TECHNICAL INFORMATION

ANALYSIS OF SOLID TANTALUM CAPACITOR LEAKAGE CURRENT

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Abstract:

The leakage current of a solid tantalum capacitor is the sum of several independent factors. From measurements of leakage over a range of test conditions some degree of separation of these components of the current can be achieved and so the relative importance of factors leading to high leakage can be assessed.

There is a background level present directly related to dielectric absorption and it contributes to the loss factor of the capacitor. It is not a true leakage.

On top of this absorption current there are other components, most of which are essentially by-passing the bulk of the dielectric. These can be moisture or manganese dioxide tracks or breakdown sites in the dielectric layer. These typical behavior patterns are described in detail.

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There is a background level present equivalent to a dielectric resistivity of about 10^{16} ohm cm. This background is directly related to dielectric absorption and it contributes to the loss factor of the capacitor. It is not a true leakage insofar as it can be recovered when the capacitor is discharged. It is proportional to voltage and, over the period usually employed for leakage current measurements, is inversely proportional to time.

On top of this absorption current there are other components, most of which are essentially by-passing the bulk of the dielectric. These can be moisture or manganese dioxide tracks or breakdown sites in the dielectric layer. The dependence of these on the measuring voltage ranges from ohmic to an extreme sensitivity. Moisture tracks can be identified by their behavior at high and low temperatures. Leakage at breakdown sites usually exhibit a strong dependence on voltage. On the other hand manganese dioxide tracks are normally ohmic.

Some typical behavior patterns are described in detail.

Introduction

The leakage current of a solid tantalum capacitor is normally expressed as a single value measured at room temperature, at rated voltage, and after 3 or 5 minutes. This value is classed as high or low in comparison with a selection limit of typically 10nA/µFV (e.g., 3.3µA for a 33µF 10V capacitor). The capability limit of a low leakage solid capacitor is in the region of 0.01nA/µFV; in terms of insulation resistance this equates to 100,000 megohm microfarads and in terms of resistivity to higher than 10^{16} ohm cm.

In any production batch there is a range of leakage current values extending from the region of 0.1nA/µFV or lower, up through the selection limit. Those near or above this limit are removed on final test. The manufacturer needs a procedure for analyzing the causes of these rejects as well as for improving the general level of performance and for examining failures on life test and in the field. This paper outlines results obtained in such analyses.

Leakage Distribution

A typical distribution of leakage currents within a production batch is shown in Fig. 1.

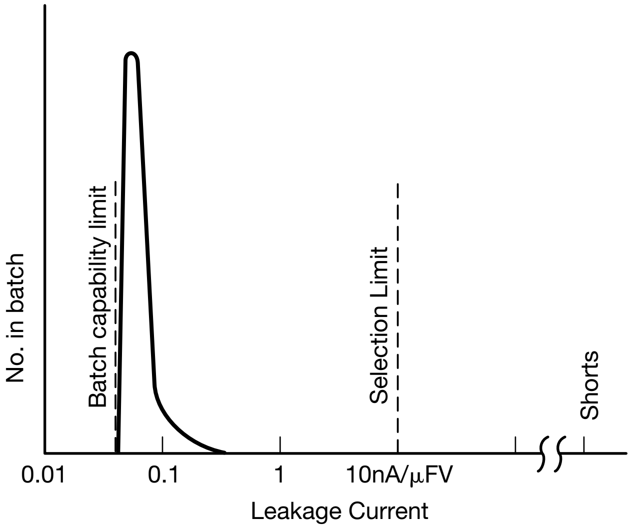

Figure 1. Batch distribution

There is a lower limit below which no values occur; this is the capability limit for that particular anode design and production process. In a perfect batch all the leakage currents would cluster close to that limit. In practice there is a tail to the distribution, some capacitors being only slightly above the normal levels and others with values extending through to short circuits with resistance values down to below 10 ohms.

In order to understand leakage current behavior it is necessary to characterize the current at the capability limit and then correct for this background level.

As a simplifying assumption, it is suggested that the contributions to the total leakage current are essentially additive, and so once the capability level has been established for a batch, that amount can be deducted from the total. The behavior pattern of the residual component of the current can then be compared with known characteristics of typical current carrying mechanisms. This residual component will be called the "fault current" as it would not be present in a perfect capacitor free from any flaws in the dielectric or external insulation.

Leakage Current Characteristics

Even though it is normally quoted as such, leakage current is not one single value; it varies markedly with time, voltage, and temperature, and also has a distinct history dependence (Fig. 2).

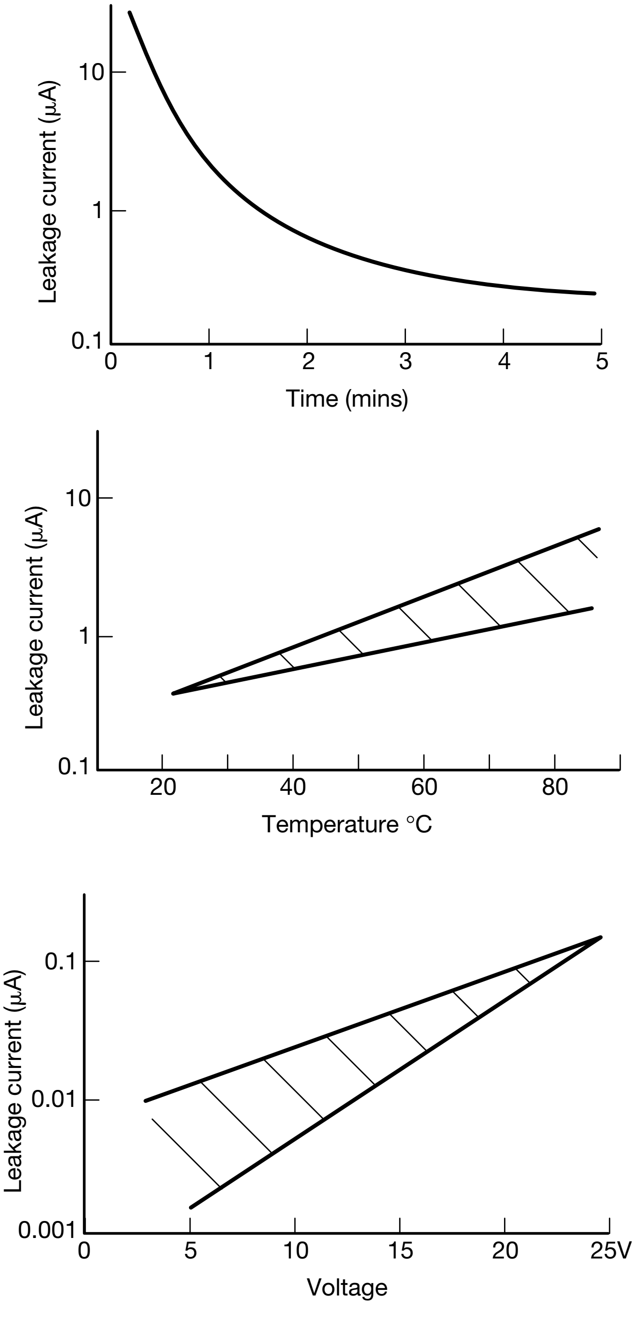

Figure 2. Typical plots of leakage current against time, voltage, and temperature

By relating these characteristics to known mechanisms, probable causes of high currents can be deduced.

Effect of time

The plot of leakage current (I) against time (t) for the first 5 minutes of electrification can often be approximated as the sum of three components (a) the charging current ($\log I = A - Bt$); (b) a current which is inversely proportional to time ($It = \text{constant}$); and (c) a current which changes only slowly with time. The charging current drops logarithmically with time and is usually negligible after a few seconds except for the highest capacitance values. In any case, it can be calculated from the capacitance and the charging resistance and so allowed for in the analysis.

Within any batch the It term tends to be similar from one capacitor to another. The fault current, which is what remains after deducting the charging current and the It current for the total leakage current, is the value which varies most between capacitors.

When the time scale is extended beyond five minutes, it is seen that this residue is not actually constant; normally it slowly drops with time although, in some instances, it can increase. As a first approximation the leakage can be split into the two components for further analysis as in Fig. 3.

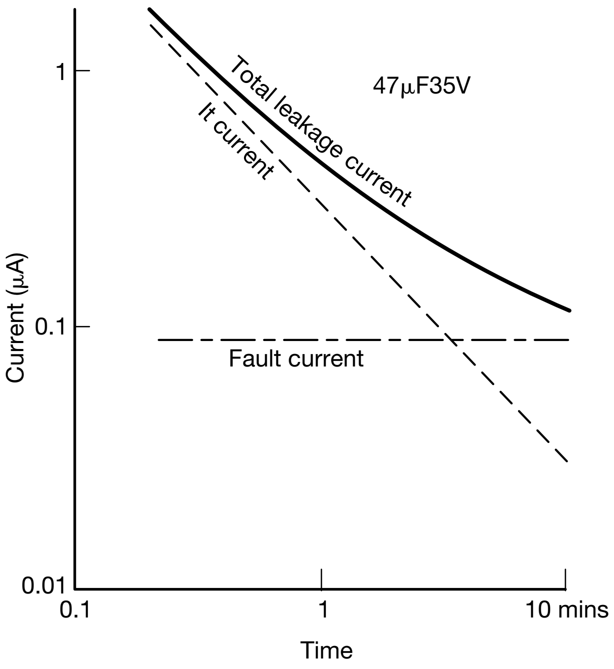

Figure 3. Analysis of leakage/time plot

A simple addition to the leakage/time measurement throws up an immediate explanation of the It term. If at the end of the test period the power supply is short-circuited, current flows back out of the capacitor, again obeying an $It = \text{constant}$ relationship. This discharge current is of the same order as the It component of leakage current. In other words, that part is not a true leakage as it does not pass through the dielectric, only into it to be stored there. It is in effect dielectric absorption. For a really low "leakage current' capacitor, almost all the current is stored in the dielectric ready to be released when the capacitor is shorted. This can be seen in Fig. 4.

The input of charge is terminated arbitrarily after five minutes, but the recovery of charge, the discharge current, has no such truncation and is capable of flowing for extended periods. In order to make a strict comparison of the quantity of charge flowing in the two directions, it would be necessary to integrate It from zero time to either the charge time or to infinity. However, such a calculation yields infinity for the charge! Obviously the It relationship cannot apply at either very

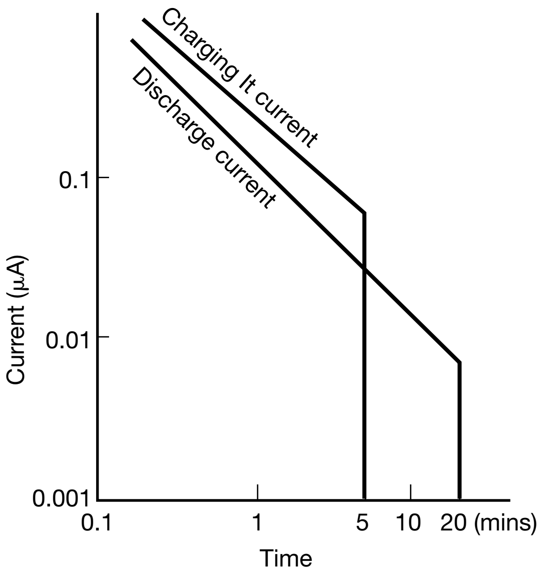

Figure 4. Comparison of currents

short or very long times. If the shortest time for the integration is taken as an arbitrary figure of 10 seconds and the longest is either 300 seconds for charging or 1200 seconds for discharging, the quantity of current flowing in Figure 4 is 21 micro coulombs and 18 micro coulombs, respectively.

It should be noted that the capability limit is when the fault current is negligible and all the current is due to this dielectric absorption effect. By choosing capacitors near the capability limit for the batch, the behavior of this component of the current can be determined with a fair degree of accuracy.

Effect of Voltage

From what is known already about dielectric absorption, it could be assumed that the discharge current is directly proportional to voltage. This has in fact been found to be true (Fig. 5)

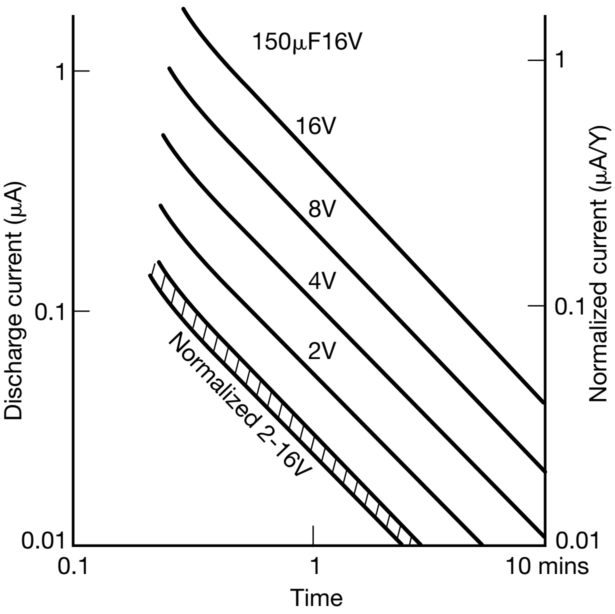

Figure 5. Effect of test voltage

Generally, the fault current is more sensitive to voltage, increasing typically 100 to 1000 fold for a 10-fold voltage increase. This difference in voltage sensitivity can result in situations where the leakage at rated voltage is mainly due to the fault current while that at 0.1 x rated voltage is mainly dielectric absorption (Fig. 6).

Unless the two components are separated, the true effect of voltage cannot be assessed.

Another aspect of voltage is the relationship to the rated voltage of the capacitor. In the measurements on our own product, the discharge current has been found to be lower in terms of nA/µFV the higher the rated voltage. Data in support of this statement will be found in Table 1.

Table 1. Effect of Time, Temperature, and Rated Voltage

Cap/Voltage	Discharge Current (nA/µFV)				Ratio 85°/RT		Ratio 1m/5m	
	Room Temperature		85°					
	1 min	5 min	1 min	5 min	1 min	5 min	RT	85°
47/6.3	.38	.084	6.4	.75	17	9	5	8
150/6.3	.23	.043	3.6	.45	16	10	5	8
680/6.3	.31	.061	3.5	.46	11	8	5	8
68/10	.17	.032	2.8	.37	16	11	5	8
220/10	.20	.035	2.7	.34	14	10	6	8
10/16	.15	.038	1.63	.23	11	6	4	7
33/16	.17	.038	1.59	.18	9	5	5	9
150/16	.22	.042	1.83	.21	8	5	5	9
22/25	.14	.022	1.44	.20	10	9	6	7
68/25	.10	.016	.79	.084	8	5	6	9
68/25	.11	.015	.53	.054	5	4	7	10
68/25	.15	.028	.52	.054	4	2	5	10
68/25	.15	.024	.66	.060	4	3	6	11
10/35	.091	.017	.56	.063	6	4	5	9
10/35	.086	.017	.48	.057	6	3	5	8
22/35	.082	.017	.33	.034	4	2	5	10

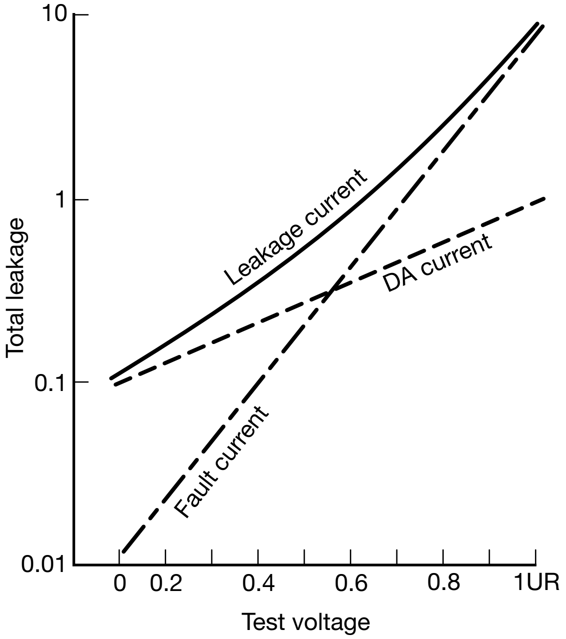

Figure 6. Analysis of voltage sensitivity

Effect of Temperature

The effect of temperature is complicated by significant deviations from the It = constant relationship at high temperature (Fig. 7).

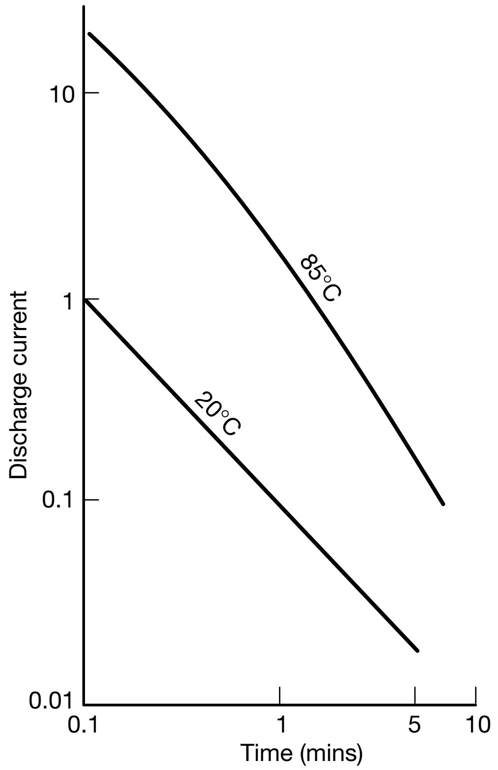

Figure 7. Effect of temperature

Also the ratio of discharge current at 85° to that at room temperature decreases with increasing rated voltage (Table 1). Points to note in this Table are:

1. The discharge current drops as the rated voltage increases
2. The ratio between the 85° and the room temperature readings drops as the rated voltage increases (note, however, the wide range within the 25V batches)
3. The ratio between the 1 minute and 5 minute readings at room temperature are close to 5 as expected from It = constant
4. The ratio between the 1 minute and 5 minute readings at 85° average about 8

When this discharge current is used to split out the fault current components from the total leakage current, even wider variations in the temperature coefficient are found. This can be of great value in pinpointing causes of high leakage as it allows the true behavior pattern of the fault current to be determined.

Causes of High Leakage Current

To summarize the position so far:

- A single valued leakage current is of no value for fault analysis
- The leakage current must be measured under a range of conditions of time, voltage, and temperature
- The leakage current must be corrected to remove the effect of dielectric absorption, which is a consistent property of all solid tantalum capacitors
- The dielectric absorption current can be estimated from the discharge current
- Unless the above correction is made, the true effect of the measurement conditions on the important component of the high current will be obtained

Although the study of the currents at the capability limit are very interesting from the scientific viewpoint, and although many more results are available for publication at some time, the main area of practical interest must be the fault current. This current could be through the bulk of the dielectric, through flaws in the dielectric, or in route bypassing the dielectric and bridging between the positive and negative contacts. Each of these paths could be further subdivided as in the following incomplete list:

bulk effects	– semiconduction in the tantalum oxide due to heat treatments – excess carriers due to previous reverse polarization
flaws	– impurity centers – electrical breakdown sites – mechanical damage
bypassing	– manganese dioxide on anode wire – conductive volatiles (usually moisture) – flux residues

Some of these mechanisms have very definite characteristic behaviors. For instance a manganese dioxide bridge from the outer layers on the anode to the positive terminal wire gives an ohmic behavior; i.e., the fault current is directly proportional to voltage, is constant with time, and it has a low temperature coefficient (about 2-fold for 60° rise).

Volatiles show up readily on a temperature plot. The current starts to rise, but above about 60° it begins to drop and usually finishes with a lower value at 85° than at room temperature (Fig. 8).

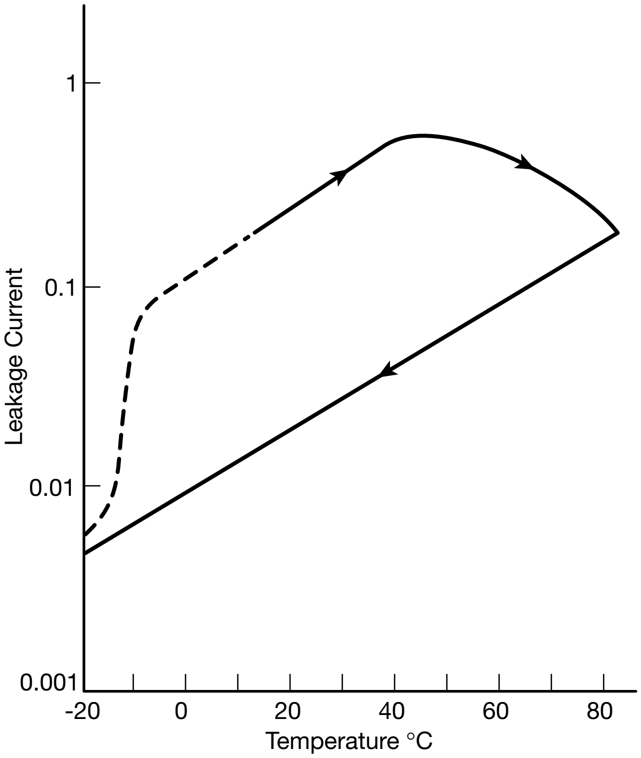

Figure 8. Effect of volatiles

Cooling quickly down to room temperature drops the value even further. Cooling to sub-zero temperatures can also show sudden drops in leakage as the moisture path freezes, but there are practical difficulties with such testing. Flux residues can have some unusual, and as yet not understood, behavior. When this mechanism occurs in a metal cased capacitor, piercing a small hole in the can sometimes causes a high current to drop almost instantaneously to a low level. It is not clear whether this is due to a volatile material passing out through the hole or something going in to counteract the flux residues.

Electrical breakdown can show in two different ways. Firstly, the fault current may increase with time rather than stay constant or dropping. This increase can be relatively slow or it may show up as instability in the current readings. The increase is probably the result of slow spread of the damage site around the original breakdown.

The second behavior characteristic is a very steep slope to the voltage/current plot — for instance, 1000 or more fold increase in current from $0.1U_R$ to U_R.

Semiconduction in the dielectric can only really develop when the tantalum oxide is heated above 300°C. Therefore, this is a problem that can hardly ever generate after the capacitor has been assembled. If it were to occur in manufacture, it would show up in capacitance measurements.

Non-Electrical Testing

Supporting evidence for some of the above mechanisms can be obtained by internal examination. Manganese dioxide bridges are often visible by eye after removal of the encapsulation. Removal of the manganese dioxide chemically allows the dielectric to be examined by optical and electron microscopy. The latter needs careful interpretation as only a small area of exposed surface can be examined at a time. When the anode is broken open for internal examination, various artifacts are generated which can give misleading impressions.

If the anode is removed and stripped extremely carefully, it can be immersed in a copper plating solution and the high current areas decorated with visible deposits of copper. This technique is especially useful for confirming mechanical damage, which will almost always be on the outer surface of the anode. A scratch due to mechanical abrasion during manufacture will show up as a line of copper deposit. The main area of mechanical damage which may not be visible on the outside is where the wire enters the anode. This can be determined after copper decoration by breaking open the anode — such breaks usually expose the wire surface within the powder slug.

Summary

1. Analysis of leakage current behavior requires measurement to be made over a range of time, voltage, and temperature.
2. The current is the combination of more than one conduction mechanism. These need to be separated before the true behavior pattern is seen.
3. There is a capability limit for any combination of anode design and process below which no values will be found.
4. At this capability limit, the current is due to dielectric absorption and not to passage of current through the dielectric.
5. To analyze the fault current, it is necessary to deduct the dielectric absorption current from the total leakage.
6. It is possible to categorize some of the fault mechanisms, giving expected values for the behavior with respect to time, voltage and temperature.
7. The main reasons for high leakage currents can be grouped into currents through the bulk dielectric, currents through localized flaws in the dielectric, or conduction path bypassing the dielectric.

Acknowledgements

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