New Jersey Institute of Technology

Digital Commons @ NJIT

Spring 5-31-1984

Reliability studies on solid tantalum electrolytic capacitors

Hamed Nassar
New Jersey Institute of Technology

Recommended Citation

RELIABILITY STUDIES

ON SOLID TANTALUM ELECTROLYTIC CAPACITORS

by

Hamed Nassar

Thesis submitted to the Faculty of the Graduate School of
New Jersey Institute of Technology in partial fulfillment of
the requirements for the degree of
Master of Science in Electrical Engineering
1984

APPROVAL SHEET

Title of Thesis: Reliability Studies on Solid Tantalum
                   Electrolytic Capacitors

Name of Candidate: Hamed Nassar
                     Master of Electrical Engineering, 1984

Thesis and Abstract Approved: ---------------------------------
                                                          Date

                                Dr. R. P. Misra
                                Professor of Electrical
                                Engineering and Reliability

                                                          Date

                                ----
                                                          Date

VITA

Name: Hamed Nassar

Degree and date to be conferred: MSEE, May 1985

Secondary education: Shebin El-Qanater Secondary School

Collegiate instituttions attended	Dates	Degree	Date of Degree
Ain Shams University, Egypt	1974-79	B.S.E.E.	May, 1979
New Jersey Institute of Technology	1983-84	M.S.E.E.	May, 1985

Major: Electrical Engineering

Position held: Teaching Assistant
                Suez Canal University, Suez, Egypt

ABSTRACT

Title of Thesis: Reliability Studies on Solid Tantalum
Electrolytic Capacitors

Hamed Nassar, Master of Science in Electrical Engineering, 1984

Thesis directed and approved by: ------------------------------
                                  Dr. R.P. Misra
                                  Professor of Electrical
                                  Engineering and Reliability

The primary objective of this thesis is to determine and analyze the failure mechanisms of solid tantalum capacitors, pinpoint the causes, and suggest the precautionary measures that prevent the occurrence of these failures. To achieve this goal, the study went in two directions, theoretical and experimental. The theoretical part is a comprehensive review of the work done on tantalum capacitors since 1960 up to date.

The experimental part of the study is a life test (1000 hours) of solid tantalum capacitors under humidity and high temperature. To avoid the misconception that could happen by investigating a particular manufacturer's product, units from five international companies are tested. For each unit, three parameters are measured before and after the life test; namely capacitance, equivalent series resistance (ESR), and leakage current. Both humidity and temperature were found to have profound effects on capacitor behaviour.

The study was also able to rank the five major capacitor producers according to their units behaviour before and after the life test.

Blank Page

ACKNOWLEDGEMENTS

I would like to express my deep appreciation and utmost
gratitude to Dr. R. P. Misra, under whose supervision this work
was undertaken. During the period I worked with him, I benefitted
considerably from his wide range of knowledge and invaluable
suggestions.

I would also like to thank Dr. S. Pandey, of the Electrical
Engineering Department, for the help he provided in the experimental
work.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I: CAPACITOR

Before going through the performance, reliability, and failure
mechanisms of solid Ta capacitor, It is necessary to give a brief
review of what capacitor is all about. History and development
of electrolytic and Ta capacitor is also given.

1-1. Capacitance:

Capacitance is present between any two adjacent conductors. A
capacitor consists basically of two metal plates seperated by a
dielectric material, such as air, gas, paper, ceramic, or an oxide
film. When voltage is applied between the two metal plates, the
capacitor will become charged, and the amount of the charge will
depend primarily on the voltage. The capacitance of the capacitor is
the ratio of the charge acquired to the voltage applied, or

$$C = \frac{Q}{V}$$

Where   Q: Charge, coulombs (or amp-sec)

              V: Voltage, volts

              C: Capacitance, farad

The farad is the unit of capacitance and a capacitor has a
capacitance of 1 farad if its potential rises by 1 volt when it
receives a charge of one colomb. This unit is inconvenient for
practical use and the pf and μf are rather used.

The energy of the charge is stored up as electrostatic energy in the dielectric and is equal to $CV^2/2$. If this energy is absorbed at a uniform rate over a time t, the power required is

$$P_{av} = \frac{\frac{1}{2} CV^2}{t}$$

Under ac condition the rate at which energy is supplied to and returned by the capacitor is

$$P_{av} = 2 CV^2 f$$

Where V r.m.s. voltage

When a dc voltage is applied to a capacitor, and the bound electric charges are polarized or displaced from their normal position of equilibrium. Work is therefore done in charging the capacitor. The work done in joules (or watt seconds), which is available as stored potential energy is

$$J = \frac{1}{2} QV \text{ or } \frac{1}{2} CV^2 \text{ or } Q^2/2C$$

The equivalent circuit of a capacitor may be represented as shown in Fig (1).

Where
C: capacitance of capacitor
R_s: resistance due to leads, contacts, etc...
R_p: resistance due to the dielectric
L: inductance of leads and the plates of the capacitor
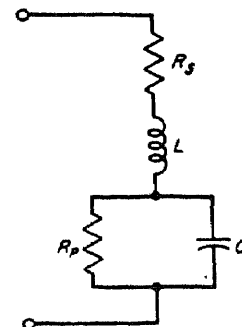
FIG. 1. Equivalent circuit of a capacitor.

1-2. Dielectric Constant:

The dielectric constant, permittivity, or specific inductive capacity of any material used as a dielectric is equal to the ratio of the capacitance of a capacitor using the material as a dielectric, to the capacitance of the same capacitor using vacuum as a dielectric. Dielectric constant of some materials is given in table Fig (2).

Dielectric Constant K

```
Vacuum ................................. 1.0
Dry Air ................................ 1.00059
Polystyrene ............................ 2.5
Polytetrafluoroethylene (Telflon*)..... 2.0
Polyethylene terrephthalate (Mylar*)... 3.0
Impregnated paper...................... 4.0 - 6.0
Mica ................................... 6.8
Tantalum oxide ......................... 25.0+
Aluminum oxide ......................... 7.0
Ceramic (magnesium titanate, etc.)..... Up to 20
Ceramic (titania)...................... 80 - 100
Ceramic (high-K )...................... 1,000 and upward
```

Fig. (2) dielectric constant for different materials

+ Approximate value, with general acceptance.

The high dielectric constant in high-K ceramic capacitors comes from the fact that the electric charges in the molecular structure of the material are very loosely bound and can move almost freely under the polarizing voltage, resulting in high total capacity.

Dielectric can be classified in two main categories: polar and non polar materials. Polar materials have a permanent unbalance in the electric charges within the molecular structure. The dipoles within the structure consist of molecules whose ends are oppositely charged. These dipoles therefore tend to align themselves in the presence of an alternating electric field (if the frequency is not

too high). The resultant oscillation causes a large loss at certain frequencies and at certain temperatures.

In nonpolar materials, the electric charges within the molecular structure are balanced and the dipoles do not rotate under applied fields although they may distort. No sharp loss peaks with frequency and temperature therefore exist. Polyvinyl chloride (PVC) is an example of a polar material, having a dielectric constant of ten at low frequency falling to 3 at a few mega hertz, while polystyrene is an example of a nonpolar material, having a dielectric constant of approximately 2.5 for dc and for ac up to a few megahertzs.

1-3. Losses in Dielectric Materials:

Losses occur due to current leakage, dielectric absorbtion, etc. depending on the frequency of operation. The loss-frequency curve for non polar and polar dielectrics is shown in Fig (3), (4).
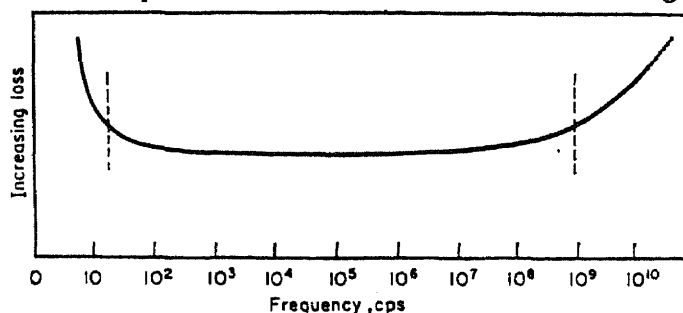
Fig. 3 Loss frequency curve for a nonpolar dielectric.
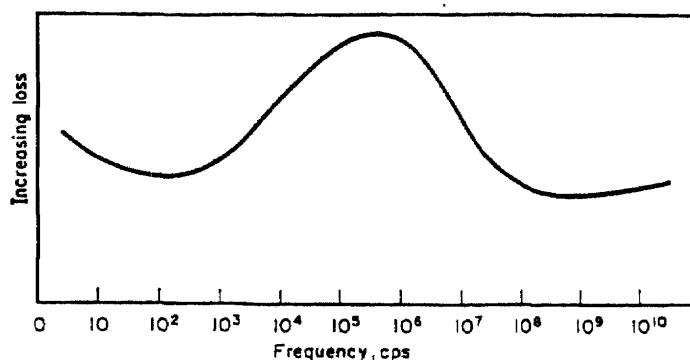
Fig. 4 Loss frequency curve for a polar dielectric.

The variation of dielectric constant with frequency is negligible so long as the loss is low. Increased losses occur when the process of alignment cannot be completed, owing to molecular collisions, and in these regions there is a fall in dielectric constant. Viscous drag in the molecular structure limits the frequency at which full alignment can be carried out. If the applied frequency is comparable with the limit frequency, losses will become high.

The power factor of the capacitor is defined as the ratio

Power wasted per cycle
Power stored per cycle

and for good dielectrics, this is dependent on the frequency.

When ac voltage is applied to a capacitor, the current leads the voltage by a little less than the theoretical 90°, Fig (5).
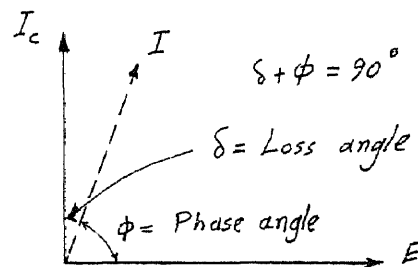
Fig. (5) Vector diagram for a capacitor

The phase angle is termed ϕ, whereas its complement is termed δ, the loss angle. The cosine of the phase angle or the sine of the loss angle is the power factor. The dielectric loss is therefore EI cos ϕ

- 5 -

or EI sin δ. The loss angle δ is normally so small that tan δ, the dissipation factor, can be considered equal to sin δ or cos $\emptyset$, since it is easier to measure.

In perfect capacitor with no dielectric loss, δ = 0. The dissipation factor is tan δ = 2 π fRC.

1-4. Dielectric Absorption:

If a capacitor were completely free from dielectric absorbtion, the initial charging or polarization current when connected to a dc supply would be

$$i = (\frac{E}{R})\ e^{-t/CR}$$

Where   i: current flowing after time t.
         E: applied dc voltage.
         R: capacitor series resistance.

and the polarization current would die off asymptotically to zero. If R is small, this takes place in a very short time, and the capacitor is completely charged. In all solid dielectric capacitors it is found that, after a fully charged capacitor is momintarily discharged and left open circuited for some time, a new charge accumulates within the capacitor, because some of the original charge has been "absorbed" by the dielectric. This produces the effect known as dielectric absorption. A time lag is thus introduced in the rate of charging and of discharging the capacitor.

Dielectric absorbtion is due to the finite time taken to displace the bound charges in the dielectric from their normal positions because of the viscous forces which resist their motion. Polarization may be almost instanteneous or it may take many hours. Even within the same dielectric, a few electrons or ions become free to move only after a period which may be seconds or even days.

The effect of dielectric absorption is to reduce the capacitance as the frequency of operation is increased and also to cause unwanted time delays in certain pulse circuits or in circuits requiring rapid charge and discharge characteristics.

1-5. Leakage Current and Time Constants of Capacitors:

Losses due to leakage currents when a capacitor is being used on direct current prevent indefinite storage capacity being realized, and the charge acquired will leak away once the source is removed. The time in which the charge leaks away to 1/e or 36.8% of the inital value is given by RC, where R is the leakage resistance and C is the capacitance. If R is measured in MΩ & C in μF, the time constant is in seconds.

Some typical time constants for various dielectrics used in capacitors are:

Polystyrene	several days
Impregnated paper	several hours
Ta-pellet electrolytic cap	1-2 hours
High dielectric constant cap. (ceramic)	several minutes
Plain-foil electrolytic cap.	several seconds

It should be borne in mind that below capacitance values of about 0.1μF, the time constant is generally determined by the structure, leakage paths, etc., of the capacitor assembly itself rather than the dielectric material. Leakage current increases with the increase of temperature (roughly exponentially). In good dielectrics at room temperature it is too small to measure, but at higher temperatures the current may become appreciable even in good dielectrics.

1-6. Insulation Resistance:

The insulation resistance of a dielectric material may be measured in terms of surface or volume resistivity in ohms or ohms-centimeter respectively. Volume and surface resistances can be measured as shown in Fig (6).
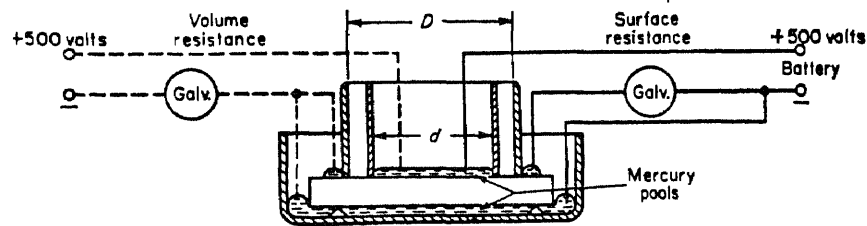
Fig. (6) Typical arrangement of apparatus for surface and volume res. test

The insulation resistance of any capacitor will be lowered in the presence of high humidity (unless it is sealed) and will be reduced when operated in high ambient temperature (whether sealed or not). For perfectly sealed capacitors used under conditions of high humidity there should be no deterioration, but for imperfectly sealed capacitors

the drop in insulation resistance will be roughly inversely proportional to the effectivness of the sealing.

Under high-temperature conditions, the fall in insulation resistance for most capcitors is given approximately by the formula

$$R_T = \frac{R_t}{e^{-k\ (T-t)}}$$

Where R_t: insulation resistance at high temperature T.

           R_t: insulation resistance at low temperature T.

           K: constant depends on the material used.

1-7.   Dielectric Strength:

The ultimate dielectric strength of a material is determined by the voltage at which it breaks down. The stress at which breakdown occurs depends on the thickness of the material, the temperature, the frequency and the waveform of the testing voltage, the method of application, etc. Therefore, comparisions between different materials should ideally be made on specimens equal in thickness and under identical conditions of measurement.

The dielectric strength of a material is always reduced when it is operated at high temperature or if moisture is present. Most dielectrics withstand a much higher voltage for brief periods. With increasing frequency the dielectric strength is reduced particularly at radio frequencies depending on the power factors etc., of the material.

1-8. The Effect of Frequency on Dielectric Materials and Capacitor
      Assembly:

      At very low frequency and also at high frequencies, there is

an increase of loss which sets a limit to the practical use of a

capacitor with any given dielectric. At very low frequencies,

various forms of leakage in the dielectric material have time to

become apparent, such as dc leakage currents and long time constant

effects, which have no effect at high frequencies. At very high

frequencies, some of the processes contributing to dielectric

polarization do not have time to become effective and therefore

cause loss. The losses might be simply and approximately repre-

sented in Fig (7).
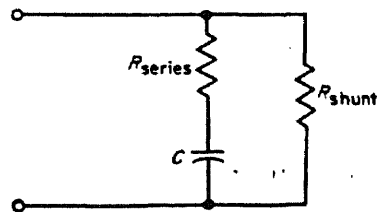
Fig. (7) Series and shunt losses in a capacitor

      At very low frequencies the circuit is entirely resistive, all

the current passing through the shunt resistance (dc leakage resistance,

etc.). At very high frequencies the current passes through the

capacitor C, but all the volts are dropped across the series resistance,

and again the circuit is lossy. This series capacitance may be due to

the resistance of the capacitance leads, contact resistance, etc, in the

capacitor assembly itself. These limit the upper frequency indepen-

dently of the dielectric material used. Similarly, leakage across the case

containing the dielectric may limit the lower frequency so that not

all the useful range of the dielectric itself may be realized.

1-9. The Impedence of a Capacitor:

The current I in a capacitor (when an alternating voltage V

of frequency f is applied is

$$I = 2\pi f C V$$

and the reactance is given by

$$X_c = \frac{1}{2\pi f C}$$

An ideal capacitor would have entirely negative reactance, but the

losses, described previously, due to dielectric, case and leads, pre-

clude this. In addition, inductance is also present in varying

amounts, and therefore as the frequency is increased the inductive

or positive reactance increases, and above a critical frequency the

capacitors behaves as an inductor.

CHAPTER II: TANTALUM CAPACITOR

2-1. Origin and Development:

The idea (2-62) of forming an insulting film on a metal

electrode to make a capacitor is generally attributed to

Wheatstone in 1855, but the idea of the electrolytic capacitor

arose in Germany some 20 years later.

The precursor of the modern electrolytic capacitor, con-

sisting of two aluminium-sheets electrodes immersed in an

electrolyte consisting of a solution of ammonium borate in a

glycerine-water mixture appears to have originated about 1908,

and in that year an important step in the reduction in size of

such capacitors was made by constructing the anodes of thin

sheets, rolling them up into cylinderical form and placing them

in containers of the same shape. However, the more bulky form

persisted for many years after this.

Solid tantalum capacitors possess unique features and

characteristics which make them invaluable in certain applications.

Chemical and physical stability of the dielectric causes tantalum

capacitors to exhibit high reliability and long life when compared

with many other dielectrics such as aluminium types. Electrical

parameters such as low dc leakage currents, stability of performance

over a wide temperature range and close capacitance tolerance

are some of the benefits available. Frequency characteristics

cover an extremely wide range.

2-2. Electrolytic Capacitor:

Essential parts of an electrolytic capacitor are:

a) A metal anode (the positive electrode), made from a film-forming metal. Aluminium, tantalum, zirconitm, niobium, hafnium, tungsten, bismuth, and antimony are able to form anodic oxide films by an electrolytic "forming" process. Only aluminium and tantalum are at present used to make electrolytic capacitors on a commercial scale. Extensive research is being carried out on zirconium and niumium, and experimental capacitors have been made successfully, but so far there is no commercial production. The principal problem appears to be obtain metal of a sufficiently high degree of purity. None of the other metals mentioned has yet yielded a practicable electrolytic capacitor.

b) Very thin oxide film, produced electrolytically on the anode, the film constituting the dielectric. The thinness of the film, coupled with its medium permittivity, is the main reason for the high capacitance per unit volume, the basic advantage of electrolytic capacitors.
The films consist of substantially pure oxide of the anode metal (e.g. Al_2O_3 or Ta_2O_5) with a possible content of adsorbed water or entrapped electrolyte ions in the more porous ones. The films are mainly amorphous and glassy in structure, showing interference colours characteristic of the thickness and refractive index of the film. These compact anode films can be made practically free from defects while still being extremely thin (about 3 Å/volt of formation) and can withstand very high electric stresses (e.g. 500 volts/micron) that in some instance approach the intrinsic dielectric strength of the oxide - 10^4 volts/micron.
The permittivity is about 8.4-10 for aluminium, 25-27 for tantalum and 41 for niobium.
To develop the oxide film, the thoroughly-cleaned metal slug is placed in a suitable electrolyte and connected to the positive terminal of a source of direct current. Electrolysis of the water in the electrolyte takes place, and the oxygen combines rapidly with the anode metal to form the surface layer of oxide, with nearly 100 per cent efficiency in the case of pure metal anodes. As the oxide film is a dielectric and practically non-conductive material, the current falls rapidly, and as the film thickens, the potential across the film rises until it is approximately the same as that of the supply.

c) An electrolyte suited to the anode metal and characteristics is required. The electrolyte is the true negative electrode. If during its life the oxide film is punctured or cracked,

the voltage across the capacitor causes a local current to
flow that in turn leads to a local growth of oxide film,
thus giving the capacitor a self-healing property. Both
this and the very small steady leakage current cause
electrolysis of water in the electrolyte, so that oxygen
and hydrogen gases are evolved in proportion to the total
electric charge that has passed. Some of the oxygen
combines with the anode in the self-healing process, but
the remainder, plus the hydrogen, accumulates as a gas and
if a suitable vent has been provided, leaks away. If the
capacitor is completely sealed, and internal gas pressure
may build up, causing the seals to bulge and leading to
an explosion in extreme instances if the current is con-
siderable. With modern types of capacitor, and particularly
if the voltage is low, the leakage current is so small that
the gas pressure is very slight.

2-3. Tantalum:

Ta (3-82) atomic weight is 180,9479, atomic number is 73, melting

point is 2990°, b.p. $5425 \pm 100^{\circ}C$, specific gravity is 16.654, valance

2?, 3, 4?, or 5. Discovered in 1802 by Ekeberg, but many chemists

thought niobium and tantalum were two different acids. The early

ivestigators only isolated the impure metal. The first relatively

pure ductile tantalum was produced by von Bolton in 1903. Tantalum

occurs principally in the mineral columbite-tantalite (fe, Mn) (Nb, Ta)$2^0{}_6$.

Tantalum ores are found in the Repuhlic of Zaire, Brazil,

Mozambique, Thailand, Portugal, Nigeria, and Canada. Seperation of

tantalum from niobium requires several complicated steps. Several

methods are used to commercially produce the element, including

electrolysis of molten potassium fluotantalate, with sodium, or

reacting tantalum carbide with tantalum oxide. Sixteen isotopes of

tantalum are known to exist. Natural tantalum contains two isotopes;

one of these, Ta^{180}, is present in very small quantity (0.0123%) and

is unstable with a very long half-life of more than 10-13 years.
Tantalum is a gray, heavy, and very hard metal. When pure, it
is ductile and can be drawn into fine wire, which is used as a
filament for evaporating metals such as aluminum. Tantalum is
almost completely immune to chemical attack at temperatures below
150° C. and is attacked only by hydrofluorec acid, acidic solutions
containing the fluoride ion, and free sulfur trioxide. Alkalis
attack it only slowly. At high temperatures, tantalum becomes
much more reactive. The element has a melting point exceeded
only by tungsten and rhenium. Tantalum is used to make a variety
of alloys with desirable properties such as high melting point,
high strength, good ductility, etc. It is also widely used to
fabricate chemical process equipment, nuclear reactors, and air-
craft and missile parts. Tantalum is completely immune to body
liquids and is a nonirritating metal. It has, therefore, found
wide use in making surgical appliances.

Over the other metals (1-71) that can have coherent oxide
layer, tantalum has numerous advantages. With tantalum, we are
able to prepare a better dielectric by anodization than with
aluminum. The result of this is that the capacitor has a better
shelf-side than does the equivalent aluminum one.

Tantalum and tantalum oxide (2-62) are much more inert mater-
ials chemically than aluminum and its oxide film, and for this
reason would be expected to make more stable and reliable capacitor

units. This inertness also makes possible a much wider choice in the range of electrolytes used. One of the common electrolytes being moderately-strong is sulphuric acid (which makes it possible to use such capacitors over a wide temperature range). Others are lithium-chloride solution and variants of the borate solutions used with aluminum anodes. Under equal conditions, the leakage current of a tantalum electrolytic capacitor is generally lower than that of the average-quality aluminum electrolytic capacitor.

For a given voltage (1-71), tantalum gives a thicker oxide than does aluminum. One can quantify this by noting that tantalum gives a thickness of 1.6 cm for every volt applied.

The only disadvantage of tantalum is that it has the cost of silver and the weight of lead and therefore it is not the adequate choice for applications are not worth.

Resistivity of tantalum is 15.5 $u\Omega$/cm, and the temperature coeffecient is 0.0031. Magnetic susceptibility of Ta is 154 10^{-6} at 293°K and 124 10^{-6} cgs at 2143°K. Magnetic susceptibility of Ta_2O_5 is -32 10^{-6} at ordinary temperature.

2-4. Types and Construction of Tantalum Capacitor:

There are (1-79, 1-71) three types of tantalum capacitor-tantalum foil, solid tantalum, and wet sintered tantalum-which all use tantalum oxide as the dielectric. This dielectric has a permittivity of about 25 compared with 7 for typical aluminium electrolytic types, so high capacitance can be provided in a relatively small space.

Tantalum foil capacitors are normally used for voltages above 100 volts and they are available up to 450 volts. The foil is either plain or etched. In the latter case, the surface area is considerably increased and therefore more capacitance per unit volume is obtained. However, the situations in which tantalum foil capacitors offer clear advantages are so rare that they need not be considered in any greater detail.

Throughout this thesis, solid tantalum capacitor will always refer to the tantalum capacitor with sintered anode and solid electrolyte, which is usually manganese dioxide.

2-5. Processing and Packaging of Tantalum Capacitor:

To make solid Ta capacitors, accurately weighed quantities of powdered Ta mixed with wax are compacted into small moulds, into each of which a Ta wire has been inserted. The purpose of the wire of course, is to provide one of the external connections. The wax has three purposes; in the initial stages it temporarily binds the particles of Ta powder together, it serves as a lubricant so that particles flow freely during compaction to form anodes of uniform density throughout their volume, and it also fills the interstices, thereby helping to prevent over-compaction. Compacting by the use of presses not only ensures good electrical contact between the metallic particles, but also makes each component strong and firm enough to be lifted from the mould for further treatment.

The next step is the removal of the wax by vaporisation in a vacuum oven. The material is then sintered; the electrical contacts

between neighbouring particles and between the Ta and surrounding particles are welded, under high vacuum, in a furnace. The temperature needed for sintering is high enough ($1800^{\circ}C$ – $2000^{\circ}C$) to vaporise any impurities, but the high vacuum prevents oxidation of the Ta (1-79). The problems (1-71) associated with the preparation of Ta capacitors using sintered powder are partly concerned with the variation of capacitance one gets with sintering conditions. The variation of capacitance as a function of time and temperature of sintering is shown in Fig (8).

The combination of exact proportions of powder and wax, accurate weighing of the mixture, and precision of the compaction and moulding produces (1-79) an open sponge-like mass of size, density, and weight known to within close limits, so that the effective surface area of Ta is also accurately known.

The particles need to be covered with a strong uniform film of dielectric, in order to make possible the small size which is characteristic of these capacitors. To form the dielectric the anodes are dipped into baths of a conductive solution such as aqueous phosphoric acid*and an electric current is passed through them. This causes oxidation which leaves a film of Ta pentoxide on the surfaces of the particles. Rate of growth of the oxide film for both constant voltage and constant current are shown in Fig (9).

---

*Dr. Misra thinks that there might be some activator in the acid, but he could not determine exactly that trade secret.

3 um powder

Fig. (8)   Capacitance as a function of time and temp. of sintering.

Fig. (9) Thickness of film with time of sintering.
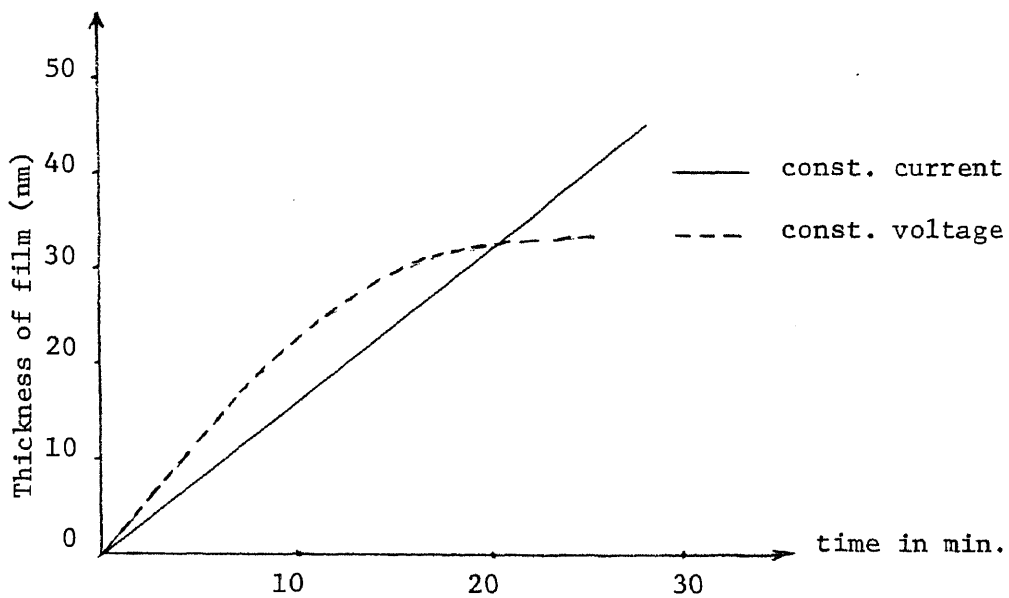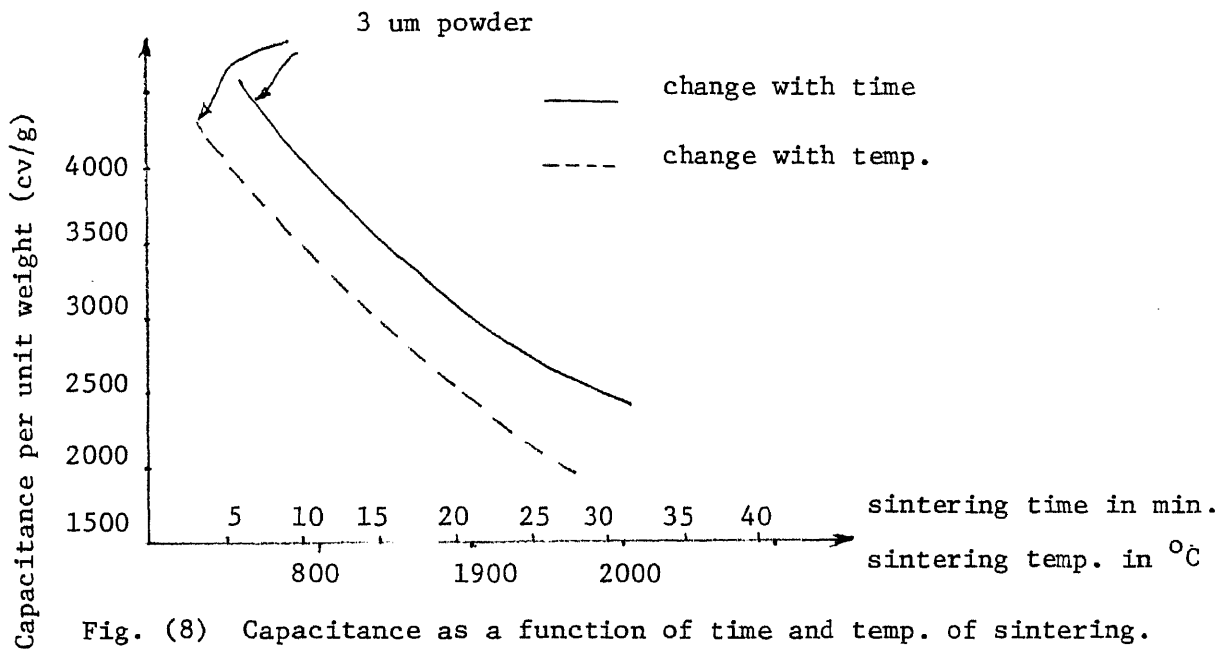
Thorough washing removes all traces of the conductive solution and leaves the anodes, now completely covered with dielectric, ready for the next process; the formation of cathodes.

Manganese dioxide, a solid semiconductor, is used as the cathode of these capacitors. It is produced and fixed in position when the anodes are repeatedly (6-20 times) dipped into a solution of manganous nitrate. After each dip in the solution impregnation the anode is converted into solid manganese dioxide by pyrolysis that is decomposition by heat. The effect of the number of impregnation and hence the thichness of the manganese oxide layer is increased but the dc leakage increases mainly due to the effect of the tempeture cycling to which the dielectric has been subjected.
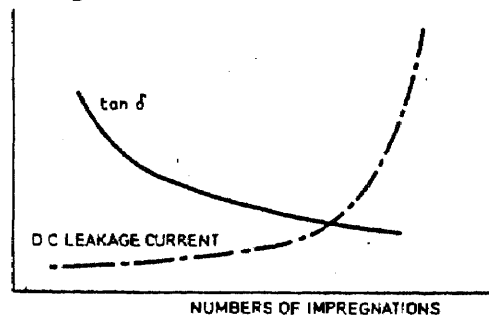
Fig. (10)   Effect of impregnations on capacitor loss
and leakage current

In this way the interstices between the particles coated with Ta pentoxide are filled completely by cathode material. The original sponge-like anodes are thus converted into solid capacitors with, at this stage, no increase in the original moulded size. However, it is not possible to attach leads directly to the manganese dioxide cathodes. This problem is overcome by dipping the capacitors into a solution of colloidal graphite. As a result, graphite, a low-

impedence conductive material, coats the surfaces and penetrates

into the pores to make good electrical contact with all the cathode

material. An exterior coat of silver is then added.

Solid Ta capacitors can be classified in five groups, based

on size, reliability (resistance to ambient conditions) and price

according to their mounting methods and lead-wire take out methods,

as shown in Fig (11).
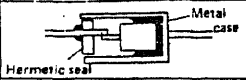
Kinds	Typical structure	Features	Usages
Metal case with hermetic and seal		Superior anti-environmental characteristics High reliability	Military use Computer
Epoxy molding		High reliability	Computer Automobile
Metal case with epoxy resin end seal		Miniature	Mobile telephone Hearing aid
Dipped epoxy coating		Low price	Consumer use Industrial use
Chip		Ultraminiature	Hybrid IC

Fig. (11) Kinds of tantalum capacitors.

1) The metal case type with hermetic end seal is hermetically sealed
    and is used for high-reliability equipment and equipment used in
    extreme operating conditions.

2) The epoxy-molded type is externally transfer-molded with epoxy
    resin. This type is somewhat inferior to the metal case,
    hermetically sealed type in resistance to ambient conditions,
    but is relatively superior in external demensional precision.
    As it is small in size and low in cost, it is used extensively
    in industrial equipment.

3) The metal case type with epoxy resin and seal is not hermetically
    sealed and has relatively smaller external dimensions and is used
    extensively in small products such as mobile radio equipment and
    hearing aids.

4) The resin-dip type, dipped in epoxy resin, is inferior in external dimensional precision, and is less resistant to external ambient conditions than the resin-molded type but as it is low in cost, this type is used extensively in consumer products and industrial equipment that is sold at low prices. Of all the Ta capacitor types, the resin-dip type is manufactured in greatest quantities.

5) Unlike the four other types, the chip type does not have lead-wires and is intended for insertion in printed circuit boards, and is used mainly for hybrid ICs (2-82).

A symbolic representation of solid Ta capacitor is shown in Fig. (12).

anode lead
(tinned nickel wire)

final solder seal

glss to metal seal
soldered to metal can

weld

anode riser

sintered powder anode

manganese dioxide

graphite coating

solder cathode
connection

metal can

cathode lead
(tinned nickel wire)
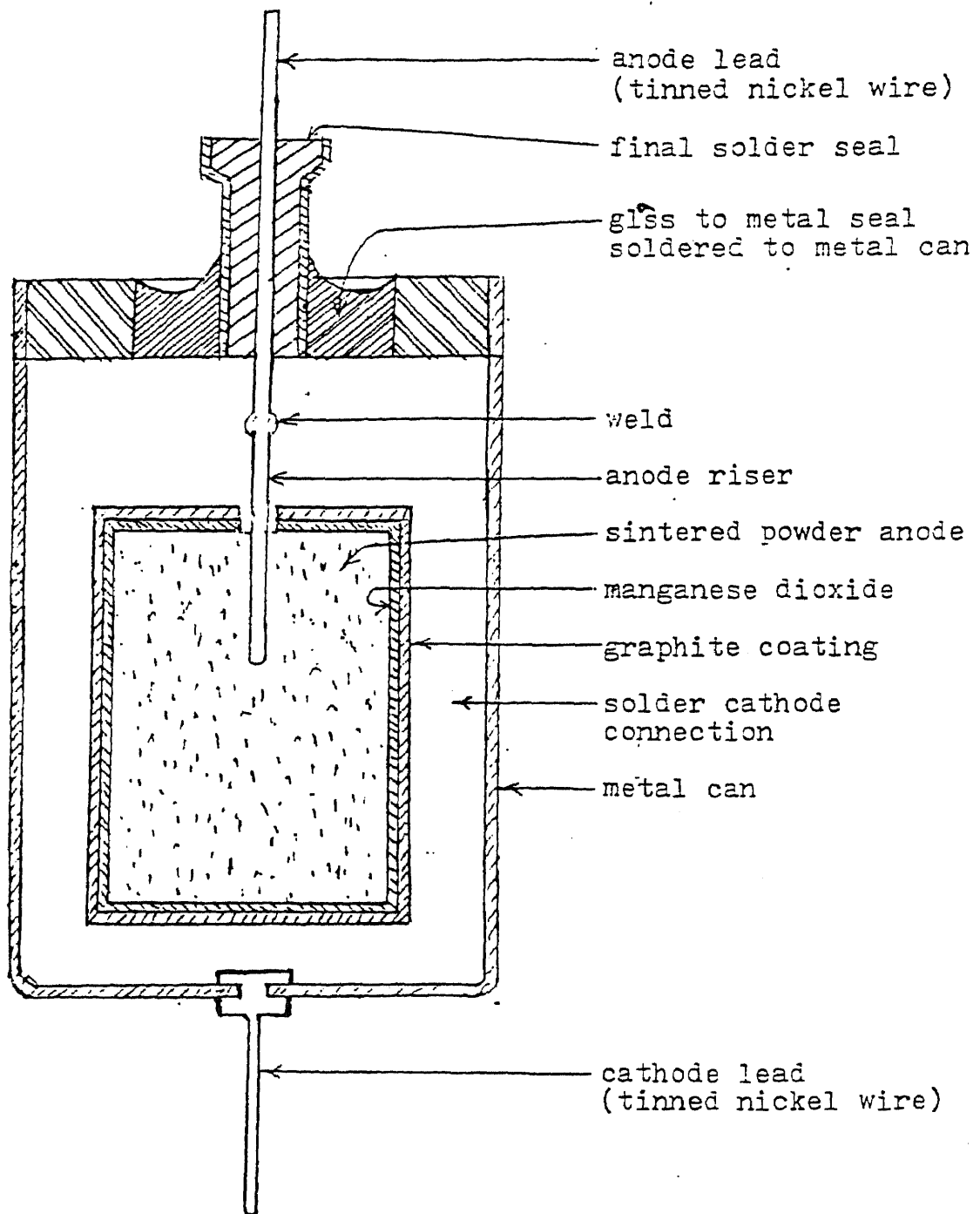
fig (12) Solid tantalum capacitor(ծ)

2-6. Tantalum Capacitors Advantages:

Solid Ta capacitors possess (2-64) the following unique

features:

1) Chemical and physical stability, which causes Ta capacitors
   to exhibit high reliability and long life.

2) Electrical parameters such as low dc leakage currents,
   stability of performance over a wide temperature range
   and close capaitance tolerance.

3) Frequency characteristics cover an extremely wide range.

4) High capacitance per unit volume.

2-7. Losses in Solid Tantalum Capacitors:

All capacitors (5-60) have some energy losses associated with

them. The losses in an electrolytic capacitor are due primarily to

its internal resistance. Fig (13) is a simplified equivalent

circuit of an electrolytic capacitor. Notice that there are two

resistances indicated. The shunt resistance represents the dc

leakage current. The series resitance is the primary contributor

to the energy loss or heating effect within the unit. In the case

of solid tantalum capacitor, this resistance is primarily in the

electrolyte-cathode system.
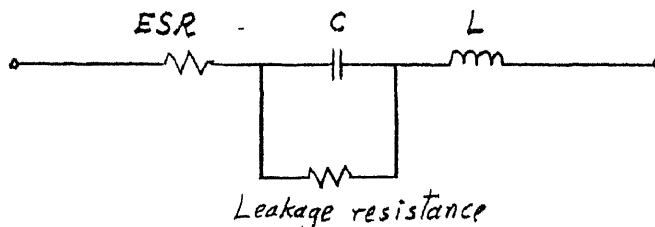
Fig. (13) Electrolytic capacitor eq. circuit.

The high frequency impedence (6-68) and the maximum allowable
a.c. ripple of a solid tantalum capacitor is determined almost
entirely by the equivalent series resistance of the capacitor.
The stability of capacitance with variations of frequency and
temperature is also under certain conditions determined by the ESR.

The ESR of a capacitor is normally obtained from a measurement
of dissipation factor and is defined as $ESR = \dfrac{\text{Dissipation Factor}}{wc}$.

Unfortunately the dissipation factor of a solid tantalum
capacitor is not a linear function of frequency and its ESR is <u>not</u>
a constant. The total dissipation factor (6-61, 3-68, 6-68) may
therefore be conveniently expressed as:

$$
\begin{aligned}
D.F. &= wC \ (R_1 + R_2) \\
&= wCR, + wCR_2 \\
&= \tan o + wCR_2
\end{aligned}
$$

where C is the capacitance, w is the angular frequency. R_2 is the
resistance of the electrolytic (MnO_2), carbon layer and leads tan o
is the dielectric contribution to dissipation factor. Fig. (14)
shows the delaits of the ESR.
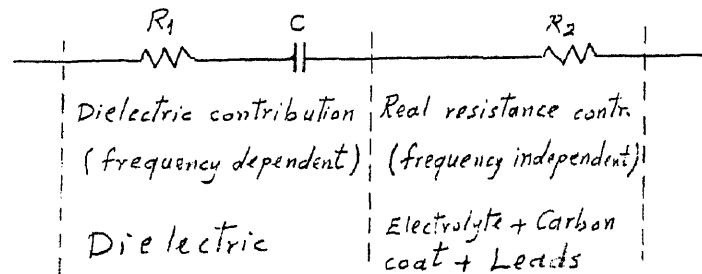
Fig. (14)   ESR of solid Ta capacitor.

Considering the dielectric loss produced in a <u>hypothetical</u>

R, it is apparant from fig (15) that at the lowest frequencies

tan δ is relatively independent of frequency. This is the region

where dissipation in the dielectric predominates. Variation in

tan δ in this region is extremely small compared to that which

would be produced by a <u>true</u> series resistance such as R_2 or by

a parallell leakage path. Furthermore, the values of tan δ at

the lowest frequencies are relatively independent of geometry and

capacitance and therefore must be a property of the oxcide film.
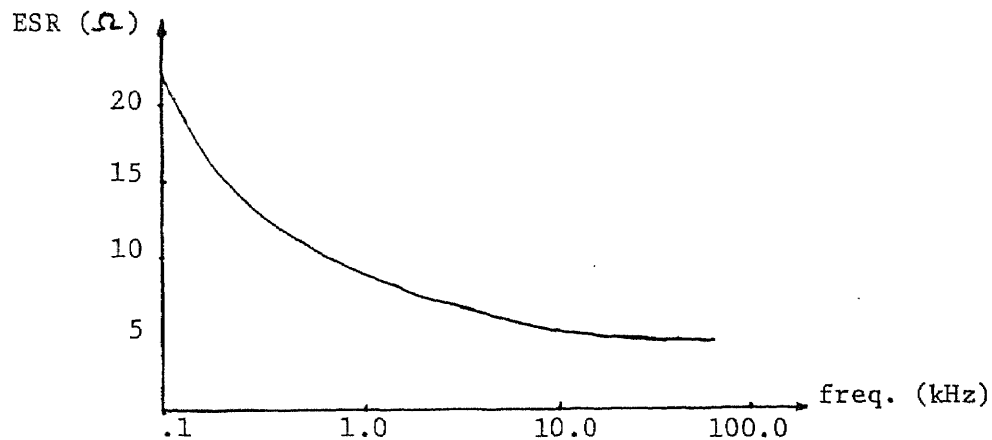
Fig. (15) ESR change with frequency.

The low frequency values of tan δ are, however, somewhat

dependent on taltalum purity and structure and on processing steps,

as might be expected since these are likely to influence the

quality of the dielectric. To have tan δ ($= wCR_1$) independent of

frequency, the hypothetical resistance R_1, must vary inversely with

frequency and can be cosidered as k/w where k is a constant.

From these considerations it can be seen that the dissipation

factor at very low frequency will be a measure of dielectric losses

(tan δ) whereas at high frequency it will be a measure of resistive

losses (wR_2C). Therefore, a frequency of 1 KHz is usually chosen

as a basic frequency to measure the ESR of capacitors, and that gives:

$$ESR = \frac{\tan \delta}{wC} = \frac{\tan \delta}{2000\pi\, C} .$$

Considering now only the resistive part of the dissipation

factor, (since it is the main factor determining high frequency

characteristics), it is convenient to think of this resistance as

composed of two parts:

a) The resistance of the electrolyte which is within the sintened
    anode of tantalum and is a distributed resistance in series
    with the capacitive elements.

b) The resistance of contact to the electrolyte, leads, etc.
    which is outside of the anode and consequently is a lumped
    resistance in series with the capacitve element.

Of the two, the electrolyte resistance is normally the greater.

Well recognized advantages of solid electrolytic tantalum

capacitors over other electrolytic capacitors (6-68) are that the

ESR of this type is relatively low and that it remains low over

a wide temperature range. These advantages are utilized in

applications where it is requried to pass relatively high AC

currents through the capacitor or where a low capacitor impedence

is requried at high frequencies and/or lower temperatures.

CHAPER III: RELIABILITY OF SOLID TANTALUM CAPACITORS

3-1. How Reliability of Electronic Parts is Guaranteed:

Any study of electronic parts reliability (1-72) should be
approached by looking at individual parts, as dependability
factors vary from one part to the next. In fact the word
"reliability" itself has different shades of meaning and has no
true, clear-cut meaning. In examining reliability, one should
ask whether he is using the word to define electronic parts
themselves of the systems or devices they form a part of.

Usually mechanical and electromechanical parts of electronic
systems, such as connectors and printed circuit boards raise
dependability problems. Particulary troublesome are the factors
of the reliability of contacts and connecting elements (soldering,
wound terminals, welding), although these are not classified as
electronic parts in the strict sense of the word.

Resistors, capacitors, and other passive parts on the other
hand pose very few reliability problems in design and manufacture,
due to the technical expertise developed over the long period
since they were first produced. Among these passive parts stands
solid tantalum capacitor which is a dielectric type device.
Although they offer outstanding reliability compared to other
types of capacitors, serious research has to be done for further
improvements.

It has been found (7-64) that reliability of dielectric type devices is a function of:

$$
\begin{cases}
\text{E} & \text{Electric Field} \\
\text{S} & \text{Surface} \\
\text{P} & \text{Package} \\
\text{T} & \text{Temperature \& Temperature Gradient} \\
\text{A} & \text{Ambient} \\
\text{SF} & \text{Special factors, encountered by the device under} \\
& \text{consideration such as thermal cycling, mechanical} \\
& \text{vibrations, etc.}
\end{cases}
$$

Therefore in studying solid tantalum capacitor's reliability, these factors should all be investigated.

3-2. Life Tests and Failure Rates:

Life tests have been used extensively to predict capacitors reliability. Most manufacturers (5-61) have some form of life test that is used in tandem with a statistical analysis to predict or guarantee the customer a certain failure rate over a fixed period of time. The most accurate single life test point, of course, would be to test a group of units at rated temperature and voltage, for the guaranteed life of the capacitor. This method is not practical because of the time involved. However many leading capacitor producers are approaching this accuracy by running a slightly accelerated life test (in the order of 1.5 times rated voltage) for a shorter period of time.

For a given operating temperature, the life of a capacitor is known to be inversely proportional to some power "N" of the applied voltage. Accelerated life tests, to avoid great outlays of time, are based on this relationship.

One of the most important factors that should be considered when determining capacitor reliability or the degree of accuracy that can be obtained when predicting the life of a particular capacitor type, is its failure rate and how it varies with time (called sometimes failure rate pattern). The complete failure rate pattern is normally composed of two types of failures; chance or random failures and wear-out failures.

Random failures are early failures caused by inherent weaknesses in the materials and by damage incurred during the manufacturing processes. The random failure rate pattern is characterized by a high initial failure rate followed by a leveling off period.

Wear-out failures in capacitors are thought to be caused principally by the slow electrochemical deterioration of the dielectric. The presence of contaminants such as rosin or moisture within the capacitor have shown to accelerate this deterioration. The wear-out failure rate pattern is usually bell-shaped and is often normal.

The actual failure frequency distributions are caused by both wear-out and random failures and therefore have a characteristic shape of their own.

3-3. Failure Modes of Capacitors:

Generally, a capacitor is said to be failed (3-62) if it
exhibits one or more of the following features:

1) Short circuit
2) High leakage current
3) Open circuit
4) Appreciable change in capacitance
5) Appreciable change in equivalent series resistance (ESR)

The first two modes are related to each other. However, the
difference is that when the capacitor is short circuited it can
not function as a capacitor anymore. The third mode is reported
(1-70) to account for the largest number of failures of solid
tantalum capacitors. The two reasons for that were a poor weld
from the tantalum risen to the external lead and poor slug
anchorage to the can.

The above mentioned failure modes can occur suddenly or
gradually. When a failure occurs suddenly, it is called
catastrophic failure. Whereas when it occurs gradually, it is called
degradational failure. Furthermore, three parts are responsible for
any failure that occurs to the product, namely, the manufacturer,
the designer, and the user.

3-4. Common Causes of Failure of Solid Tantalum Capacitors:

The most common causes of failure of capacitors in general
and solid tantalum capacitors in particular can be summarized as
follows:

1) Seal failure, which allows moisture and other contaminants
   to infiltrate and hurt the capacitor.

2) Dielectric failure, which could be either gradual growth
    in thickness of the oxide film leading to reduced capacitance,
    or field crystalization of the essentially amorphous
    dielectric oxide. Field crystalization occurs in tantalum
    capacitors at high (e.g. over 100°C) temperature and high
    electric stresses. Starting from minute nuclei, the
    amorphous oxide film is replaced by crystaline tantalum
    pentoxide, see fig. (16). This process is accompanied by
    increased leakage current. It has been found (2-60, 2-62,
    5-64, 1-77, 5-80) that dielectric crystalization is the basic
    failure mechanism of solid tantalum capacitor.
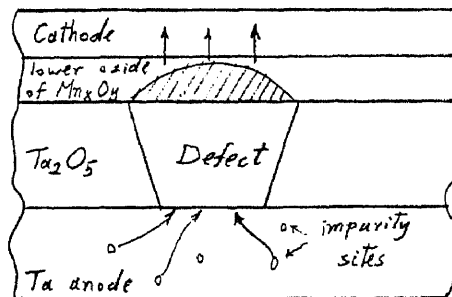
Fig. (16) Migration of impurity molecules.

3) Corrosion of electrodes, As a matter of fact this was the
    case in all failure cases of a supplier whose units were
    covered in this study.

4) Bulging or bursting due to intenal evolution of gas.

5) Formation of oxide film at one of the metal-to-metal joints
    leading to a rising series resitance increasing the value of
    tan δ

6) Mechanical failure, in contacts, welds.

7) Thermal runaway, since oxides of manganese are semiconductors
    with a negative (5-80) temperature coefficient of resistivity,
    therefore excessive temperature in a dielectric zone can
    cause loss of control of leakage current.

8) Air gaps creation in the interfaces, specially between
    tantalum and tantalum oxide because of the radical difference
    of their coeffecients of thermal expansion*.

_____

* Dr. Misra thinks that this is the most likely cause of failure
  but still needs some more research.

Since an airgap in series with tantalum oxide will have 25 times as much electric field as that in the tantalum dioxide (ϵ_r for Ta_2O_5 = 25). Meanwhile the breakdown voltage for air is much less than that for Ta_2O_5 which means a breakdown inside the air gap is inevitable which in turn leads to a whole destruction of the capacitor.

CHAPTER IV: FACTORS AFFECTING RELIABILITY OF SOLID
TANTALUM CAPACITORS

4-1. Effect of Temperature:

Temperature (5-80) is a critical factor since the migration

rate of impunity molecules, from the tantalum dioxide to the

cathode, is directly affected (see fig.17):
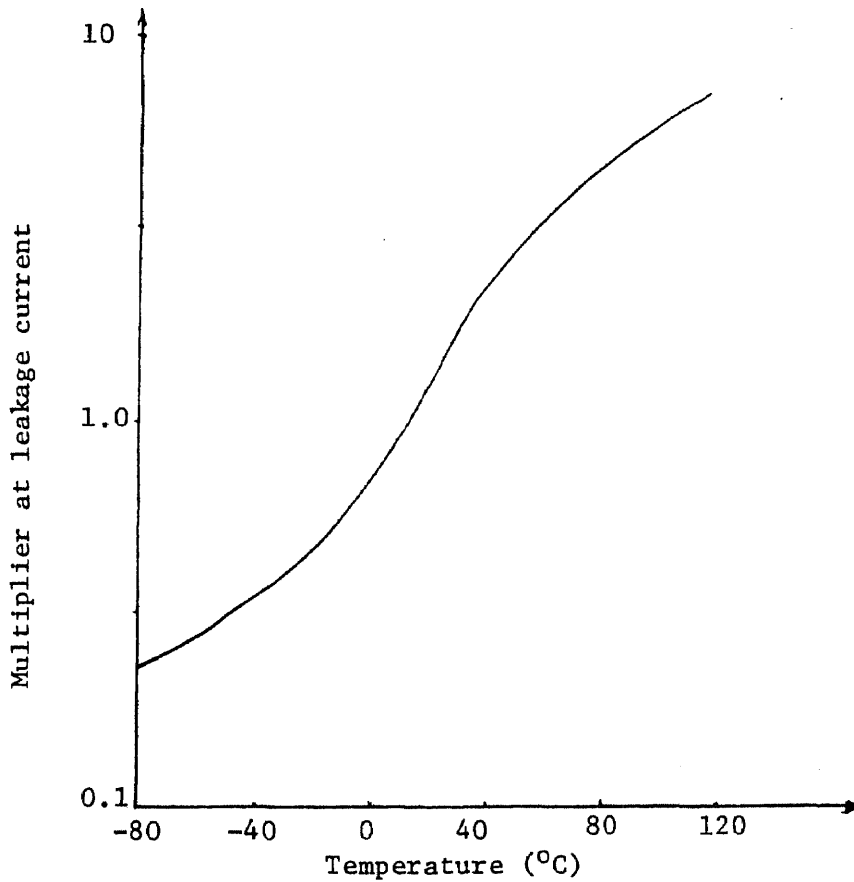
Fig. (17)   Typical effects of temperature upon leakage current

It is believed that a certain proportion of capacitors have
impurities that create defects which are too large to heal, but as
a rule these become obvious during manufacture and are screened out
at this point. In others they migrate to the surface some time later.

The oxides of managanese are semiconductors with a negative
temperature efficient of resistivity, therefore excessive tempera-
ture in the defect zone can cause loss of control of leakage
current. This leads to thermal runaway and catastrophic failure.

4-2. Effect of Humidity:

Infrequently (5-64) failures due to increases in capacitance
and/or dissipation factor are found. A defective hermetic seal
which allows moisture to enter the unit is the most common cause
for such failures. Since more of the available tantalum oxide
surface is contacted by the moisture than by the MnO2, the
capacitance shows an increase. The increase in dissipation
factor results from an increase in the resistivity of the MnO_2
due to the presence of moisture.

When enviromental factors were examined (1-77), only water
vapour was found to have any effect on the leakage current/time
plots of the capacitors on life test. The effect of water vapour
was examined more closely by life testing capacitors in capsules
attached to a vacuum line so that known pressures of water vapour
could be introduced to, or removed from, the capacitor at will
during the test. It appeared from the observations that two
independent processes were occuring. Firstly there was the basic

degradation mechanism which caused the leakage current to rise
steadily and irreversibly with time, and which was unaffected
by water vapour.

Secondly, superimposed on this steady increase in current
short term reversible decreases could be made to occur by intro-
ducing water vapour. This effect was in contrast to the effect
of liquid water where leakage current rises sharply because water
makes electrical contact with damaged areas of oxide previously
uncontacted by manganese dioxide. It appears that water vapour
at 125°C probably enters the manganese dioxide structure and
increases its resistivity, thus lowering leakage current.

In another study (4-73), solid tantalum capacitors were
measured for capacitance and dissipation factor under various
conditions of relative humidity. The capacitance increased
monotonically with relative humidity while the dissipation factor
had a maximum in mid relative humidity.

The cause of change of dissipation factor is the change of
dielectric properties of the interface between tantalum pentoxide
dielectric film and manganese dioxide counter electrode by the
effect of the amount of adsorbed water.

The forming voltage of a capacitor plays an important role
as to what extent the moisture affects that capacitor. In high
forming-voltage capacitors, the capacitance and the dissipation
factor changed mainly with the change of dielectric dispersion
frequency caused by the change of conductivity of dielectric
surface with water molecules absorbed. In the case of low

forming-voltage capacitors, the capacitance changed mainly with the change of series capacitance in the interface, while the dissipation factor scarcely changed. These changes were observed to be reversible, because they are apparently due to physical adsorbtion.

4-3. Effect of Circuit Impedence:

Commercial experience suggests that solid tantalum capacitors are more stable in service if they have an impedence in series with them than if they have voltages applied from a low voltage source. To check this and investigate the mechanism of circuit impedence effect, life tests were performed (1-77) with an added circuit impedence. The addition of a circuit impedence resulted in a much lower and more stable leakage current which increased very slowly over a long period of time. The morphology of the oxide surface before and after life test showed different characteristics. With a high circuit impedence, bumps in the film, although increasing in number during life test as in the low circuit impedence case, do not generally crack. A further important feature was the initial absence of large electrical discharge sites, only one of these being found. It appears that an added circuit impedence not only presents the development of large electrical discharge sites, but also the growth of un-cracked bumps into somewhat larger cracked bumps.

4-4. Effect of Impurities of Tantalum Anodes:

It is generally beleived that the dc leakage of a sintered-anode tantalum electrolytic capacitor is affected highly by the

chemical purity of the tantalum metal from which it is made. To
substantiate this belief it is necessary to correlate the dc
leakage of the capacitor with the impurity content of the sintered
anode rather than with that of the original tantalum powder since
impurity levels change during sintering to an extent dependent
on sintering conditions. The impurities found (2-60) in tantalum
anodes included O, C, N, Na, Al, Cr, Cu, Fe, Mo, Nb, Ni, Si, and Ti.
On the other hand, leakage current was found to be a direct
function of quantity and quality of contaminants. High leakage due
to copper contamination has occasionally been observed in other
powders. Field crystalization as discussed in chapter III stem
always from where these impurities are.

Sintering was found to change appreciably impurities such as
oxygen, carbon and sodium, while other contents change to a lesser
extent.

CHAPTER V: EXPERIMENTAL WORK

5-1. Procedure and Description:

Solid tantalum capacitors were randomly obtained from five different manufactures. The suppliers are called in this study, 1, 2, 3, 4, and 5 according to their standing after the life test, e.g. Supplier #1 is the company whose capacitors showed the least amount of failures, due to the test, and Supplier #5 is the company whose capacitors showed the highest amount of failures. Out of the samples gathered, which ranged between 150 - 250 units each, fifty units of each sample were introduced to the life test.

The life test was performed in a sealed humidity chamber and lasted for one thousand hours. Throughout the test, the relative humidity and temperature were kept at (96 $\pm$ 3) % and 95°C respectively. Three parameters were measured for each unit before applying the life test, capacitance, equivalent series resistance, and leakage current. The same parameters were measured again immediately after the 1000-hour life test was over. Then the units were kept in room temperature and humidity for 48 hours when the three parameters were measured for the third time. The values @ 0 hours and @ 1000 + 48 hours are the values on which the calculations in this study are based. The values @ 1000 hours are disregared to avoid any misleading transient or dynamic effects, influences. However, the values @ 1000 hours give some idea on the selfhealing behaviour of solid tantalum capacitor.

The leakage current measurements were done in a shielded room to avoid any stray currents which might have affected the tiny, actual values.

The simple circuit shown in Fig (18), was used to avoid waiting the charging time, after which the leakage current reaches a steady state, for every individual capacitor.
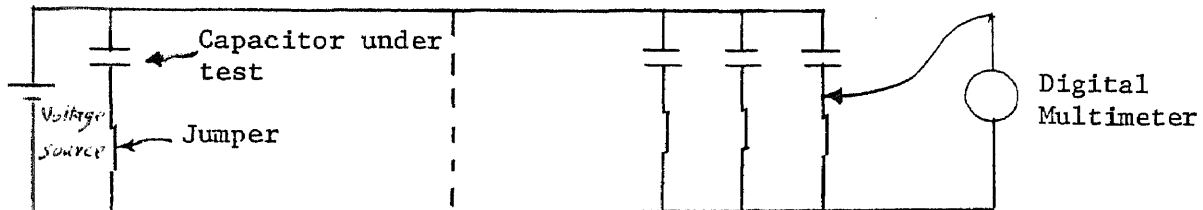
Fig. (18)   Circuit used for leakage current measurements.

The charging time ranged between five (supplier # 5) and twenty minutes (supplier #1). To avoid intruppting the current, the ammeter is connected first across a jumper in series with the capacitor, then the jumper is opened and the reading is recorded.

Capacitance and equivalent series resistance (ESR) were easier to measure. Digital meters were used in both cases and the values were taken instantaneously.

5.2 Experiment Results:

The following tables show the measurements for each capacitor supplied by the five Suppliers. The unit number is the actual number given to that particular unit before the test; it is not a serial number. At the bottom of each column, the mean and standard deviation for that column are given. As I mentioned in the previous sections, calculation for measurements @ 1000 hrs. are not given to avoid any misleading, transient effects.

To understand the tables, however, the following notations are interpreted as follows:

C1: Capacitance in μF measured @ 0 hours

C2: Capacitance in μF measured @ 1000 hours

C3: Capacitance in μF measured @ 1000 + 48 hours

ESR1: Equivalent series resistance in ohms measured @ 0 hours

ESR2: Equivalent series resistance in ohms measured @ 1000 hours

ESR3: Equivalent series resistance in ohms measured @ 1000 + 48 hours

I_L1: Leakage current in nA measured @ 0 hours

I_L2: Leakage current in nA measured @ 1000 hours

I_L3: Leakage current in nA measured @ 1000 + 48 hours

$\bar{x}$: Arithmatic mean

σ_n: Standard deviation of the entire population

σ_{n-1}: Standard deviation for a sample of the entire population (our case)

Table 1

SUPPLIER #1

22 µF: 16V

Failure Rate* = 10%

Unit No.	C1 (µF)	C2 (µF)	C3 (µF)	ESR1 (OHMS)	ESR2 (OHMS)	ESR3 (OHMS)	I_L1 (NA)	$I_L2/10^4$ (NA)	$I_L3/10^4$ (NA)
2	Fail								
3	22	22.6	22.6	.49	3.44	3.37	1.8	6.4	1.24
4	21.2	21.7	21.7	.54	4.72	4.99	0.36	6.10	.88
5	21.4	21.9	21.8	.55	3.39	3.49	6.40	2.7	1.37
6	21.7	22.4	22.3	.55	5.13	5.73	.27	2.3	.64
7	20.7	18.4	16.1	.64	3.42	3.77	15.	14.78	.43
8	21.9	22.4	22.5	.57	4.46	4.67	.65	3.2	1.
9	22.2	22.5	22.3	.54	4.38	4.87	.56	15.9	.3
10	20.9	12.9	13.2	.54	5.25	5.8	1.2	15.75	15.65
11	22.1	22.6	22.5	.51	2.37	2.46	2.	8.	1.7
13	21.4	22.0	21.9	.53	4.4	4.68	2.5	6.3	1.6
14	21.9	22.4	22.3	.57	6.11	6.33	.81	5.2	1.4
15	22.3	22.8	22.0	.59	4.54	4.79	1.2	9.5	4.38
17	21.8	22.4	22.2	.54	4.8	5.58	1.1	5.6	1.16
19	21.7	22.5	22.4	.54	5.32	5.61	.65	5.	1.18
20	22.2	22.7	22.7	.54	5.4	5.72	1.6	3.3	.69
21	21.7	22.4	22.3	.53	4.25	4.44	1.3	4.8	.71
22	21.7	21.8	22.5	.50	4.93	6.09	6.3	5.7	.5
23	21.8	22.4	22.4	.49	2.62	2.79	3.7	2.82	.63
24	21.2	21.6	21.6	.50	2.57	2.69	2.3	3.1	2.
25	21.1	22.6	21.7	.51	6.3	5.15	3.1	2.27	.9
26	22.3	22.8	22.7	.48	2.23	2.3	6.5	3.7	.77
27	21.7	21.8	22.3	.50	4.5	4.57	2.7	15.77	1.79
28	21.6	22.8	22.4	.5	4.35	4.53	1.8	8.	1.89
29	21.8	22.4	22.2	.51	4.52	5.04	1.40	0.94	.67
30	21.1	22.8	22.7	.51	7.78	7.99	2.9	5.6	.86
31	Fail								
32	21.5	22.2	22.2	.66	2.0	2.04	27.0	6.4	1.28
33	21.2	21.8	21.7	.61	3.28	3.69	25.3	8.4	1.13
34	Fail								
35	21.6	22.2	22.3	.63	3.36	4.04	36.	4.3	4.3
36	21.9	22.7	22.6	.51	2.22	2.32	3.4	7.5	1.72
37	21.7	22.3	22.2	.57	2.	2.19	9.19	6.8	1.42
39	21.8	22.5	22.4	.58	2.47	2.02	33.0	3.34	.195
40	21.9	22.5	22.4	.68	2.84	3.17	5.8	3.7	.34
41	Fail								

*It should be noted that Supplier #1 failures are all loss of lead(s).

Table 1 (cnt'd)

Unit No.	C1 (μF)	C2 (μF)	C3 (μF)	ESR1 (OHMS)	ESR2 (OHMS)	ESR3 (OHMS)	I_L1 (NA)	$I_L2/10^4$ (NA)	$I_L3/10^4$ (NA)
42	21.9	22.5	22.4	.53	1.49	1.55	7.0	1.9	.43
43	22.1	22.5	22.6	.54	2.31	2.33	100.0	8.9	3.6
45	21.0	22.4	21.6	.54	2.97	5.74	10.0	2.1	.195
46	21.7	21.6	21.0	.63	5.45	3.37	35.0	6.0	3.0
47	21.9	22.4	22.4	.53	1.8	1.82	2.6	6.6	.465
48	21.1	21.7	21.7	.5	1.67	1.72	2.7	6.0	1.85
49	20.8	21.4	21.4	.49	1.81	1.83	6.2	4.7	.72
50	22.0	22.5	22.9	.51	1.22	2.12	33.0	15.6	.86
52	22.4	22.9	22.6	.5	2.12	2.3	2.4	4.5	.29
56	21.0	21.6	21.5	.63	2.56	3.4	3.4	3.5	.70
57	21.6	22.3	22.2	.5	2.79	3.1	20.	6.2	1.2
58	21.3	20.2	21.6	.57	2.95	2.8	9.3	11.37	9.6
59	Fail								
60	22.	22.4	22.5	.52	3.91	1.27	.7	7.8	1.37
$\bar{x}$	21.64		21.85	.54		3.68	9.54		1.76
σ_{n-1}	.43		1.65	.05		1.6	16.97		2.64

Table 2

SUPPLIER #2

20 μF: 20V

Failure Rate = 18%

Unit No.	C1 (uF)	C2 (uF)	C3 (uF)	ESR1 (OHMS)	ESR2 (OHMS)	ESR3 (OHMS)	I_L1 (NA)	$I_L2/10^4$ (NA)	$I_L3/10^4$ (NA)
1	21.5	21.8	21.7	.39	.49	.49	60	.21	.04
2	23.	23.	23.1	0.42	.53	.53	20	.21	.20
3	21.9	22.2	22.1	.37	.40	.4	100	2.4	.8
4	21.9	22.3	22.3	.41	.824	.8	200	.4	.18
5	Fail								
6	22.8	23.	23.	.4	.44	.44	150	.95	.46
7	23.4	24.	24.	.43	.52	.53	130	.95	.99
8	22.3	22.6	22.5	.4	.49	.49	70	.68	.21
9	Fail								
10	22.7	22.9	22.8	.42	.45	.45	200	.38	.49
11	23.5	23.7	23.7	.43	.40	3.5	100	1.1	.17
12	22.4	22.8	22.8	.41	.45	.45	20	.229	.66
13*	22.4	22.7	22.7	.44	.66	.66	160	.04	.02
14	21.8	22.	22.	.39	.43	.43	30	.16	.06
15	21.5	21.8	21.8	.39	.4	.4	30	.71	.16
16	Fail								
17	22.3	22.6	22.6	.4	.50	.5	80	.073	.03
18	22.7	23.	23.0	.39	.43	.42	25	.68	1.4
19*	22.1	22.2	22.2	.38	.45	.45	250	.26	.03
20	22.2	22.4	22.4	.37	.37	.37	50	2.2	.95
21	22.8	23.1	23.	.4	.43	.43	60	.38	.2
22	21.7	22.	22	.39	.37	.36	50	2.5	1.27
23	Fail								
24	23.1	23.2	23.2	.62	.87	.88	45	1.5	1.42
25	22.	22.5	22.5	.4	.41	.41	10	.39	.14
26	22.7	23.2	23.2	.34	1.13	1.05	50	.98	.22
27	22.5	22.6	22.7	.38	.4	.41	35	.76	14.6
28	21.2	21.4	21.4	.45	.38	.38	40	.23	.08
29	23.2	23.5	23.5	.38	.39	.34	35	.53	.38
30	22.1	22.3	22.3	.39	.33	.34	55	.13	.04
31	Fail								
32	Fail								
33	21.7	21.7	21.7	.38	.41	.56	7	3.	.59
34	21.4	21.6	21.6	.38	.41	.41	10	1.14	.45
35	22.5	22.6	22.6	.4	.63	.62	80	1.2	.35
36	Fail								
37	21.8	22.2	22.2	.39	.4	.4	200	1.00	.57
38	22.	22.6	21.7	.48	.44	.44	40	.83	17.0

*Capacitor with no change in characteristics.

Table 2 (cnt'd)

Unit No.	C1 (uF)	C2 (uF)	C3 (uF)	ESR1 (OHMS)	ESR2 (OHMS)	ESR3 (OHMS)	I_L1 (NA)	$I_L2/10^4$ (NA)	$I_L3/10^4$ (NA)
39	22.3	22.6	22.7	.4	.41	.41	40	.63	.2
40	Fail								
41	22.6	23.2	23.1	.33	.64	.63	10	.4	.17
42	22.2	22.1	22.7	.36	.39	.39	30	.47	.22
43	21.9	22.1	22.1	.42	.68	.68	80	1.1	.20
44	23.1	23.2	23.2	.42	.50	1.25	100	.47	.05
45	22.2	22.7	22..8	.4	.46	.43	110	.50	.07
46	23.	22.2	23.3	.44	.49	.49	200	.16	.05
47	23.1	23.4	23.4	.42	.43	.52	40	.71	.27
48	Fail								
49	22.3	22.6	22.5	.43	.41	.42	25	.77	.4
50	21.5	21.7	21.7	.38	.37	.37	25	.57	.1
$\bar{x}$	22.23		22.55	.41		.58	74		.71
σ_{n-1}	.56		.62	.05		.51	63.4		2.26

Table 3

SUPPLIER #3

22 µF: 20V

Failure Rate = 50%

Unit No.	C1 (µF)	C2 (µF)	C3 (µF)	ESR1 (OHMS)	ESR2 (OHMS)	ESR3 (OHMS)	I_L1 (NA)	$I_L2/10^4$ (NA)	$I_L3/10^4$ (NA)
1	21.9	22.1	22	.52	2.14	2.72	.2	1.16	.83
2	22.5	22.7	22.6	.43	.98	1.0	71	.6	.212
3	22.7	23.	23	.45	2.04	2.02	12	2.52	1.86
4	22	24.8	22.3	.46	1.81	1.76	89	8.9	3.04
5	Fail								
6	Fail								
7	22.7	23	22.9	.4	.887	.9	20	1.04	11.01
8	Fail								
9	22.6	22.8	22.7	.5	1.6	1.64	.22	1.94	1.31
10	Fail								
11	22.1	22.2	22.2	.48	2.58	2.47	9.4	.314	.22
12	Fail								
13	22.3	22.5	22.5	.6	10.09	9.74	7.3	4.15	2.59
14	Fail								
15	Fail								
16	22.7	23	23	.5	2.26	2.11	40	4.6	3.45
17	Fail								
18	Fail								
19	Fail								
20	Fail								
21	Fail								
22	Fail								
23	22.6	22.8	22.7	.35	1.68	1.67	2.5	2.09	1.7
24	Fail								
25	22.6	23	22.9	.52	2.09	2.14	13	3	1.8
26	22	22.1	22.1	.48	1.9	1.72	70.	.13	.046
27	22.8	23	23	.42	.66	.67	6	3	1.34
28	21.8	21.9	21.9	.53	3.68	3.53	53	3.3	3.01
29	22.6	22.7	22.7	.61	6.41	6.23	9.8	1.77	1.2
30	22.8	23	23.1	.48	1.65	1.61	26	1.28	.62
31	Fail								
32	Fail								
33	21.9	22.	22.	.41	.94	.98	10	.09	.033
34	22.4	22.7	22.7	.5	2.46	2.4	3.2	6.16	2.18
35	Fail								
36	Fail								
37	22.5	23	22.5	.47	.67	4.51	1.3	1.68	2.02
38	Fail								
39	Fail								
40	Fail								

Table 3 (cnt'd)

Unit No.	C1 (μF)	C2 (μF)	C3 (μF)	ESR1 (OHMS)	ESR2 (OHMS)	ESR3 (OHMS)	I_L1 (NA)	$I_L2/10^4$ (NA)	$I_L3/10^4$ (NA)
41	22	22.3	22.3	.49	1.6	1.49	2.6	.36	.24
42	22.4	22.5	22.6	.43	1.095	1.1	280	.091	.017
43	22.8	23.2	23.2	.65	6	5.92	1790	3	1.77
44	Fail								
45	22.4	22.6	22.6	.42	.89	.9	.06	.18	.056
46	Fail								
47	Fail								
48	22.7	22.9	22.9	.48	2.1	2.01	9.7	.08	.04
49	Fail								
50	22.4	22.8	22.8	.52	1.88	1.87	79	2.17	1.36
$\bar{x}$	22.4		22.6	.48		2.5	104		1.68
σ_{n-1}	.32		.37	.068		2.1	356		2.2

Table 4

SUPPLIER #4

100 μF: 20V

Failure Rate = 68%

Unit No.	C1 (μF)	C2 (μF)	C3 (μF)	ESR1 (OHMS)	ESR2 (OHMS)	ESR3 (OHMS)	I_L1 (NA)	$I_L2/10^4$ (NA)	$I_L3/10^4$ (NA)
1	105	109.4	109.3	.16	2.79	1.77	33	1.44	.68
2	Fail								
4	Fail								
5	Fail								
6	105.7	110.2	110	.16	.747	.542	11	1.5	.73
7	Fail								
8	Fail								
9	Fail								
10	Fail								
11	104.8	108.7	108.6	.16	1.84	1.634	9.4	1.4	.54
12	Fail								
13	Fail								
14	Fail								
15	Fail								
16	Fail								
17	Fail								
18	Fail								
19	Fail								
20	104.6	109.1	109.1	.16	.84	.668	26	.27	.15
21	106	110.3	110.2	.16	1.37	1.04	8	2.2	.88
22	Fail								
23	Fail								
24	104.8	108.6	108.6	.3	.596	.448	9	5.8	.37
25	105	109.4	109.8	.17	1.274	.923	7	.1	.11
26	Fail								
27	Fail								
28	105.5	109.4	109.3	.16	2.09	1.719	6	.86	.44
29	Fail								
30	Fail								
31	104.7	109.3	109.3	.16	1.7	1.26	15	.72	.3
32	Fail								
33	Fail								
34	Fail								
35	106.1	111.2	111.1	.16	,387	.308	2	1.2	.52
36	Fail								
37	Fail								
38	Fail								
39	106.5	111	111	.17	.186	.129	47	.46	.18
40	105.5	110.9	110.8	.16	.266	.16	5.3	2.54	1.48

Table 4 (cnt'd)

Unit No.	C1 (μF)	C2 (μF)	C3 (μF)	ESR1 (OHMS)	ESR2 (OHMS)	ESR3 (OHMS)	I_L1 (NA)	$I_L2/10^4$ (NA)	$I_L3/10^4$ (NA)
41	Fail								
42	Fail								
43	Fail								
44	105.1	110.	109.9	.15	.84	.676	3.2	2.4	.75
45	Fail								
46	104.7	109.8	109.7	.20	.757	.568	3.8	.64	.17
47	Fail								
48	Fail								
49	105.1	109.2	109.1	.15	1.32	1.17	5.6	1.85	.9
50	Fail								
51	106.6	110.9	110.9	.15	.67	.55	3.2	.85	.78
$\bar{x}$	105.4	109.8	109.8	.17		.81	12		.5
σ_{n-1}	.65		.82	.036		.5	12.6		.27

Table 5

SUPPLIER #5

40 µF: 20V

Failure Rate

Unit No.	C1 (μF)	C2 (μF)	C3 (μF)	ESR1 (OHMS)	ESR2 (OHMS)	ESR3 (OHMS)	$I_L 1$ (NA)	$I_L 2/10^4$ (NA)	$I_L 3/10^4$ (NA)
1	40.7	41.4	41.2	.29	.49	.51	53	.45	.28
2	Fail								
3	42.2	43.1	42.9	.31	.59	.59	26	.12	.44
4	Fail								
5	37	37.9	37.8	.28	.55	.57	23	2.7	3.4
6	Fail								
7	Fail								
8	36.1	36.9	38.7	.38	.63	.65	5	1.3	.88
9	Fail								
10	Fail								
11	Fail								
12	Fail								
13	Fail								
14	Fail								
15	Fail								
16	Fail								
17	34.6	36.6	35.4	.43	35.6	.65	20	3.7	3.9
18	Fail								
19	Fail								
20	Fail								
21	Fail								
22	Fail								
23	Fail								
24	Fail								
25	Fail								
27	Fail								
28	Fail								
29	Fail								
30	Fail								
31	Fail								
32	Fail								
33	Fail								
34	Fail								
36	Fail								
37	39	27.6	28	.26	.46	.46	30	.67	6.8
38	Fail								
39	38.2	38.9	36.7	.45	.66	.71	5	.41	.17
40	Fail								

Table 5 (cnt'd)

Unit No.	C1 (μF)	C2 (μF)	C3 (μF)	ESR1 (OHMS)	ESR2 (OHMS)	ESR3 (OHMS)	I_L1 (NA)	$I_L2/10^4$ (NA)	$I_L3/10^4$ (NA)
41	39.3	39.5	39.3	.43	.58	.59	10	.27	.07
42	Fail								
43	Fail								
44	Fail								
45	Fail								
46	Fail								
47	Fail								
48	Fail								
49	Fail								
50	Fail								
51	38.2	38.9	38.7	.3	.6	.61	21	1.1	.94
52	27.4	38	37.9	.32	.45	.46	2	2.2	.94
$\bar{x}$	38.26		37.66	.345		.58	19.5		1.8
σ_{n-1}	2.1		3.95	.069		.09	14.8		2.3

5-3. Capacitance Analysis:

Capacitance change before and after the test for the same

supplier, along with a comparison of the same parameter among the

different suppliers are given in Table 6.

Supplier #	Before			After			
	$\bar{c}$	σ	$\sigma/\bar{c}$	$\bar{c}$	σ	$\sigma/\bar{c}$	c_a/c_b
1	21.64	.43	.02	21.85	1.65	.075	1.01
2	22.23	.56	.025	22.55	.62	.027	1.01
3	22.4	.32	.014	22.6	.37	.016	1.01
4	105.4	.65	.006	109.8	.82	.007	1.04
5	38.25	2.1	.055	37.66	3.95	.010	0.98

Table 6
Capacitance mean and standard deviation
before and after the test.

A look at ca/cb gives an idea on the change in capacitance for

the same supplier. Theoretically, as mentioned in Chapter IV,

capacitance is supposed to increase with humidity and temperature.

Humidity infiltrates and eliminate series capacitances in the in-

terfaces inside the capacitor, giving rise to increasing the overall

capacitance. Temperature effect in this study is not really profound

since most capacitors and designed to work without change in the

range $30^{\circ}C$ - $150^{\circ}C$. Therefore, Ca/Cb reflects mainly the effect of

humidity which coincides with the previous work on tantalum capacitors.

From a commercial point of view, it reflects in this study the sealing

effectiveness of different companies. From Table 6, if we want

to rank capacitor sealing of different suppliers, it would be:

First	Second	Third	Fourth	Fifth
#5	#1	#2	#3	#4

5-4. ESR Analysis:

ESR has usually been overlooked by different researchers, even though it gives good understanding on capacitor design and future performance. The figures given in Table 7 are the ESR values for the five suppliers included in this study.

Supplier #	Before			After			ESRA/ESRB
	$\overline{ESR}$	σ	σ/ESR	$\overline{ESR}$	σ	σ/ESR	
1	.54	.05	.092	3.68	1.6	.434	6.81
2	.41	.05	.12	.58	.51	.88	1.41
3	.48	.07	.145	2.5	2.1	.84	5.2
4	.17	.04	.23	.81	.5	.61	4.76
5	.35	.07	.2	.58	.09	.155	1.66

Table 7

ESR mean and standard deviation
before and after the test.

The effect of putting capacitor in high temperature for a long time (1000 hrs). The effect of temperature on real resistors is known to be reversable, that is it goes when the temperature goes. That means there is no difference between the real resistance contribution to ESR before and after the test because the value, after the test, was taken after allowing the unit to cool down for 48 hours. What might be there is a permanent effect on the dielectric loss produced through letting the capacitor in a high temperature for one thousand hours. Also humidity effect theories stated by other researchers may not be taken as final. The results obtained for ESR in this study contradict with the work done by previous researchers, as given in Chapter IV. While those researchers said that humidity effect is to decrease ESR beyond mid freq., the units of the five different suppliers

showed all obvious increase in ESR. Therefore there are two possibilities: either the previous work was not accurate enough, or the factor of temperature is very influential on ESR. Considering that ESR represents two different resistances: hypothetical one representing the dielectric loss and a real one representing the resistance of M_nO_2 and leads, we should find the increase in ESR can be interpreted as that humidity has radical effect on the polarizability of Ta_2O_5 which governs the dielectric loss, the main contribution to ESR at low frequencies (the ESR meter used had 1kHz internal frequency).

5-5. Leakage Current Analysis:

Leakage current is the most crucial factor when capacitors are to be evaluated. A direct look at Table #8 shows the differences in leakage current among the different companies before the test. However, this look is misleading and such a simple judgement would be totally erroneous.

Supplier #	Before			After			
	$\overline{IL}$	σ	$\sigma/\overline{IL}$	$\overline{IL}/10^4$	$\sigma/10^4$	$\sigma/\overline{IL}$	ILA/ILB
1	9.54	16.97	1.78	1.76	2.64	1.5	1845
2	74	63.4	.86	.71	2.26	3.18	96
3	104	356	3.42	1.68	2.2	1.30	162
4	12	12.6	1.05	.5	.27	.54	416
5	19.5	14.8	.76	1.8	2.3	1.28	923

Table 8
Leakage current mean and standard
deviation before and after test

Leakage current is actually a function of both rated voltage and capacitance of a certain capacitor.

The proof for that is as follows:

$$I_L = \frac{V_{rated}}{R}$$

$$R \propto \frac{d}{A} \;,\; C \propto \frac{A}{d}$$

$$\text{i.e.} \; R \propto \frac{1}{c}$$

$$I_L \propto V_{rated} \cdot C$$

where R, d, and A are resistance, thickness and area of dielectric
respectivelly. Therefore, a normalization of the current values
we got should be done before any comparison between the different
suppliers. The leakage current for each supplier will be divided
by the multiplication of $\bar{c}$ V rated, and the result will reflect how
good the manufacturing is. Table 9 shows the leakage ratio for
the five suppliers. The smaller the ratio the better the design
and manufacturing processes.

Supplier	$\bar{C}$ V rated nA	$\bar{I_L}$ nA	Leakage Ratio $= \dfrac{IL \times 100}{\bar{C} \text{ v rated}}$
1	22 X 16 = 352	9.54	2.71
2	20 X 20 = 400	74	18.5
3	22 X 20 = 440	104	23.64
4	100 X 20 = 2000	12	.6
5	40 X 20 = 800	19.5	2.44

Table 9
Leakage Ratio

From Table 9 we find that supplier #4 is the best (before applying
the life test) as far as leakage current is concerned followed by #5,
#1, #2, then #3.

To summrize the experimental work, Table 10 shows an overall view of all units. The rank of each supplier is shown as a digit from 1 to 5 which can be interpreted as follows:

I_L: 1 means the least leakage current

P: 1 means the least failure rate

Δ c: 1 means the least change in capacitance

Δ ESR: 1 means the least change in ESR due to test

Δ I_L: 1 means the least change in I_L due to test

$\dfrac{\sigma}{\bar{c}}$:   1 means sample values are closest to the mean

$\dfrac{\sigma}{ESR}$:   1 means sample values are closest to the mean

$\dfrac{\sigma}{I_L}$:   1 means sample values are closest to the mean

Supplier #	P	I_L	C	ESR	I_L	$\dfrac{\sigma}{\bar{c}}$	$\dfrac{\sigma}{ESR}$	$\dfrac{\sigma}{\bar{I_L}}$
1	1	3	1	5	5	3	1	4
2	2	4	1	1	1	4	2	2
3	3	5	1	4	2	2	3	5
4	4	1	2	3	3	1	5	3
5	5	2	3	2	4	5	4	1

Table 10
Overall evaluation of study units

It should be noted that I_L, $\dfrac{\sigma}{\bar{c}}$, $\dfrac{\sigma}{ESR}$, and $\dfrac{\sigma}{\bar{I_L}}$ refer to the values before the test. An average for each supplier should have been calculated in Table 9 except for the importance of different factors are not equal. For instance, leakage current and failure rate

are always of primary concern when capacitors are to be evaluated, whereas change in ESR is not as important.

Therefore, the order of suppliers used in this study reflects to a great extent their superiority among each others.

As to failure, humidity is not a primary cause as long as good sealing is provided. That was quite obvious because of the fact that Supplier #1 did not show any failures if we exclude the loss of lead cases.

On the other hand, since temperature is not prevented by good sealing, it seems that up to $100^{\circ}C$ does not have any effect on units failure.

CHAPTER VI: CONCLUSIONS

As the name of this study indicates, the ultimate goal is to obtain a reliable solid tantalum capacitor. In order to do that, common failure modes have to be analyzed so that the reason of failure can be pinpointed and the precautionary measures can be suggested. Some of the reasons of failure are pertaining to the manufacturer, while others are pertaining to the designer or the operator. Thorough investigation of the previous work, besides experimental work covered by this thesis have come out with the following summary.

Failure mode 1: Short circuit or high leakage current.

Possible reason(s):

1) Field crystalization of the originally amorphous dielectric. This is a manufacturing defect and can be avoided by using highly-purified tantalum anodes.

2) Bulging or bursting due to an internal evolution of gas. This is a manufacturing defect and can be eliminated by improving anodization and impregnation processes.

3) Thermal runaway, due to the negative coefficient of resistivity of MnO_2. This is an operational defect can be eliminated by not operating the capacitor in high temperature condition and also by avoiding over voltages.

4) Air gaps created in the interface between Ta and Ta_2O_5 due to the difference in their coefficients of expansion. This is a manufacturing defect and can be avoided by improving the anodization process so that a greater adhesion between Ta and Ta_2O_5 can be obtained.

Failure mode 2:   Open circuit.

Possible reason(s):

Mechanical failure in contacts or welds. This is a
manufacturing defect and can be eliminated by adopting
better packaging techniques.

Failure mode 3: Change in capacitance

Possible reason(s):

1) Seal failure leading to moisture infiltration which in-
creases capacitance. This is a manufacturing defect and
the solution is improving sealing techniques.

2) Gradual growth in thickness of the oxide film leading to
a reduction in capacitance. This is a manufacturing defect
and can be avoided by improving anodization process.

Failure mode 4: Change in ESR

Possible reason(s):

1) Seal failure and moisture infiltration (as in mode 3) the
effect here as shown in the experimental part of this study
is a drastic increase (300%) in ESR. A better sealing
process is recommended.

2) Formation of oxide film at one of the metal-to-metal
joints leading to a rising ESR. This is an operational
defect and can be avoided if the capacitance is kept
away from moisture.

BIBLIOGRAPHY

<u>1983</u>

1-83:   "Tantalum Chip Capacitors Become More Popular"
        S. Onoda, T. Vemura
        JEE (Japan), Vol. 20 #193, pp. 42-4
        Jan. 1983

2-83:   "Selecting Electrolytic Capacitors for Longer System Life"
        C. Forge (Boschert, Inc., Sunnyvale, CA, USA)
        Electron Devices, Vol. 31 #4, pp. 145-8
        Feb. 1983

3-83:   "Small Electrolytic Capacitors: A Suitable Case for
        Treatment"
        R. Dettmer
        Electron & Power (GB), Vol. 29 #3, pp. 241-3
        March 1983

4-83:   "Survey of the Problems Concerning the Thin Layer Capacitors
        with Ta_2O_5 Dielectrics"
        D. Ruzinska
        Elektrotech. Obz. (Czechoslovakia), Vol. 72 #4, pp. 205-11
        April 1983

<u>1982</u>

1-82:   "Electrolytic capacitors - Comparisons. I."
        P. Petrick
        Mess. & Pruef. (Germany), No. 10, pp. 669-73
        Oct. 1982

2-82:   "Challenges Face Smaller Tantalum Capacitors"
        Y. Shibata
        JEE (Japan), Vol. 19 #191, pp. 44-6
        Nov. 1982

3-82:   "Handbook of Chemistry and Physics"
        CRC Puplish. Co., 63rd edition 1982-1983
        March 1982

<u>1981</u>

1-81:   "Accelerated Life Test and Analysis of Characteristic and
        Degradation of Tantalum Solid Electrolytic Capacitors"
        T. Harda, H. Shiomi
        Bulletin of Electrotech, Lab. (Japan), Vol. 45 #5-6, pp. 275-310
        1981

1981

2-81:   "Process to Improve Electrical Properties of Metaloxide
        Capacitor Materials"
        J.K. Howard (IBM Corp., USA)
        IBM Tech. Disclosure Bulletin, Vol. 23 #9, pp. 4103-5
        Feb. 1981

3-81:   "Sal Contra Tantalum"
        J. Both (Philips Gmbh, Hamburg, Germany
        Nachr. Elektron. (Germany), Vol. 35 #4, pp. 153-6
        April 1981

4-81:   "Tantalum Bead-type Capacitors"
        P. Petrick
        Electron, Entwick (Germany), Vol. 16 #5, pp. 12-15
        May 1981

5-81:   "Tantalum Dry and Aluminum Wet Electrolytic Capacitors
        Compared"
        P. Hille
        Elektronik (Germany), Vol. 30 #13, pp. 55-9
        July 1981

6-81:   "Miniature Decoupling Capacitors for h.f. Applications"
        J.A. Sunda
        Elektron Applications (Germany), Vol. 13 #8, pp. 54-5
        Aug. 1981

1980

1-80:   "New Devekopment in Tantalum Capacitor Welding"
        Electron Packaging & Production (USA)
        Vol. 20 #5, pp. 227-29
        May 1980

2-80:   "Price Reductions Accompany Miniaturization of Dip
        Tantalum Capacitors"
        T. Ollara (Elna Co. Ltd., Janpan)
        JEE (Japan), Vol. 17 #163, pp. 49-50
        July 1980

3-80:   Tantalum Capacitors Behaviour Under Load"
        P. Petrick
        Electro-Anz (Germany), Vol. 33 #15-16, pp. 23-6
        Aug. 1980

1980

4-80:   "New Resin Molded Tantalum Capacitors Designed for Severe
        Environment"
        K. Shirai, et al (Nippon Electric Co. Ltd., Tokyo, Japan)
        Oct. 1980

5-80:   "Failure Mechanisms in Tantalum Capcitors"
        A. Cooke-Sanderson
        Electron. Ind. (GB), Vol. 6 #11, pp. 57-9
        Nov. 1980

1979

1-79:   "Tantalum Cpacitors"
        A.P. Carpenter
        New Electron (GB), Vol. 12 #6, pp. 126-7
        March 1979

2-79:   "Dielectric Studies on Sintered Tantalum Electrolytic
        Cap."
        F. Meca, A.K. Jonsher
        Thin Solid Films (Switzerland), Vol. 59 #2, pp. 201-19
        May 1979

3-79:   "Ramshackle the Solid Tantalum Capacitors"
        J.D. Moyniham
        Proceedings of the 29th Electronic Component Conference
        Cherry Hill, NJ, IEEE, pp.295-302
        1979

1978

1-78:   "Component Reliability Assessment - Capacitor New Tendency"
        J. Guyonnet
        Technoinform pp. 355-65 OMKDK
        1978

2-78:   "Failure Intensity of Components Under Normal Operating
        Conditions"
        M. Prazewska
        Elektronika (Poland), Vol. 19 #10, pp. 429-30
        Feb. 1978

1978

3-78:   "All-Tanlalum Wet Slug Capacitor Overcomes Catastrophic
        Failure"
        A.M. Holladay
        Electronics (USA), Vol. 51 #4, pp. 105-18
        Feb. 1978

4-78:   "High Reliability Resin Molded and Tantalum Electrolytic
        Capacitors"
        ·Tilribura (Massachusita, Japan)
        Nat. Tech. Rep. (Japan), Vol. 24 #1, pp. 77-84
        Feb. 1978

5-78:   "All Tantalum Capcitors, Slugged, Reliable & Simple to Use"
        J.O. Aberlund
        Elter, Artuell Elektron (Sweden), Vol. 21 #11, pp. 18-20
        June 1978

6-78:   "Characteristics & Failure Analysis of Solid Tanlalum Cap."
        Y. Hasegroq and K. Morimoto
        Nec. Res. & Dev. (Japan), #50, pp. 79-94
        July 1978

7-78:   "Capacitors Packaging Technique"
        M.D. Loesch
        IBM Tech. Disclosure (USA), Vol. 21 #3, pp. 967-9
        August 1978

1977

1-77:   "Failure Mechanism in Solid Electrolytic Capacitors"
        J. Brettle, N.I. Jackson
        Electro. Compo. Sci. & Tech. (GB), Vol. 3 #4, pp. 233-46
        March 1977

2-77:   Tantalum Cased Wet-Slug Tantalum Capacitors"
        W.F. England
        27th Electronic Compo, Conf. Arlington, VA, USA
        IEEE - NY, USA, pp. 379-86

3-77:   "The Recent Capacitor Techniques"
        K. Kinugawa
        JEE (Japan) #125, pp. 56-9
        May 1977

1977

4-77: "The Tantalum Electrolytic Capacitors"
       Funkschau (Germany), Vol. 49 #18, pp. 814-2
       Aug. 26, 1977

5-77: "The Influence of the Oxidation Voltage on the Electrical
       Characteristics of the Tantalum Dielectric from the Tantalum
       Electrolytic Capacitors with Synthesized Anode"
       S. Rau, M. Manfu. E. Auram
       Autom. & Electron (Rumania), Vol. 21 #3, pp. 107-11

1976

1-76: "Tantalum Capacitors, What are They Really Capable Of?"
       Radio Elektron Schau (Austria), Vol. 52 #3, pp. 36-8
       1976

2-76: "Tantalum Solid Electrolytic Capacitors II, Properties of
       Dielectric (Tantalum)"

3-76: "Tantalums Increase Capacity for Miniaturization"
       D.G. Wilson
       Electron (GB), Vol. 19 #3, 00. 134-42
       Jan. 1976

4-76: "Electrolytic Condensers"
       B. Waterman
       Elektron & Elektrotek (Netherlands), Vol. 31 #770, pp. 34-6, 45
       Feb. 1976

5-76: "Failure Mechanisms in Wet Tantalum Capacitors"
       D. Haywoard
       Electrocompo. Sci. & Tech. (GB), Vol. 2 #4, pp. 249-51
       March 1976

6-76: "Effects of High Current Transients on Solid Tantalum Cap."
       H.W. Holland
       Electron Equip. News (GB), pp. 20-1
       March 1976

7-76: "Solid Tantalum Capcitors Small in Size, but Capable of
       High Power"
       T. Uemura, S. Onaoda
       JEE (Japan) #119, pp. 49-51
       Nov. 1976

8-76: "Choosing a Tantalum Capacitors"
       D.G. Wilson
       Tonte Electron (France) #405, pp. 44-7
       Dec. 1976

1975

1-75: Tantalum Solid Electrolytic Capacitors I. Anode Characteristics"
J.M. Albella, J.M. Martinez
Electron & Fis. Apl. (Spain), Vol. 19 #2, pp. 83-90
1975

2-75: "Developments in Electrolytic Capacitor Design"
P.J. Harrop
Electron Engg. (GB), Vol. 47 #567, pp. 47-51
May 1975

3-75: Tantalum Capacitors"
M.J. Wilks
New Electron (GB), Vol. 8 #9, pp. 83-4
April 1975

4-75: "New Capacitor Construction"
J.J. Coniglio
Inc. Patent USA 3863116
Jan. 1975

5-75: "On the Absorption Current in Tantalum Capacitors"
K. Hirata et al
Fijitsu Sci. Tech. J. (Japan), Vol. 11 #4, pp. 43-56
Dec. 1975

6-75: "Component Reliability I. Failure Data Bears Watching"
L. Mattera
Electronics (USA), Vol. 48 #20, pp. 91-8
Oct. 1975

1974

1-74: "Effects of Ag-electrolyte Interface Phenomena on
Properties of Wet Tantalum Capacitors"
B. Rehak
TESLA Electron (Czechoslovakia), Vol. 7 #3, pp. 85-90
Sept. 1974

2-74: "Trends in Design and Performance of Tantalum Capacitors"
L.F. Harris (Plessey Col. Ltd., GB)
Vol. 1 #1, pp. 11-16
Sept. 1974

1974

3-74: "Technical and Economical Evolution of Solid Electrolytic
Tantalum Capacitors"
A.J. Piolok, D. Prince
Onde Elect. (France), Vol. 54 #8, pp. 385-92
Oct. 1974

4-74: "Wet Tantalum Capcitors Rediscovered"
M.M. Bruce
Electron. Compo. (GB), Vol. 16 #21, pp. 13-16
Dec. 1974

5-74: "Capacitance Tolerances for Solid Tantalum Capacitors"
R.W. Franklin
Electron. Compo. (GB), Vol. 16 #21, pp. 23, 26
Dec. 1974

6-74: "The Significance of Long Term Tests for Reliability
Assertions for Capacitors"
W. Ackmann
Electrotech. Z (ETZ) B. (Germany), Vol. 26 #26, pp. 690-2
Dec. 1974

7-74: "Current Voltage Characteristics of Tantalum Solid Electro-
lytic Capacitors"
N. Koda, K. Hirata, Y. Nishimura
Fujitsu Sci. P. Tech. J. (Japan), Vol. 10 #4, pp. 139-55
Dec. 1974

8-74: "Stored Charges in Tantalum Capacitors Latend and Manifest
Mavericks"
T.M. Flanagan
IEEE Transaction on Neuclear Science, Vol. NS-21
Dec. 1974

1973

1-73: Powder Geometry and Structural Design of the High Volumetric
Efficiency Tantalum Electrolytic Capacitors"
S.E. Hluchan
IEEE - N.Y., USA, pp. 283-91
1973

1973

2-73: "Solid Electrolyte Tantalum Capacitors - Index of Quality"
R.K. Ho
Insulation (USA), Vol. 13 #3, pp. 69-73
March 1973

3-73: "Photovoltaic Effect in Ionization Response of Tantalum Capacitors"
P.T. Baker
J. Appl. Phys. (USA), Vol. 44 #3, pp. 995-1002
March 1973

4-73: "The Effect of Moisture on Solid Tantalum Capacitors"
K. Morimoto (Nippon Ltd., Japan)
23rd Electronic Comp. Conf., W.D.C., USA
IEEE - N.Y., USA, pp. 292-301
May 1973

5-73: "Epoxy Molded Rectangular Solid Tantalum Electrolytic Capacitors"
K. Klopping
Seimens Electron Components Bull. (Germany) Vol. 8 #2, pp. 41
May 1973

6-73: "Porous Ancdes for Tartalum Capacitcrs"
J.N. Allen
Jew Electron (GB), Vol. 6 #14, p. 84
July 1973

7-73 Wet Tantalum Electrolytic Capacitors"
G.P. Klein
IEEE - N.Y., USA, pp. 111-24
May 1973

1971

1-71: "Electrolytic Capaci^or "
D.C. Capmpell
Radio and Electronic Eng. (GB), Vol. 41 #1, pp. 5-16
Jan. 1971

2-71: "Tantalum Capacitors for Space Flight Electronics"
R. Koppe (Ero-Tantal GmbH, Germany
Radio Mentor (Germany), Vol. 37 #2, pp. 84
Feb. 1971

1971

3-71:   "DC Capacity of Tantalum Capacitors"
B. Petrick
Radio Mentor (Germany), Vol. 37 #2, pp. 80-3
Feb. 1971

4-71:   "Failure Distribution of Mechanical vs. Electrical
Components"
W.J. Quinn
American Society of Mech. Eng., p. 8
1971

5-71:   Tantalum Sintered Capacitors"
J. Haselmann
Electrotechnic (Germany), Vol. 53 #8, pp. 30-3
April 1971

6-71:   "Electrical Breakdown and Selfhealing in Solid Tantalum
Capacitors"
J. Burham
IEEE - N.Y., USA, pp. 314-23
May 1971

7-71:   "Solid Type Capacitors"
B.A. Shenoi
Electrotechnology (India), Vol. 15 #3, pp. 79-85
May - June 1971

1970

1-70:   "Solid Tantalum Capacitor Failure Modes & Analysis"
D.A. Tabor (Honeywell, Inc.)
Annual Rel Phy. Symp., Las Vegas, USA, April 7-9, pp. 64-5
N.Y., USA, IEEE
April 7-9, 1970

2-70:   "Effects of Water & Other Polar Liquids on Solid Tantalum
Capacitors"
J. Burham
IEEE- N.Y., pp. 348-65
May 1970

3-70:   "Tantalum Capacitors"
R. Ranien
Industrial Itallian Electrotech. Electronic, Vol. 23, #6,
pp. 452-3
June 1970

1970

4-70:   "Humidity Influence of Reliability of Capacitors"
        J. Tuszynska
        Prace Insti. Tel. Radiotech. (Poland), Vol. 14 #2, pp. 61-76
        1970 (In Polish)

1969

1-69:   "Sulfuric Acid Electrolyte Tantalum Capacitors with
        Platinized Gold Cathodoes"
        P.L. Bourgault, J.M. Booe, G.H. Frazer
        Proceedings 1969, Electronic Compo. Conf. Washington D.C.
        (USA), IEEE, pp. 218-22
        April 1969

2-69:   "Electrolytic Capacitors"
        Mallory & Co., Inc.
        Patent U.K. 1174492, USA 546817,
        May 1967

3-69:   "Method for the Manufacture of Tantalum Powder for Condener
        Purposes"
        G. Dandliker, H. Fuerer, Ciba Ltd.
        Patent USA 3430108
        March 1966

4-69:   "Physics of Failure of Thin Film Passive Components"
        G.U. Mattana, G.F. Piacentini
        Atta Frequenza (Itali), Vol. 38 #7, pp. 536-42
        July 1969

5-69:   "Statistical Evaluation of Influence of Technological
        Process Conceptions of Thin Film Capacitors Properties With
        Si Oxide Isolation"
        A. Baranska, B. Liznerski
        Perzgland Electron, Vol. 10 #4, 0. 166 (Polish)
        1969

6-69:   "Accelerated Reliability Tests of Capacitors of Receivers"
        E. Przybyl
        Perzgland Electron (Poland), Vol. 10 #1, pp. 30-42
        1969

1968

1-68:   "Dielectric NB and Ta Electrolytic Capacitors & Method
        of Producing Same"
        G. Berhard (Seimens AG)
        Patent USA 3496424, (Germany)
        Feb. 1968

2-68:   "The Activities, Energies of Production in Tantalum
        Anoidic Films"
        G.J. Kornek
        Electrochem. Tech. (USA), Vol. 6, #3-4, pp. 108-9
        March-April, 1968

3-68:   "The ESR of Tantalum Solid Electrolytic Capacitors"
        B. Goudsward
        Electrochem. Tech. (USA), Vol. 6, #5, pp. 178-82
        May-June, 1968

4-68:   "A Report on the Development of Solid Electrolytic
        Tantalum Capacitors"
        J. Vardhan, R. Kumar
        J. Insti. Telecom. Eng., Vol. 14, #7, pp. 296-300
        July 1968

5-68:   "Mass Spectrographic Technique for the Molybednum
        Additive in Tantalum Oxide Capacitor Films"
        D.L. Malm (Bell Tel., NJ)
        Appl. Sspectoros. (USA), Vol. 22, #4, pp. 318-20
        July 1968

6-68:   "Low ESR Solid Tantalum Capacitors"
        P.L. Bourgadt
        Electronics Comp. Conf. W.D.C. 1968, NY-IEEE, pp. 38-43
        1968

7-68:   "Factors Affecting the Reliability of Wet Tantalum
        Capacitor"
        W.M. Rowe
        6th Annual Rel. Ph6. Sym. Proc., Los Angeles, 67
        (NY, USA, IEEE), pp. 243-55
        1968

1967

1-67:   "Capacitors Reliability Life and the Relevance on
        Corcuit Design"
        D.S. Girling
        Micro-Electronics & Reliability (GB), Vol 6 #1, pp. 33-51
        Feb. 1967

1967

2-67:   "Anisotropy in Layers of Anodic Oxides of Tantalum and
        Titanium"
        P. Jourdain & J. Pompei
        One Elect. (France), Vol. 47, pp. 382-91
        March April 1967

3-67:   "Influence of Anode Design on Some Performance Characteristics
        of Miniaturized Solid Tantalum Capacitors"
        J.S. Wiley & W.W. Plumee
        Electrochemical Society, P J2, pp. 51-2
        Oct. 1967

1966

1-66:   "Electrolytic Tantalum Capacitors"
        W. Rajewicz
        Prezglad Electron. (Poland), Vol. 7 #2, pp. 65-87
        1966

2-66:   "Tantalum Electrolytic Capacitors"
        T. Watanabe
        JEE (Japan) #8, pp. 31-8
        1966

3-66:   "Service Life and Reliability of Mullard Electrolytic
        Capacitors"
        M.G. Sage
        Mullard Tech. Commun. (GB), Vol. 8, pp. 275-82
        Jan. 1966

4-66:   "On the Mechanism of Electrolytic Rectification"
        J.C.W. Kruishoop
        Solid State Electronic (GB), Vol. 9 #6, pp. 663-4
        June 1966

5-66:   "New Test Methods for the Accelerated Qualification
        of Electrolytic Capacitors"
        T. Barna
        Hiradaastechnika (Hungary), Vol. 17 #7, 211-14
        July 1966

6-66:   "Charge-Discharge Mechanisms in Electrolytic Capacitors"
        W.J. Bernard
        J. Electrochem. Soc. (USA), Vol. 113 #7, pp. 749-51
        July 1966

7-66:   "Role of Production Conditions in the Improvement of the
        Reliability of Electrolytic Capacitors"
        T. Kormany & M. Mezey
        Hiradestechnika (Hungary), Vol. 17 #10, pp. 298-303
        Oct. 1966

<u>1965</u>

1-65:   "The Reliability of Tantalum Capacitors"
        P. Petrick
        Elektronik (Germany), Vol. 14 #1, pp. 15-16
        Jan. 1965

2-65:   "TAG, A New Type of Solid Electrolyte Tantalum Capacitors"
        G. Helwig
        El Nacher (Germany), Vol. 13 #1, pp. 43-4
        1965

3-65:   "Tantalum Thin Film Capacitors Producing Leakage Current
        Minimizing Process"
        M.D. Karithers, Collins Radio Co.
        Patent USA 3466230, March 2, 1965, USA 436681 (Published
        Sept. 9, 1969)
        March 2, 1965

4-65:   "A New Approach to the Highest Possible Reliability in
        Tantalum Capacitors"
        J. Burnham
        IEEE Trans. Compo. Parts (USA) Vol. CP-12 #1, pp. 21-9

5-65:   "Electrolytic Capacitor Anodes Derived From Ta-Ti and
        Nb-Ti Alloy"
        T.L. Kolski
        J. Electrochem. Soc. (USA), Vol. 112 #3, pp. 272-9
        March 1965

6-65:   "Properties and Performance of Tantalum Oxide Thin Film
        Cap."
        B.H. Vromen and J. Klerer
        IEEE Trans. Pts. Materials Packaging (USA, Vol. PMP-1
        #1, pp. S 194 - S 204
        June 1965

7-65:   "The Life of the Electrolytic Capacitors"
        L. Kahn
        Electrotech. (USA), Vol. 76 #2, pp. 4850-2
        Aug. 1965

8-65:   "Nomograph and Chart Pinpoint Source of Ripple Voltage
        Limitation"
        W.H. Fritz
        Electronics (USA), Vol. 38 #18, pp. 64-7
        Sept. 1965

9-65:   "Determination of the Density and Dielectric Constant of
        Thin Ta_2O_5 Films"
        J. Klerer
        J. Electrochem. Soc. (USA), Vol. 112 #9, pp. 896-9
        Sept. 1965

1965

10-65: "The Characteristics of Tantalum Capacitors"
W. Ackermann
Electrotech. 7 (ETZ) A (Germany), Vol. 86 #19, 632-5
Sept. 1965

11-65: "Problems in the Manufacture of Tantalum Capacitors of
High Charge and High Voltage"
J. Vergnolle
One Elec. (France), Vol. 45, pp. 1093-1101
Sept. 1965

1964

1:64: "Charge Storage Effects in Tantalum Oxide Films"
R. Dreimer
J. Electrochem. Soc. (USA), Vol. III #1, pp. 27-34
Jan. 1964

2-64: "Dielectric Breakdown in Solid Electrolytic Tantalum
Cap."
L.F. Howard and A.W.H. Smith
I.E.E.E. Trans. Compo. Parts (USA), Vol. GP-11 #2, pp. 187-93
June 1964

3-64: "Foil Type Solid Electrolytic Tantalum Capacitors"
A.L. Jenny
IEEE Trans Compo. Parts (USA), Vol. CP-11 #2, pp. 182-6
June 1964

4-64: "Basic Failure Mechanisms in Semiconductor and Dielectric
Type Devices"
R.P. Misra
Proceedings of Conference of Basic Failure Mechanisms
Newark College of Engineering
June 1964

5-64: "Reliability and Mechanisms of Failure of Solid Tantalum
Capacitors"
R.J. Millard
Proceeding of Conference of Basic Failure Mechanisms
Newark College of Engineering
June 1964

6-64: "Failure Analysis of Electronic Parts"
D.C. Porter
IEEE Trans. Aerospace (USA), Vol. AS-2 #2, pp. 328-37
April 1964

1964

7-64: "Electrolytic Capacitors"
F.J. Burger and L. Young
Progress in Dielectrics, Vol. 5, p. 136
1964

8-64: "Factors Affecting the Anodization of Tantalum"
J.L. Parmee and S.G. Barrow
Conference of Dielectric and Insulating Materials (London
Institute of Elec. Engrs.), p. 19
1964

1963

1-63: "The Development of Special Quality Tantalum Capacitors"
D.S. Girling and W.E.R. Evans
Brit. Commun. and Electronics, Vol. 10 #6, pp. 438-41
June 1963

2-63: "Electrical Characteristics and Sintering Conditions
for Pellets Used in Tantalum Electrolytic Capacitors"
H. Ishida & Y. Lieno
Elec. Eng., Japan, Vol. 83 #7, pp. 72-81
July 1963

3-63: "Heat Treatment of Anodic Oxide Films on Tantalum I, The
Effects on Dielectric Properties"
D.M. Smyth, G.A. Shirn & T.B. Tripp
J. Electrochem. Soc. (USA), Vol. 110 #12, pp. 1264-71
Dec. 1963

4-63: "Heat Treatment of Anodic Oxide Films on Tantalum II Temperature
Dependence of Capacitance"
D.M. Smyth and T.B. Tripp
J. Electrochem. Soc. (USA), Vol. 10 #12, pp. 1271-71
Dec. 1963

1962

1-62: Tantalum Capacitors for Exacting Requirements"
C. Wiegand
Siemens-Z (Germany), Vol. 36 #4, pp. 352-4
April 1962

2-62: "Electrolytic Capacitors and Their Reliability"
A.A. New
Post Off. Elect. Engrs. J. (GB), Vol. 55 #2, 115-24
July 1962

1962

3-62: "Expressing Capacitor Reliability Accurately"
D.E. Maguire
Electronic Industr. (USA), Vol. 21 #12, pp. 100-5
Dec. 1962

1961

1-61: "Contribution on Questions of The Reliability of Components
Under Working and Fatigue Conditions"
F. Beyeriein
Nachrichtentech Fachber (Germany), Vol. 24, pp. 72-95
1961

2-61: "Application Characteristics of Solid Tantalum Capacitors"
R. Rhodes
IRE Internat. Convention Record (USA), Vol. 9, pt. 6, pp. 229-66
1961

3-61: "Capacitor Grade Tantalum"
L.H. Belz
J. Electrochem. Soc. (USA), Vol. 108 #3, pp. 229-35
March 1961

4-61: "Reliability of Ta-Foil Type Electrolyte Capacitors"
E.E. Smith
Proc. Instru. Elect. Engrs. (GB), Paper 3621, Vol. 109B,
pp. 543-7, 553-8
June 1961

5-61: "Accelerated Long-Term Tests and Predictions of the Life of
Capacitors"
D. Marnheim and R. Russel
Radio Mentor (Germany), Vol 27 #9, 00. 755-8
Sept. 1961

6-61: "The A.C. Properties of Tantalum Solid Electrolytic Capacitors"
D.A. McLean (Bell Labs)
J. Electroch. Soc. (USA) Vol. 108, #1, pp. 48-56
Jan. 1961

1960

1-60: "Properties and Behaviour of Solid Electrolytic Tantalum
Capacitors"
W. Ackmann
Nachrichtentech Z (N.J.Z.), Vol. 13 #6, pp. 261-5
June 1960 (Germany)

2-60: "Purification of Tantalum Anodes During Sintering"
       C.J.B. Fincham and G.L. Martin
       J. Electrochem. Soc., Vol. 107 #7, pp. 658-60
       July 1960

3-60: Tantalum Capacitors With Sintered Anode & Solid Electrolyte"
       W. Mosebach
       Electron Rundschay (Germany), Vol. 14 #9, pp. 371-3
       Sept. 1960

4-60: "Statistical Approach to Reliability Improvement of the
       Tantalum Capacitor"
       N.P. Demos
       IRE Trans. Reliability and Quality Control (USA), Vol. RQC
       9 #2, pp. 29-33
       Sept. 1960

5-60: "Symposium on Tantalum Capacitors"
       W.M. Allison & R.J. Millard
       IRE Trans. on Component Parts, pp. 88-105
       Sept. 1960

6-60: "Fixed and Variable Capacitors"
       G.W.A. Dummer and Harold M. Nordenberg
       McGraw-Hill Book Company, Inc., pp. 11-25
       1960