

Capacitor Selection in Aviation Equipment

Shengxing Gu
L-3 Communications Wescam
649 North Service Road W. Burlington
Ontario Canada L8R 2X2
Shengxing.gu@l-3com.com

Except for MIL and COTS, more commercial capacitors are used in aviation equipment. The selection of the capacitors becomes a more significant issue as without strict tests, inspections, burn-in and screening stated within military system used for selection and procurement of components. The quality of commercial capacitors is to rely entirely and solely on manufacturing process control, routine and final tests. Besides the tests on circuit card assembly and final tests of the equipment, the selection on purpose among manufacturers seems to be the only remain effort to try to ensure reliability. This selection cannot identify and remove infant mortality, but to use commercial parts in the application began in 1994. In the original interpretation of COTS, it should be commercial parts, but many COTS solutions end up being sole source due to modifications to meet environment and performance requirements.

As not all dielectric materials, electrodes and termination solutions are entirely compatible, manufacturers keep improving and researching in capacitor designs and processes, exercising great cares from materials to structures to produce capacitors with suitable designs and process, also have the programs to make their product as defects free as possible. But even so, capacitors are still not perfect in applications and there are the differences among manufacturers in quality and reliability. The results of life test or HALT from technical papers also show that failure rate and TTF time of the capacitors vary from vendor to vendor [1], such as table 1 listed the difference of MLC capacitor from three manufacturers [2].

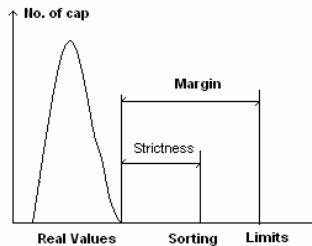


Fig 1: Relationship of the values

Table 1: Tests results of three mfg A, B and C;
Failures out of 80 parts for 1K hours

Manufacturer	Type	Failures (85/85 Test)	Failures (STD Test)
A	C0G	NIL	NIL
B	C0G	NIL	NIL
C	C0G	13 (DF, IR)	5 (Cat)

Although the differences among manufacturers exist in fact, it is not easy to make the selection by comparing the parameters on datasheets due to the identity for the most commercial capacitors. The limits and parameters on specifications listed by vendors are often much bigger than the criteria limits for control in production, not the real values that capacitors possess. The identity is caused by plenty margins between the limits and the real values, Fig 1. The narrower the margins, the more the specifications can reflect the differences with other products. Also the sorting value may vary by strictness of the tests. Moreover, not all manufacturers in markets put detailed specifications and test methods on datasheets because of its commercial application. Obviously for commercial capacitors to be used in aviation, it is necessary to try to find out what factors to be considered in the selection.

Reality of capacitors selection and application currently

The operating environment for components built into aviation equipment can be both extremely severe and benign. Temperature range from -40 to $+85$ deg C is experienced normally, but severe extreme temperature range is -55 to $+125$ deg C. Generally the capacitors are located inside the electronic sub-assemblies and protected from severe environment and will be within their manufacturer guaranteed operating temperature extremes. In order to ensure the reliability in the application, the selection of the capacitor still should be made by considering more severe conditions than commercial applications, also should maintain electrical stress well within the limits under worse case conditions by derating, although capacitors operate under moderated conditions generally.

The types used in aviation equipment mainly are ceramic, multilayer ceramic (C0G, X7R, X5R), solid tantalum and a few plastic film capacitors. Aluminum electrolytic capacitors are getting less and less in this application due to the structure and gas-out. Similar with

commercial and industry applications, the designs are using more capacitors than before because of more functionality integrated onto each IC chip, and then fewer IC chips and more passives on the board required. On the other hand, lower IC voltages and higher digital operating frequency require more capacitors to maintain signal integrity. Capacitors are remaining and getting to be the more important role in the electronic circuits.

Generally, average about 75% of the components on bill of material in electronic circuits is passive parts (capacitor, inductor, resistor and connector etc) and about 50% of them are capacitors. For the recent years, the percentages above are up respectively. As an example, the capacitors increased average 22.5% to total parts by counting three BOMS from year 2003 to 2007 version. To the proportion of the capacitor types in electronic circuits of aviation equipment and other applications, ceramic capacitor shows the highest percentages in different fields, particularly MLCC type, but aluminum and tantalum electrolyte capacitors are with variable percentages in different application fields as different working conditions and requirements.

Surprisingly, no matter the applications, the number one effect on selecting capacitors is not the capacitor manufacturers and their technique papers in real electronic circuits designing, but the IC parts manufacturers and application notes, information in datasheets of IC chips, application papers from IC manufacturers as well. It is very common situation if the datasheet of the IC indicated external capacitors with type and part numbers in its application section, the part numbers will probably appear on the BOM together with the IC parts in designing, even though these capacitors are not available, orderable or even phased out, superseded already.

In practice, circuit designers' considerations in capacitor selection rarely focus on the differences among the manufacturers, but on dielectric type, rated voltage, temperature range, capacitance value, ESR, etc only for the specific design. Selection on purpose in reliability and quality between manufacturers is often not an issue in most designing practice mainly because of identical specifications of capacitors. Some application cases experienced higher failure rate, or sudden anomaly failures for specific capacitors of a manufacturer will switch to other manufacturers to avoid the failures.

Selecting Factor for Ceramic Capacitors

Three main typical failure modes in ceramic capacitors are electrical shorts or low insulation resistance, open circuit and capacitance value out of tolerance. The most common of them is short circuit or low insulation resistance failure mode. By the failure of analysis, all failure root causes of ceramic capacitor can be finally belonged to one of following defects: voids, cracks, delaminations, thickness variation, thin spots, impurities, moisture, short end margin, inadequately end metallization, poor attached lead, improper stacking. Some defects of them can be traced to poor workmanship and stacking. The defects in voids, cracks, thickness, spots impurities and delaminations are the result of process and materials and they are considered as the causes to the leakage. Others defects, end-metallization, attached lead, terminal and electrodes, can be the contributors to dissipation factor DF. Obviously leakage, represented by insulation resistance IR, and DF are the important parameters for the selection of ceramic capacitors.

Moisture is considered as an accelerate factor to failure of ceramic capacitors, it can cause low IR. The 85°C/85%RH 1K hours test is a better test to reveal the potential defects, but

only very few top manufacturers put the limits of the test on their specifications with the confidence to their products. Humidity load test with 40°C/95%RH 500 hours is popular to the most manufacturers. In most HALT tests at high multiples rated voltage and high temperature, IR increasing and leading to failure were observed [3]. Higher electrical stress will accelerate the revelation.

As we known by the structure of the capacitor, if IR reflects the leakage path or place, then the capacitance changes implies the quantities of the paths and also plus other defects that cause the change inside the capacitor. The dissipation factor DF dominates low frequency behavior and represents defects in electrodes, terminal and contacting, as dielectric C0G, X7R and X5R possess electron displacement, ion displacement and small dipole rotation polarizations that contribute less to DF in low frequency range. Now ΔC is the capacitance change post life tests, if suppose Y represents changes of DF post life tests to initial in times. Then ΔC can be considered the sum of the each leakage path and defect contributes:

$$\Delta C = \sum_{n=1}^k \text{Path (n)} + \sum_{m=1}^k \text{Defect (m)}$$

Assuming the selecting factor is F_s , and then the relationship between post life IR, ΔC and Y should be as following, higher value of F_s shows a better selection with less leakage paths, smaller affects of the paths and better terminal:

$$F_s = (\text{IR}) / (\Delta C * Y)$$

[For example, to Mfg A: $F_s = 30 / (0.125 * 2.0) = 120$]

Table 2 listed the values from seven manufacturers most used in design reality and the results of F_s calculated, also the limits of MIL-PRF-55681 for comparison although it has different electrode material (PME). The results of F_s just reflect the levels of reliability and quality correctly. The values of DF and IR in manufacturers' specifications are not the real values capacitors possess, but the limits for production batches. Making selection by these values will not have accuracy due to the margin mentioned previously, but really be a comparison means for selecting between manufacturers. Some vendors do not offer these values for comparing, such as Mfg E in table 2 [4]. There is no comparison for the selections at all under this situation.

Mfg	IR initial	IR post LT	Max DF (50V rated)	Max DF post LT	Y (Times to initial DF)	ΔC (post LT)	Fs
MIL-55681	100 G Ω / 1000 ΩF	30 G Ω / 300 ΩF	0.025	0.030	1.2	10%	250
A	100 G Ω / 1000 ΩF	30 G Ω / 300 ΩF	0.030	2 times	2.0	12.5%	120
B	100 G Ω / 1000 ΩF	10 G Ω / 100 ΩF	0.025	0.030	1.2	20%	41.6
C	100 G Ω / 1000 ΩF	1 G Ω / 50 ΩF	0.025	0.050	2.0	10%	5
D	10 G Ω / 500 ΩF	1 G Ω / 50 ΩF	0.025	0.050	2.0	12.5%	4
E	100 G Ω / 1000 ΩF	X	0.035	X	X	X	
F	10 G Ω / 500 ΩF	1 G Ω / 50 ΩF	0.150	0.250	1.6	20%	3.1
G	10 G Ω / 500 ΩF	1 G Ω / 50 ΩF	0.025	0.040	1.6	12.5%	5
H	10 G Ω / 500 ΩF	1 G Ω / 50 ΩF	0.025	0.070	2.8	20%	1.8

(i) X7R dielectric and BX for mil; (ii) Rated voltage 50V; (iii) Life test: 125 deg C, 2 times voltage, 1K hours;

Table 2: IR, Fs values of MLCC from different manufacturers

Solid Tantalum Capacitors

Over 95% of tantalum capacitor failures in the field are due to leakage current increases and impedance increases, but mainly caused by leakage current, DCL [5]. Short-circuits and catastrophic failures occur as an avalanche in DC leakage current. DCL is more variable than capacitance and DF [6]. Leakage is the critical parameter that helps define the performance of tantalum capacitors. Obviously from the above, DCL is the key factor to be considered for the selection, and then it will be the ratio DCL/CV with the volume consideration, so it can be in unit nA/uFV or uA/uFV.

Unfortunately for commercial solid tantalum capacitor, the selection becomes more difficult than ceramic capacitors due to exactly identical DCL and parameters on specifications, although the designs and process make the differences between the vendors, such as in the pellet (powder, pressing and sintering parameters), MnO₂ or polymer (temperature, pressure, cycles etc), contact resistance (graphite, silver layer), screen and tests. The DCL values on specifications are not actual leakage currents, but manufacturers' listed limits that are far bigger than control and real values. Most batches of tantalum capacitors are with about 0.1 nA/uFV leakage current, and a material research considered this value was caused only by dielectric itself [7]. But the range of real DCL values in production is from 0.03 to below 1 nA/uFV [8] by manufacturer.

By a manufacturer's testing, leakages current nA/uFV values of solid tantalum capacitor can be related to IR limit of ceramic capacitor and have equivalent values of IR respectively (100 M Ω uF \rightarrow 0.01 uA/uFV) [8]. Table 3 listed the comparison for DCL and IR values; tantalum capacitor has much lower leakages, but higher limits than ceramic capacitor. In real

production, leakage currents of the tantalum capacitors from different manufacturers sometimes show several folds variations caused by processing conditions [9], but sorting limit 10 nA/uFV is hundred folds of normal leakage value. The big margin of DCL limit leads to the identity of the specifications. Only a few manufacturers in current markets are with 8 nA/uFV limits, most others list 10 nA/uFV limits on their specifications.

Ceramic capacitor X7R	IR (ceramic)	DCL (tantalum)	Leakage current Density	Tantalum capacitor Ta-MnO₂
Limit on spec → Limit on spec →	100K MΩuF	0.01 nA/uFV	0.4 uA/m ²	← Most values
	10K MΩuF	0.1 nA/uFV	4.0 uA/m ²	
	1K MΩuF	1 nA/uFV	40 uA/m ²	← Max values
	500 MΩuF	5 nA/uFV	2 mA/m ²	
	100 MΩuF	10 nA/uFV	4 mA/m ²	← Limit on spec

Table 3: DCL of tantalum capacitor and IR of MLCC capacitor

This situation of specifications makes the selection impossible by comparing leakage due to the big margin although nA/uFV value is the factor for the selections. If the limits on specifications move to smaller value similar with the level of ceramic capacitor, selection seems to be easier relatively. In practice the capacitors with 8 nA/uFV limits do performance better than that with 10 nA/uFV limits in the application indeed.

Plastic Film Capacitor

Some stacked construction and winding type metallized plastic film capacitors in radial or axial leads are used for the application. The selection should focus on the capacitance loss ΔC and dissipation factor DF increasing after endurance test or life test at maximum temperature.

The failures of metallized film capacitor are mostly due to the air trapped between film layers or between winding and terminals, impurities and pinholes in dielectric. Self-healing of metallized film can eliminate the smaller defects, leaving very small blank area with neat edge. The capacitance loss contributed by the electrodes loss will be little. But for the air trapped in, voids and big defects, partial discharges will be developed instead of self-healings when electrical stress reaches to certain level. The discharges lead to dielectric surface carbon, carbonizing, and causing big electrodes loss with non-neat edge and much bigger area than self-healing. Fig 2 shows the comparison of self-healing and partial discharge on metallized polypropylene film. Capacitance loss always indicates the partial discharges inside. The capacitance changes post life test reveals the defects that will lead to failure in the application.

Weak contact between spaying terminals and metallized electrodes is another common failure root cause particularly under pulse, transient or alternating currents. As the DF of the plastic materials are not very high due to polarization type, contacting resistance is the main contributor to ESR comparing to other components (leads and electrodes), dissipation factor

DF, defined to the ratio of ESR, reflects the potential defects in the spaying terminals. The selection should consider DF changes after life test.

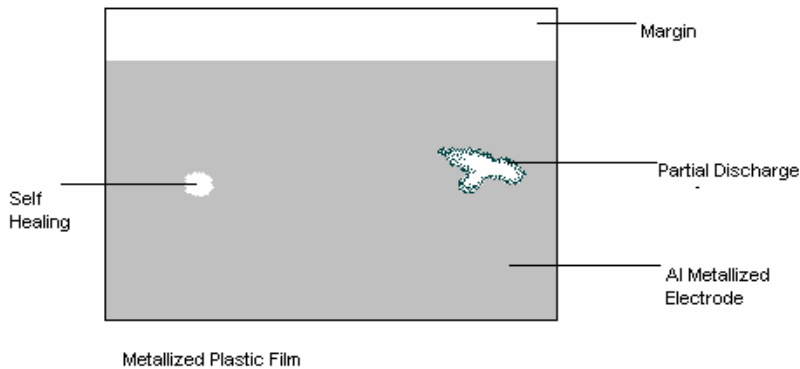


Fig.2: Self-healing and partial discharge

Summary

The difference in quality of commercial capacitors does exist; selection among manufacturers is a remaining effort to ensure reliability although it cannot remove infant mortality. Some factors are discussed for the selection although it is not easy as identical limits on specifications. For ceramic capacitor, the factors are results IR and $\Delta C/C$ after life test or 85%RH/85°C LT, the higher the test voltage, the better to reflect the difference; For tantalum capacitor, the factors are defect sites in thin dielectric represented by DCL/CV (nA/uFV) that cause electric breakdown following thermal breakdown, then failure, but they values are identical in specifications. For metallized plastic film capacitor, the parameters linked to partial discharge and contacts of spray layer are the factors.

- [1] Michael S. Randall etc “Lifetime Modeling of Sub 2 Micron Dielectric Thickness BME MLCC’ CARTS 2003 p3-5
- [2] Dr. Phil Ward “Some Observations on Recent MLCS Quality ...” p7, AVX
- [3] Michael S. Randall etc “Lifetime Modeling of Sub 2 Micron Dielectric Thickness BME MLCC’ CARTS 2003 p1
- [4] Manufacturers’ specifications
- [5] NEC “data book 2005”
- [6] Kemet “Application Notes for Tantalum Capacitors”
- [7] Ben Whittle “A New Polymeric Carbon Undercoat for Improved Leakage Current Performance of Tantalum Capacitors” p1, DuPont (U.K) Limit
- [8] R.W. Franklin “An Exploration of Leakage Current” p1, AVX
- [9] R.W. Franklin “An Exploration of Leakage Current” p3, AVX

