Evaluation of Polymer Counter-Electrode Tantalum Capacitors for High Reliability Airborne Applications

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Abstract

One of the few disadvantages of a traditional M_nO_2 counter-electrode tantalum capacitor is that when it fails it can produce momentary combustion and create substantial residual damage to a PWB if significant current is available. This damage can often result in the failure of other adjacent components due to the intense heat generated during failure causing parts at adjacent locations to fail. Polymer tantalum capacitors have the great advantage of a benign failure mode which is desirable for critical or manned applications. It was because of this benign failure mode that it was decided to evaluate polymer tantalum capacitors to replace legacy devices in several applications although the new components were heavier and more costly than the heritage parts. This evaluation faced several challenges. For example, can you obtain a polymer capacitor with a known failure rate? As has been published elsewhere, polymer tantalum capacitors should share common failure modes with traditional M_nO_2 products but suppliers insist that they cannot obtain failures using standard Weibull testing. Should polymer capacitor undergo surge current test, if so what should the test conditions be? Is voltage conditioning necessary? What are the equivalent screens and qualification test methods for polymers to those documented in M55365? How do we answer these questions? This paper will describe one approach to this problem and the results of our evaluation.

Introduction

It has been more than 10 years since polymer tantalum capacitors were introduced. Initially they were only available in low voltage ratings and therefore, were not attractive to designers of higher voltage systems. However, this limitation has been overcome and users are now being attracted to polymers because of their benign failure mode and low ESR. In part, it has been reported that these improvements are related to the usage of a new generation of pre-polymerized polymer materials. The most intriguing of these improvements is the benign failure mode. Figure 1 illustrates what can happen when tantalum capacitors fail and there is significant current available.

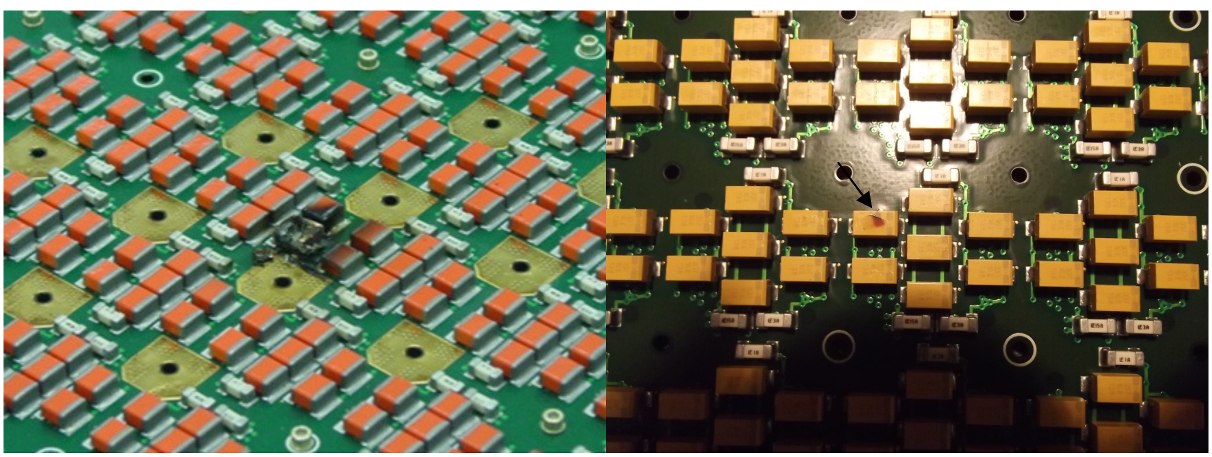


Figure 1
Damage comparison between M_NO_2 (left) and polymer Tantalum Capacitor Failures

While these fireballs are momentary, the damage that can be created is lasting and can impact both function and safety. This effort was initiated after of a series of failures of M_NO_2 based capacitors. These failures had caused substantial board damage. After the first failures, subsequent parts had been up-screened using a combination of surge current testing and Weibull grading. While this approach improved the situation, failures continued to occur- some of which were detected immediately following reflow soldering or during early stages of board testing. This resulted in the addition of a capacitor burn-in in-situ following reflow. These tests identified some additional failures but did not identify all failures that eventually did occur. Attempts to determine the root cause of these failures were unsuccessful. Therefore, it was decided to investigate the replacement of the MnO_2 based tantalum capacitors used in the heritage design with a polymer based counter-electrode tantalum capacitor. The accept criteria was to be that if the polymers performance was roughly comparable to M_nO_2 based product but the failure mode was benign, the design would switch to the polymer parts. Once this decision was made, a significant amount of discussion was had regarding how this product should be screened and qualified since there was concern that the acceleration factors used for standard military tantalum capacitor product were not suitable for polymer based product. On one hand, the dielectric and the construction was the same for both products which intuitively was felt to suggest that the failure modes would be the same. On the other side, papers published in recent years have indicated that the acceleration factors for polymer tantalum capacitors are different than for M_nO_2 tantalum capacitors.

Selection of Screening and Qualification Tests

Tantalum capacitors are usually screened by a combination of surge current testing and Weibull screening. There was an opinion that due to technology improvements, surge current testing at 25°C no longer adequately stressed a tantalum capacitor enough to cause any failures and therefore was unnecessary. The supplier responded that surge current testing does tend to pull out a very small portion of marginal parts. While the number of removed parts may be fewer than for M_NO_2 based product, the supplier still considers surge current testing to be useful in improving outgoing quality by catching these strays, even if it is at a low PPM rate. Surge testing the parts at elevated temperatures adds even further stress to the part and therefore serves as a further improvement in outgoing quality. (Much of this gets back to the quality of the dielectric at the end of the cathode process.) It had been reported by the supplier that Weibull screening was not useful for screening polymer tantalum capacitors because no failures typically occur at the points in time at which the failure rate is calculated. These comments were viewed with some cynicism since both M_NO_2 and polymer tantalum capacitors share the same dielectric. After some discussion it was decided to perform a special aging process. However, there was still concern that while the reliability of the legacy parts was known we had no way of verifying the reliability of the polymer product. To resolve this concern, the supplier developed a proprietary sample test to validate a minimum lot quality level. These choices resulted in the selection of the qci program listed below.

Appendix A
QCI Test/Inspection Methodology

Inspection	Sampling Procedure
Subgroup 1 Thermal shock (unmounted) Voltage aging Reflow conditioning Surge current 1/ DC leakage Capacitance Dissipation factor ESR	100%
Subgroup 2 Physical dimensions	Table IX of MIL-PRF-55365
Subgroup 3 Simulated breakdown screening Radiographic inspection Visual examination	100%
Subgroup 4 Polymer capacitor reliability assessment	100 devices
Subgroup 5 Solderability	13 devices; 0 failures
Subgroup 6 Stability at low and high temperatures	13 devices; 0 failures

Another question regarding how to use polymer tantalum capacitors was how to relate life test results to actual usage conditions. The supplier had reported that standard Weibull testing of polymer capacitor produced few failures. It was considered that the most likely explanation was that the acceleration factors generally used for M_NO_2 based tantalum capacitors were not well suited for polymer parts and therefore an insufficient number of accelerated hours were being accumulated to generate failures. This is considered credible based upon facts surrounding the origin of the standard acceleration factors[1]. The acceleration factors in M55365 have their basis in the testing of 29,000 parts from 5 suppliers of M39003 parts in the 1970's. That testing resulted in widely differing results which were fitted to a three parameter Weibull distribution using a maximum likelihood estimating technique. In this study, it was determined that the acceleration factor tended to increase with increasing rated voltage and case size. Acceleration also varied substantially from supplier to supplier. However, this detail or variation was not included in the military standard for the sake of simplicity. This phenomenon has also been reported for polymers. Paulsen[2], et al reported varying voltage exponents and activation energies when testing low voltage polymer capacitors. Reed[3] has reported that the failure distributions for higher voltage polymer tantalum parts resemble those of traditional M_NO_2 based tantalum capacitors at very high multiples of rated voltage. Reed reported that both infant and wear out failures were achieved in his testing. From the resulting data it was possible to establish appropriated accelerated test conditions to estimate the reliability of a lot.

Sample Selection and Test Procedures

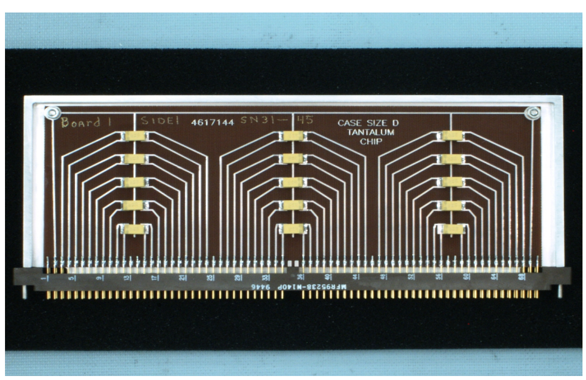
The capacitors initially selected for this evaluation were a supplier's T520 series since they roughly corresponded to the level of the heritage parts. However, at the strong recommendation of the supplier, a decision was made to change to the T541X337M016AH4752 (330 ufd, 16 volt) militarized component. Although the Program plan allowed for usage of unscreened COTS capacitors, the effects of a failure justified the extra cost in providing a "better than" part.

Qualification consisted of four elements:

- Polymer Capacitor Qualification. Quality conformance and qualification testing was performed in accordance with the general requirements of MIL-PRF-55365.
- Module Performance Characterization. An engineering evaluation comparing hardware performance to specification with either legacy or polymer capacitors.
- Engineering Characterization. Capacitor performance under severe conditions.
- Production Testing and Qualification. Assembly into flight configuration and evaluation through a standard production sequence.

The actual applications utilize >2,000 to 8,000 capacitors that are mass reflowed onto backplanes. However, rework procedures allow for replacements to be hand soldered. Therefore, capacitors were hand soldered to test boards using standard S_NP_b solder and a 600^{o}F iron (Figure 2) by a NASA certified technician to simulate the more stressful installation method.

Figure 2
Typical Test Board



Test conditions were selected after consultation with the supplier and some internal consultation. It was decided to perform life test on an increased sample size at rated voltage and 105°C (although testing is usually performed at 85°C and 125°C). A scanner was used to monitor each part once a minute and fuses were selected to blow at 590 ma.

Part Qualification

The qualification plan used for this product was a modification of a standard MIL-PRF-55365 qualification test sequence (see Table I below). The modification was to increase the number of parts which were to be placed on life test and to perform life test at 105°C instead of the usual 85°C or 125°C temperatures. The decision to increase the sample size was not based in statistics or any deep analysis. It was just the sum of the subgroup V and VI sample sizes in the military standard. Temperature selection was based on a review of the predicted shift in ESR at the end of life test. 105°C was selected as the test temperature in light of the possible significant increase in ESR with time at 125°C being greater than the Program was comfortable with.

Table I
Polymer Tantalum Qualification Plan

Inspection	Number of Samples	Number of failures allowed
Subgroup 1 DC leakage Capacitance Dissipation factor ESR Visual examination	178	N/A
Subgroup 2 Thermal shock (mounted)	12	1 for subgroups 2-4 combined
Subgroup 3 Resistance to soldering heat Moisture resistance	18	
Subgroup 4 Surge voltage	12	
Subgroup 5 Life (at +105 deg C)	126	1
Subgroup 6 Resistance to solvents	10	0

Qualification Test Results

One thousand hours of the planned two thousand hour life test had been completed as the paper was being written (Christmas 2011). As of this point there have been no catastrophic failures although some leakage current anomalies had been noted. Leakage current data is recorded in the Table below. Measurements were measured initially, after reflow soldering to circuit boards, and then at designated time periods.

Table II

	Leakage (25C) Measurements During Life Test						
						Maximum Requirement	
	Initial	Mounted	250 hours	500 hours	1000 hour	Initial	Post life
avg	3.06E-06	1.9E-6	37.3E-6	35.8E-6	27.6E-6	528.0E-6	660.0E-6
delta	N.A.	-1.2E-6	35.4E-6	-1.5E-6	-8.2E-6		
SD	N.A.	1.16E-06	7.38E-05	3.58E-05	2.73E-05		
Maximum	3.42E-05	5.90E-06	5.65E-04	1.14E-04	1.18E-04		

Note that the maximum leakage current value recorded at 250 hours was outside the initial specification limit. In addition, when these parts were next measured at 85^{o}C and then 105^{o}C, the leakage current was found to decrease from the 25^{o}C limit which is not what was expected (Table III). The supplier was contacted and they provided the following response: "We have observed this behavior in some polymer capacitors. We have no evidence that this indicates dielectric degradation or that there is any reduction in device reliability at normal operating conditions (-55C to +125C). Longer charge time during leakage current measurements usually produces acceptable leakage results. The parts usually fall below the catalog limit within 5 minutes, but sometimes it takes a little longer. The supplier believes this behavior is related to mobile charge on the dielectric to polymer interface which affects the MIS behavior of the capacitor. Investigation of this behavior is in progress in cooperation with Clemson University. Our life test results verified the supplier's contention that these parts will not fail. We also followed the supplier's recommendation and found the DCL did decrease when the measurements were made as recommended.

Table III
DCL verses Measurement Temperature

	DCL (A)	DCL (A)	DCL (A)	DCL (A)
S/N	25C	85C	105C	25C
33	19.5E-6	5.6E-6	8.2E-6	75.7E-6
65	75.1E-6	4.5E-6	8.6E-6	8.0E-6
70	214.9E-6	9.1E-6	12.8E-6	27.1E-6
72	564.5E-6	19.8E-6	12.7E-6	334.2E-6
74	246.6E-6	6.2E-6	9.4E-6	13.8E-6
75	308.8E-6	4.8E-6	8.0E-6	13.2E-6
76	103.9E-6	5.0E-6	6.6E-6	6.7E-6
89	83.6E-6	6.7E-6	11.5E-6	4.9E-6
93	266.8E-6	5.8E-6	8.5E-6	107.4E-6
101	119.6E-6	3.5E-6	6.4E-6	6.4E-6
103	149.0E-6	6.7E-6	11.3E-6	11.1E-6
104	191.0E-6	3.0E-6	4.1E-6	1.5E-6
107	149.5E-6	3.1E-6	5.0E-6	4.9E-6
116	156.8E-6	3.6E-6	5.9E-6	6.9E-6
119	195.0E-6	3.1E-6	4.9E-6	4.5E-6
127	57.2E-6	4.4E-6	8.2E-6	8.3E-6
128	80.8E-6	3.9E-6	7.0E-6	9.6E-6
130	55.2E-6	7.6E-6	12.9E-6	11.3E-6
133	93.6E-6	5.2E-6	9.1E-6	13.6E-6
135	107.1E-6	4.5E-6	7.7E-6	16.5E-6
146	101.2E-6	6.2E-6	10.5E-6	7.7E-6
147	54.8E-6	3.6E-6	18.2E-6	6.7E-6
149	77.7E-6	3.1E-6	4.1E-6	3.5E-6

Leakage current measurements were also recorded at 85^{o}C and 105^{o}C at each test end point (Table's IV and V).

Table IV

	Leakage (85C) Measurements During Life Test				
	Initial	Mounted	250 hours	500 hours	~1000 hours
avg	7.79E-06	6.1E-6	5.0E-6	5.7E-6	6.1E-6
delta	N.A.	-1.7E-6	-1.1E-6	733.8E-9	394.2E-9
SD	N.A.	4.04E-06	3.45E-06	4.20E-06	3.85E-06
Maximum	2.83E-05	2.25E-05	1.98E-05	3.02E-05	2.17E-05

Table V

	Leakage (105C) Measurements During Life Test				
	Initial	Mounted	250 hours	500 hours	~1000 hours
avg	1.09E-05	13.2E-6	8.0E-6	9.6E-6	11.4E-6
delta	N.A.	2.3E-6	-5.2E-6	1.6E-6	1.8E-6
SD	N.A.	3.89E-05	4.83E-06	5.97E-06	7.09E-06
Maximum	4.96E-05	4.48E-04	2.91E-05	3.36E-05	4.16E-05

DCL performance and consistency was noted to be excellent, capacitance was stable, and ESR increases were within expectations (Table VI).

Table VI

	ESR Measurements During Life Test						
						Maximum Requirement	
	Initial	Mounted	250 hours	500 hours	~1000 hours	Initial	Post life
avg	7.01E-03	11.1E-3	12.8E-3	13.2E-3	12.8E-3	25.0E-3	50.0E-3
delta	N.A.	4.1E-3	1.6E-3	434.1E-6	-386.2E-6		
SD	N.A.	3.86E-04	1.06E-03	1.18E-03	1.25E-03		
Maximum	8.01E-03	1.34E-02	1.56E-02	1.62E-02	1.65E-02		

The remaining test groups were all successful without any surprises.

Module Performance Characterization

To assure that the polymer capacitors could be utilized and not affect either DC or RF performance, polymer capacitors when installed into engineering units. It was determined that:

- **Transmit power and currents:** Compliant to specification
- **Transmit pulse droop:** Identical pulse droops for both capacitors
- **Regulator stability and oscillations:** No oscillations noted
- **AM/FM noise:** Compliant to specification
- **Ripple rejection:** Identical ripple rejection

Therefore, system performance appeared to be identical.

Engineering Characterization

Characterization consisted of:

- Manufacturing test. Manufacturing test consisted of a series of short voltage conditioning steps at increasing voltages. The goal of these tests was to identify latent failures while minimizing damage to the hardware. Testing was completed with a 0.14% failure rate for the legacy capacitors and a 0.01% failure rate for the polymers after assembly and test of 32 production boards. Polymer failures proved to be benign.

- Destructive testing. Destructive testing consisted of an extreme program of step stress testing to failure. A total of 27 tests were performed. (Figure 3 illustrates the test setup.) The conclusions were that:
  - the polymer capacitors require much more voltage to fail than the legacy parts,
  - the polymer failures are much more benign and result in 15A PWB fuse blowing whereas the legacy parts would cause severe damage prior to the fuse opening,
  - the PWB can withstand damage of a polymer failure and still be repairable,
  - and based on this testing, the polymer capacitors will not lead to catastrophic hardware failure or board damage.

- Tests were also performed with fused versions of the legacy parts. The first series used were too slow in response to protect the hardware. A second product with a faster fuse gave satisfactory results but had excessive ESR for optimum circuit performance.
- Transient testing. Transient testing was performed with worst case voltage transients occurring before system protective circuitry would trigger. Accumulated >600 test hours with no failures of the 29 legacy or 40 polymer parts on test.
- RMS current test. A life test was completed operating at "worst case" duty factor and PRF for maximum ripple current through capacitors. 40 parts of each type capacitor successfully passed >300 hours of test.
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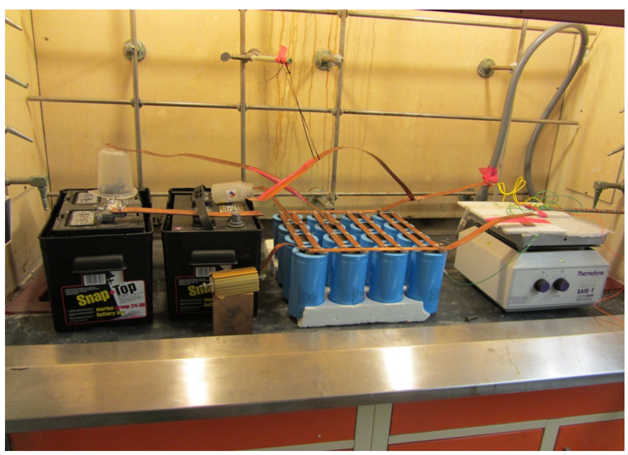

Figure 3
Step Stress Circuit

Production Testing and Qualification

20 capacitors of each type (traditional tantalum vs. polymer) underwent the full gamut of manufacturing processes including electrical screening at the board level.

- 10 capacitors of each type underwent reflow solder (normal process)
- 10 capacitors of each type underwent hand soldering (to simulate rework)

The capacitors were electrically characterized after each process step. One legacy capacitor was found to have failed electrical limits post solder reflow. This part later failed catastrophically during board conditioning at 14 volts. There were no polymer failures during standard processing and testing.

Conclusions

The goal of this task was to determine if polymer tantalum capacitors could be substituted into existing airborne applications without any performance or reliability impact. To date, the polymer capacitors have proven to be interchangeable for the legacy product, more reliable in the application than the legacy part and benign as advertised during failure. (In this case benign means a less sustained burn and no permanent damage to the board such that it can be easily repaired.) The only consideration required was a board respin to allow either the legacy or the polymer part to be installed. While life testing is still in process, the estimated equivalent life is already in the hundreds of years and more than satisfactory for the application. The final word on how successful this effort was will be sounded in several years after systems have been successfully fielded for some time.

Recommendations

1. It is recommended that a military specification or slash sheet be generated for polymer based counter-electrode tantalum capacitors.
2. It is recommended and hoped that efforts will be spent to update the acceleration factors in MIL-PRF-55365 and generate acceleration factors appropriate for polymer tantalum capacitors.

Acknowledgement

We would like to thank Carl Townsend of Raytheon for his image of capacitor failure and the results of his evaluation of capacitors under extreme overstress conditions. We also would thank D. Scott Gordon (Raytheon) and the supplier for their useful discussions and recommendations during this evaluation.

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