**Is it necessary to re-form electrolytic capacitors that have been stored for years?
Why do tantalum capacitors fail short circuit?
Do electrolytic capacitors have an extremely high dielectric constant?
Cyril Bateman knows.**

Understanding capacitors

Aluminium and tantalum options

Aluminium and tantalum electrolytic capacitors uniquely balance *CV* product against physical size. While film or ceramic capacitors are readily available up to 10μF, higher capacitance values are physically large and very expensive. Very large value electrolytic capacitors are available at low cost, and in physically small packages.

The possibility of forming an insulating film on the surface of aluminium was first observed by Wheatstone in 1854. In 1908 a rolled type aluminium capacitor was produced in USA and a viscous electrolyte of ammonium tetraborate and glycerine was developed in Germany.[1] These two essential discoveries resulting ultimately in the modern electrolytic capacitor.

Regardless of construction or dielectric used, every capacitor is composed essentially of two conducting surfaces, called electrodes, separated by an insulator.[2] Insulation materials produce differing capacitance values for the same area and thickness, according to their dielectric constant, or 'K' value.

The permittivity of free space is used as the base unit since all other materials – including air – exhibit increased capacitance. These K values, which range from 1.00059 for air to greater than 12000 for high-K ceramics, significantly influence the capacitance achieved.

Electrolytic capacitors are manufactured using so-called valve metals, the most common being aluminium and tantalum. Valve metals have the ability to form an insulating, semi-conducting and protective surface oxide film. Aluminium oxide has a K value of 8, while that for tantalum pentoxide is 27.6, approximately.[3]

Aluminium oxide and tantalum pentoxide films grown on the highest purity metals provide very high-quality, low-loss insulators. Aluminium oxide has a dielectric strength approaching the theoretical strength[4] as predicted by the ionic theory of crystals.

Capacitance value depends on the product of the electrode area and the K value of the insulating dielectric. It is inversely proportional to the distance separating the electrodes. For any chosen dielectric, the capacitance attained depends totally on the insulators thickness and surface area.

Fig. 1. Edge on view, much enlarged, of a 100 micron thick etched and formed foil showing large tunnels connecting both foil faces. Taken using an electron microscope. This foil has become porous to liquids.

When a flexible electrode system that conforms precisely with the insulator's surface is used. The effective or apparent area can then be increased by roughening or abrading, increasing capacitance without increase of physical size. This effect is called surface gain.

Frequently, electrolytic capacitors have been described as having an extremely high dielectric constant. This is wrong, the K values of 8 and 27.6 are correct,[3] so how can such high capacitance values be attained?

Compared to metallised-plastic film capacitors, which use dielectric film thickness of a micron and above, electrolytic capacitor dielectric films are some fifty times thinner.

This extremely thin dielectric results in electrolytics being the most highly voltage stressed of all capacitors. However this combination of a very thin dielectric having a K value of 8, or even 27.6, still does not explain how such large capacitance values can be attained.

Surface gain – aluminium

I mentioned roughening or abrading the insulators surface to increase its apparent area. You can see an example of this by closely examining a piece of aluminium kitchen foil. Usually, one side is smooth and shiny, the other matt. Under a times-ten magnifying glass, this matt surface is visibly embossed, providing some surface gain.

The earliest electrolytic capacitors attained usable surface gains by spraying molten aluminium onto a carrier. Known

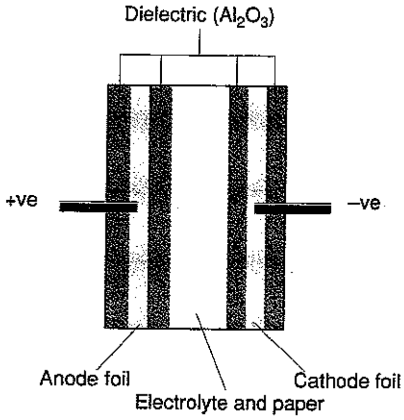


Fig. 2. Simplified sketch of an aluminium electrolytic capacitor, showing anode and cathode aluminium oxide dielectric films in contact with highly conductive electrolyte.

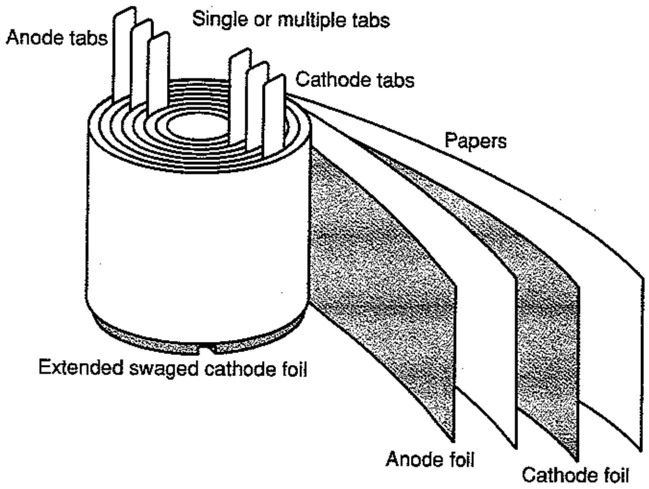


Fig. 3. This view of a partially wound element, shows a large multiple tabbed radial leaded capacitor. An alternative arrangement using a single anode and cathode tab is more common. Also shown is an extended cathode foil, which improves heat dissipation. With its turns swaged to connect each other, this extended cathode foil can substantially reduce capacitor equivalent series resistance.

as 'fabricated plate', this technique was popular for high voltage capacitors. It was quickly superseded for low voltage capacitors though by chemical etching methods.

Today, the surface gain of aluminium electrolytic capacitor foils is attained by electro-chemical etching in a bath of electrolyte. Reduced to basics, an electrolyte is simply a liquid that conducts electricity, having a low resistance or high conductivity, **Fig. 1**.

Common examples of electrolytes are car battery acid and sea water. The aluminium to be etched is placed in a bath of electrolyte and current is passed. There's more about this in the panel entitled 'Aluminium etching.'

Surface gain – bead tantalum

The modern bead tantalum capacitor is fabricated from fine particles of tantalum powder surrounding a small tantalum wire. These particles are compressed into pellets or slugs. Compression pressure is controlled to restrict the pellet's density.[5] The object is to produce a porous body having a very large internal surface area.

To increase the cohesion of these tantalum particles and ensure electrical conductivity, the compressed slugs are sintered at very high temperatures in vacuum furnaces. This provides a mechanically rugged, porous structure.

The high sintering temperature performed in vacuum has a purifying effect. Tantalum is a refractory metal and needs a sintering temperature approaching 2000°C. At such temperature, most impurities evaporate, and are removed by the vacuum pumping system.

Having attained a large surface area, both aluminium and tantalum oxide dielectrics are grown *in situ* onto all-metal surfaces. This involves an electro-chemical process called 'forming'. The 'formed' oxide fully covers and insulates all visible metal surfaces and all invisible cavities within the metal.

Forming aluminium oxide

Placed in a bath of suitable electrolyte and with a positive voltage applied to the foil, aluminium oxide, Al_2O_3, grows on the foil's surfaces.

Depending on the electrolyte used, two main forms of this oxide can be grown. A hard non-porous oxide layer is deliberately grown when the aluminium foil is to be used as a capacitor dielectric or other insulator. When the aluminium is to be 'anodised' to provide a coloured decorative finish, a porous oxide is grown.

An aggressive electrolyte simultaneously re-dissolves some existing oxide, resulting in a porous oxide layer. This process is commonly called anodising. In other applications, the pores in the oxide are be filled with coloured dyes, resulting in the popular decorative finish.

Using a non-aggressive electrolyte, a slowly growing, impervious and continuous oxide film is obtained. This non-porous, hard oxide film grown on super-pure aluminium is an excellent insulator that can be formed to withstand at least 600 volts.

I mentioned earlier that the dielectric oxide formed is very thin. Its thickness is self limiting. Oxide growth at any one voltage slows and almost ceases with time, ultimately attaining some 14Å thickness[3] for each volt applied.

Foil used in commercial capacitors is formed at a voltage at least 120% of the capacitor's rated voltage. This ensures low leakage current and provides the overvoltage capability needed for the 'surge voltage' claimed.A commercial 10V aluminium electrolytic capacitor will have a dielectric thickness of some 0.02 microns. There's more on this topic in the panel entitled 'Aluminium forming'.

Forming oxide for tantalum devices

Being less reactive than aluminium oxide, tantalum pentoxide is generally grown in an acidic bath. Since the current paths into the centre of a slug can be quite tenuous, a strong, highly conductive electrolyte is used.

Tantalum pentoxide is an excellent insulator, growing to a thickness of 17Å per formation volt applied to the slug.[3] This oxide makes a highly amorphous film, but if subjected to a high field strength at a fault site, it can become crystalline, resulting in a short circuited capacitor.[5] To reduce the risk of this happening, tantalum capacitors are usually formed at much higher voltages than are aluminium capacitors, for the same rated voltage.

Putting it together

Mainstream aluminium electrolytic capacitors are wound then impregnated with liquid electrolyte, while most tantalum capacitors are porous slugs impregnated with a dry electrolyte. However many permutations on these techniques are possible.

Dry or solid aluminium electrolytic capacitors offer an intermediate approach between these two extremes, and wound foil tantalum also wet electrolyte slug tantalum capacitors are also produced.

Wet tantalum capacitors are usually fully hermetically sealed using glass metal seals, for good reason. While protecting the capacitor from moisture, the glass seals also protect the outside world from the electrolyte. For example, sulphuric acid or lithium chloride based electrolytes have been used.[6]

Many wet tantalum capacitors use similar strong electrolytes, so casual dismantling is not advised.

For brevity I only detail the mainstream products here, i.e. those that are commonly available from distributors.

Aluminium – winding methods

Aluminium is non-rusting because, on exposure to air, it forms a protective visually transparent oxide film on its surface. If this naturally occurring oxide film is mechanically removed, aluminium has a characteristic smell, which disappears as the oxide film regrows.

As a result, all aluminium electrolytic capacitor foils and connecting tabs, whether deliberately formed or not, are covered in oxide. Obviously thickness of the oxide coating differs. Naturally occurring oxide is extremely thin, equivalent perhaps to some 1.5 electrical volts of formation. The lowest voltage foil is formed to 8-10 volts, and is thus 5 or 6 times thicker.

Similar in construction to the foil and paper capacitors described in a previous article,[7] aluminium electrolytic capacitors comprise two aluminium electrode foils, interwound with separating papers and using tab connections. The whole winding is then vacuum impregnated.

Here all similarity ends. Being an extremely good insulator, the impregnant used in paper capacitors is the true dielectric. Aluminium capacitor electrolyte on the other hand is an extremely good conductor, the aluminium oxide layers form the dielectric, **Fig. 2**.

When the lowest possible equivalent series resistance is needed, multiple connecting tabs, dispersed along the foils, are common – especially for large windings. Smaller low esr windings can be wound using single tabs, connected to the centre of each foil.

The cathode foil only of low voltage radial capacitors can also be wound extended beyond the papers along one edge. Each cathode turn can then be short circuited to all other cathode turns by passing over the rim of a high speed rotating aluminium 'swaging' wheel, **Fig. 3**.

I used this intermediate approach many years ago to design some very low profile 4000µF, 63V capacitors. These were custom designed for the first mass-produced 100W per channel, hi-fi stereo amplifier. They probably represented the first production capacitors to combine a central tabbed anode with an extended and swaged cathode foil. The construction ensured extremely low esr and inductance, in a case 45mm diameter and only 50mm tall.

Most small aluminium electrolytic capacitors however are wound using a buried-foil winding. External connections are made using two formed aluminium connecting tabs, frequently placed towards the outer end of the winding.

One exception to this is some very small diameter axial capacitor elements that are wound onto an aluminium spindle or riser. The anode foil is attached to this riser, which remains as part of the finished capacitor, **Fig. 4**.

The cathode connection for this style of axial capacitor can be made using short tabs connected to the outer end of the cathode foil. Pressure contact with the capacitor case is made by trapping the tabs between the case and its rubber end-seal. Alternatively an extended cathode tab is welded to the bottom of the case, before inserting the wound element. These constructions exhibit from 20 to 85nH of self inductance, according to case size.

Inductance myth

Since these capacitors are wound, many writers erroneously ascribe very high self-inductance as being inevitable in aluminium electrolytic capacitors. The largest inductance value found browsing several catalogues, was less than 100nH. This is equivalent to some 10-12cm of connecting wire or printed circuit track.

Radial-mounting electrolytic capacitors use multiple distributed tab connections, or single tab connections made close to the mid-turn of each winding. These exhibit an extremely small winding inductance – less than 20nH and 35nH respectively.[8] The major contribution to this is from the connecting tabs and the capacitors leadout wires, **Fig. 5**.

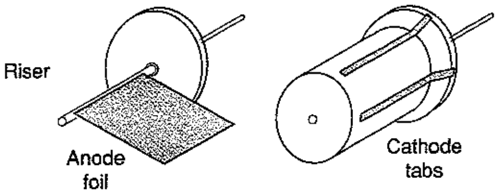


Fig. 4. One common construction used for the smallest axial wound capacitors. Disadvantages are its pressure contact between cathode tabs and case and increased self inductance due to foil connections being at extreme opposite winding ends. But with small windings, self inductance remains acceptable.

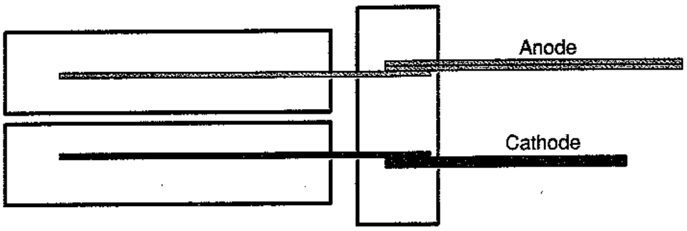


Fig. 5. Sectional view of typical small radial capacitor showing centre foil tab connections, minimising self inductance, which is typically much less than 20nH.

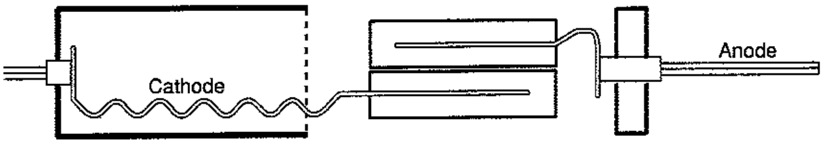


Fig. 6. Sectional view of a typical axial capacitor construction used for medium and larger sizes. While having centre foil tab connections, self inductance is increased due to the excess cathode tab length needed to permit assembly.

Axial-leaded capacitors exhibit more inductance. While larger sizes may be centre tabbed, connecting the cathode foil to the case, requires a longer tab. Surplus tab is folded when inserting the capacitor winding into the case.

Inevitably, an axial capacitor exhibits higher self inductance compared with the same sized radial leaded alternative, as illustrated in **Fig. 6**.

To demonstrate the effects constructional differences of small aluminium electrolytic capacitors have in practice. I used the application test circuit and phase meter,[9] described in 'Fazed by Phase' to make comparison measurements.

I measured four capacitor from 10µF to 100µF. These values are frequently used in audio amplifier coupling circuits. When possible, I selected 50V rated bi-polar radial, polar radial and polar axial aluminium electrolytic capacitor constructions. Since 10µF 35V tantalum bead capacitors were available, they too were measured.

The un-sanitised measured plots, **Figs 7-10**, show departure from ideal or theoretical behaviour starting at well below 1kHz. The esr curves are almost constant with frequency, resulting in capacitor phase angles approaching 45° at the critical mid-audio frequencies. The bi-polar capacitor clearly out-performs the other aluminium types.

Regardless of these differences in construction, to ensure a long service life, the electrolyte used must provide the oxygen needed to regrow any damaged oxide film. It must also be chemically inert to both aluminium and its oxides. Due to electro-chemical potential effects, no other metal can be permitted to contact the electrolyte. Being in contact with electrolyte, the capacitor case must be made of aluminium or a non-metal.

Any two pieces of aluminium in contact with electrolyte and subjected to a voltage differential will grow aluminium oxide. So pressure contacts, as used in foil and paper capac-

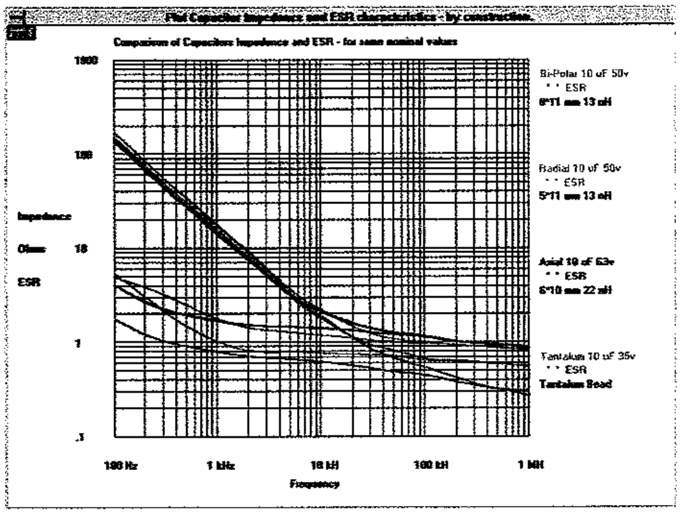


Fig. 7. As measured, plots of impedance and esr for bi-polar radial, polar radial, polar axial and bead tantalum 10μF capacitors. Shows the Panasonic bi-polar performs best of aluminium variants, but all types have near 45° phase by 10kHz and deteriorating performance from as low as 1kHz.

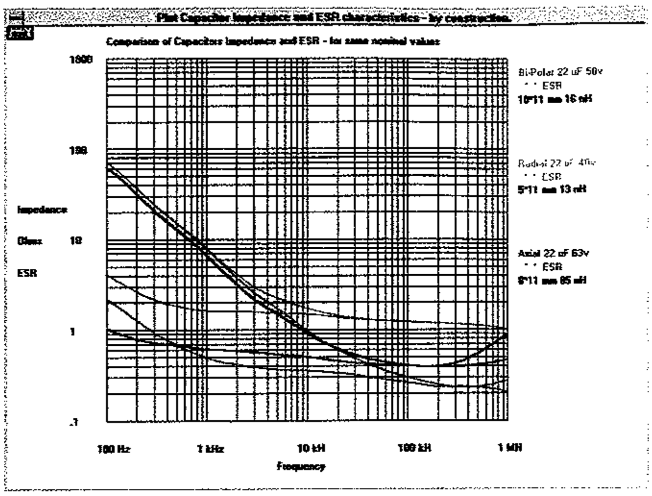


Fig. 8. As for Fig. 7 aluminium types but 22μF values. Where possible, 50V ratings or nearest possible were used for these comparisons. At this value the bi-polar capacitor is the best choice.

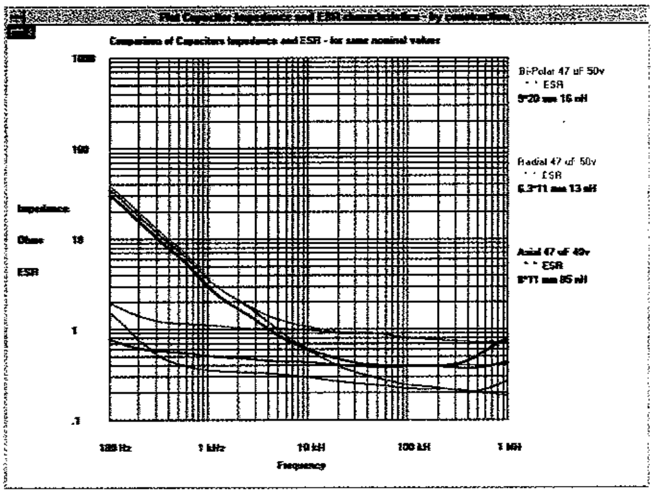


Fig. 9. As for Fig. 8 but this time using 47μF values. Due to the larger size and foil area, the Panasonic bi-polar style easily outperforms the smaller alternatives.

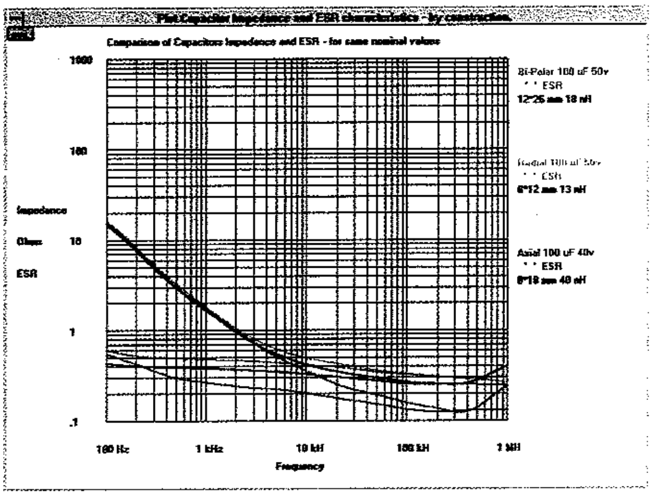


Fig. 10. With 100μF values the Panasonic bi-polar remains a notably better performing capacitor for these tests.

itors, cannot be used to connect the inserted tabs to the electrode foils.

Two common methods to ensure low resistance connections between the electrode foils and connecting tabs are used. Small or low cost capacitors may use a 'stitched' connection. Here, a shaped needle point is burst or punched through the connecting tab and electrode foil. Small 'ears' of tab material are forced out, then turned over and well flattened down. This effectively rivets the two parts together. While simple and crude looking, a good long-life connection results, **Fig. 11**.

A much better technique, called 'cold pressure welding' is used in larger or more professional capacitors. Here, a specially profiled, small press tool is used. It is given enough pressure and time to allow the metals from the electrode and tab foils to interchange, forming a molecular bond. As with a conventional hot weld, the two joined metals cannot be separated.

This excellent joint results from the tool pattern used. By compressing and displacing metal, the pattern removes the oxide layers, allowing direct metal to metal bonds. Cold welds are easily identified by the press tool's outline and inner patterns. No bursting through as for a stitched connection can be seen, **Fig. 11**.

Welding, using either cold pressure or laser, is the preferred method for all aluminium electrolytic capacitor internal connections. However a rivetted connection between connecting tabs and the external solder tags, can be a satisfactory alternative – especially for smaller capacitors.

Aluminium-dielectric systems

The anode electrode foil of an aluminium electrolytic also provides the dielectric oxide which is in intimate contact with the electrolyte – the true second electrode.

Electrical connection to this electrolyte is provided by a second foil, or cathode electrode, which is also covered with dielectric oxide. In other words two foils comprise two distinctly separate capacitances in series, inter connected by the conductive electrolyte.

A polarised aluminium electrolytic possesses two capacitors, the desired one in series with a much larger 'cathode' capacitance. This cathode capacitance has a lower voltage withstand, typically 1.5V and is of opposing polarity to the

Aluminium 'forming'

Placed in a bath of suitable electrolyte and with a positive voltage applied to the foil, aluminium oxide, Al_2O_3, grows on the foil surfaces to a thickness 14 Angstroms for each volt.

As mentioned in the main text, two forms of aluminium oxide can be produced, one porous, the other a non-porous and hard oxide. The hard oxide film is an excellent insulator that can be produced to withstand 600V using super-purity aluminium. Aluminium and electrolyte purity are important, since impurities result in weakness in this insulating oxide film, increasing leakage current.

Pure aluminium can be attacked by pure water at modest elevated temperatures, unless this oxide film has first been hydrated by boiling in water, or is chemically inhibited.

The oxidation process is self regulating. Initially most forming current passes through visible and exposed surfaces. With continued oxide growth, current at these exposed surfaces reduces, slowing local growth and diverting current to less accessible areas. Current flow and oxide growth almost cease when all metal surfaces are insulated.

The aluminium oxide dielectric formed is highly amorphous, xcept for the outermost surface layer, which may be porous when formed at high voltages. Boiling in very pure water hydrates the oxide sealing this porosity, resulting in very low leakage current capacitors.

Aluminium oxide is visually transparent, but the etched foil surfaces are covered with minute voids and tunnels which absorb light, hence the dark appearance, **Fig. 11**.

In general, foils are etched and formed from wide rolls of aluminium, then slit to the desired widths for capacitor manufacture. Each width has thin exposed raw aluminium edges. These edges, together with any mechanical handling damage, will have the oxide film renewed after capacitor winding, as part of the ageing process.

To avoid consuming excess electrolyte, following impregnation and before final assembly, high voltage capacitors may be 'wet aged' while immersed in baths of electrolyte.

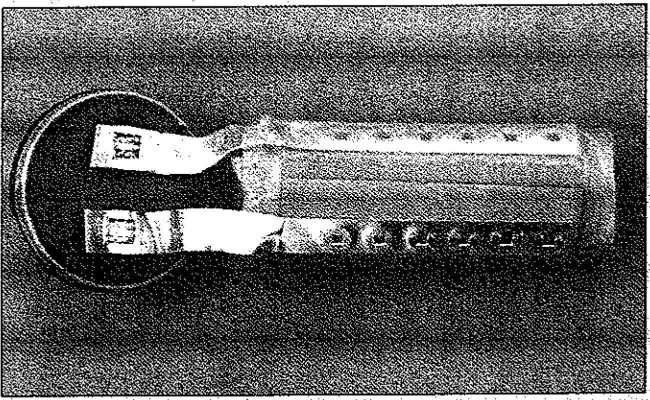


Fig. 11. Photograph of a dismantled and partially unwound capacitor shows a good example of the stitched technique used to connect both anode and cathode foils to their respective tab foils – central tabbed in this example. Also the cold pressure welded joints connecting anode and cathode tabs to the external tag rivets are clearly visible. This excellent joint results from the tool pattern which, by compressing and displacing metal, removes the oxide layers allowing direct metal to metal bonds.

anode capacitor, **Fig. 2**.

A non-polarised, or bi-polar capacitor is usually made using two identical anode foils. This provides two equal value and equal voltage capacitors in series, each double the required capacitance and again of opposing polarity.

Being a semi-conductor, aluminium oxide withstands its formed voltage in one direction only, passing a small 'leakage' current. As for a semi-conductor diode, with reversed polarity it conducts at a low voltage, typically 0.4 to 0.5V while passing a high current.

Regardless of level, this current disassociates some water in the electrolyte, depositing oxygen at the positive electrode, hydrogen at the negative electrode. The oxygen is consumed to generate aluminium oxide.

Many electrolytes contain a hydrogen absorber, to absorb the hydrogen released by normal leakage currents. Even so, with reversed polarity, much of the hydrogen must be allowed to escape.

With the above information, it is now possible to develop an equivalent circuit model of an aluminium electrolytic capacitor, **Fig. 12.**

Reverse bias effects

In a polarised capacitor the 'cathode' foil capacitance, being in series with that of the anode foil, reduces the net or measured capacitance. It also contributes two advantages not present with the tantalum slug styles.

The withstand voltage of the cathode foil's dielectric oxide allows the capacitor to accept small reverse voltages for a significant time, both in service and in approval testing.

This cathode foil's *C/V* product, if equal or greater than that of the anode foil, enables charge displacement from anode foil to cathode foil. The cathode foil in a capacitor subjected to ormal charge and discharge currents, does not then become reverse biased with respect to the electrolyte. Such capacitors are described as being charge-discharge proof, **Fig. 12**.

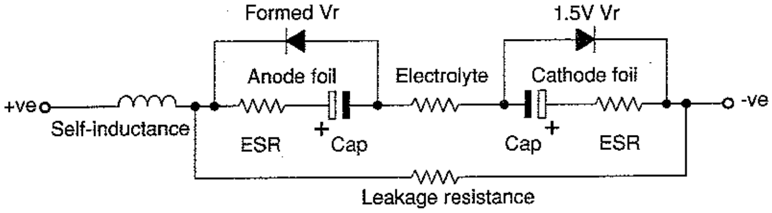


Fig. 12. Equivalent circuit of a polarised aluminium electrolytic capacitor. Since leakage current can be significant, it is shown as a shunt resistance rather than converting to its series equivalent, as more usual for other capacitor types. Simple Spice analysis shows how easily the electrolyte of a polarised capacitor, used to couple irregular or pulse waveforms, can become internally reverse biased to the cathode foil, resulting in early failure.

Many quality aluminium electrolytic capacitors are subjected to a million charge-discharge cycles with rise and fall times of 100ms as part of their approvals testing. For IEC 384-4 charge-discharge approval, capacitance change in this test must be less than 10%.

Note, though, that capacitors that are repeatedly 'crash' charged and discharged, as in photoflash or strobe equipment, require special construction. Commercial capacitors used for these duties – regardless of their voltage rating – have quickly and very dramatically failed.

The current that flows when polarity is reversed can generate sufficient gas to drive electrolyte out of the winding. Pressure builds up in the capacitor case, resulting ultimately in a capacitor failure.

Direct-current polarity reversal at the capacitor terminals is of course easily measured and avoided.

A less obvious problem occurs when the capacitor is used to couple irregular or pulse waveforms. A repetitive charge

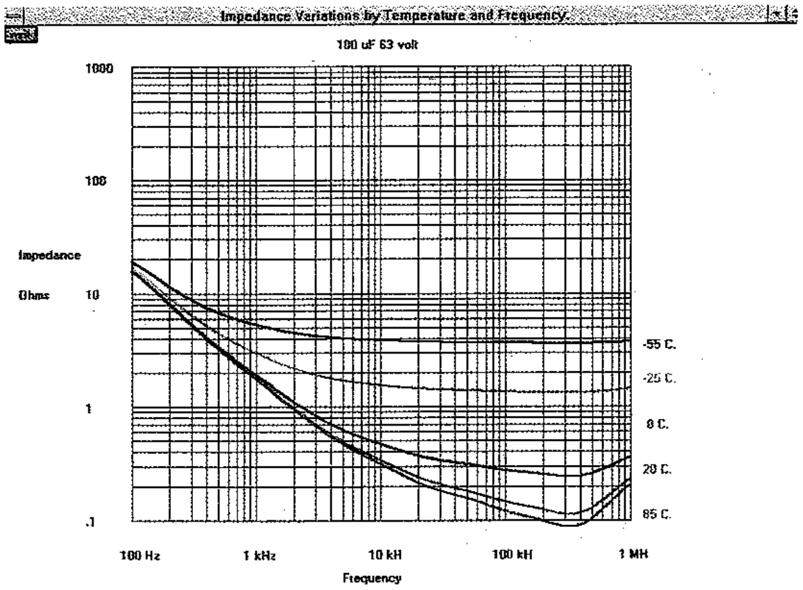


Fig. 13. Plot showing how impedance versus frequency characteristics change with ambient temperature, for a typical 100µF 63V capacitor.

transfer from anode to cathode of a polar capacitor can result in the electrolyte becoming reverse biased relative to the cathode. As a result, a non-polarised or bi-polar capacitor should be used here.

Should this reverse bias exceed permitted levels, oxide growth at the cathode reduces its capacitance. In turn, this further increases the reverse bias voltage. Gas pressure developed drives out electrolyte, resulting in capacitor failure.

Bead or slug tantalum

To produce a capacitor, the formed and sintered tantalum slug only needs impregnating with electrolyte and providing with its connecting cathode electrode.

In most cases the 'dry' electrolyte used is manganese dioxide, while the cathode is a graphite or carbon coating. Electrical connection to this coating is provided by layers of silver loaded ink or epoxy.

As the manganese dioxide is a solid, it is not possible to directly impregnate it. It has to be converted from a suitable liquid medium that can be vacuum impregnated into all voids inside the sintered slug – no matter how small.

Resulting from these voids and passageways, the tantalum slug exhibits a level of self inductance. The device becomes self resonant typically between 500kHz and 5MHz,[10] according to bead size and capacitance.

In many cases, the medium used is liquid manganese nitrate. Easily impregnated into the slug and converted into manganese dioxide by pyrolysis, or thermal decomposition, at 400°C. Many repeated impregnations and pyrolysis cycles are needed to ensure sufficient manganese dioxide.

Contact to this manganese dioxide electrolyte generally uses successive layers of colloidal graphite with silver loaded paints or conductive epoxy resins. This is frequently, finished by dipping in molten solder. The external cathode connection is easily attached either by soldering to the solder coating or with conductive epoxy to the silver loaded paint/epoxy coating.[5]

Since the manganese dioxide electrolyte is directly connected to the capacitor's negative lead, only one polarised dielectric is present. Consequently, reverse voltage should not be applied. The Siemens Matsushita data book for example restricts any reverse voltage application to five applications of a minute maximum each hour.

Two dry tantalum beads can be connected back to back to simulate a bi-polar capacitor. To prevent damage to the reversed polarity capacitor, protection diodes must be placed in parallel with each capacitor. These are detailed in the Siemens Matsushita data book.

Bead tantalums made with liquid electrolytes must not be subject to any reverse voltages. Excess gassing resulting from reversed polarity builds up internal pressure, destroying the capacitor. Silver from the cathode electrode can also transfer to the anode, leading to a short circuit.

Surge currents for all bead tantalums, should be restricted by series impedances of typically an ohm minimum per applied volt.[10]

Aluminium electrolytes

The manganese dioxide used in solid aluminium electrolytics has already been discussed, but for wet or non-solid aluminium electrolytic capacitors, many different formulations exist. These usually comprise a neutralised weak acid in a suitable solvent.

The solvent used must not freeze or boil at the extremes of the capacitor's working temperature range, nor must they attack pure aluminium.

One old but still usable electrolyte is a mixture of ammonia and boric acid dissolved in pure ethylene glycol. Most older electrolytes contained small quantities of water. Prepared using liquid ammonia, they were boiled to reduce water content.

This water content combined with lesser purity foils resulted in early electrolytics having a reputation for leakage current deterioration in storage. They needed re-forming before use.

For the past 30 years, this water attack could easily be inhibited by a chemical additive in the electrolyte, in much the same way that steel is passivated to prevent rust, using phosphoric acid. This, and the use of super purity aluminium foils, has effectively eliminated the need to re-form capacitors.

As an experiment, I recently measured the leakage current of three unused prototype 16 and 25V capacitors, made almost 30 years ago and stored since then in a box in my garage. All three easily passed their catalogued leakage claims without reforming.

Modern electrolytes use many different acid formulations and solvents. These range from simple solutions of ammonium borate or ammonium succinate in glycol to organic acids and solvents such as di-methyl-formamide. In principle, many weak acids or their ammonium salts can be used, leading to a wide choice.

A hydrogen absorber, able to cope with hydrogen released by normal leakage current, is provided in many modern electrolytes.

While very conductive electrolytes are used in the lowest voltage capacitors, such electrolytes cannot be used at high voltages. In this context one must view the separating paper tissues used as being part of the electrolyte system. Thick, low-density 'rag' tissue paper can be used at low voltages, while for high voltage work, higher density thin tissue paper – and even multiple tissues – may be needed.

While most aluminium capacitor electrolytes are innocuous, it is as well to check the makers literature before dismantling a capacitor to investigate its construction. In any case, you are well advised to wear suitable rubber or plastic gloves, and use eye protection against electrolyte splashes.

Formic acid for example stings the eyes and any broken skin. It may also trigger an allergic reaction in hay fever sufferers, as I can well testify from past experience.

nishing processes

Following final mechanical assembly, both capacitor types are subjected to temperature and voltage ageing or burn in. This allows minor dielectric fault areas to be removed, and leakage current reduction to catalogue specifications.

In aluminium electrolytic capacitors leakage current is reduced by deliberately growing new oxide, replacing any mechanically damaged during the assembly processes. This regrowth consumes some of the oxygen available from the liquid electrolyte.

A level of regrowth continues throughout the capacitor's service life, stabilising and reducing leakage current. Ultimately at the end of service, the capacitor fails usually as a high impedance or open circuit when the available oxygen in the electrolyte has been consumed.

Tantalum and aluminium solid electrolyte capacitors behave quite differently. Fault repair and leakage current reduction does not occur by oxide regrowth, but rather in a similar fashion to metallised film capacitor self healing, by isolating the faulty area.[5]

The increased current due to a minor fault locally heats the manganese dioxide, which spontaneously degenerates to lower oxides. These exhibit much increased resistivity com- ed to manganese dioxide, effectively isolating this faulty area.

Should a major fault occur in a bead tantalum capacitor used in a low source impedance circuit, excess heat is generated. This excess may be sufficient to locally crystallise the surrounding area of tantalum pentoxide. Energy available from the circuit may then be sufficient to promote an avalanche failure condition,[5] the capacitor failing short circuit. Given sufficient externally supplied power, the capacitor can burn.

In the early days of bead tantalums in order to prevent this avalanche failure mode, a common recommendation was that they should only be used on power rails via a current limiting source impedance of at least 3Ω/V.

Improvements in materials and manufacture of bead tantalums have much reduced this problem – but they have not eliminated it. While not well publicised, many makers offer low-impedance burnt in and even fuse protected tantalum capacitors. However the advice in MIL-STD-198 is best heeded.[10] It says you should ensure a 1Ω/V source impedance minimum together with substantial capacitor voltage de-rating for high reliability,

One hybrid capacitor combining the best aspects of the two aluminium-foil construction with the long shelf and service life characteristics of the solid tantalum is the solid aluminium wound foil capacitor.[11] These characteristics provide reliable service in automotive applications, surviving vibration, temperature extremes and voltage surges. Unfortunately this excellent capacitor style is not usually stocked by mainstream distributors.

Temperature effects

Some capacitance variation with temperature is exhibited both by aluminium oxide and tantalum pentoxide. Their leakage currents will follow the Arrenhuis law, roughly doubling or halving for each 10°C change of temperature.

By far the most notable effect of temperature is the way the

Aluminium etching

The surface gain of modern aluminium electrolytic capacitor foils is attained by electro-chemical etching in a bath of electrolyte. The aluminium to be etched is placed in a highly conductive bath, usually brine and a high current is passed.

In practice, large rolls of aluminium foil are fed at a controlled speed through a very long etching bath. The foil passes over contacting rollers which supply it with the very high etching current needed. While pure dc can be used, dc with a superimposed alternating component is more common.

Depending on the foil's intended formation voltage or end use, different feed speeds, temperature, current density etc., will be used. Low voltage capacitor anodes for example use only thin oxide growth but need the maximum possible capacitance. The foils are etched to maximise surface gain, creating the smallest possible voids and tunnels, while using the thickest foil base, **Fig. 14**.

High surface-gain foils usually have much of their original aluminium removed by this process. Tunnels can be formed connecting both foil faces. While remaining visually opaque, as with a filter paper, they become highly porous to liquids.

If 'formed' to a high voltage these tiny tunnels would become choked with xide, rendering the foil useless. High-voltage anode foil is etched deliberately to provide much larger tunnels which will not block with oxide, usually on a thinner foil base, **Fig. 15**.

Various cathode foil etchings and foil thicknesses are needed for differently rated capacitors. The lowest voltage capacitor cathode needs the highest possible surface gain etching. Cathode foil for higher voltage capacitors is much thinner, and modestly etched.

In each case, the object is to provide a cathode *C/V* equal to or larger than that of its anode while minimising size and cost.

Regardless of thickness and etching methods, anode foils use only the highest possible purity aluminium foil – better than 99.99% purity being essential.

By comparison, the cathode foil is not deliberately formed; indeed accidental formation in service is undesirable. Consequently, cathode foils can be made with lower purity material, of typically 99.3% aluminium.

Following etching, the aluminium foil must be most carefully washed using extremely pure water to remove all traces of chloride residues. Minute traces of chloride increase capacitor leakage current and reduces working life.

All foil batches are checked to ensure much less than 1 milligram of chloride contaminant remains, per square metre of foil.

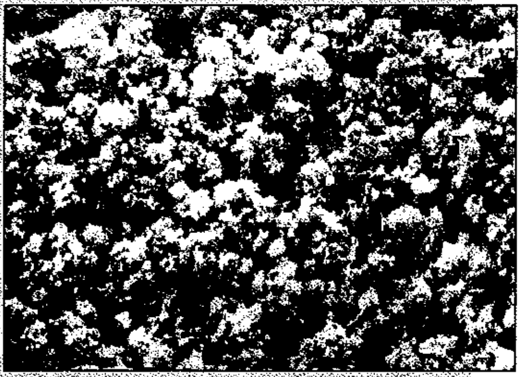


Fig. 14. Large magnification electron microscope view of the surface of a very high 'gain', low-voltage anode foil. Etching and forming methods are optimised for low voltage capacitor use.

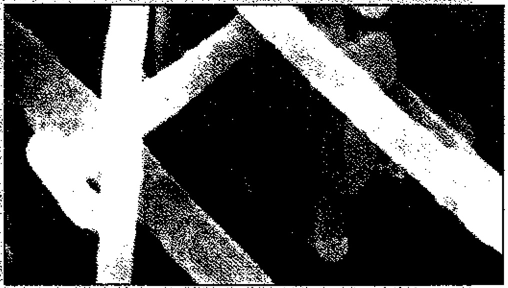


Fig. 15. Very large magnification electron microscope sectional view of low surface gain, very high voltage etched foil. Shows extensive large diameter tunnels able to accept thicker oxide growth needed for high forming voltages. Only the oxide tunnels are seen, the metal having been dissolved away to permit this sectional view.

impedance of wet aluminium electrolytic capacitors changes versus frequency with change of temperature.

The wet electrolyte and separating papers used in aluminium electrolytic capacitors, combined with the minute and tortuous paths into the inner recesses of the anode foils, contributes much of the capacitors series resistance. At 85°C, resistivity of the electrolyte-paper combination is typically half its room temperature value.

At lower temperatures – and especially with higher voltage capacitors – electrolyte viscosity increases more rapidly. By 0°C, resistivity of the electrolyte/paper combination is typically double its room temperature value.

At the lowest temperatures the normal impedance frequency curve becomes a nearly constant resistance plot. This low temperature behaviour fortunately is of no importance for most decoupling applications, which only require the capacitor to be a low impedance path. **Fig. 13.**

The conductivity of solid electrolytes is also temperature dependent. But at very low temperatures, increase of impedance is modest, compared to that of the wet aluminium electrolytic capacitor.

Ripple ratings

These temperature and frequency effects on capacitor esr reflect directly into the capacitors ripple ratings above room temperature. At lower temperatures, any ripple current generated heat serves to warm up the capacitor.

Every capacitor has an internal hot-spot maximum temperature that should not be exceeded. Frequently this cannot be measured, except by manufacturing special test capacitors. A more practical method with aluminium electrolytics is to measure the surface temperature at the aluminium case end, underneath any plastic insulation, using a 0.2mm wire, naked-bead thermocouple with PTFE insulation.

Especially with wet-aluminium electrolytic capacitors, hot-spot temperature directly influences the rate at which electrolyte evaporates through the end seals and thus capacitor life. End-seal materials are chosen to minimise electrolyte losses while allowing excess hydrogen to diffuse out, avoiding undesirable pressure build up.

Makers' ripple current ratings are usually determined in practice by using 100Hz sinusoidal waveforms. Consequently, other frequencies and non-sinusoidal voltage and current waveform requirements must be related to these 100Hz catalogue ratings, using appropriate methods.

Frequently this requires the current for each harmonic component be determined using Fourier transforms.[8] Each harmonic's power is determined from the capacitor's actual esr at that frequency and ambient temperature.[12] The total capacitor power is calculated as the rms sum of all these powers.

Designers interested in a step by step description of this process for calculating capacitor power dissipation for any repetitive waveform will find details in my April 1995 capacitor article.[13]

Alternatively, having calculated the rms current for each frequency, some makers specify suitable frequency correction multiplying factors.[14] The rms sum of these corrected currents is then related to the 100Hz catalogue claims.

In many instances, the waveform may not be sufficiently repetitive, so these methods may not be possible. In that case, a conservative and long-standing rule of thumb is to assume any case temperature rise of less than 5°C should be acceptable. This is subject to the *proviso* that the case operating temperature at the maximum expected equipment ambient does not exceed the maximum service temperature of the capacitor.

Readers interested in this simplistic approach are referred to the IEC 384-4 or CECC 30 300 specifications. These provide tables of permissible case temperature rises for differing ambient temperatures.[12]

Ripple-voltage peaks superimposed on any applied dc level must not exceed the capacitor's rated voltage. The resulting current must not exceed the permitted ripple current at that frequency and with polar capacitors, no polarity reversal is allowed.[8]

While capacitors generally have a small permitted surge voltage level, this is intended to cover equipment switch on conditions. It should not be used when calculating permitted ripple voltages.

Should it become necessary to bank capacitors in series or parallel to provide the needed ratings, voltage and current sharing arrangements are essential to avoid early and dramatic failures.[10]

Whenever possible capacitors should be used de-rated from the permitted catalogue levels. This extendsß service life. All capacitors – and especially electrolytics – provide a much prolonged service life when operated at a reduced operating voltage, and exhibit no adverse side effects.[2]

Washing

Aluminium electrolytic capacitor end seals need to be taken into account when choosing a flux removal fluid so check the capacitor maker's literature. In principle, any seal designed to allow hydrogen to escape might also permit ingress of chlorinated hydrocarbon solvents. Once inside the case, these could supply free chlorides, causing internal capacitor corrosions and leading to failure.

Chlorinated hydrocarbon solvents, used to clean light metals like copper and aluminium quickly become acidified unless frequently replenished. Acidified solvents cause considerable damage to many components, so must be avoided.

Capacitor mounting

It is common practice to conveniently mount large aluminium electrolytic capacitors, terminals down. In many constructions the hydrogen venting seal will then be mounted as the lowest point of the capacitor.

If the capacitor is used well within its voltage and ripple current ratings, having the vent at the bottom should not present a problem. If the device is used incorrectly though, excess gassing can force electrolyte to exude – probably forcibly – from this venting seal. This usually results in corrosion damage to surrounding areas.

Capacitors designed to mount terminals down usually have a vent at the opposite end of the case from the terminals. For satisfactory service life, again the capacitor maker's mounting instructions, voltage and ripple ratings should be observed. ■

References

1. International Conference on Components, Proc IEE 1961 p. 548.
2. Bateman, C, 'Understanding capacitors', *Electronics World*, December 1997.
3. Reference Data for Radio Engineers, Pub. Newnes, Oxford.
4. *Electronic Components & Applications*, Vol. 8, No 1, p. 46 (Philips).
5. Engineering Bulletin F-2695D, Kemet, PO Box 5928, Greenville C29606, USA.
6. International Conference on Components, Proc IEE 1961, p. 529.
7. Bateman, C, 'Understanding Capacitors II' *Electronics World*, Feb. 1998.
8. Data Handbook – Electrolytic Capacitors, pub. Philips Components.
9. Bateman, C, 'Fazed by Phase?' *Electronics World*, Nov. 1997.
10. Technical Summary & Application Guidelines, AVX Tantalum Capacitor Data cd rom.
11. *Electronic Components & Applications*, Vol. 8 No 4, p. 194 (Philips).
12. Aluminium Electrolytic Capacitors, CD-Rom Data Book, pub. Siemens-Matsushita.
13. Bateman, C, 'Power Dissipation in Capacitors', *Electronics World*, April 1995.
14. Electrolytic Capacitors 1997-1998, Evox Rifa AB, Box 98 S-563 22 Granna, Sweden.

Many apologies. These diagrams did not reproduce properly in Cyril's last article. I sincerely hope that they appear in full this time round, but WYSIWYG doesn't seem to have filtered through to the printing world yet. Ed.

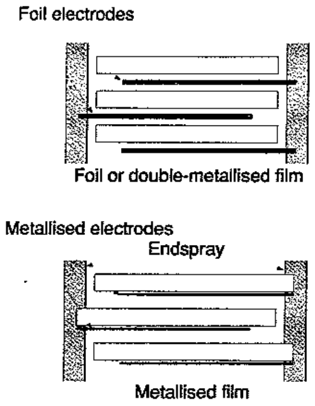
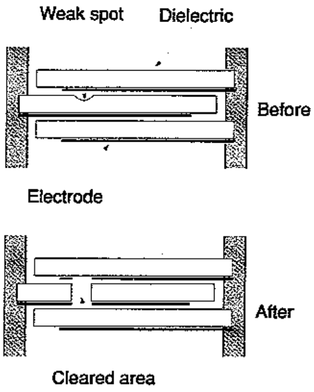


Fig. 1. Having no discrete electrodes, the metallised film capacitor maximises capacitance and voltage for a given size, but has limited current handling. Use of foil electrodes maximises current handling but reduces capacitance. Double metallised film electrodes, described in a German Patent, offer intermediate capacitance and current handling.

Fig. 2. Metallised film capacitor cross section, illustrating self-healing action. Before and after views show how electrodes and dielectric film are both involved when 'clearing' a fault.



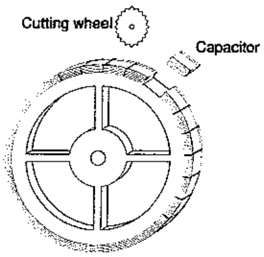


Fig. 3. Stacked film production technology. Large rings of metallised film, of width equal to the final capacitor body length, are wound on 'core' wheels. These rings are metal end sprayed, then sliced to make individual capacitors.

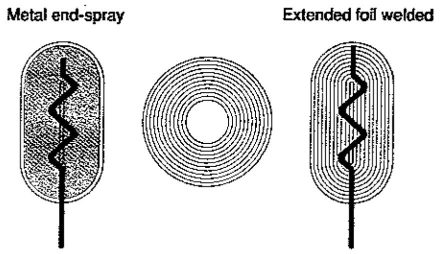


Fig. 4. Winding on a larger diameter mandrel allows the roll to be flattened to form the capacitor element. Both metallised and extended-foil electrode capacitors can take advantage of sprayed-metal end connections. Foil electrodes that extend beyond the dielectric roll allow resistance welded, directly attached lead wires. In the centre is the wound capacitor before compression.

Nine year index – new update

Hard copies and floppy-disk databases both available

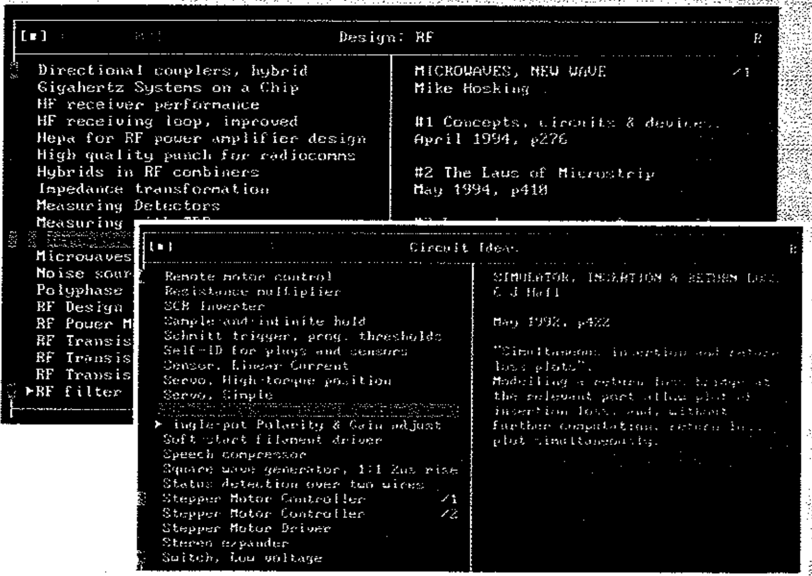
** Includes over 600 circuit idea references**

Whether as a PC data base or as hard copy, SoftCopy can supply a complete index of *Electronics World* articles going back over the past nine years.

The computerised index of *Electronics World* magazine covers the nine years from 1988 to 1996, volumes 94 to 102 inclusive is available now. It contains almost 2000 references to articles, circuit ideas and applications – including a synopsis for each.

The *EW* index data base is easy to use and very fast. It runs on any IBM or compatible PC with 512k ram and a hard disk.

The disk-based index price is still only £20 inclusive. Please specify whether you need 5.25in, 3.5in DD or 3.5in HD format. Existing users can obtain an upgrade for £15 by quoting their serial number with their order.



```
[■]                         Design: RF
 Directional couplers, hybrid          MICROWAVES, NEW WAVE
 Gigahertz Systems on a Chip           Mike Hosking
 HF receiver performance
 HF receiving loop, improved           #1 Concepts, circuits & devices
 Hepa for RF power amplifier design    April 1994, p276
 High quality punch for radiocomms
 Hybrids in RF combiners               #2 The Laws of Microstrip
 Impedance transformation              May 1994, p410
 Measuring Detectors
 Measuring
 Microwaves
 Noise sour
 Polyphase
 RF Design
 RF Power M
 RF Transis
 RF Transis
 RF Transis
►RF filter

[■]                    Circuit Ideas
 Remote motor control
 Resistance multiplier
 SCR Inverter
 Sample and infinite hold
 Schmitt trigger, prog. thresholds
 Self-ID for plugs and sensors
 Sensor, Linear Current
 Servo, High-torque position
 Servo, Simple
► ingle-pot Polarity & Gain adjust
 Soft start filament driver
 Speech compressor
 Square wave generator, 1:1 2us rise
 Status detection over two wires
 Stepper Motor Controller          /1
 Stepper Motor Controller          /2
 Stepper Motor Driver
 Stereo expander
 Switch, Low voltage
```

Photo copies of *Electronics World* articles

Hard copy *Electronics World* index

Ordering details

The *EW* index data base price of £20 includes UK postage and VAT. Add an extra £1 for overseas EC orders or £5 for non-EC overseas orders.

Postal charges on hard copy indexes and on photocopies are 50p UK, £1 for the rest of the EC or £2 worldwide.

For enquiries about photocopies, etc, please send an sae to SoftCopy Ltd at the address below.

Send your order to SoftCopy Ltd., 1 Vineries Close, Cheltenham GL53, tel 01242 241455, or e-mail at softcopy@compuserve.com. Please make cheques payable to SoftCopy Ltd – not *EW* or Reed Business Publishing. Please allow up to 28 days for delivery.