remarkable degree, but kinked wire, even of this type should not be used for inductors or transformers.

Wire size can be expressed as the diameter of the conductor in millimetres, Standard Wire Gauge (SWG) or American Wire Gauge (AWG). The sizes and recommended current carrying capacity are given in the general data chapter at the end of this book. Precise current carrying capacity is difficult to quote as it depends upon the allowable temperature rise and the nature of the cooling. **Tables 2.1 and 2.2** give data and a guide to usage.

Radio frequency currents only penetrate to a limited depth; for copper this is $6.62/\sqrt{(F_{HZ})}$ cm. For this reason, coils for the higher frequencies are sometimes silver plated; silver has a marginally better conductivity than copper (see Table 2.2) and is less liable to corrosion, though it will tarnish if not protected. Generally the cost is not justified. For high currents, tubing may be used for reduced cost, as the current flows on the outside.

From some 10kHz up to about 1 MHz, a special stranded wire called 'Litz' gives lower radio frequency resistance due to the skin effect mentioned above. The strands are insulated from each other and are woven so that each strand takes its turn in the centre and outside of the wire. Modern Litz wire has plastic insulation, which has to be removed by one of the methods already described. Self-fluxing covering is also made. Older Litz wire has oleo enamel and silk insulation, needing careful heating in a meths flame for removal. There has been considerable dispute over the effect of failing to solder each strand; it is the writer's experience that it is essential to solder each strand, at least if the coil is to be used at the lower range of Litz effectiveness. Litz loses its usefulness at the high end of the range because of the inter strand capacitance making it seem to be a solid wire. This may explain why some authorities maintained that it was unnecessary to ensure that each strand was soldered - at the top end of the range it may not make much difference.

Data on radio frequency cables will be found in the general data chapter.

For some purposes high resistivity is required, with a low temperature coefficient of resistivity. Table 2.2 gives values of resistivity and temperature coefficient of commonly used materials. For alloys, the values depend very much on the exact composition and treatment.

FIXED RESISTORS

These are probably the components used most widely and are now among the most reliable if correctly selected for the purpose. As the name implies, they resist the passage of electric current - in fact the unit 'Ohm' is really the Volt per Amp.

Carbon composition resistors in the form of rods with radial wire ends were once very common. There is no excuse for using them now, as they are bulky, and suffer from a large negative temperature coefficient, irreversible and erratic change of value with age or heat due to soldering. Due to the granular nature of the carbon and binder, more than thermal noise is generated when current flows, another reason not to use them!

Tubes of carbon composition in various diameters with metallised ends are made for high wattage dissipation. These may bear the name 'Morganite' and are excellent for RF dummy loads (**Fig. 2.1**).

Carbon films deposited by 'cracking' a hydrocarbon on to ceramic formers are still used. To adjust the value, a helix is cut into the film, making the component slightly inductive. Protection is either by varnish, conformal epoxy or ceramic tube. Tolerance down to 5% is advisable, as the temperature coefficient (tempco) of between -100 and -900 parts per million per degree Celsius (ppm/°C) makes the value of closer tolerance doubtful.

In the 1930s, Dubilier made metal film resistors similar in appearance to carbon composition ones of that era, but they never became popular. In the 1950s, metal oxide film resistors were introduced, with tempco of 300ppm/°C, soon to be replaced for lower wattage by the forgotten metal film types. These were more stable, less noisy and more reliable than carbon film, now only little more expensive. They use the same helical groove technique as carbon film, and little difficulty should be experienced due to this up to say 50 MHz. The tempco (temperature coefficient) is of the order of ±15ppm/°C, allowing tolerance of 1% or better. Protection is either by conformal or moulded epoxy coating.

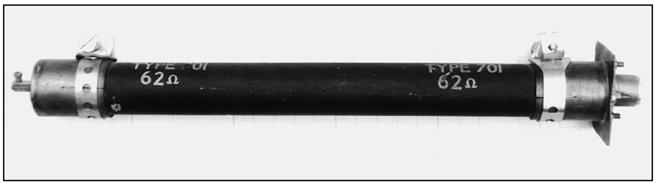

Fig 2.1: An amateur-made 62-ohm dummy load with UHF coaxial connector. It is made from a 50 watt resistor but is suitable for 200W for short periods

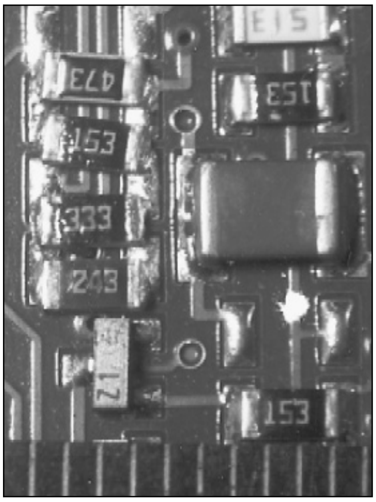

Fig 2.2: Surface mounting components. The small dark components on the left labelled '473', '153', '333' and '243' are resistors, the larger grey one on the right is a capacitor and the light-coloured one labelled 'Z1' (bottom left) is a transistor. The scale at the bottom is in millimetres

Surface mounting has now become universal in the commercial world, and amateurs have to live with it. **Fig. 2.2** shows a typical board layout. More about this later in this chapter, and in the construction chapter.

Resistor values are quoted from a series that allows for the tolerance. The series is named according to the number of members in a decade. For example, E12 (10%) has 12 values between 1 and 10 (including 1 but not 10). In this case, each will be the twelfth root of ten times the one below, rounded off to two significant figures (**Table 2.3**) E192 allows for 1% tolerance, the figures now being rounded off to three significant figures. Unfortunately E12 is not a subset of E192, and some unfamiliar numbers will be met if E12 resistors are required from E192 stock. Values can either be colour coded (see the general data chapter) or for surface mounted ones, marked by two significant digits followed by the number of noughts. This is called the 'exponent system'. For example, 473 indicates 47k, but 4.7 Ohms would be 4R7. Metal film resistors can also be made into integrated packages either as dual in line, single in line or surface mount. By using these, space is saved on printed circuit boards.

For higher powers than metal oxide will permit, wire wound resistors are used. The cheaper ones are wound on a fibre substrate, protected by a rectangular ceramic tube or, rarely, moulded epoxy. More reliable (and expensive) ones are wound on a ceramic substrate covered by vitreous or silicone enamel. For even greater heat dissipation, it may be encased in an aluminium body designed to be bolted to the chassis or other heat sink. Vitreous enamelled wound resistors can be made with a portion of the winding left free from enamel so that one or more taps can be fitted. Wire wound resistors, even if so-called 'non-inductively' wound, do have more reactance than is desirable for RF use. However Ayrton Perry wound resistors in gas filled glass bulbs are suitable for use in the HF bands, but hard to come by.

Unless an aluminium-clad resistor is used for high power, care should be taken to ensure that the heat generated does not damage the surroundings, particularly if the resistor is mounted on a printed circuit board. The construction chapter gives practi-

E3 ±40%	E6 ±20%	E12 ±10%	E24 ±5%
1.0	1.0	1.0	1.0
-	-	-	1.1
-	-	1.2	1.2
-	-	-	1.3
-	1.5	1.5	1.5
-	-	-	1.6
-	-	1.8	1.8
-	-	-	2.0
2.2	2.2	2.2	2.2
-	-	-	2.4
-	-	2.7	2.7
-	-	-	3.0
-	3.3	3.3	3.3
-	-	-	3.6
-	-	3.9	3.9
-	-	-	4.3
4.7	4.7	4.7	4.7
-	-	-	5.1
-	-	5.6	5.6
-	-	-	6.2
-	6.8	6.8	6.8
-	-	-	7.5
-	-	8.2	8.2
-	-	-	9.1

The values shown above are multiplied by the appropriate power of 10 to cover the range.

Table 2.3: 'E' range of preferred values, with approximate tolerance values from next number in range

cal advice about this. Marking is by printed value, perhaps including wattage and tolerance as well.

Fig. 2.3 shows photographs of many of the fixed resistors that have just been described.

VARIABLE RESISTORS

Often a resistor has to be made variable, either for control or precise adjustment purposes; the latter is usually called a trimmer. Generally variable resistors are made with a moveable tapping point, and the arrangement is called a potentiometer or 'pot.' for short, the name coming from a laboratory instrument for use in measuring voltage. If only a variable component is required, it is advisable to connect one end of the track to the slider.

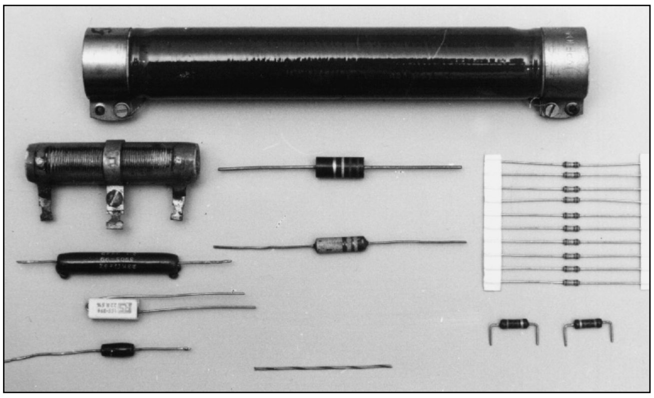

Fig 2.3: Fixed resistors. Top: 50W wire wound, vitreous-enamel covered. Left, top to bottom: 10W wire wound with adjustable tapping, 12W vitreous enamelled, 4W cement coated and 2.5W vitreous enamelled. Centre: 2W carbon composition, 1W carbon film. Right, top: ten ¼W metal film resistors in a 'bandolier' of adhesive tape, two carbon film resistors with preformed leads. Bottom: striped marker is 50mm long

Tracks are made from carbon composition, cermet or conductive plastic, or they may be wire wound. Circular tracks with either multi-turn or single turn sliders are made, both for pots and trimmers, in varying degrees of accuracy and stability. The HiFi world likes linear tracks for control purposes, as do some rigs available to amateurs. Wire wound types have the disadvantage of limited resolution and higher price, but have the advantage of higher wattage and good stability. It is not always possible to tell the type from the external appearance as the photograph of **Fig. 2.4** shows.

Single turn rotary pots for volume control and many other uses usually turn over a range of 250°-300°, with a log, anti-log or linear law connecting resistance with rotation. Ganged units and pots with switches are common. Precision components generally have a linear law (some for special purposes may have another law) and turn some 300°. For greater accuracy, multi-turn pots are used, some in conjunction with turn counting dials. There are multi turn linear trimmers using a screw mechanism to move the slider over the linear track. Available values are frequently only in the E3 range, to 20% tolerance, the value being printed on the component, possibly in the exponent system.

NON-LINEAR RESISTORS

All the resistors so far described obey Ohm's Law closely, that is to say that the current through them is proportional to the applied voltage (provided that the physical conditions remain constant, particularly temperature). Resistors, except metal film and wire wound, do change their value slightly with applied voltage, but the effect can generally be ignored. For some purposes, however, specialist types of resistor have been developed.

Thermistors are sintered oxides or sulphides of various metals that have a large temperature coefficient of resistance, and are deliberately allowed to get hot. Both positive (PTC) and negative (NTC) tempco thermistors are made. Of all the forms of construction, uninsulated rods or discs with metallised ends are the most interesting to amateurs. Bead thermistors have special uses, such as stabilising RC oscillators or sensing temperature, one use being in re-chargeable battery packs.

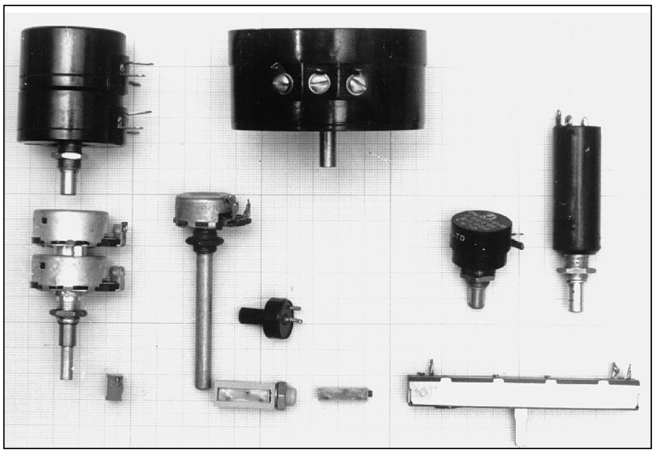

Fig 2.4: Variable resistors. Top, left to right: double-gang 2W wire wound, 5W wire wound. Middle, left to right: two independent variable resistors with coaxial shafts, standard carbon track, single-turn preset, standard wire wound and 10-turn variable resistor. Bottom, left to right: 10-turn PCB vertical mounting preset, 10-turn panel and PCB horizontal mounting preset. Right: a slider variable resistor

PTC thermistors are used for current limitation. The thermistor may either operate in air or be incorporated into the device to be protected. Self-generated heat due to excess current or rise of ambient temperature will raise the resistance, and prevent further rise of current They should not be used in constant current circuits because this can result in ever increasing power dissipation and therefore temperature (thermal runaway), so destroying the device.

Unlike metals, PTC thermistors do not exhibit a positive tempco over the whole range of temperature likely to be encountered. **Fig. 2.5(a)** shows this behaviour for a particular thermistor.

One type of PTC 'thermistor', though not usually classed as such, is the tungsten filament lamp. Tungsten has a large tempco of about 5000ppm/°C (Table 2.2) and lamps operate with a temperature rise of some 2500°C. An increase to about 12 times the cold resistance can be expected if the lamp is lit to full brilliance. These lamps are relatively non-inductive and can be used as RF loads if the change of resistance is acceptable.

NTC thermistors find a use for limiting in-rush currents with capacitor input rectifier circuits. They start with a high resistance, which decreases as they heat up. (**Fig. 2.5(b)**). Remember that they retain the heat during a short break, and the in-rush current will not be limited after the break. When self-heated, the thermistor's temperature may rise considerably and the mounting arrangements must allow for this.

PTC bead thermistors are the ones used to stabilise RC oscillators. Also, they are used in temperature compensated crystal oscillators where self-heating is arranged to be negligible and the response to temperature is needed to offset the crystal's tempco.

Non-ohmic resistors in which the voltage coefficient is large and positive are called voltage dependant resistors (VDRs) or varistors. VDRs having no rectification properties, ie symmetrical VDRs are known by various trade names (eg Metal Oxide Varistors). Doped zinc oxide is the basis, having better properties than the silicon carbide (Atmite, Metrosil or Thyrite) formerly used, as its change of resistance is more marked (**Fig. 2.5(c)**). VDRs are used as over-voltage protectors; above a certain voltage the current rises sharply. As the self-capacitance is of the order of nanofarads, they cannot be used for RF. Alternative over-voltage protectors are specially made zener diodes or gas discharge tubes.

Light dependent resistors are an improvement of the selenium cell of yesteryear. Cadmium sulphide is now used, its resistance decreasing with illumination. The Mullard ORP12 is an example. In the dark it has a resistance of at least 1MΩ, dropping to 400Ω when illuminated with 100 Lux. Photo-diodes are more useful!

FIXED CAPACITORS

To get the values wanted for radio purposes into a reasonable space, fixed capacitors are made with various dielectrics, having a value of dielectric constant (ε_r) according to the intended use of the capacitor. **Fig. 2.6** shows a selection of fixed capacitors.

Ceramic Capacitors

The smallest capacitors have a ceramic dielectric, which may be one of three classes. Class 1 has a low ε_r and therefore a larger size than the other two for a given capacitance. The loss factor for Class 1 is very low, comparable with silvered mica, and the value stays very nearly constant with applied voltage and life.

The designations 'COG' and 'NPO' refer to some members of this class of ceramic capacitor, which should be used where stability of value and low loss factor are of greater importance than

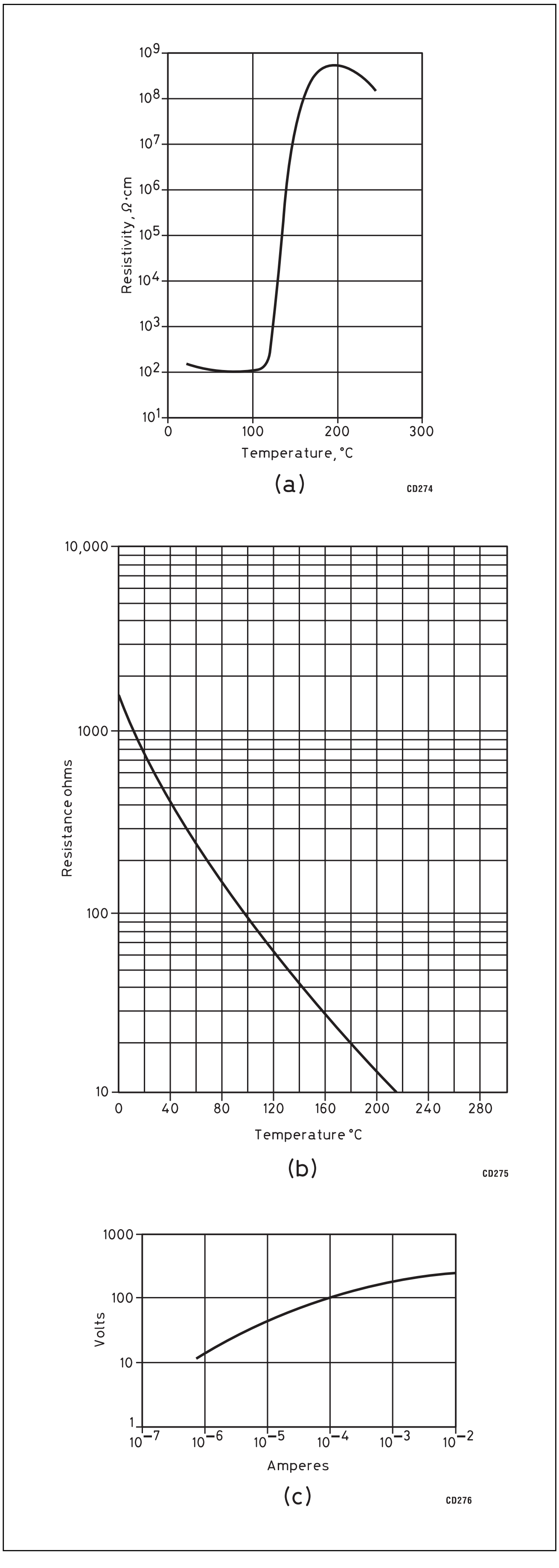

Fig 2.5: Characteristics of thermistors

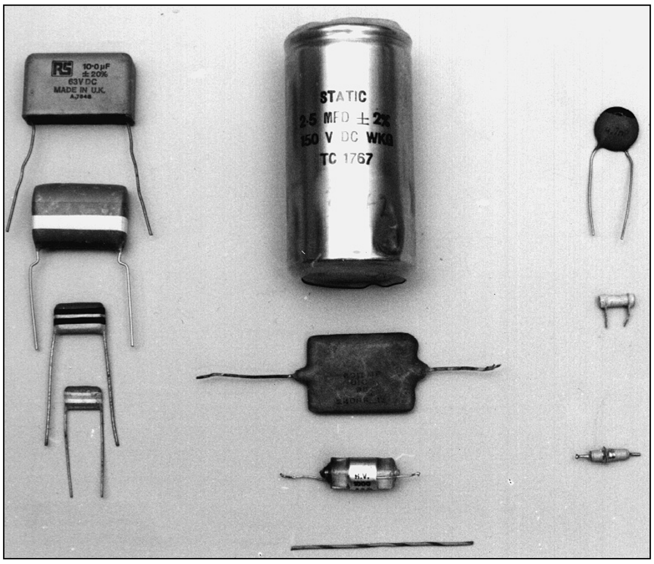

Fig 2.6: Fixed capacitors. Left column (top to bottom): 10µF, 63V polycarbonate dielectric, 2.7µF 250V, 0.1 F, 400V, 0.033µF, 250V all polyester dielectric. Centre column from top: 2.5µF 150V ±2% polyester, 240pF ±1% silver mica, 1nF ±2% polystyrene (all close tolerance). Right column from top: 4.7nF disc ceramic, 220pF tubular ceramic, 3nF feedthrough. Striped marker is 50mm long

small size. Other low loss ceramic capacitors are available with either N*** or P*** identification, where *** is the intentional negative or positive tempco in ppm/°C. These are for compensation to allow for the opposite temperature coefficient of other components in the circuit.

Class 2 comprises medium and high ε_r capacitors. They both have a value depending on voltage, temperature and age, these effects increasing with ε_r. It is possible to restore the capacitance lost by ageing by heating above the Curie temperature, this being obtained from the manufacturer - not really a technique to be done at home!

'X7R' refers to a medium ε_r material, Z5U, 2F4 and Y5V to higher ε_r ceramic. **Fig. 2.7** shows the performance of COG, X7R and Y5V types. This class should not be used where stability is paramount, but they are very suitable for RF bypassing, lead through capacitors being made where low inductance is required. Class 1 and 2 capacitors are made in surface mount, either marked in the exponent system, or unmarked.

Class 3 have a barrier layer dielectric, giving small size, poor loss factor and wide tolerance. Z5U dielectric has made this class obsolete, but some may be found as radial leaded discs in surplus equipment.

Large high voltage tubular or disc capacitors are made for transmitter use which, if they can be found, are particularly useful for coupling the valves in a linear amplifier to the matching network.

Table 2.4 summarises ceramic capacitor properties and recommended usage. The value colour coding is to be found in the general data chapter and **Table 2.5** gives the dielectric codes used.

Mica Capacitors

These are larger than similar ceramic capacitors for a given value and have a tempco of between +35 and +75ppm/°C, the variation being caused by them being natural rather than synthetic. Today, silver electrodes are plated directly on to the mica sheets and the units encapsulated for protection.

Function	Type	Advantages
AF/IF coupling	Paper, polyester, polycarbonate	High voltage, cheap
RF coupling	X7R ceramic	Small, cheap but lossy
	Polystyrene	Very low loss, low leakage but bulky and not for high temperature
	COG ceramic or silver mica	Close tolerance
	Stacked mica	For use in power amplifiers
RF decoupling	X7R or Z5U ceramic disc or feedthrough	Very low inductance
Tuned circuits	Polystyrene	Close tolerance, low loss, negative temperature coefficient (150ppm)
	Silver mica	Close tolerance, low loss, positive temperature coefficient (+50ppm)
	COG ceramic	Close tolerance, low loss
	Class 1 ceramic	Various temperature coefficients available, more lossy than COG

Table 2.4: Use of fixed capacitors

Class 1 - r < 500

COG, NPO temperature coefficient ±30ppm/°C
N*** Temperature coefficient: ***ppm/°C
P*** Temperature coefficient: +***ppm/°C

Class 2 - r > 500

EIA coding

Working temperature range Lower		Upper		Capacitance change over range	
Letter	**Temp**	**Figure**	**Temp**	**Letter**	**Change**
Z	+10°C	2	+45°C	R	±15%
Y	30°C	4	+65°C	S	±22%
X	55°C	5	+85°C	T	+22 to 33%
		6	+105°C	U	+22 to 56%
		7	+125°C	V	+22 to 82%
		8	+150°C		

X7R and Z5U are commonly met. X7R was formerly denoted W5R.

CECC 32100 coding

Code	Capacitance change over range		Temperature range (°C)				
	At 0V DC	At rated voltage	55 +125	55 +85	40 +85	25 +85	+10 +85
			Final code figure				
			1	2	3	4	6
2B*	±10%	+10 to 15%		*	*	*	
2C*	±20%	+20 to 30%	*	*	*		
2D*	+20 to 30%	+20 to 40%				*	
2E*	+22 to 56%	+22 to 70%		*	*	*	*
2F*	+30 to 80%	+30 to 90%		*	*	*	*
2R*	±15%		*				
2X*	±15%	+15 to 25%	*				

Reference temperature +20°C.

Example: X7R (EIA code) would be 2R1 in CECC 32100 code, tolerance ±15% over 55 to +125°C.

Class 3 barrier layer

Not coded but tolerance approximately +50% to 25% over temperature range of 40 to +85°C. Refer to maker for exact details.

Table 2.5: Ceramic capacitor dielectric codes

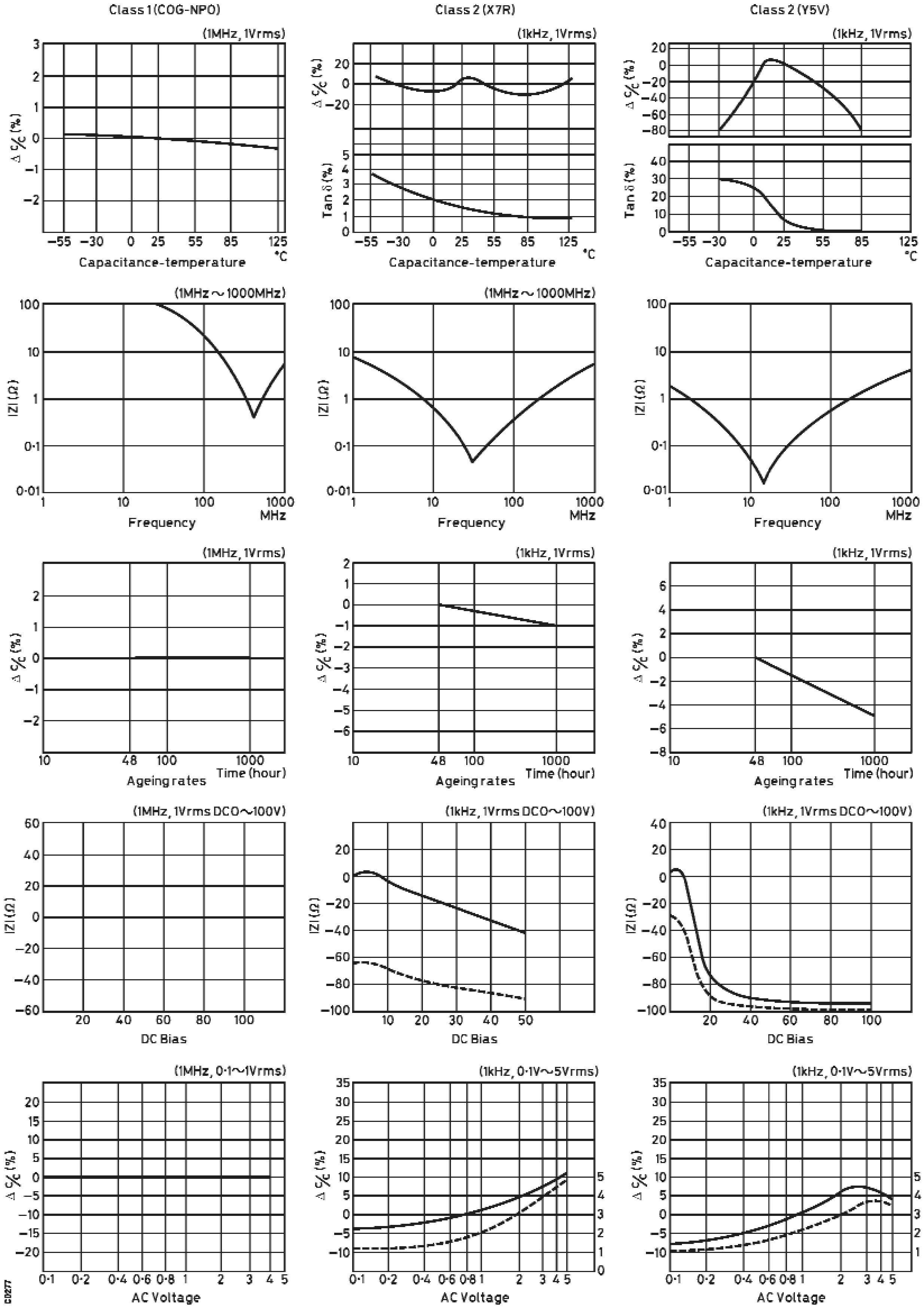

Fig 2.7: Ceramic capacitor networks

Because they generally remain stable over life and have low loss, they are popular for tuned circuits and filters. Occasionally however, mica capacitors will jump in value and this effect is unpredictable. High voltage and current stacked foil types were used for coupling in transmitters, but are not easy to get now. The value and voltage rating is usually marked on the body of mica capacitors.

Glass Capacitors

These are used for rare applications where they have to work up to 200°C. Because of this, they do not appear in most distributors catalogues, but may be found in surplus equipment.

Paper Dielectric Capacitors

At one time paper dielectric capacitors were much used, but now they may only be found in some high voltage smoothing capacitors and interference suppression capacitors. Paper capacitors are large and expensive for a given value, but are very reliable, especially when de-rated. There can be trouble if inferior paper is used, with voids in it. The capacitors tend to break down at the voids, where the electric stress is concentrated. Both foil and metallised electrodes are used and the units can be somewhat inductive if not non-inductively wound. A resistor can be included if the unit is to be used for spark suppression.

Plastic Film Capacitors

These have replaced paper capacitors, and there are two distinct types of plastic used, polar and non-polar.

Polar plastics include polycarbonate, polyester and cellulose acetate. These are characterised by a moderate loss, which can increase at frequencies where the polar molecules resonate. They also suffer from dielectric absorption, meaning that after a complete discharge some charge reappears later. This is of some importance in DC applications. The insulation resistance is very high, making the capacitors suitable for coupling the lower frequencies of AC across a potential difference (within the voltage rating of course).

Commonly, values range from about a nanofarad to several microfarads at voltages from 30V up to kilovolts, thus replacing paper. Tolerances are not usually important as these capacitors are not recommended for tuned circuits, but as they may be used in RC oscillators or filters, 5% or better can be bought at increased cost. Polycarbonate is the most stable of this group and cellulose the worst and cheapest.

Polyethylene terephthalate (PETP) is used for polyester film and is also known as Mylar (in USA) and. domestically as Terylene or Melinex. PETP exhibits piezo-electric properties, as can be demonstrated by connecting a PETP capacitor to a high impedance voltmeter and squeezing the capacitor. PETP capacitors therefore behave as rather poor microphones, which could introduce noise when used in mobile applications.

Non-polar plastics suitable for capacitors are polystyrene, polypropylene and polytetrafluoroethylene (PTFE). These exhibit very low loss, independent of frequency, but tend to be bulky. Polystyrene capacitors in particular have a tempco around -150 ppm/°C which enables them to offset a similar positive tempco of ferrites cores used for tuned circuits. Unfortunately polystyrene cannot be used above 70°C and care must be taken when soldering polystyrene capacitors particularly if you use lead free solder. The end connected to the outer foil may be marked with a colour and this should be made the more nearly grounded electrode where possible.

Polypropylene capacitors can be used up to 85°C and are recommended for pulse applications. They are also used at 50Hz for power factor correction and motor starting. Again, take care when soldering.

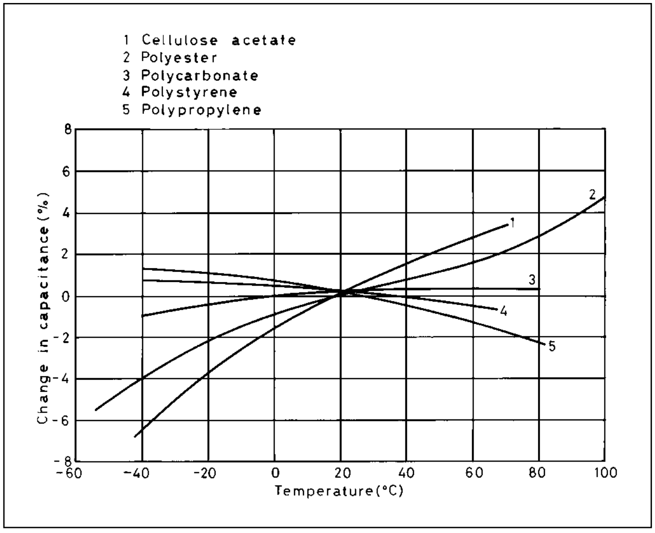

Fig 2.8: Temperature coefficients of plastic capacitors

Encapsulation of plastic foil capacitors is either by dipping or moulding in epoxy or it may be omitted altogether for cheap components where environmental protection is not considered necessary. The value is marked by colour code or printing along with tolerance and voltage rating. Small values are mostly tubular axial leaded, but single ended tubular and boxed are commonly available. You can get surface mount ones.

Fig. 2.8 shows the effect of temperature on five different types.

PTFE fixed capacitors are not generally available, but variable ones are, see later in this chapter. Small lengths of PTFE or, if unobtainable polystyrene coaxial cable, make very good low loss high voltage capacitors for use as tuning elements in multiband HF antenna systems.

Cutting to an exact value is easy, if you know the type, as the capacitance per metre is quoted for cables in common use. The length must be much shorter than the wavelength for which the cut cable is to be used, to avoid trouble due to the inductance.

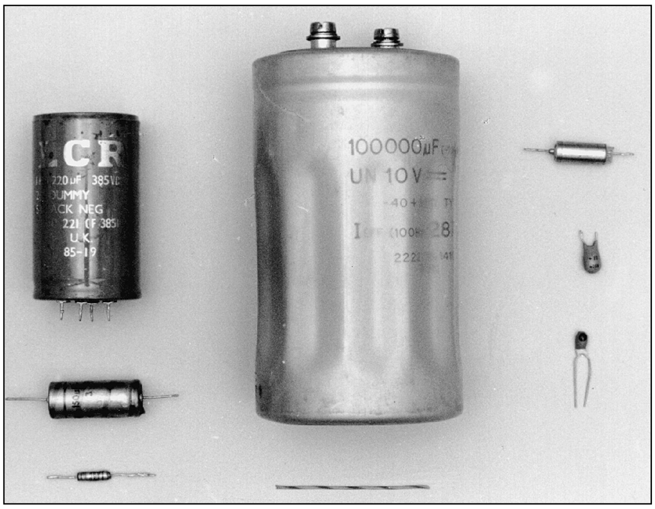

Fig 2.9: Electrolytic capacitors. Left, from top: 220µF 385V, 150µF 63V, 2.5µF 15V, electrodes. Centre: 100,000µF, 10V, all with aluminium. Right, from top: 68µF 15V, 22µF 25V and 22µF 6.3V, all tantalum types. Striped marker is 50mm long

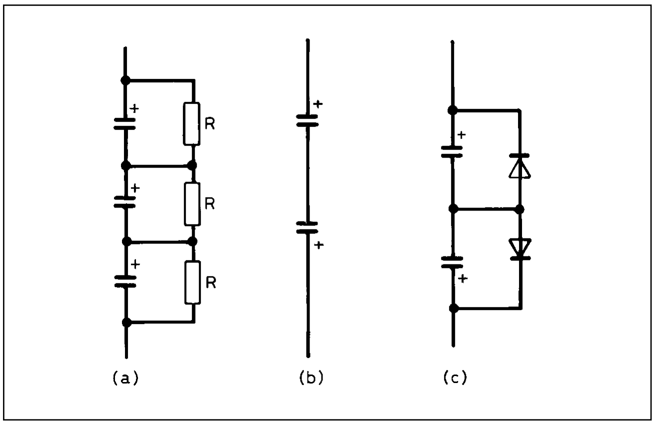

Fig 2.10: Circuits for electrolytic capacitors

Electrolytic Capacitors

This type is much used for values bigger than about 1µF. The dielectric is a thin film of either aluminium, tantalum, or niobium oxide on the positive plate.

An electrolyte (liquid or solid) is used to connect to the negative plate (**Fig. 2.9**). For this reason the electrolytic will be polarised, unless constructed with two oxide coated plates. This is not common in amateur usage, but can be used for motor starting on AC, and in the output or cross-over circuits of some HiFi amplifiers. Alternatively back-to-back capacitors can be used (see **Fig. 2.10**).

Both tantalum and niobium oxide capacitors can stand a reverse voltage up to 0.3 volts. Aluminium capacitors cannot withstand any reverse voltage. The oxide film is formed during manufacture, and deteriorated if the capacitor is not used. Capacitors, unused for a long time, should be reformed by applying an increasing voltage until the rated voltage is reached, and leakage current falls.

Electrolytics are rated for voltage and ripple current at a specified maximum temperature, and it is here that de-rating is most advisable. At full rating some electrolytics have only 1000 hours advertised life. There is always an appreciable leakage current, worst with liquid aluminium ones.

Tantalum and niobium oxide capacitors should not be allowed to incur large in-rush currents. As the capacitor may fail, add a small resistance in series. Niobium oxide capacitors fail to an open circuit; all others go to a short circuit. For all types the maximum ripple current should not be exceeded to prevent rise of temperature. This is particularly important when the capacitor is used after a rectifier (reservoir capacitor). There is more on this in the power supplies chapter.

Although capacitive reactance decreases with frequency, electrolytics are unsuitable for radio frequencies. The innards may have considerable inductance and the equivalent series resistance increases with frequency. To avoid this, a small ceramic capacitor should be paralleled with the electrolytic, 0.1µF to 1nF being common. For switch-mode converters, special considerations apply. Again see the power supplies chapter for more information.

VARIABLE CAPACITORS

These are most often used in conjunction with inductors to form tuned circuits, but there is another use, with resistors in RC oscillators - see the oscillators chapter. Small values (say less than 100pF) with a small capacitance swing are used as trimmers to adjust circuit capacitance to the required value (**Figs. 2.11 (a) and (b)**).

Capacitors with vacuum as the dielectric are used to withstand large RF voltages and currents, for example in valve power amplifiers. The capacitance is adjusted through bellows, by linear motion. The range of adjustment usually allows one amateur band to be covered at a time. For the power allowed, the expense of new vacuum capacitors is not justified.

Air spaced variable capacitors are widely used both for tuning and trimming. For precise tuning of a variable frequency oscillator (VFO) the construction must be such that the capacitance does not vary appreciably with temperature or vibration. This implies low loss, high grade insulating supports for the plates and good mechanical design. These are not factors that make for cheapness.

For valve power amplifiers, the plate spacing must be wide enough to withstand both the peak RF voltage, including the effects of any mismatch, and any superimposed DC. Rounded plate edges minimise the risk of flash over, and application of DC should be avoided by use of choke-capacity coupling. However, extreme stability is not required owing to the low Q of the circuit in which they are used.

As the moving plates are generally connected to the frame, it may be necessary to insulate this from the chassis in some applications. Ceramic shafts have been used to avoid this. It is possible to gang two or more sections, which need not have the

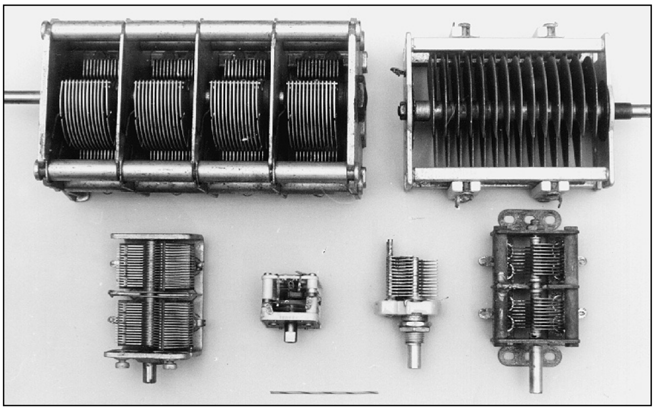

Fig 2.11(a): Variable capacitors. Left: 500pF maximum, four-gang air-spaced receiver capacitor. Right: 125pF max transmitter capacitor with wide spacing. Bottom, left to right: 500pF max twin-gang receiver capacitor. Solid dielectric receiver capacitor. Single-gang 75pF max receiver capacitor. Twin-gang 75pF max receiver capacitor

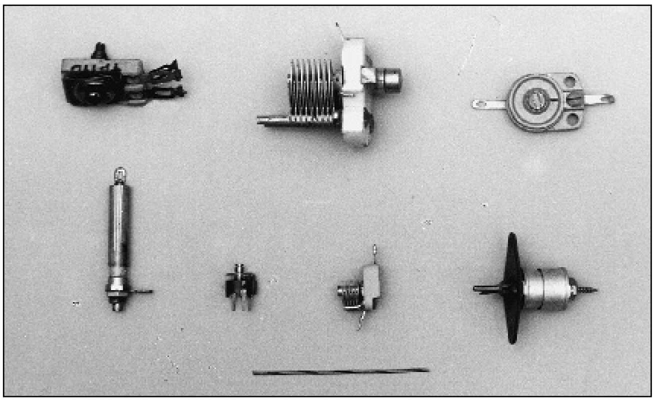

Fig 2.11(b): Trimmer capacitors. Top, from left: 50pF max 'postage stamp', 70pF max air dielectric, 50pF max flat ceramic. Bottom, from left: 27pF max tubular ceramic, 30pF max plastic film, 12pF max miniature air dielectric, 30pF max 'beehive' air dielectric

same value, but it is usual for the moving vanes to be commoned, with the exception mentioned above. The plates need not be semi-circular, but can be shaped so as to give a wanted law to capacitance versus rotation angle. In early superhet receivers specially shaped vanes solved the oscillator-tracking problem.

For small equipment, plastic film dielectric variable capacitors are much used but do not have the stability for a VFO. Trimmers may have air or film dielectric, the latter being a low loss non-polar plastic or even mica. Both parallel plate and tubular types are used for precise applications, and mica compression ones now only occasionally where stability is of less importance than cost.

Junction diodes can be used as voltage variable capacitors - they are described in the semiconductors chapter.

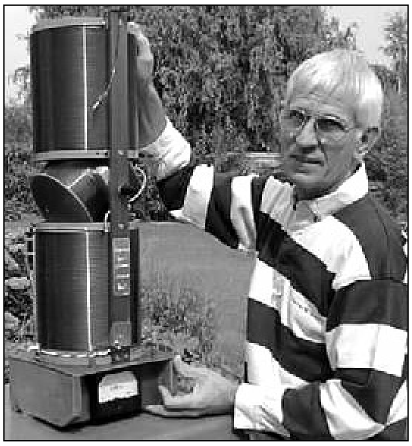

Fig 2.13: A variometer made by ON6ND for use with his 136kHz transmitter. The inductance is varied by altering the mutual coupling between the fixed and variable coils

INDUCTORS

Inductors are used for resonant circuits and filters, energy storage and presenting an impedance to AC whilst allowing the passage of DC, or transforming voltage, current or impedance. Sometimes an inductor performs more than one of these functions simultaneously, but it is easier to describe the wide range of inductors by these categories.

Tuned Circuits

Either air or magnetic cored coils are used - in the latter case different cores are selected for optimum performance at the operating frequency and power level. The criterion for 'goodness' for a tuning coil is Q, the ratio of reactance to resistance at the operating frequency. With air-cored coils, the ratio of diameter to length should be greater than 1 for maximum Q, but Q falls off slowly as the length increases. It is often convenient to use a long thin coil rather than a short fat one, accepting the slight loss of Q.

Calculation of the inductance of air-cored coils is difficult and usually done by the use of charts or computer programs. However there is an approximate formula {1} which may be used:

$$L(\mu\mathrm{H}) = \frac{r^2N^2}{25.4\,(9r + 10l)}$$

where r is the radius, l is the length of the coil, both in millimetres and N the number of turns. If you use inches, omit the 25.4 in the denominator. The formula is correct to 1% provided that $l > 0.8r$, ie the coil is not too short.

Figs 2.12 (a) and (b) show some different air-cored coils including a much sought after 'roller coaster' used for antenna and power amplifier tuning networks. **Fig 2.13** shows another type of variable inductor.

Magnetic cores may be either ferrite or iron (carbonyl powder for RF, iron alloy for AF). Screw cores can be used for adjustment in nominally air-cored coils or in pot cores (**Fig 2.14**). For closed magnetic circuits, a factor called A_L is quoted for extreme posi-

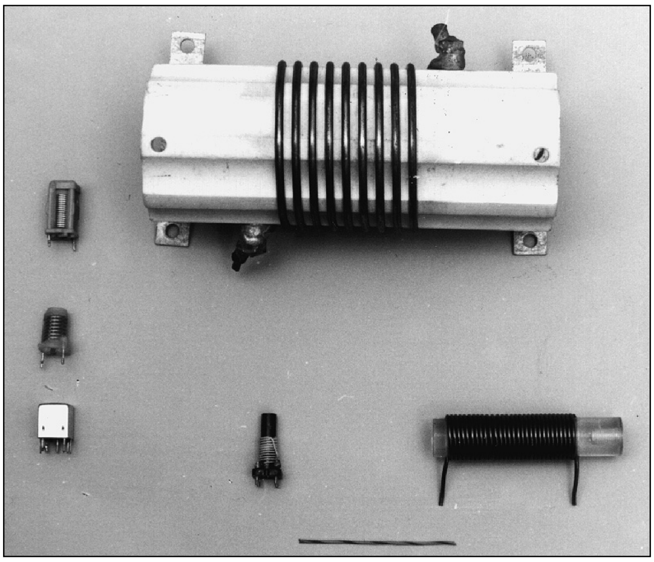

Fig 2.12(a): Air-cored inductors. Top: high-power transmitting on ceramic former. Left: VHF inductors moulded in polythene, the bottom one in a shielding can. Centre: small air-cored HF inductor (could have an iron dust core). Right: HF inductor wound on polystyrene rod. The striped marker is 50mm long

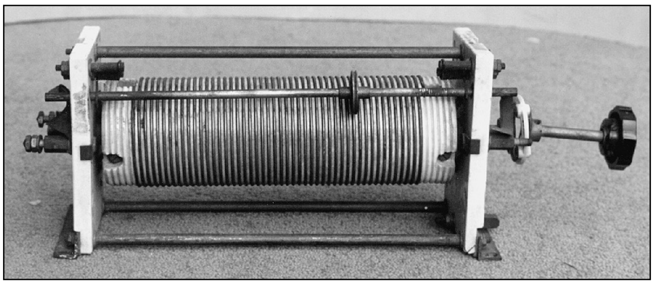

Fig 2.12(b): 'Roller-coaster' variable inductor

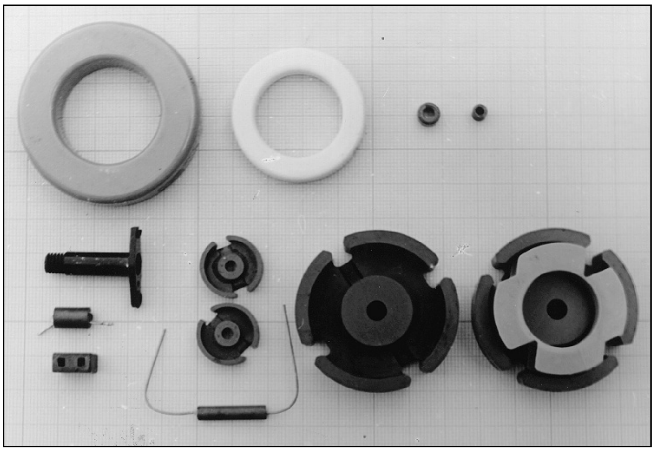

Fig 2.14: RF magnetic materials. Top, left to right: large, medium and small ferrite rings, and a ferrite bead with a single hole. Below, left top: tuneable RF coil former; middle: six-hole ferrite bead with winding as an RF choke; bottom: ferrite RF transformer or balun former. Centre: small pot cores and an RF choke former with leads moulded into the ends. Right: large pot core with former

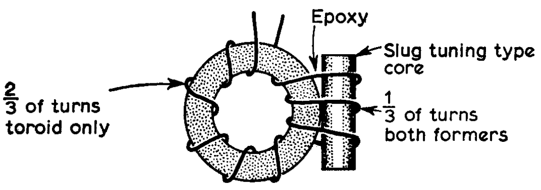

Fig 2.15: Tuneable toroid technique. About 10% variation in inductance can be achieved

tions of the core. A_L is the inductance in nanohenries that a one turn coil would have, or alternatively millihenries per thousand turns. For a coil of N turns the inductance will be N^2A_L nanohenries. Checking by grid dip oscillator is difficult because of the closed nature of the magnetic circuit.

Fig 2.15 shows a technique for adjusting the inductance where it is not important to preserve a completely closed magnetic circuit. Trimming by removing turns is more easily done with the aid of a small crochet hook. Also shown in Fig. 2.14 are toroidal cores.

There are two common types of ferrite, manganese-zinc (Mn/Zn) and nickel-zinc (Ni/Zn). Mn/Zn has lower resistivity than Ni/Zn and lower losses due to hysteresis. The latter is caused by the magnetic flux lagging behind the magnetic field, so offering a resistive component to the alternating current in any coil wound round the material. As the applied frequency is increased, eddy currents and possibly dimensional resonances play a greater part and the higher resistivity Ni/Zn has to be used. Unfortunately, Ni/Zn has greater hysteresis loss. Both types of ferrite saturate in the region of 400mT, this being a disadvantage in high power uses (saturation is when increasing magnetic field fails to produce the same increase in magnetic flux as it did at lower levels). More will be said about this in non-tuned circuit applications.

There are many proprietary ferrites on the market and reference must be made to the catalogues for details. If you have a piece of unmarked ferrite, one practical test is to apply the prods of an ohmmeter to it. Mn/Zn ferrite will show some resistance on a 100k range, but Ni/Zn will not. Further tests with a winding could give you some idea of its usefulness.

Microwave ferrites such yttrium iron garnet have uses for the amateur who operates on the Gigahertz bands.

Inevitably, coils will possess resistance and distributed capacitance as well as inductance. The latter confuses the measurement of inductance, and hence both confuses and limits the tuning range with a variable capacitor. When winding a tuning coil, it may be necessary to use a coating for environmental protection. All 'dopes' have an ε_r greater than one and will increase the self-capacitance. Polystyrene with an ε_r of only 2.5, dissolved in toluene (a hazardous vapour) or cellulose thinners is recommended. Polythene or PTFE would be attractive, but there is no known solvent for them.

Energy Storage Inductors

The type of core will depend on the operating frequency. At mains supply frequency, silicon iron or amorphous iron are the only choices To minimise eddy current loss caused by the low resistivity of iron, either thin laminations or grain orientated silicon strip (GOSS - the grains of which lie along the length of the strip in which the magnetic flux lies), is used. If magnetic saturation would be a problem, an air gap is left in the magnetic circuit. The calculation of core size, gap, turns and wire size is outside the scope of this book. Advice on winding is given later, under the heading 'Transformers'.

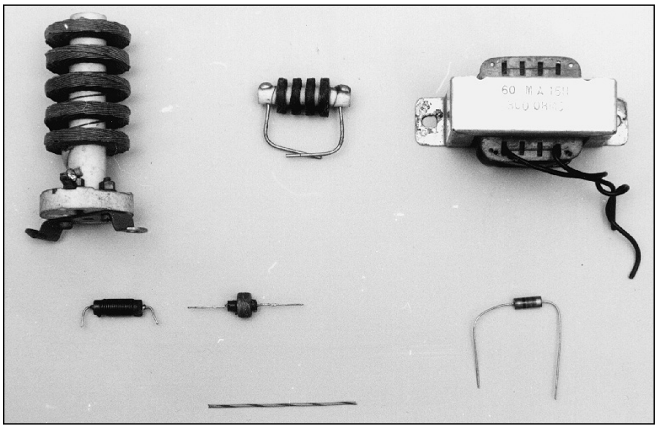

Fig 2.16: RF and AF chokes. Top, left to right: 1mH large, 1mH small RF chokes and 15H AF type. Bottom, left to right: 10µH single layer, 300µH 'pile' wound, 22µH encapsulated. Striped marker is 50mm long

At higher frequencies such as for switch mode converter use, ferrites and amorphous alloys are widely used in the form of E shaped half cores, in pairs. As with silicon iron, an air gap is required to prevent saturation. The core manufacturers' data books give the information needed for design

Chokes

While energy storage inductors are most often called chokes, the term was originally applied to inductors used to permit the passage of DC, while opposing AC, and it still does. The cores used are as for energy storage for the lower frequencies, but at higher frequencies, where ferrites are too lossy, carbonyl powdered iron is used. At VHF and above, air-cored formers are used, surface mounted ones being available.

There is a problem with self-resonance in RF chokes. It is impossible to avoid capacitance, and at some frequency it will resonate with the inductance to give a very high impedance - ideal - but at higher frequencies the so-called inductor will behave as a capacitor whose impedance decreases with frequency. The situation is complicated by the fact that the self-capacitance is distributed and there may be multiple parallel and series resonances. For feeding HT to valve anodes, the choke should not have series resonances in any of the bands for which it is designed. Where available, a wave winder should be used to wind different numbers of turns in separate coils which, being on the same former, are in series. A less efficient, but simpler alternative, is to sectionalise a single layer solenoid winding. **Fig. 2.16** shows a variety of chokes.

Transformers

The Principles chapter described mutual inductance, and this property enables transformers to be made. The magnetic flux from one coil is allowed to link one or more other coils, where it produces an EMF. Two types of transformer are met, tightly coupled and loosely coupled. With tight coupling the object is to make as much as possible of the flux from the first (primary) coil link the other (secondary). In this case the ratio of the applied EMF to induced EMF is that of the turns ratio secondary to primary. Formulas for calculating the required turns are given in the general data chapter.

Leakage inductance caused by incomplete flux linkage is minimised by interleaving the primary and secondary windings, how-

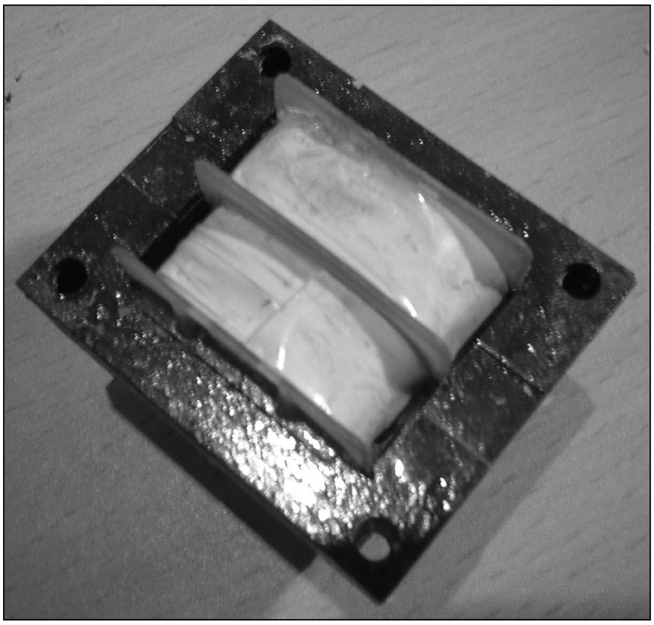

Fig 2.17: A transformer with the primary and secondary wound separately with an insulated divider

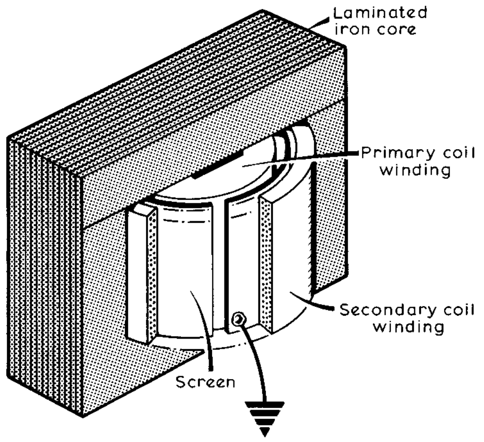

Fig 2.18: A Faraday screen is an earthed sheet of copper foil between the primary and secondary windings. For clarity, a gap is shown here between the ends, but in reality they must overlap while being insulated from one another to avoid creating a shorted turn. As copper is non-magnetic, mutual induction is not affected. The screen prevents mains-borne interference from reaching the secondary winding by capacitive coupling. Some transformers may have another screen (shorted this time) outside the magnetic circuit to prevent stray fields

ever this does increase the self self-capacitance. This may not matter at 50Hz. Some modern transformers wind the primary and secondary separately, with an insulating divider instead of on top of each other (Fig 2.17). This provides greater safety at the cost of poorer regulation (the decrease of output voltage with current). An alternative is to use two concentric bobbins. Many small commercial transformers suffer from poor regulation due to this effect.

If capacitance between primary and secondary is to be minimised, a Faraday screen is inserted - see Fig 2.18 for the way to do this. It is essential that the screen should not cause a shorted turn.

Insulation, if required, is best made with Kapton or Nomex tape, which will withstand as high a temperature as the wire.

Fig 2.19: Examples of the use of ‘C’ cores and toroids

Toroidal or 'C' cores (Fig 2.19) are used to reduce the external magnetic field and in Variacs^{tm} (see later and Fig 2.20). Beware of making a shorted turn with the fixing arrangements. As toroidal transformers are worked near the maximum permissible flux density, a large in-rush current may be noticed when switching on. If the supply is switched on as the voltage crosses zero, doubling of the current will occur as the voltage and current establish the correct phase relationship; it could even saturate the core momentarily.

This is particularly noticeable with the Variac. Fig 2.21 shows a comparison between a switch mode transformer, which runs at 500kHz, and a standard 50Hz transformer. Where the stray

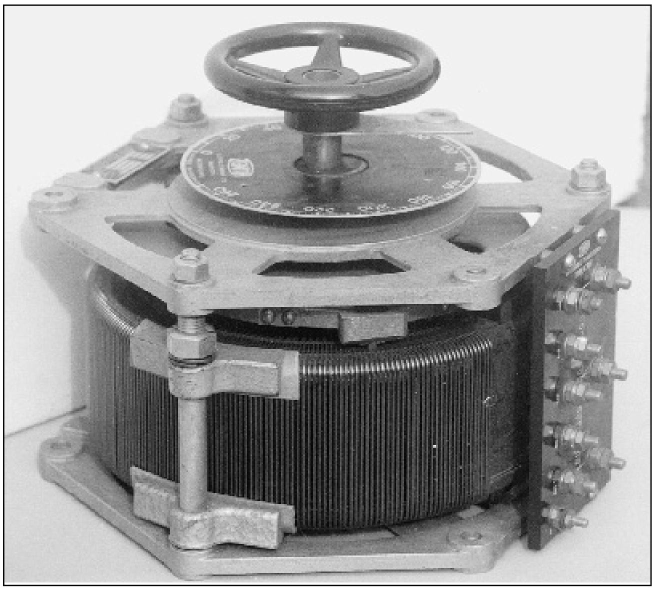

Fig 2.20: A variac

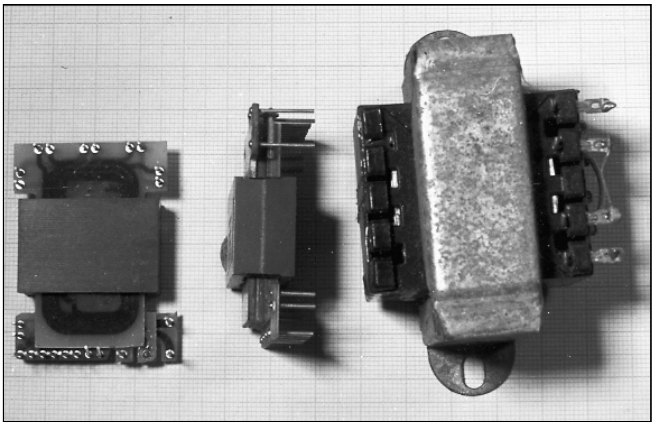

Fig 2.21: The two transformers on the left are 125W devices for 500kHz operation and weigh 40g each, while the one on the right is a 12W transformer for mains frequency (50Hz) and weighs in at 420g. The standard graph paper background has 1cm squares and 1mm subdivisions

Fig 2.22: Copper foil under the 'Danger' label surrounds the winding and the outer limbs of the core to reduce radiation

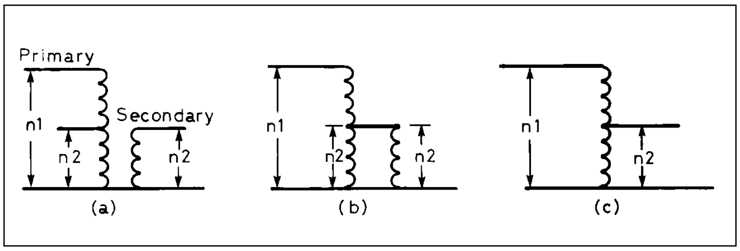

Fig 2.23: The auto-transformer

magnetic field has to be reduced, a shorted turn of copper foil outside the whole magnetic circuit is used - see **Fig 2.22** .

Practical note: When winding on E and I or T and U laminations, remember that part of the bobbin's cheeks will later be covered by the core, so do not bring the leads out in this region! If the wires are very thin, skeining them before bringing them out makes a sounder job.

If isolation is not required between input and output, an autotransformer can be used. This will increase the power handling capacity of a particular core. The primary and secondary are continuous - the transformation ratio being still the ratio of the number of turns, as in **Fig 2.23 .** Wire gauge is chosen to suit the current. Since the secondary is part of the primary (or vice versa), more use is made of the winding window. The tapping point can be made variable to allow adjustment of the output voltage, the device then being known as a Variac.

In loosely coupled transformers, if the windings are tuned by capacitors, the degree of coupling controls the bandwidth of the combination (**Fig 2.24**). Such transformers are widely used in intermediate frequency stages and wideband couplers. Again, ferrite, iron dust or brass slugs may be used for trimming in the appropriate frequency range. Loose coupling is used on mains in ballasts for sodium lamps and in microwave ovens, whose magnetron needs a constant current supply. Beware of trying to use a microwave oven to supply a valve linear amplifier, apart from loose coupling, the inner of the secondary is either earthed or not well insulated.

MATERIALS

Earlier in this chapter conductors were described - here some of the insulators used in amateur radio will be considered first. These will be grouped into three categories: inorganic, polar and non-polar plastics. Mica (mainly impure aluminium silicate), glass and ceramics are the most likely to be used (asbestos is potentially dangerous). Vitreous quartz is one of the best insulators, but is not generally available. It has nearly zero temperature coefficient of expansion, and would make a good former for VFO inductors. Mica is not generally used except in capacitors. Glass has a tendency to collect a film of moisture, but the leakage is hardly likely to be troublesome. If it is, the glass should be coated with silicone varnish. Porcelain antenna insulators do not suffer from this trouble. Ceramic coil formers leave little to be desired but are becoming increasingly more difficult to obtain.

Non-polar plastics like polystyrene, polypropylene and PTFE are all very good. Polypropylene rope avoids the use of antenna insulators (except where very high voltages are encountered as when using a Marconi antenna on the 136kHz band) which is particularly useful in portable operation.

Polar plastics such as phenol-formaldehyde (Tufnol and Bakelite), Nylon, Perspex and PVC have higher losses that are frequency sensitive. The test using a microwave oven is not the best, as the loss at 2450MHz may not be the same as at the required frequency. Tests involving burning are not advised. Because of possible loss, they are not recommended to withstand high RF voltages. **Fig 2.25** shows two coils, one on polythene and the other on Tufnol. The one on the polythene former has a Q of 300, but the Tufnol one only 130 at 5MHz. Some protective varnishes are polar, being made for 50Hz. Only polystyrene dope previously described should be used where RF loss is important.

Permanent magnets may be a special ferrous alloy, ceramic rare earth alloy or neodymium-boron-iron. Ferrous alloys such as Alnico and Ticonal were much used in DC machines, headphones and loudspeakers. The others now replace them.

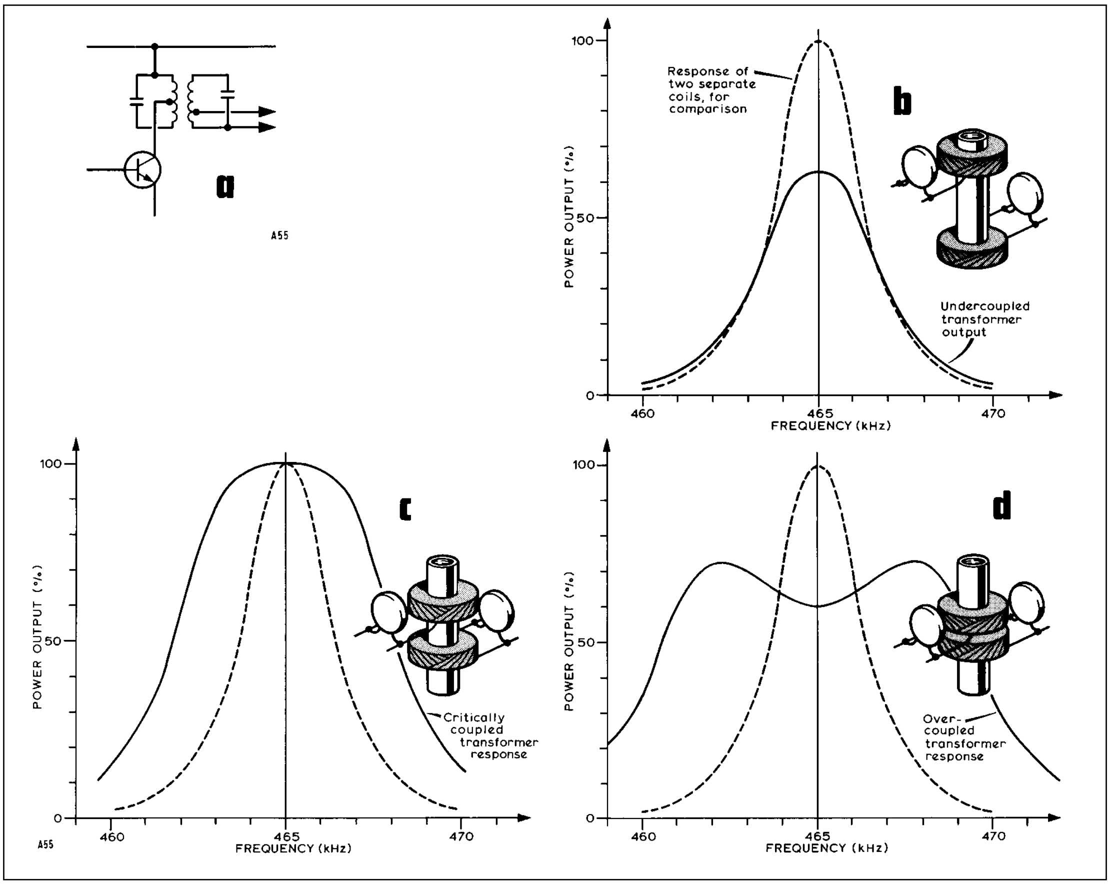

Fig 2.24: Bandwidth of coupled circuits

Ceramic magnets are cheap and withstand being left without a keeper better than ferrous alloys. The other two store more magnetic energy, are very good on open magnetic circuits but are expensive.

RELAYS

The 'Post Office' types 3000 and 600 are still available in amateur circles (**Fig 2.26**). However they are not sealed, and many sealed relays are now available. Newer relays need less operating current, some being able to operate directly from logic ICs. Contacts are made from different materials according to the intended use, such as very high or low currents.

The abbreviations 'NO', 'NC' and 'CO' apply to the contacts and stand for 'normally open', 'normally closed' and 'change over', the first two referring to the unenergised state. Some manufacturers use 'Form A' for NO, 'Form B' for NC and 'Form C' for CO. Multiple contacts are indicated by a number in front of the abbreviation.

Latching relays are stable in either position and only require a set or reset momentary energisation through separate coils or a pulse of the appropriate polarity on a single coil. These relays use permanent magnet assistance, meaning that correct polarity must be observed.

It is possible to get relays for operation on AC without the need for a rectifier, the range including 240V, 50 Hz. Part of the core has a short circuited turn of copper around its face - this holds the relay closed while the current through the coil falls to zero twice per cycle.

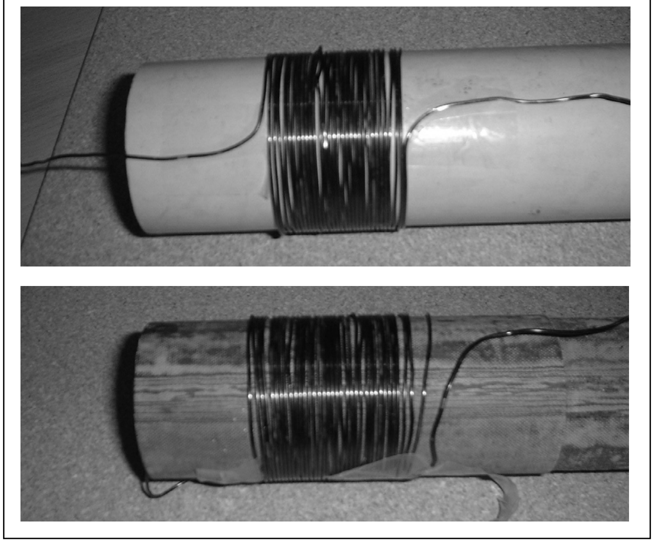

Fig 2.25: Similar coils wound on (a) polythene and (b) Tufnol have different Q values

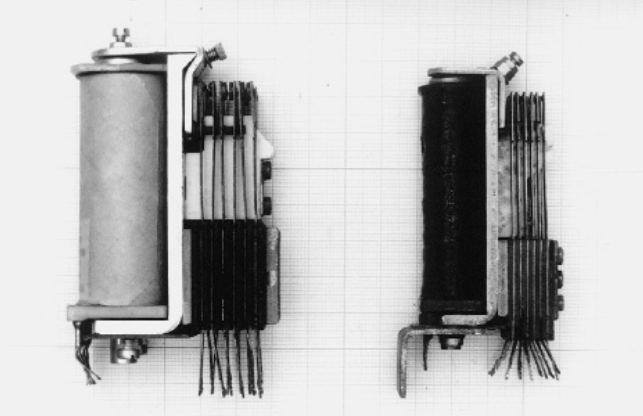

Fig 2.26: Post Office relays. Left type 3000, right type 600

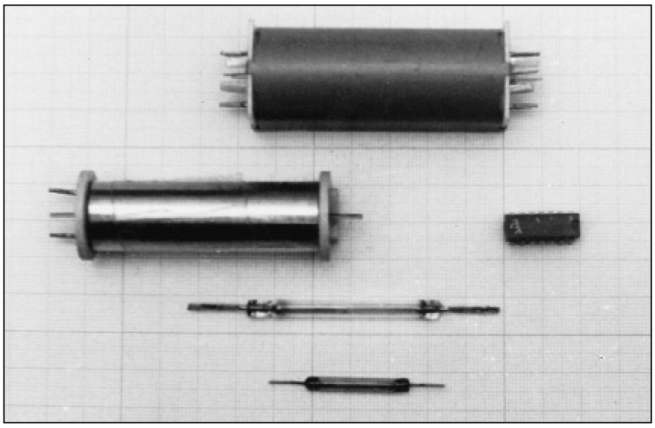

Fig 2.27: Reed relays. Top: four reeds in one shielded coil. Middle left: reed in open coil. Right: miniature reed relay in 14-pin DIL case. Below: large and small reed elements

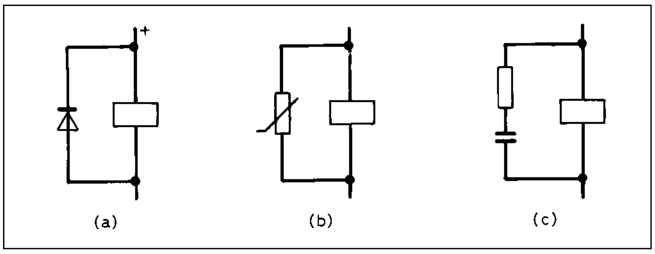

Fig 2.28: Relay coil suppression circuits

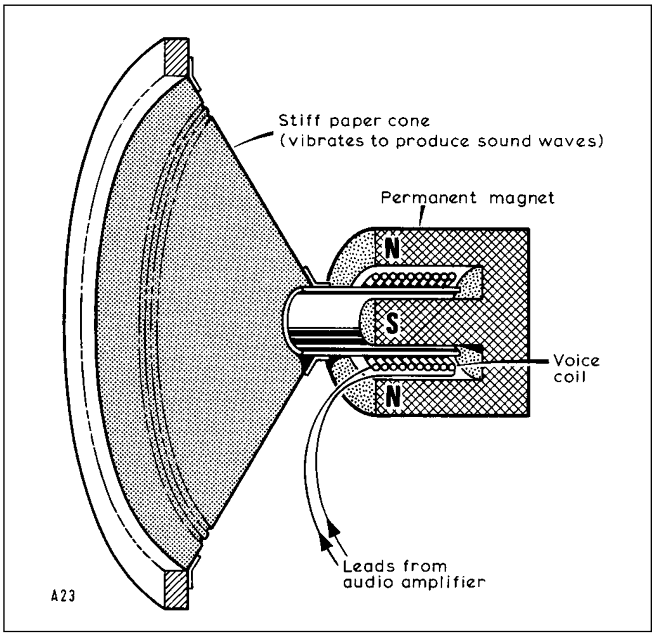

Fig 2.29: Moving-coil loudspeaker

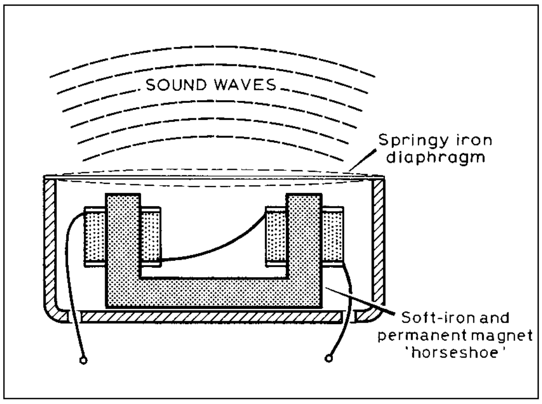

Fig 2.30: Moving iron headphone

If RF currents are to be switched, reed relays (**Fig. 2.27**) or coaxial relays which maintain a stated impedance along the switched path should be used. Reed relays, either with dry or mercury wetted contacts, are among the fastest operating types, and should be considered if a relay is needed in a break-in circuit.

As a relay is an inductive device, when the coil current is turned off, the back EMF tries to maintain, possibly creating a spark. The back EMF may damage the operating transistor or IC, so it must be suppressed (**Fig. 2.28**). A diode across the coil, connected so that it does not conduct during energisation will conduct when the back EMF is created, but in so doing it slows down the release of the relay. Varistors or a series RC combination are also effective. If rapid release is required, a high voltage transistor must be used with an RC combination which will limit the voltage created to less than the maximum of this transistor.

Another undesirable feature of relays is contact bounce, which may introduce false signals in a digital system. Mercury wetted reed relays are one way over this problem, but some will only work in a particular orientation.

ELECTRO-ACOUSTIC DEVICES

Moving coil loudspeakers (and headphones) use the force generated when a magnetic flux acts on a current carrying coil (**Fig. 2.29**). The force moves the coil and cone to which the coil is fastened. Sound is then radiated from the cone. Some means of preventing the entry of dust is provided in the better types.

Sounders

The piezo-electric effect is used to move a diaphragm by applying a voltage. The frequency response has a profound resonance so the device is often used as a sounder at this frequency.

Headphones

Small versions of the moving coil and piezo-electric loudspeakers are used as headphones. The in-ear headphone is a moving coil element, with a neodymium-boron-iron magnet to reduce the size. Deaf aid in-ear headphones use the piezo-electric effect, with a better response than the sounder has.

Another type has a magnetic diaphragm, which is attracted by a permanent magnet with the audio frequency field superimposed on it (**Fig. 2.30**) The permanent field is necessary because magnetic attraction is proportional to the square of the flux (and current). Without the permanent flux, second harmonic production would take place. The over-riding steady flux prevents this.

Microphones

The moving coil loudspeaker in miniature forms the dynamic microphone. It is possible to use the same unit both as a loudspeaker and microphone, often in hand-held equipment.

The piezo-electric element shown in **Fig 2.31** is reversible and forms the basis of the crystal microphone. The equivalent circuit

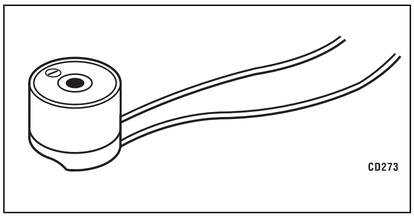

Fig 2.31: Piezoelectric loudspeaker

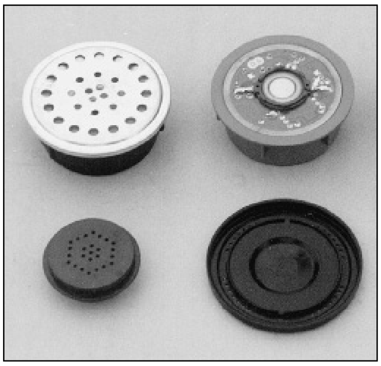

Fig 2.32: Microphone inserts. Left: carbon mic. Right: dynamic mic

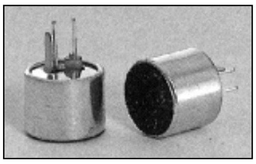

Fig 2.33: Electret microphone

is a small capacitance in series with a small resistance. This causes a loss of low frequencies if the load has too low a resistance. FETs make a very suitable load. Moisture should be avoided, as some crystals are prone to damage.

It is possible to use the diaphragm headphone as a microphone since the effect is reversible, and some ex-service capsules are made this way.

Probably the carbon microphone is the oldest type still in telephone use; one type is shown in **Fig 2.32**. Sound waves alternatively compress and relieve the pressure on the carbon granules, altering the current when energised by DC. It amplifies, but is basically noisy and subject to even more unpleasant blasting noises if overloaded acoustically. It is rarely used nowadays in amateur radio. The impedance is some hundreds of ohms.

The above types can be made (ambient) noise cancelling by allowing noise to be incident on both sides of the diaphragm (or element) with little effect. Close speaking will influence the nearer side more, improving the voice to ambient noise ratio.

The so-called condenser microphone has received a new lease of life under the name of electret microphone. The condenser microphone had a conductive diaphragm stretched in front of another electrode and a large DC potential difference maintained, through a resistive load, across the gap. Variations in the position of the diaphragm by sound waves caused a variation of capacitance, and so an AF current flows through the load resistance. As the variation in capacitance is small, a large load resistance is required. A valve amplifier was included in the assembly to avoid loss of signal in leads and possible unwanted pick up. In the electret microphone, the need for a high polarising voltage is obviated by using an electret as the rear electrode and an FET in place of the valve. An electret is the electrostatic counterpart of a permanent magnet, and maintains a constant potential across the electrodes without requiring any power. The FET provides impedance transformation to feed low impedance leads. A point worth remembering it that the field from the electret attracts dust! Two small ones are shown in **Fig 2.33**.

QUARTZ CRYSTALS

Quartz is a mineral, silicon dioxide and the major constituent of sand. In its crystalline form it exhibits piezo-electric properties. The quartz crystal is hexagonal in section, and has hexagonal points. The useful piezo-electric effect takes place only at certain angles to the main axis from point to point. If a slice is cut at one of the correct angles, it can act like a bell and ring if struck. Ringing is an oscillation and with small slices this will take place in the MHz region. Mechanical ringing is accompanied by electrical ringing, and with proper amplifier connection this can be sustained (see the chapter on oscillators).

Charge is applied to the quartz element from metal plates sprung on to it, or better by silver electrodes plated on.

The type of deformation that the charge produces, stretching, shearing or bending, depends on the angle of cut and mode of mechanical oscillation to be excited. Various different cuts have different temperature coefficients, DT having a parabolic curve, AT a third order curve and SC virtually no tempco. More detail of this can be found in the oscillators chapter.

Naturally occurring quartz always had defects in the crystal, which made for unpredictability, but now crystals are made by dissolving sand in water, and crystallising it out. Very high pressure and temperature are used.

The Q of the crystal is much higher than can be obtained with LC circuits. As an example, a 7MHz crystal may have a Q of 10,000. The equivalent circuit is in **Fig. 2.34** where C_s, L_s and R_s represent the properties of the crystal and C_p the shunt capacitance of the holder. The measured values of these parameters are strange when compared with the LC circuit, as **Table 2.6** reveals. Note the very large inductance of the crystal; also a Q of 300 for the LC circuit is good.

A quartz crystal is not a primary standard of frequency; it has to be compared with another. Not only this, all crystals age, even if not excited. Switching on and over excitation add to ageing, which is usually towards a higher frequency.

Crystals can normally be cut, ground or etched for the kilohertz region up to about 30MHz, above this they are too fragile to be of practical value. An overtone crystal can be used, which

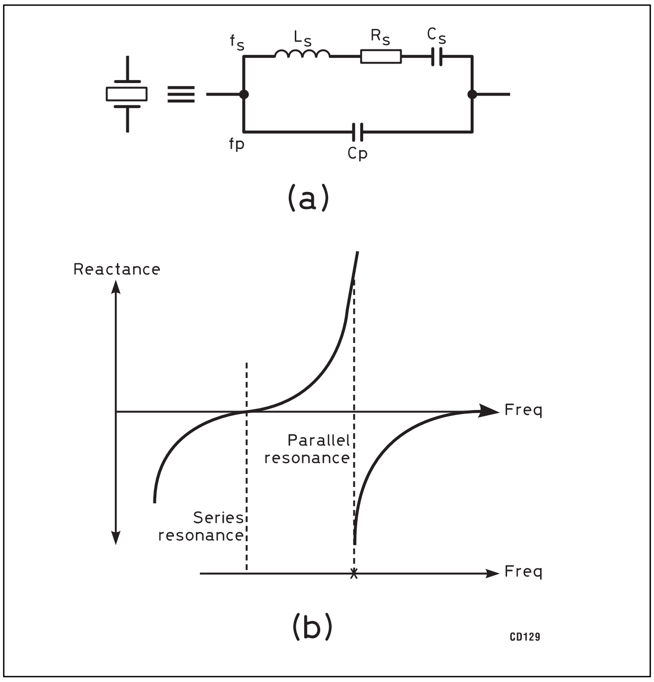

Fig 2.34: (a) Equivalent circuit of a piezoelectric crystal as used in RF oscillators or in filter circuits. Typical values for a 7MHz crystal are given in Table 2.6. Cp represents the capacitance of the electrodes and the holder. (b) Typical variation of reactance with frequency. The series and parallel reactances are normally separated by about 0.01% of the frequencies themselves (eg about a kilohertz for a 7MHz crystal)

Parameter	7MHz crystal	7MHz LC
Ls	42.5mH	12.9 H
Cs	0.0122pF	40pF
Rs	19	0.19
Q	98,000	300

Table 2.6: Parameters of a crystal compared with an LC circuit

is excited at a frequency that is nearly equal to an odd number times the fundamental. It will still try to oscillate at the fundamental, but the external circuit must be made to prevent this.

Since crystals act as tuned circuits, they can also be used as filters; piezo-ceramics being much used. More information can be found in the chapters on receivers and transmitters. The use of cheap, readily available computer or colour TV crystals in filters has been well documented [3]. [4].

Mechanical Design

Quartz crystals must be protected from the environment and are mounted in holders; these are usually evacuated. There are several types and sizes (**Fig 2.35**) but basically they are either in metal or glass. If in metal, the cheapest is solder sealed, next is resistance welded and the most expensive cold welded.

Ceramic Resonators

Certain ceramics, mainly based on titanium and/or zirconium oxides, have similar properties to quartz and are used as oscillators or filters. They have a lower Q, a lower maximum frequency and a higher temperature coefficient, but these are offset by a lower price. They are also only available for a limited range of frequencies.

There is another type of ceramic resonator that works at microwave frequencies and is widely used in satellite TV receivers.

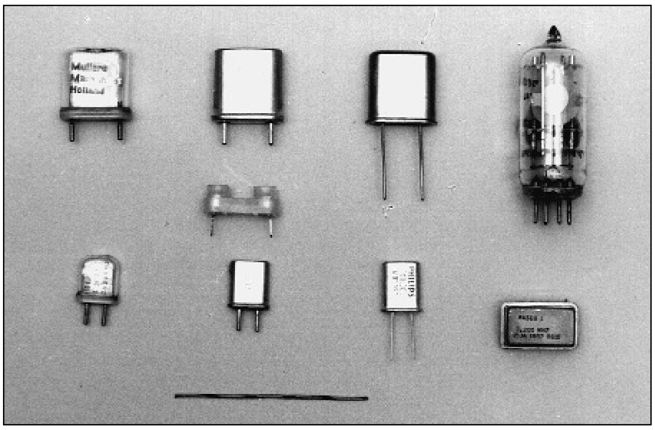

Fig 2.35: Quartz crystals in different holders. Top, from left: HC27U, HC6U, HC47U (wire ended) and B7G. Holder for HC6U between the rows. Bottom, from left: HC29U, HC25U, HC18U (wire ended) and a packaged crystal oscillator. The striped bar is 50mm long

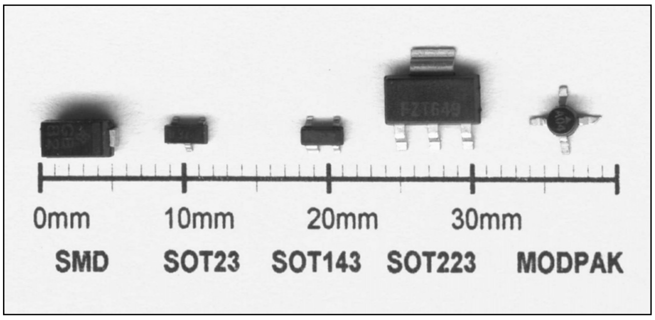

Fig 2.36: Discrete SMT packages

SURFACE MOUNT TECHNOLOGY

Although most people have seen surface mount technology (SMT), relatively few without a professional involvement in electronics have used it in construction. SMT dominates commercial technology where its high-density capability and automated PCB manufacture compatibility is of great value. The arrival of SMT combined with the increasing dominance of monolithic IC parts over discrete components means that amateurs will have to move with the technology or rapidly lose the ability to build and modify equipment. SMT has an image of being difficult but this is not necessarily the case and it is quite practical for amateurs to use the technology. An incentive is that traditional leaded components are rapidly disappearing with many recently common parts no longer being manufactured and new parts not being offered in through-hole format. The cost of SMT parts in small quantities has fallen dramatically and through-hole construction will become increasingly expensive in comparison when it is possible at all.

The variety of available SM components is enormous and growing rapidly. While the fundamental component types are familiar, the packaging, benefits and limitations of SM components are significantly different to their through-hole equivalents and a brief review is worthwhile (**Fig 2.36**).

Surface Mount Resistors

Typical sizes of resistors continue to shrink due to market pressure for ever-higher densities and lower costs. The surface-mount parts are often referred to by their nominal case sizes such as '1206' which is approximately 12 hundredths of an inch long by 6 hundredths of an inch wide. **Fig 2.37**.

Table 2.7 lists the commoner sizes but the largest volume is currently in the 0603 size. The 0805 is probably slightly better for the amateur as smaller parts tend not to bear any markings. One standard technique with surface mount is to use the space between the two pads under a component to run a surface track under the component and save a wire link. Below 0805 size this technique becomes demanding of amateur PCB processes. Tolerances of resistors have also improved with standard parts being 1% tolerance and 100ppm stability. Such has been the improvement in manufacturing processes looser tolerance parts are generally not available. The 0201 size is in restricted commercial use but is of limited relevance to the

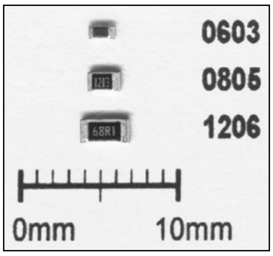

Fig 2.37: SMT resistors

Style	Size (mm) L	Size (mm) W	Rating (mW)
1206	3.2	1.60	250
0805	2.0	1.25	125
0603	1.6	0.80	100
0402	1.0	0.50	63
0201	0.6	0.30	50

Table 2.7: SMT resistors

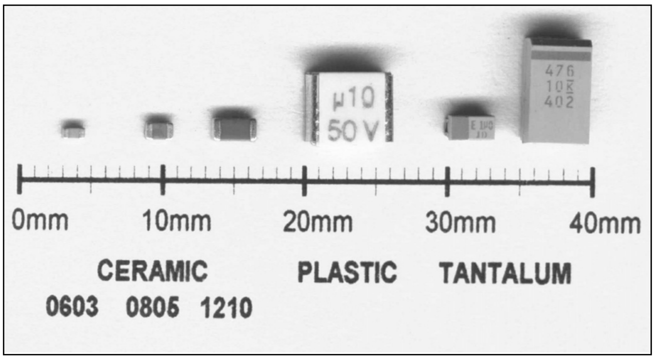

Fig 2.38: SMT capacitors

Dielectric type	Relative permittivity	Tolerance (%)	Typical temperature stability (%)
COG, NPO	low	±5	±0.5
X7R	medium	±10	±10
Z5U	high	+80/ 20	60/+20
Y5V	high	+80/ 20	80/+20

Table 2.8: Ceramic capacitors

amateur. The power ratings are for comparison purposes only as in practice they are partly dependent on the PCB design and other factors.

Surface Mount Capacitors

Capacitors are available in similar sizes to resistors but due to physical constraints it is not possible to settle on a single case size for all requirements. The dominant type is the monolithic multi-layer ceramic type with tantalum dielectric as the next most common. Progress has been made with ceramic capacitors to decrease size and to increase maximum values to over 10μF, displacing electrolytic parts in some applications. Plastic film parts are also available but suffer from a number of problems. See **Fig. 2.38**.

Ceramic capacitors

When selecting these, choices must be made on tolerance, stability and voltage rating which will result in a number of size alternatives. The voltage rating is important since larger values may have quite low ratings. The choice of dielectrics is wide but some of the commoner choices are given in **Table 2.8** with some typical properties. The structure of these parts is a multi-layer monolithically fabricated structure.

Although the parasitic inductances of these surface-mount devices are superior to leaded equivalents there are special parts available for microwave frequencies that have better-defined parasitic properties and high-frequency Q, albeit at a cost penalty. The monolithic multi-layer capacitors are more fragile than they may appear at first and unfortunately seldom give any external sign of failure.

Mechanical shock can damage the parts quite easily and at least one supplier warns that the parts should not be dropped onto a hard surface. When hand soldering, avoid any contact between the iron and the unplated body of the component. The damage will often take the form of shattering of some of the internal plates resulting in a significant capacitance error. Commercially an ultrasonic microscope or x-ray investigation can identify the problem.

The parts can suffer permanent value changes due to soldering and the values also change slightly with the DC voltage applied to them. The higher-permittivity dielectrics are particularly subject to these effects.

Tantalum and niobium oxide capacitors

These capacitors are available in many variants and should be chosen carefully for the particular application. In addition to the standard types there are parts that provide lower effective series resistance (ESR), usually for PSU filter applications, and parts that provide either surge resistance or built-in fuses. It is important to consider safety, as an electrolytic failure on a power rail will often result in debris being blown off the PCB and even a small capacitor can cause eye damage. This means using appropriate voltage ratings, and using parts that will tolerate maximum current surges and have appropriate power dissipation and temperature ratings.

Plastic dielectric capacitors

Although available, these have only made a limited impact due to the problem that the dielectric has to withstand direct solder temperatures and many manufacturers simply will not approve them for their solder processes. Parts typically use polyester and care must be taken to avoid overheating them while soldering. Even with care the parts may change value significantly due to heating and the resultant mechanical distortion.

Aluminium electrolytic capacitors

These are available in SMT, often as slight variations of a leaded package to allow surface soldering. Although they have been displaced to an extent by tantalum parts they still have a role to play.

Surface Mount Inductors and Ferrites

A large range of inductive devices exists, based on either traditional wound structures or layered ferrite structures (**Fig. 2.39**). The advantage of smaller size in many SMT parts may be offset by reduced performance, often with lower Q and poorer stability in comparison to large leaded parts. The wound parts come in a number of styles and an additional option is often whether the part is to be shielded, ie the magnetic field is mostly self-contained as in a toroid. The current rating needs to be carefully watched as the parts will saturate and lose performance long before any other effects are noticed. The ferrite parts are available in multi-layer structures, a little like a monolithic multi-layer capacitor and can be very useful for RF suppression. A vast range of devices exist that integrate capacitors into the package to make various filters usually for EMC purposes, but monolithic low-pass filters are available for VHF and UHF transmitter harmonic suppression.

Surface Mount Connectors

Surface mount connectors are now relatively common for both multi-way interconnects and for coaxial connections. There is little to say specifically about them since they are essentially similar to the equivalent through-hole parts. The small size and the reliance on solder connections for mechanical strength means that they should be treated with care as they can readily be torn

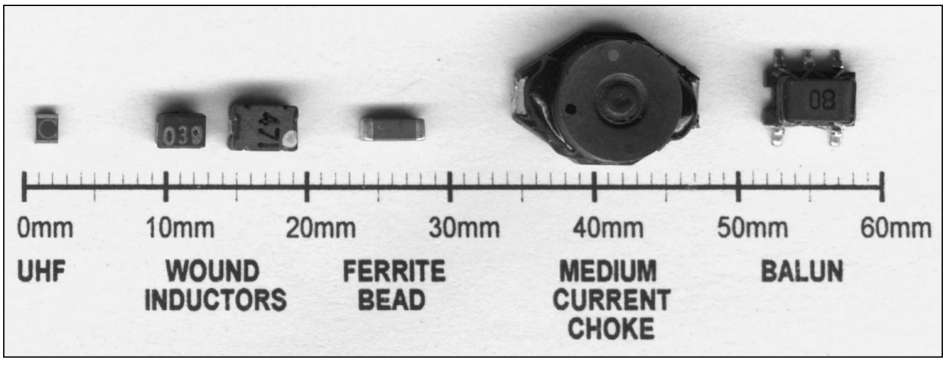

Fig 2.39: SMT inductors

Alpha	Numeral								
chr	9	0	1	2	3	4	5	6	7
A	0.10p	1.0p	10p	100p	1.0n	10n	100n	1.0	10
B	0.11p	1.1p	11p	110p	1.1n	11n	110n	1.1	11
C	0.12p	1.2p	12p	120p	1.2n	12n	120n	1.2	12
D	0.13p	1.3p	13p	130p	1.3n	13n	130n	1.3	13
E	0.15p	1.5p	15p	150p	1.5n	15n	150n	1.5	15
F	0.16p	1.6p	16p	160p	1.6n	16n	160n	1.6	16
G	0.18p	1.8p	18p	180p	1.8n	18n	180n	1.8	18
H	0.20p	2.0p	20p	200p	2.0n	20n	200n	2.0	20
J	0.22p	2.2p	22p	220p	2.2n	22n	220n	2.2	22
K	0.24p	2.4p	24p	240p	2.4n	24n	240n	2.4	24
L	0.27p	2.7p	27p	270p	2.7n	27n	270n	2.7	27
M	0.30p	3.0p	30p	300p	3.0n	30n	300n	3.0	30
N	0.33p	3.3p	33p	330p	3.3n	33n	330n	3.3	33
P	0.36p	3.6p	36p	360p	3.6n	36n	360n	3.6	36
Q	0.39p	3.9p	39p	390p	3.9n	39n	390n	3.9	39
R	0.43p	4.3p	43p	430p	4.3n	43n	430n	4.3	43
S	0.47p	4.7p	47p	470p	4.7n	47n	470n	4.7	47
T	0.51p	5.1p	51p	510p	5.1n	51n	510n	5.1	51
U	0.56p	5.6p	56p	560p	5.6n	56n	560n	5.6	56
V	0.62p	6.2p	62p	620p	6.2n	62n	620n	6.2	62
W	0.68p	6.8p	68p	680p	6.8n	68n	680n	6.8	68
X	0.75p	7.5p	75p	750p	7.5n	75n	750n	7.5	75
Y	0.82p	8.2p	82p	820p	8.2n	82n	820n	8.2	82
Z	0.91p	9.1p	91p	910p	9.1n	91n	910n	9.1	91
a	0.25p	2.5p	25p	250p	2.5n	25n	250n	2.5	25
b	0.35p	3.5p	35p	350p	3.5n	35n	350n	3.5	35
d	0.40p	4.0p	40p	400p	4.0n	40n	400n	4.0	40
e	0.45p	4.5p	45p	450p	4.5n	45n	450n	4.5	45
f	0.50p	5.0p	50p	500p	5.0n	50n	500n	5.0	50
m	0.60p	6.0p	60p	600p	6.0n	60n	600n	6.0	60
n	0.70p	7.0p	70p	700p	7.0n	70n	700n	7.0	70
t	0.80p	8.0p	80p	800p	8.0n	80n	800n	8.0	80
y	0.90p	9.0p	90p	900p	9.0n	90n	900n	9.0	90

The letter may be preceded by a manufacturer's mark such as a letter or symbol. Typically, a part by Kemet Electronics may be marked as in Fig 17.45.

Table 2.9: EIA-198 capacitor marking system, showing the capacitance (pF, nF, µF) for various identifiers

from a PCB. An additional problem is that due to their small size and low mating forces the connectors are very vulnerable to pollution on the contacts arising from flux or dirt and it is essential that they are kept very clean if problems are to be avoided.

Although Pressfit connectors are through-hole components they are included here as they are common on surface-mount boards. These connectors typically have square pins that are inserted into slightly undersize round-plated through holes so that the pins cut into the copper hole plating, resulting in a cold weld requiring no soldering. Considerable force may be required for large multi-way connectors but the construction is attractive to PCA assemblers as it can eliminate an additional solder process.

This technique is starting to appear on miniature coaxial PCB-mounting sockets. If unsoldered connectors are seen on a PCA it should not be automatically assumed that some mistake has been made! These parts can be used by the amateur - they should be treated as ordinary through-hole parts and hand soldered.

SMT Component Markings

Resistors

The small size of these parts means that often no markings are printed onto parts smaller than 0805. If they are marked, resistors are printed with their value using a three or four digit number, for example:

393 = 39 x 10^3 = 39kΩ
1212 = 121 x10^2 = 12.1kΩ
180 = 18 x10^0 = 18.0Ω
3R3 = 3.3 = 3.3Ω

Capacitors

Unfortunately capacitors are seldom marked in this manner and if marked normally use a code system (EIA-198) of a letter followed by a number to indicate value. Access to a capacitance measurement device is extremely useful since the majority is unmarked. The EIA-198 capacitor marking system is shown in **Table 2.9**.

Inductors

These are usually marked with their value in microhenrys using a similar system to resistors, for example:

3u3 = 3.3µH
333 = 33mH

REFERENCES

[1] 'Simple inductance formulae for radio coils. Proc.IEE, Vol. 16, Oct 1928, p 1398

[2] *Shortwave Wireless Communications*, Ladner and Stoner, 4th edition, Chapman & Hall, London 1946 pp 308-339. This is an old reference and it does not show modern crystal designs, but does explain the 'cuts' very well.

[3] G3JIR, *Radio Communication* 1976 p896, 1972, pp28, 122 and 687, RSGB

[4] G3OUR, *Radio Communication* 1980, p1294, 1982 p863.

The chapter author is grateful for the assistance given by the AVX Corporation of the USA on the subject of Niobium Oxide capacitors.