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SOME MECHANISMS OF FAILURE OF CAPACITORS WITH MICA DIELECTRICS

By A. A. NEW, M.Sc., F.R.I.C., A.Inst.P.

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SUMMARY

During investigations of mica capacitor failures of various equipments during the last ten years and studies to improve their reliability, many mechanisms of failure have been examined. The principal features of the mechanisms are described and illustrated, and are summarized in tabular form for quick reference. Some methods of examination and dissection of these capacitors with the minimum loss of evidence are given in detail.

This work does not imply that the proportion of mica capacitors which fail in service is excessive. Some of the causes of failure would occur in other types of capacitor, perhaps to a similar extent.

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(1) INTRODUCTION

Mica capacitors made from the best quality mica under suitable well-controlled conditions are generally reliable and stable, but under other conditions failures are liable to occur.

During a number of investigations of causes of failure of certain of these capacitors during the last ten years, particularly in line telecommunication equipment, and in amplifiers intended for submerged repeaters over the years 1954–58, it was necessary to augment the scattered published information with experimental work on the exact appearance and characteristics of faults arising in mica capacitors.

This summary of the work, which, with extracts from the literature, forms Sections 2, 3 and 4, is intended to simplify any similar investigations in future and to assist in improving the reliability and stability of mica and similar types of capacitor.

(2) CAUSES OF SHORT- AND OPEN-CIRCUITS

(2.1) Puncture of Dielectric due to Excessive Voltage

The intrinsic electric strength of Muscovite mica is usually stated to be about 10×10^6 volts/cm for thicknesses in the range 0·02–0·07 mm, corresponding to 25 000 volts/mil. Nevertheless, when laminations of good-quality mica are subjected to an increasing potential, it is generally found that they break down at voltages of the order of one-fifth of this. Manufacturers generally allow a safety factor of 10–20 on the latter figure in assigning a continuous working voltage for capacitors made from the mica, to cover random variations in strength.

A number of capacitors that had either broken down under known conditions of service or been deliberately broken down under controlled conditions were dissected as described in Section 8 and examined. The results and other relevant data are given in Table 1, and photographs of the seat of breakdown in two of them are shown in Figs. 1 and 2. From consideration of the data and photographs it was apparent that the following features are frequently associated with breakdown due to excess voltage:

(*a*) A small puncture in one or more plates.

(*b*) About five to eight cracks radiating from the main puncture.

(*c*) Location of the puncture at a region of high electrical stress, particularly at the edge or corner of an electrode.

(*d*) In a stack, adjacent plates have indentations (and perhaps cracks) in exact register with the puncture, which extend through the stack with decreasing intensity to an extent which is related roughly to a fractional power of the energy dissipated at breakdown and to the rigidity of the capacitor. Occasionally the marks may terminate abruptly at a very thick plate (e.g. where a cover plate three to ten times the thickness of the laminations has been inserted).

Table 1

SOME BREAKDOWN CHARACTERISTICS

Protection and impregnation	Capacitance (numbers in brackets are externally added capacitances)	Mica plates		Breakdown voltage	Charge	Broken down mica, sheet number	Point of breakdown	Number of marked micas each side of breakdown	Insulation resistance after breakdown
		Number	Thickness						
	pF		in	kV	μC				kΩ
Wax-coated and wax-impregnated	3 300	3	0·001 8	5·4	18	2	C	*1, 1*	$>10^7$
	3 300(+3 300)	3	0·001 8	4·0	26	3	B	*2, 0*	$>10^7$
	3 300(+6 600)	3	0·001 8	3·0	30	3	C	1, 0*	$>10^7$
	30 000	34	0·001 3	about 0·1	3	15	B	0, 0	60→12
Encapsulated in epoxy resin and oil-impregnated	4 600	23	0·001 6	3·5	16	21	E	6, 4*	140
	5 700	26	0·001 4	5·5	31	7	EC	7, 3*	500
	10 500	49	0·001 5	4·5	47	43	EC	9, 6*	400
	15 000(+ 6 000)	71	0·001 5	4·2	63(88)	33	EC	8, 5*	
	37 000(+68 000)	116	0·001 7	0·75	28(78)	8 and 9	B	0, 0	12→50 (9 volts)
	33 895(+2 000)	95	0·001 5	0·38 a.c. (twice)		21	E	12, 12	100→140→5·2

C = Corner of plate.
E = Edge of plate.
B = Body of plate.
* The next plate in the stack was an extra thick one not carrying electrodes.

Mr. New is at the Post Office Research Station.

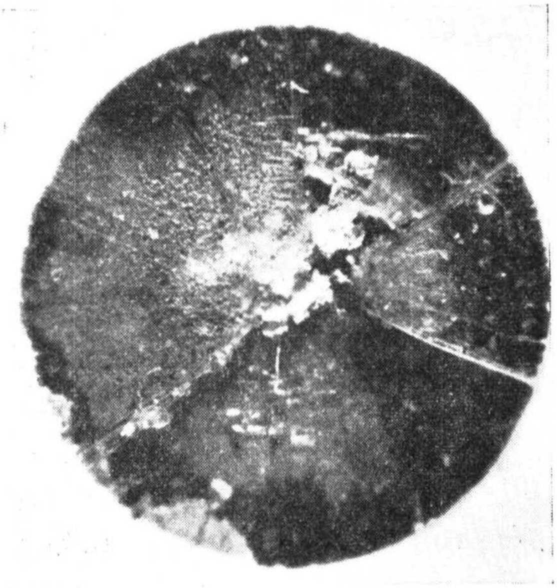

Fig. 1.—Enlarged view of point of breakdown due to excessive voltage.
Magnification, ×33.

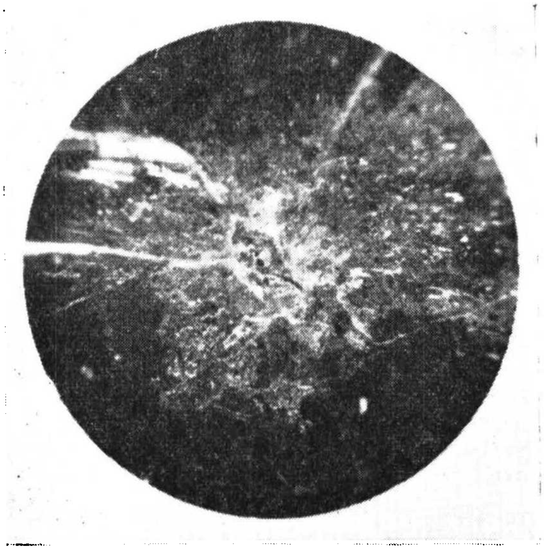

Fig. 2.—Enlarged view of point of breakdown at a few hundred volts, due to a fault in the mica.
Magnification, ×33.

(2.2) Surface Flashover or Breakdown due to Excessive Voltage

Under normal conditions when the surface of the mica is clean, initial flashover is almost entirely a gaseous phenomenon.[3] To estimate the clearances necessary to avoid flashover a knowledge of the breakdown potential is required. The breakdown voltage between surfaces of the order of 1 cm radius separated by 2 mm is about 8 kV in air under ordinary conditions; with a radius of 0·1 mm the value[1, 2] is about 3 kV, and extrapolating to a radius of 0·01 mm (half the thickness of the electrode of a silvered mica capacitor), about 2 kV. Since mica capacitors are usually given a short proof test at three to five times their working voltage, the spacing between the edges of electrodes is usually made not less than 2 mm (0·08 in).

In some cases the tendency to flashover may be increased by the presence of very thin and irregular deposits of silver in the nominally clear space outside the electrodes, caused by faulty printing or spraying of the silver. If oil, wax or other organic matter is present, a discharge may decompose some of it to carbon. This may lead to branched markings of carbonized material known as tracking[3] or 'treeing'.

The commonly-occurring symptoms of flashover, apart from the spark or discharge pulse, are the absence of any puncture in the dielectric and, if enough charge has been dissipated, a series of characteristic markings (see Fig. 3) across the surface of the dielectric joining the points where flashover took place. These may be of sputtered electrode metal, or may be black and perhaps of tree-like form if any organic matter is present to lead to charring or tracking. It follows from the first two paragraphs that the location of the fault will be at the point of lowest electric strength through air, which will depend partly on nearness of approach of parts at different potentials and the effect of their shape on the field strength. Experimental data on some capacitors that flashed over are given in Table 2.

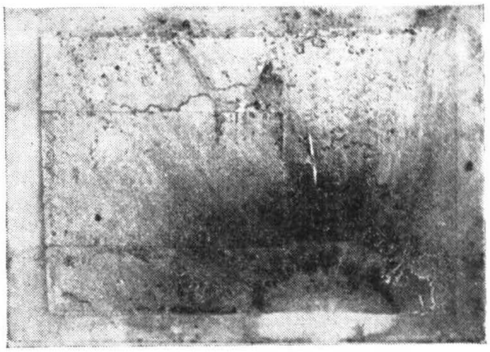

Fig. 3.—Silvered mica on which flashover has taken place.
Magnification, ×2.

(2.3) Puncture or Damage due to Enclosed Particles

Adventitious particles may cause damage if they are harder than the mica and of dimensions greater than about a quarter the thickness of the mica plates. The likeliest origins of such particles are grit from industrial atmospheres, fragments of wire, filings, solder, etc., or sand from the weathering of mortar. Failure may occur by the particle making a partial or complete puncture of a plate when a stack of plates is pressed together, or, in the case of metal particles, by forming a short-circuit.

In some cases the appearance after dissection resembles that of a capacitor that has failed from excessive potential, particularly if, as is often the case, the particle itself has been destroyed.

The majority of such cases are eliminated during the proof testing, but partly-punctured plates may withstand the proof test and yet fail later under working voltage. Under some circumstances, where direct evidence of the conditions at the time of failure is not available or is in doubt, it may be important to determine by subsequent examination whether excessive voltage or an enclosed particle was the cause of the fault.

Three lines of experimental work were followed: detection of particles by microscopic examination, detection of particles by radiography, and microscopic examination of the mechanical damage.

(2.3.1) Detection of Particles by Microscopic Examination.

There is a wide range of types of construction of mica capacitors. It is possible with care to dissect the simpler ones with sufficiently little disturbance to find any particles which may be

Table 2

SOME FLASHOVER CHARACTERISTICS

Protection and impregnation	Capacitance	Mica plates		Flashover voltage	Charge	Flashover distance	Insulation resistance after flashover
		Number	Thickness				
	pF		in	kV	µC	in	MΩ $\times 10^3$
Wax, wax-impregnated	1 000	1	0·001 7	8·1	8·1	0·12	5·0
	1 000	1	0·001 7	6	6·0	0·09	60
	3 300	3	0·001 8	4	13·2	0·06	44
	5 600	5	0·001 8	1·9	10·6	0·10	220
	5 600	5	0·001 8	2·2	12·3	0·08	250
	5 600	5	0·001 8	2·2	12·3	0·10	230
	220	1	0·001 8	2·9	0·6	0·08	1 300
	220	1	0·001 8	1·4	0·3	0·05	1 500
	220	1	0·001 8	2·1	0·4	0·06	1 000
	100(+200)	1	0·001 8	7·5	2·3	0·05	60
	100(+100)	1	0·001 8	7·5	1·5	0·06	60
	100	1	0·001 8	9	0·9	0·06	60
Phenolic resin, wax-impregnated	3 300(+6 600)	10	0·001 7	6	59·0	0·08	450
	6 200	18	0·001 8	3·3	20·5	0·05	0·37
	6 200	18	0·001 8	2·5	15·5	0·07	140
	6 200	18	0·001 8	5·0	31·0	0·08	100
	220	4	0·001 8	2·9	0·6	0·04	2 000

present, but the difficulty increases with the number of plates in the stack. Methods for removing various types of casing or encapsulation are given in Sections 8.1 to 8.3. In processes for making silvered-mica capacitors where the plates are given a second firing in stack form they often become firmly bonded together and it is impossible to separate them satisfactorily as silvered-mica plates. By an alkaline treatment they can sometimes be separated fairly well into micas and detached silver electrodes, and by an acid treatment the micas alone can be separated excellently. However, the first process would eliminate all particles soluble in alkali, and the second, all of those soluble in acid. The processes are described in Sections 8.4 and 8.5.

(2.3.2) Detection of Particles by Radiography.

Since the degree of stopping of X-rays by a capacitor is a function of the thicknesses and densities of its constituents, there must be a range of conditions within which embedded particles can be detected. To determine whether this range includes conditions likely to be met in practice, some 10-plate silvered-mica capacitors were prized open and small fragments of fine wires of known diameters were inserted, after which the capacitors were closed and X-rayed under various conditions.

In one of these capacitors (which have thick mica cover plates at each end of the stack) there were inserted ten short pieces of copper wire of diameters 0·006, 0·004, 0·002 5, 0·001, 0·000 5, 0·000 5, 0·001, 0·002 5, 0·004 and 0·006 in, in that order. Each piece of wire was tightly knotted with a single knot in the middle, representing a particle of about twice the diameter of the wire. In the original negative (sideways view) even the 0·000 5 in diameter wire can be clearly distinguished in the optimum exposure, but the knots in the 0·000 5 in wire are only just detectable, suggesting that particles of metal as dense as copper (density 8·9 g/cm^3) would be detectable down to about 0·001 in under these conditions, but that thinner sections than this would be visible only if the particle extended several thousandths of an inch in at least one direction. This only applies when using the optimum back illumination and a magnification of about ×10. With an ordinary naked-eye examination, the limit is probably nearer 0·003 in. Some of the larger wires could be seen in two of the radiographs taken edgewise, but this was largely a matter of good fortune, and in general edgewise views are not very helpful.

The effects would be more pronounced with denser metals, with capacitors of lower X-ray stopping power, or with capacitors having a more even distribution of X-ray stopping power, and would be less pronounced with the opposites of these conditions. The amount of silver electrode in the above capacitor was more than would be present in the average case, but the silvering was fairly even in thickness. In some types of silvered mica the silvering is less even, giving a mottled effect in a radiograph and making detection of particles more difficult.

(2.3.3) Observing Mechanical Damage due to Particles of Known Size.

Stacks of unsilvered mica plates 0·001 5 in thick were assembled with measured particles inserted in them, and were compressed in the same way as in normal manufacture. The pressure was then released and the stack was opened and examined. Impressions were found on the adjacent plates and for a number of plates on either side, depending on the size of the particle. Detailed examination of the damaged plates showed that:

(*a*) The shape of the particle is often copied in the nearest marks.

(*b*) Clear impressions show on two plates and with decreasing intensity successively on others on either side in accurate location.

(*c*) There are cracks round the impressions, but fewer and shorter than in the case of excess voltage impressions.

(*d*) The location of the point of failure may obviously be anywhere on a plate.

Table 3

SOME CHARACTERISTICS OF MECHANICAL DAMAGE DUE TO FOREIGN PARTICLES

Particle	Diameter	Number of micas in stack	Number marked	Remarks
	in			
Brass wire..	0·030	40	20 + 20	whole stack marked
Brass sphere	0·023	40	8 + 8	
Brass sphere	0·015	40	4 + 4	
Brass sphere	0·007	40	1 + 1	
Sand ..	0·015	40	1 + 1	grain of sand broken
Grit ..	0·003	40	1 + 2	

In an investigation on causes of failure of drystack mica capacitors in 1944, Thomas[4] estimated that of those examined about 50% were caused by mechanical damage from dust particles introduced during assembly.

(2.4) Faulty Mica Laminations

Mica is formed naturally in the earth's crust during the cooling of molten rock, and hence is liable to contain adventitious faults.

There is no British Standard covering visual quality of mica laminations, but A.S.T.M. D351–57T[5] adopts a perfectly clear transparent flat specimen of mica as a visual standard of perfection, independent of the basic colour of the mica. The highest quality, V–1 clear, is hard and does not contain any crystallographic discolorations, air inclusions, cloudy stains, black, red or green dots or stains, clay stains, waviness, sandblast, stones and holes, buckles, reeves, ridges, tears, cracks, hairline cracks, wedges, tangle sheets or herring bones.

A decreasing standard is represented by grades V–2, V–3, etc., and the lowest, V–10A, permits the above faults with the exception of the last ten.

A.S.T.M. D748–52T[6] discards the visual classification of mica films (for capacitors) and does not discriminate against colour, spots or stains, provided that the mica meets specific electrical and physical requirements, namely electrical conductivity (using a spark-coil test set with which conducting spots, veins, or areas are shown up by sparking or a glow, and pinholes, tears, cracks, etc., by breakdown), Q-factor at 1 Mc/s, electric strength, weight loss on heating to 600° C, thickness uniformity, and visual qualities.

For capacitors used in the transatlantic telephone cable it was required that mica laminations should be uniform in shape and thickness, hard, and free from inclusions, stains, cracks, creases waves and buckles, but a proportion of iridescence and air inclusions were permitted. An investigation in the Post Office Research Branch in 1954 showed that iridescence had very little effect on the quality of mica for capacitor purposes.

Thomas[4] has described how minute black spot in mica plates can be the cause of subsequent failure, and how a number of capacitors made up from stained mica plates showed no failures. In a further report[7] he stated that he was unable to recommend visual inspection for the purpose of reducing the percentage of defective finished mica capacitors.

When failure is due to a defect in the mica it often takes place at a low voltage, and as the energy released is small there are no cracks. Also, adjacent plates are unmarked unless an exceptionally large amount of energy is released at breakdown, in which case the puncture will be abnormally large.

(2.5) Mica Plates Damaged during Manufacture of Capacitors

In an investigation on causes of failure of mica capacitors in 1944, Thomas[4] ascribed about one-third of the cases examined to prior mechanical damage of the plates, such as abrasion of the surface and knocks, and pointed out that previous mechanical damage of this kind will usually be visible adjacent to the puncture. Several illustrations are attached to the report. Surface scratches were found not to reduce the electric strength of the mica.

In a study made in the Post Office in 1954–55 of the variability under working conditions of silvered-mica capacitors in certain amplifiers, it was found that an appreciable proportion of the micas had been damaged mechanically during manufacture and it was considered that the failure, which took place at comparatively low voltages and with a high-value series resistor, were due to an ionic mechanism acting through these or inherent faults in the micas. Scratches with a depth as small as 0·00001 in can be seen plainly with good illumination but are not thought to have a harmful effect, but obviously deep scratches weaken the mica electrically and should not be allowed.

Some recent failures of mica capacitors have been found to be due to the burr on the edge of an enveloping metal clamp cutting nearly through the mica cover-plate.

(2.6) Faulty Electrodes

A few types of defect which are normally eradicated in the manufacturer's inspection may be classed as due to faults in the electrodes. On rare occasions a mica capacitor is found with a loose electrode which can be detected by a high value of tan δ and by the capacitor emitting a faint note when tested at audio frequency. Generally, of course, the capacitor will be clamped so tightly that the effect is very slight.

High values of tan δ may be due to carbonaceous matter from the organic binder used in the silver printing ink not being completely burnt off in the firing process. Alternatively, they may be due to over-firing of the lamination to the extent that the silver has attacked the mica.

High values of tan δ at 1 Mc/s in capacitors having normal values at 1 kc/s may be due to electrodes which are too thin and give a series resistance which is significant at the higher frequency only.

(2.7) Faulty Connections

Where solder is used to make the connection to a silver electrode, the thermal contraction of the solder on cooling has sometimes been found to cause it to tear away from the silver, but to leave so narrow a gap that it is invisible to the naked eye.

Where pressure connections are made to the electrodes by tabs of thin metal ribbon (virtually forming intentional dry joints), it has been found that, unless substantial contact pressure is present, a surface oxide film may form on it in a long period of time if it is of copper or aluminium, and a sulphide film if it is of silver. If this happens, tan δ increases with the passage of time until the electrode is virtually disconnected. The film may sometimes be broken down by the sudden application of a potential.

(3) CAUSES OF IMPERFECT PERFORMANCE

(3.1) Silver-Ion Migration

Reference has been made in Section 2.5 to work done in 1954 when it was suspected that an ionic mechanism acting through faults in the plates was the cause of failures in silvered-mica capacitors. At this time silver-ion migration through phenolic laminates was well known, and so work was started to see if similar phenomena could be made to occur on or in mica.

A number of silvered-mica laminations were carefully removed from some capacitors and cleaned by washing successively with trichloroethylene and absolute alcohol. They were then placed inside a vessel humidified by a beaker of distilled water and were wired up in series with individual microammeters, 1-megohm resistors, and a 240-volt battery. The two portions of silver at different polarities were separated by a clear strip of mica 2–3 mm wide. Similar samples were set up in the laboratory atmosphere but protected from contamination.

After three months, some of the humidified samples were passing a small current and were removed for microscopic examination. A large number of dark markings had appeared on the clear mica in the gap between the two silvered areas. They appeared to stretch out from the negative area and are shown in Fig. 4. As it was obvious that the silver-ion migration had reached an advanced stage, the experiment was repeated

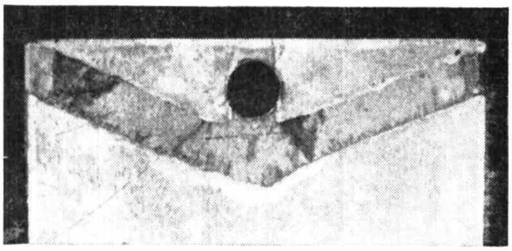

Fig. 4.—Silvered mica showing silver-ion migration. Magnification, × 3.

and the samples were examined each day. After a week, markings were showing clearly, but faintly compared with the previous test. No traces of silver-ion migration were detected in the samples that had been at room humidity. The humidified samples can be considered to have been at 95–100% relative humidity, and the room samples at 60–70% relative humidity.

Subsequently, two papers[8, 9] on the subject were published suggesting that the effect is based on the anodic solution of silver oxide in water,

$$Ag_2O + H_2O \rightleftarrows 2AgOH \rightleftarrows 2Ag^+ + 2OH^-$$

and that the only features necessary to produce silver-ion migration are silver electrodes with a difference of potential, a surface (as with mica) or internal surfaces (as with cellulose) on which water can be adsorbed, and a humidity high enough for this to take place to a significant extent. Under some circumstances silver migration has been observed at humidities as low as 75% relative humidity in the presence of traces of hygroscopic salts.

The studies described refer only to surface migration, which is fairly easily observed. The effect never takes place through a sound mica lamination, but it seems probable that it can take place through a flaw which is equivalent to a hole or porosity in the mica. This is almost impossible to prove by dissection of faults in silvered-mica capacitors, but it could be decided by silvering a number of micas having known faults of this type (leaving a very large surface clearance, which could also be waxed to prevent surface moisture adsorption) and observing their behaviour under high humidity and a potential.

(3.2) Growth of Whiskers

When undisturbed for periods of some months it is possible for fine metal whiskers[11] to grow out from the surface of certain metals, in particular from solid or plated tin, cadmium, or zinc, and especially at angular sites where the metal beneath the plating has been heavily stressed. Silver plating on nickel silver is known to grow whiskers in the presence of atmospheres containing a trace of sulphur dioxide, but the composition of the whiskers is unknown. Black whiskers (presumably sulphide) will also grow on silver (and copper) but only in the presence of sulphur. They are usually shorter and rougher in appearance.

The main relevance of this to mica capacitors is the possibility of the growth of whiskers from a lead or connection to another part of the circuit in close proximity.

(3.3) Islands in Silver Electrode causing Capacitance Fluctuation

This effect has been investigated thoroughly by the Electrical Research Association[10] and only a description and the explanation will be given here.

Certain types of silvered-mica and silvered-ceramic capacitors are liable to spontaneous capacitance fluctuations when under r.f. stress. This shows clearly if an a.f. note is obtained by beating two r.f. oscillators, one of which contains the faulty capacitor in its tuned circuit, when there will be periodic jumps in the frequency of the beat note corresponding to capacitance changes of the order of 0·01–0·1 pF. A rapid flutter sometimes arises from changes of about 0·001 pF. These fluctuations are caused by areas of silver separated from the main electrode by a high-resistance bridge of thinly-deposited metal of varying resistance. It is occasionally possible to identify the offending area visually, but proof rests mainly on the fact that, when the electrodes of such capacitors are backed with extra metal by electroplating, the fault disappears.

(3.4) Faults arising from Impregnating, Filling and Coating Compounds

Mica-capacitor stacks are often impregnated with oil or wax to improve insulation resistance, raise the a.c. ionization voltage and retard the ingress of moisture. Unsuitable impregnants used in this way may lead to environmental cracking of cast- or moulded-resin housings. Draining of the impregnant in unsuitable designs may result in a gradual drift of capacitance.

Filling compounds in older types of mica capacitors (with metal-foil electrodes) were sometimes bituminous materials with a high value of tan δ and relatively low insulation resistance, and these in impregnated or unimpregnated types were liable to migrate or diffuse between the plates, causing a little drift in capacitance but particularly a fall in insulation resistance and a rise in tan δ.

Some form of material to surround and protect the capacitor has been used since mica capacitors were invented. Occasionally the following faults have been met: ebonite surrounds lead to sulphiding of the electrodes and rise in tan δ; wax, while satisfactory in dry situations, may crack and allow ingress of moisture; plasticizers or other liquids from moulded or cast surrounds may creep or diffuse between the plates, alter the capacitance slightly, and cause an increase in tan δ.

(3.5) Faults arising from Moisture

Reference has been made in Section 3.1 to the role of water in the migration of silver ions, and in Section 3.3 to ingress of water through cracks in wax. It should be added that no organic coating material acts as a complete barrier to moisture-vapour diffusion, and mica in such coatings will gradually absorb[12] an amount of moisture corresponding to the average humidity of the surrounding atmosphere over a long period and remain so with small fluctuations on either side of this value. This, however, is a valuable protection against temporary peak periods of very high humidity. The protection is not obtained if there are cracks or fissures in the coating, e.g. at the points where the leads enter.

If moisture is taken up, either by foil-mica or silvered-mica capacitors, there is a slight increase[12] (of the order of 0·1% from 0–60% relative humidity) in capacitance, a marked increase[12] (of the order of 0·0001 to 0·0006 from 0–60% relative humidity) in tan δ and a decrease in insulation resistance.

(3.6) Intermittent Faults

Intermittent faults are sometimes the most difficult to locate and diagnose. They generally fall into two broad classes:

(*a*) Faults usually arising under low-voltage conditions which clear themselves abruptly when the voltage (or available energy) is raised.

(*b*) Faults which come on and off in phase with some operating condition, e.g. temperature, humidity, voltage, or mechanical pressure or tension.

Disconnections of class (*a*) are nearly always due to a dry joint at which an oxide film slowly builds up but which can be

Table 4

TABULATION OF EFFECTS OBSERVED

Class of fault	Observed effects	Possible mechanism
Breakdown	Short-circuited or low insulation resistance. Puncture on edge of electrode. No signs of foreign particles or marks on micas other than those described in Section 2.1	Excessive voltage. (Perhaps capacitor unimpregnated or oil-impregnated)
	High insulation resistance on low voltage but will only withstand low voltage. Otherwise as last	Excessive voltage. (Perhaps wax-impregnated)
	Either of above with puncture not at edge of electrode, and particles or marks as described in Sections 2.3, 2.4, 2.5	Foreign particles. Faults in mica or damage to mica
	High insulation resistance and will withstand 1 000 volts d.c. for 1 min. No puncture but marks as in Section 2.2	Flashover
Low insulation resistance	Low insulation resistance but not broken down. Marks as in Section 2.2	Flashover
	Low insulation resistance but clears on raising voltage Marks as in Section 2.2	Flashover
	As last, but marks as in Section 3.1	Silver-ion migration
	As last, but no marks. Perhaps evidence of whiskers. Clears suddenly under voltage	Metal whiskers
	Insulation resistance improves greatly on drying	Moisture film between terminals. Moisture absorbed by housing material Moisture in mica. Silver-ion migration
Capacitance change	Capacitance reduced to a few picofarads	Disconnection in lead or between lead and electrode
	Capacitance reduced by value of one plate	Disconnection of one plate
	Capacitance reduced by less than value of one plate	Disconnection of adjusting plate or part of one electrode
	Capacitance changed 0·2–0·5% with little or no change in tan δ	Mechanical drift of plates with time. Loss of impregnant. Compression or relaxation of housing
	Capacitance occasionally fluctuates a fraction of 1 pF under r.f. stress. No change in tan δ	Islands in silvered electrode
Rise in tan δ	Capacitance increases a few per cent and tan δ increases	Lossy impregnating, filling or coating compound migrating between plates
	Tan δ increases but no change in capacitance	Dry joint in lead gradually oxidizing
Noise	Capacitance fluctuates widely on handling	Loose lead or electrode
	No capacitance change	Dry joint
	Low insulation resistance which may clear	Silver-ion migration or metal whiskers
	Noise occurs frequently and regularly with nominal working alternating voltage but only initially with direct voltage	Gaseous ionization in spaces between or in micas

broken down by increased voltage: short-circuits or low insulation resistance faults of class (*a*) are sometimes due to metal whiskers or silver-ion migration, but may also be singly-occurring results of types described in Sections 2.1–2.5.

With class (*b*) intermittent faults, diagnosis is greatly helped if they can be related to an operating condition, and frequent measurements made of capacitance and tan δ at a low voltage while the capacitor is successively warmed, cooled, pressed or pulled.

(4) TABULATION OF EFFECTS OBSERVED

Table 4 offers suggestions regarding possible mechanisms of failure of mica capacitors when only observations by the investigator are available. Any accurate detailed information about the history of the capacitor and conditions at the time of failure will greatly increase the probability of a quick and accurate diagnosis. Of necessity, the indications in the Table are vague and reference should be made to the main text when the possibilities have been narrowed down.

(5) DISCUSSION

There are many possible mechanisms of failure of mica capacitors, some inherent in the mica but most resulting from faulty manufacture. Few of them can be detected easily by inspection after manufacture. The nature of a fault can often (though not always) be deduced by thorough inspection, including dissection, of a faulty capacitor after failure; it is often helpful in doing so to know the working conditions, both electrical and ambient, and particularly the exact conditions at the time of failure. There are, however, many types of failure where the conditions at the time of failure can be deduced from the dissection and detailed examination of the capacitor.

It is suggested that, to use the information in the paper to the best advantage in any particular case, Table 4 should be consulted first, followed by reference to the body of the paper and the illustrations, and lastly, if more detail is required, to the references.

This work does not imply that the proportion of mica capacitors which fail in service is excessive. Some of the causes of failure are liable to occur in other types of capacitor as much as in those using mica.

(6) ACKNOWLEDGMENTS

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(8) APPENDIX: SOME METHODS OF DISSECTION OF MICA CAPACITORS

(8.1) Removal of Waxes and Lacquers

Most of the waxes used for coating capacitors are hydrocarbon waxes with melting points in the range 70–80° C, and can be removed by heat or by solvents with very little disturbance of the capacitor unit as follows:

(*a*) Suspend the waxed capacitor over a small beaker in an oven at 80–90° C for an hour or so, or

(*b*) Immerse it in a boiling aromatic hydrocarbon such as benzene (b.p. 80° C) or toluene (b.p. 111° C)*.

Chlorinated hydrocarbons will dissolve the waxes more quickly but are liable to attack any aluminium that may be present.

Cellulose lacquers are sometimes used for coating capacitors and can be removed by immersion in cold or hot acetone (b.p. 56° C) or methyl ethyl ketone (b.p. 80° C).*

(8.2) Removal of Phenolformaldehyde and Other Moulded Casings

Phenolformaldehyde and similar mouldings can often be removed by cutting off the leads and grinding away the edges of the mouldings until the edges of the micas are just exposed, when the remainder of the moulding can be gently prized off. This, however, requires care and uses up a great deal of an operator's time if many capacitors are involved.

Another method is to place the cased capacitor in 16% aqueous caustic soda solution at about 60° C for about 5 hours (small capacitors) to 30 hours (large capacitors), when the structure of the casing will be broken down to an extent depending on the individual resin and degree of cure. The casing and unit should be washed in water and finally allowed to stand for some hours in several changes of distilled water before draining and drying.

Certain materials, e.g. aluminium or zinc, are attacked by caustic soda, but provided that such materials are absent a clean removal of the casing can often be made without damage to, or destroying evidence in, the capacitor unit.

Occasionally one meets capacitors having moulded casings of polystyrene, acrylic resins, polythene, p.t.f.e. or p.c.t.f.e. The first three of these can generally be melted off at temperatures of the order of 120–150° C, but if it is not desired to heat them so strongly as this, solvents may be used. Polystyrene casings can usually be dissolved in aromatic hydrocarbons, such as benzene, toluene or xylene.* Acrylic resins will generally dissolve in ketones such as acetone or methyl ethyl ketone.* Polythene casings can often be made to crack and partially granulate by immersion in acetone, to such an extent that they can be removed.* P.T.F.E. and p.c.t.f.e. are so resistant to heat and solvents that only mechanical methods are likely to be successful.

(8.3) Removal of Potting Compounds

Many capacitors are encapsulated in epoxy-type resins. At the commencement of this work information on the removal of such resins was limited to mechanical or thermal methods, neither of which could be employed without almost certain damage to the capacitor unit. Chemical means would be more suitable, but information was scarce as to the solubility of epoxy resins. Sample blocks of the resin were cast and the effect of different classes of solvent upon them was studied, with the results shown in Table 5.

Methyl ethyl ketone was obviously the solvent to concentrate upon, and so a capacitor was placed in this liquid in a stoppered container, at 50° C. After 20 hours most of the epoxy resin had crumbled away from the unit, and standing thus, with periodic agitation, all the resin was removed without damage to the capacitor unit. This was successfully repeated many times with other capacitors. The work was carried out on one type of epoxy resin only, but others would be expected to behave in a similar manner, though they may be slightly more or less resistant to the solvent.

Subsequently, the author has been informed that one manufacturer uses boiling methylene dichloride (b.p. 40° C) for this purpose.

(8.4) Separation of Silvered Micas in a Stack

With some makes of silvered-mica capacitor it is a simple mechanical operation to separate out the individual silvered micas, after proceeding as described in Sections 8.1, 8.2 and 8.3; with others a little unsoldering is involved, but with at least one make the adjacent silver surfaces are fused together, and it is impossible to separate the laminations as silvered micas without damage. They may be separated as micas and double-thickness silvers by warming in a 16% caustic soda solution for a few minutes, or by boiling in a 10% solution of sodium carbonate for several hours. The micas can, however, be recovered intact and unaltered without their silver by the method of Section 8.5.

The effect of this treatment on the mica is negligibly small, but it may remove part of the characteristic appearance of tracking or flashover.

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* Suitable precautions should be taken against fire hazards.

Table 5

EFFECTS OF SOLVENTS ON EPOXY RESINS

Class	Individual	Boiled, 3–5 min	Cold, 17 h
Water	Water	No effect	No effect
Alcohols	Ethyl alcohol	Little effect	Slightly softened
Esters	Ethyl acetate	Little effect	No effect
Ketones	Methyl ethyl ketone	Little effect	Crumbled
Chlorohydrocarbons	Trichlorethylene	Little effect	No effect
Carboxy acids	Acetic acid	Slightly softened	Softened
Polyhydroxy alcohols	Glycerol	Slightly softened	Softened
High b.p. amines	Aniline	Slightly softened	Softened
High b.p. phenols	Phenol	Slightly softened	Softened

(8.5) Removal of Silver from Silvered Micas

Silver electrodes can be removed from micas without any attack on the mica by heating gently in 25% (approximately) nitric acid. Solution takes place in a few minutes with single silvered-mica laminations, but with stacks, attack can only take place along the edges and 2–8 hours must be allowed. Finally, the micas should be washed with numerous changes of distilled water and dried on filter paper.

The correct sequence and orientation of micas in a stack can be retained by lightly binding it with platinum wire before treatment.