

Accelerated Tests for the Effects of Power Cycling on Tantalum Capacitors in a Humid Environment

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Abstract—Power cycling may occur in electrical devices used in the field, and it may often take place in a humid environment with high temperature, further accelerating stress effects. This study focuses on testing the effects of power cycling; especially the effects of a single off period on surface mount tantalum capacitors in a humid environment. First, the effects of temperature and humidity on tantalum capacitors are introduced. Research was done by using the standard 85/85 test and new kind of power cycling tests that were developed based on the 85/85 test. These new tests were done in 85/85 conditions, with a single power off period of 70 h in the beginning of a test or in the middle of a test. Also, the moisture absorption of tantalum capacitors was examined. The moisture absorption results show that when the devices are off, they absorb moisture faster than when they are on. The accelerated test results suggest that humidity is absorbed during a high humidity/high temperature test, especially during the off period, and catastrophic failures occur when devices are turned on afterward. The new kind of reliability tests that were developed on the basis of the standard 85/85 test could be efficiently used for examining the effects of power cycling in a humid environment.

Keywords—Humidity, power cycling, reliability testing, tantalum capacitors

INTRODUCTION

For electrical devices used in the field, power cycling periods are common. Some devices are used only during the workday and power is then turned off until the next day, whereas other devices are powered off most of the time, and then turned on for a little while. These on/off periods often occur in a humid environment, which is an environmental condition affecting the reliability of a device. Thus, these effects should be considered in the reliability development of a product and there is a need for a quick way to examine the effects of power cycling in a humid environment.

The reliability of a product can be defined in several ways. It is often defined as the probability that the product will perform throughout its intended mission life, within specified tolerances, and under specified life-cycle loads [1]. One important part of practical reliability engineering is reliability testing and it is often done at the component level. The intent of many traditional reliability test plans is to simulate the component's use environment. This kind of testing is very time-consuming and that is why accelerated life testing is needed [2, 3].

Accelerated life testing techniques help investigate the reliability of electronic components as regards certain dominant failure mechanisms occurring on the field. Results are achieved in a shorter time than under normal operating conditions. The objective of accelerated reliability testing is to determine the component's limits by applying stresses high enough to stimulate failures: to discover the failures which will occur in the field, and to achieve reliability improvement as quickly as possible [3].

The commonly used accelerated reliability test is the Steady-State Temperature Humidity Bias Life Test (in which temperature is held at a constant 85°C and at 85% relative humidity (RH), known as the 85/85 test), according to the standard JESD22-A101-B [4]. Heat from power dissipation tends to keep the die dry and prevent moisture-related failure mechanisms. In contrast, a cycled bias allows moisture to collect on the die during off periods when the device produces no heat. According to standard [4], the die temperature should be quoted with the results whenever it exceeds the chamber ambient by 5°C or more, and the cycled bias should be chosen if the die temperature exceeds the chamber ambient by 10°C or more. However, such a test takes no account of the possibility of a single off period in the middle of a noncycled bias test. Furthermore, research has shown that a standard accelerated test according to the standard [4] may not be the best possible choice to detect failures in the case of tantalum capacitors [5]. The Highly Accelerated Temperature and Humidity Stress Test (HAST) according to standard JESD22-A110C [6] would be another possibility for testing. It usually activates the same failure mechanisms as the 85/85 test, but is more difficult to use. That is why the 85/85 test was chosen to be the base high humidity/high temperature test in this paper.

The objective of this research is to produce accelerated tests that can help to examine the effects of power cycling in a humid environment in the case of tantalum capacitors. Tests were developed based on the standard 85/85 test and could be used in addition to the standard 85/85 test. Also, the moisture absorption of tantalum capacitors was examined with a 100% RH moisture absorption test. Further failure analysis of tantalum capacitors is beyond the scope of this paper. The present goal is mainly focused on developing new tests.

TANTALUM CAPACITORS

A tantalum capacitor consists of three main elements: anode, cathode, and a dielectric layer of tantalum pentoxide that separates them. There is a pellet of compressed tantalum powder that

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works as an anode. This embedded tantalum wire is surrounded by tantalum pentoxide, an amorphous dielectric layer. The cathode is a semiconductor, manganese dioxide. This pellet has a carbon coating and then is further coated with a silver to provide the final connection layer to the cathode terminal. The tantalum wire passes through these layers and connects the positive terminal to the tantalum. The carbon layer is used to prevent the silver layer from coming into direct contact with the manganese dioxide. Negative termination of the capacitor is attached to the silver paint layer with a silver adhesive [7]. The surface mount tantalum capacitor structure is shown in Fig. 1.

EFFECTS OF HUMIDITY AND TEMPERATURE

The reliability of tantalum capacitors is greatly affected by environmental conditions such as humidity and temperature. Tantalum capacitors are typically manufactured in a non-hermetic plastic case [8], which means that they absorb moisture, as is shown in this paper. The reliability of a tantalum capacitor is heavily influenced by humidity, which can have different kinds of effects inside a capacitor. Moisture can penetrate the polymer encapsulating material and degrade the characteristics of the solid electrolyte, cathode attachment materials, and tantalum pentoxide dielectric. These effects can later cause the capacitor to fail [9-11].

There are reports of several humidity-related failure mechanisms, but the clear reason for failure mechanisms of tantalum capacitors in humid environments has remained elusive. One possible failure mode for tantalum capacitors in humid environments is based on the sleeping cells model and the oxidation of manganese oxide at self-healing sites. Changes in capacitance in dry and humid environments have been explained by the passive cells remaining inactive until activated by absorbed moisture. In humid environments, moisture diffuses into the passive cells and creates a conductive layer on the surface of the dielectric material. This water layer then works as a cathode electrode, which connects the passive area to the surrounding manganese dioxide, increasing the capacitance of the part. In humid environments, sleeping cells may become active in various ways. Furthermore, they differ in their kinetics and effectiveness in developing the conductive cathode electrode. These processes of activation include formation of a moisture-adsorbed layer, capillary condensation, and moisturizing of the hygroscopic remnants in the cell [9, 11]. Humidity-induced failures may also be related to the moisture-generated silver dendrite growing on cathode contacts. After shorting, these dendrites arc, ignite the manganese oxide, and create a chemical reaction [10].

Temperature varies the rates of physical and chemical reactions that cause failure mechanisms. Thus, temperature is often used in reliability testing as an accelerating parameter. However, at high temperatures, new failure mechanisms that were previously dormant because of their high activation energy may be activated. So if a test is run at temperatures that are too high, failure may occur because of a mechanism unlikely during normal operating conditions [12]. Heat, whether generated externally or internally, degrades the performance and reliability of tantalum chip capacitors [13]. The

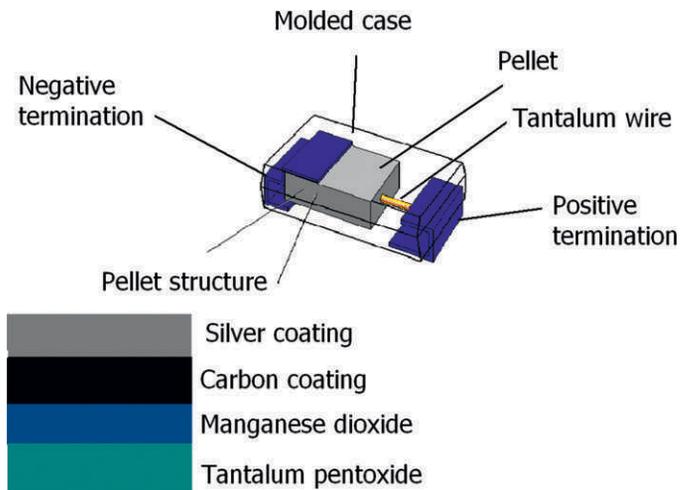


Fig. 1. Structure of a tantalum capacitor.

use of tantalum capacitors at high temperatures has been studied and is found to be a challenge [14].

In addition, thermomechanical stresses can generate new fault sites in the components. A tantalum capacitor package may undergo material expansions at different rates depending on each material's thermal expansion and suffer from tensile forces on the pellet structure. At high temperatures, there are shear forces exerted on the anode wire. The molded case pushes on the lead frame in one direction and the pellet in another. This generates forces that pull it away from the anode structure. Once capacitor's elements are shrinking while cooling, they may not fit together as they did before the expansion. Compressive forces may appear on the pellet structure and produce fractures. A crack in the dielectric at the corner or edge, when exposed to high stress, may lead to catastrophic failure [15-17].

Furthermore, field crystallization may become a factor under high temperatures. A crystal may start growing in small areas of the crystalline order in the dielectric. The phase change of the dielectric from amorphous to a crystal state needs some initial energy, and thermal energy provides the extra energy necessary for crystallization. Conductivity of the crystallized structure is reported to be 1,000 times more than when the dielectric is in an amorphous state [18, 19]. However, field crystallization may have only a limited impact on the use of tantalum capacitors [19].

MEASUREMENTS

We examined tantalum chip capacitors of a maximum voltage of 50 V, a capacitance of 10 μF , and an operating temperature of -55°C to $+125^\circ\text{C}$. These capacitors are used in LED matrix display units (capacitors on a display unit shown in Fig. 2), in field conditions that include humid environment and power on/off periods. Their field operating voltage on a display unit is 15 V. The ripple voltage is 30 mV and the frequency is 100 Hz because of full-wave rectification of the power supply. Before testing, the moisture saturation state of the capacitors on a display unit was representative of dry storage, since they were maintained in dry packaging.

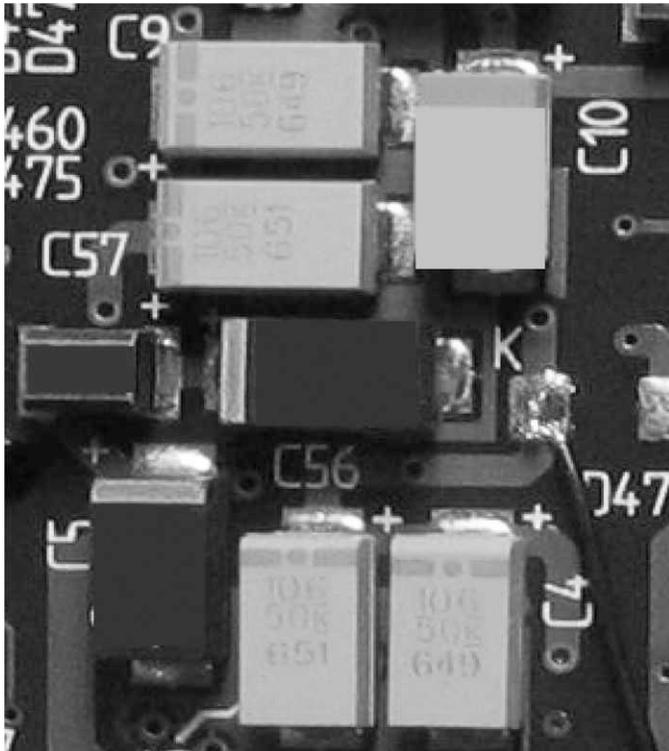


Fig. 2. Tantalum capacitors on a display unit. The reliability of the capacitors on the display units was assessed with the standard 85/85 test. Display units were tested at 85°C and 85% RH in a temperature/humidity chamber. The test arrangement is as shown in Figure 3. Display units are turned on and off from the control unit.

The units were tested in three batches, labeled Test 1, Test 2, and Test 3.

- Test 1: The standard 85/85 test, lasting for 1,000 h, with 11 display units tested.
- Test 2: A test similar to the standard 85/85 test conditions, lasting for 1,620 h, after which the devices were turned off for 70 h. The power was then turned on for an additional 810 h. This test also used 11 units.
- Test 3: The initial 1,620 h of operation in Test 2 was omitted. A test similar to the 85/85 test conditions was done such that for the first 70 h display units were turned off, and the power was then turned on for 2,430 h. This test was performed on seven units.

The functionality of the display units was visually checked twice a day with the criterion that the LED matrix display on the display unit was to show correct output, that is, no LEDs off and no extra LEDs on (Fig. 3).

The temperature distribution in an operating display unit was measured with a thermal imaging camera (Fig. 4) and temperatures were calculated near the capacitors. The image shows that near the capacitors the temperature was about 8°C above the display unit's surroundings. Thus, the components heated up with the power on, making it difficult for moisture to be absorbed. Note that the image in Fig. 4 was taken at room temperature. However, since heat transfer is a linear phenomenon [20], any excess heat should be independent of the ambient temperature. Thus, in the 85/85 test, a maximum temperature of 93°C may be expected.

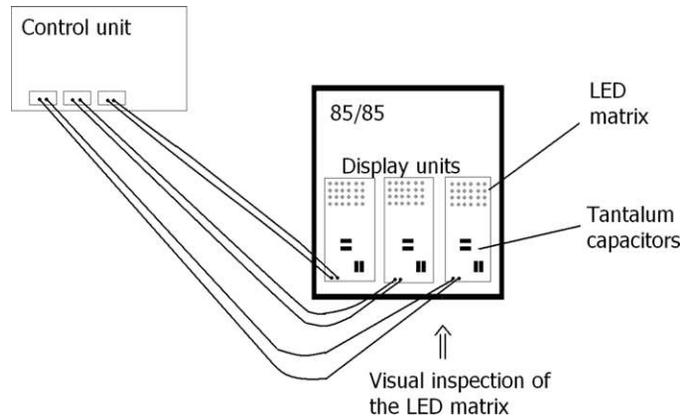


Fig. 3. Test arrangement: LED matrix display units in an 85/85 chamber and the control unit.

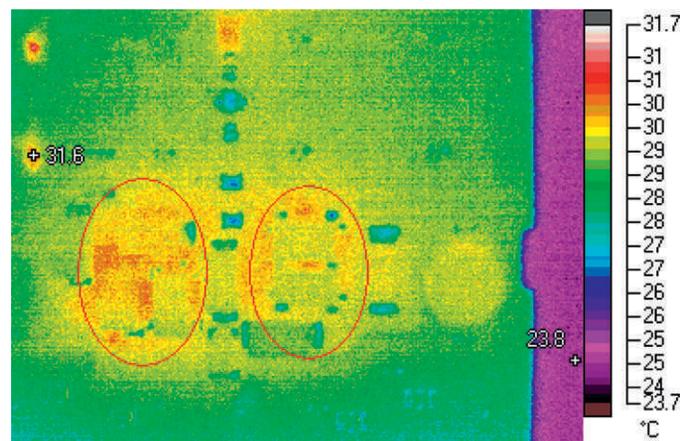


Fig. 4. A thermal image of capacitors on a display unit, voltage on.

The air can hold more water vapor as the temperature increases. Relative humidity, therefore, decreases with increasing temperature if the amount of water vapor remains the same. At 85°C, the saturated vapor pressure was 578.1 mbar. If the relative humidity was 85%, the vapor pressure was then $0.85 \times 578.1 \text{ mbar} = 491.4 \text{ mbar}$. At 93°C, the saturated vapor pressure was 787.46 mbar; consequently, the relative humidity near the capacitors was 62%. Thus, in an 85/85 test, a maximum temperature of 93°C can be expected with a relative humidity near capacitors of 62%. Since 93°C is less than 10 degrees above 85°C, a noncycled bias should be chosen, according to the standard [4].

RESULTS AND DISCUSSION

A. Moisture Absorption

Moisture absorption of tantalum capacitors was examined. Before the moisture absorption measurements, the capacitors were at dry-out baked for 24 h at 125°C, in order to remove all the moisture from the components. This is the condition given in standard JESD22-A113F [21]. Tantalum capacitors were weighed after 70, 120, 168, and 240 h at 85°C and 85% RH (simulating device off time) and at 93°C and 62% RH (simulating device on time) to determine their moisture absorption. Weighing results of the capacitors (shown in Table I) show that

Table I
Capacitor Weights

| Time (h) | Weight after 85°C and 85% RH (g) | Weight after 93°C and 62% RH (g) |
|----------|----------------------------------|----------------------------------|
| 0 | 0.4981 | 0.4981 |
| 70 | 0.4998 | 0.4993 |
| 120 | 0.5010 | 0.4995 |
| 168 | 0.5012 | 0.4996 |
| 240 | 0.5012 | 0.5001 |

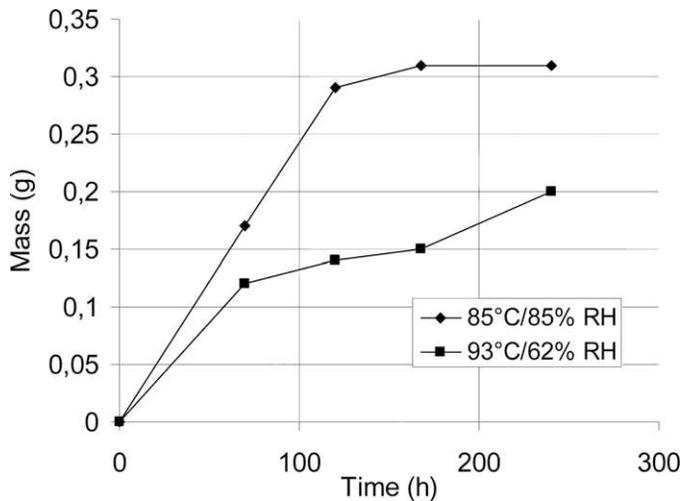


Fig. 5. Moisture mass increases in 85/85 and 93/62 conditions.

when the devices are off, they absorb moisture faster than when they are on. This is because the RH near capacitors is higher when they are off.

For most polymer materials in electronics packaging, saturated moisture concentration does not depend on temperature but on relative humidity as long as the temperature is far below the glass transition temperature [22]. In this case, probably both high temperature and high RH affect the moisture absorption. Moisture mass increases as a function of time in 85/85 conditions and 93/62 conditions can be seen in Fig. 5. Moisture seems to saturate at 85/85 conditions within 250 h. In 93/62 conditions, mass increase and saturation seems to happen slower than in 85/85 conditions.

In Test 2, the power was first on for 1,620 h, corresponding to 93/62 conditions. After that, the degree of moisture saturation was probably near 100%. After this, the capacitors were tested for 70 h at 85/85, since the power was off. Thus, they probably were almost fully wet when the power was turned back on.

In Test 3, after 70 h at 85/85 (power first off), when the power was turned on, the degree of saturation was about 55%. The saturation in Test 3, when the power was turned on, was clearly lower than in Test 2, when the power was turned on.

B. Test Results

All three tests, their conditions, and results are shown in Table II. Test 1 was a standard 85/85 test lasting for 1,000 h and showing no failures. In Test 2, four out of the 11 tested tantalum display units failed before 1,620 h, that is, before the

Table II
All Three Tests, Their Conditions, and Results

| Test | Time (h) | Conditions | F | N |
|------|----------|---|---|----|
| 1 | 1,000 | 85°C 85% RH, 15 VDC, 30 mVAC | 0 | 11 |
| 2 | 2,500 | 85°C 85% RH, 15 VDC, 30 mVAC, off period in the middle | 9 | 11 |
| 3 | 2,500 | 85°C 85% RH, 15 VDC, 30 mVAC, off period in the beginning | 3 | 7 |

Table III
Times to Failure in Test 2

| N | TTF (h) | |
|---|-------------|------------------------------|
| 2 | 1,300-1,400 | |
| 1 | 1,450 | |
| 1 | 1,560 | |
| 4 | 1,690 | Immediately after off period |
| 1 | 1,840 | |
| 2 | 2,500 | Not failed |

power was turned off: two failed between 1,300 and 1,400 h and two more failed between 1,400 and 1,600 h. Consequently, the standard 85/85 test with 1,000 h is not long enough for failures to occur. Before the power was turned off, failures followed a constant pattern. However, four capacitors failed right after the off period at 1,690 h, when the power was turned on again. One capacitor failed after 1,840 h. After 2,500 h of testing, two tantalum display units were still active (times to failure in Test 2 are shown in Table III).

Test 2 produced the same number of failures right after the power off period as during the 1,620 h before it. This marks not a slow progressive failure mechanism, but rather a special case variation in failure frequency, likely brought on by moisture absorption during the off and subsequent on period, together resulting in an electrical breakdown when the power is turned on, as later seen in failure analysis.

Failed components were removed from the board for further examination and cross-sectioned for failure analysis. Cross-sectioning of the tantalum capacitors that failed before the off period showed redness in the pellet corners where overheating resulting from electrical breakdown had burned the capacitors' internal materials and molding (the capacitor failing after 1,450 h is shown in Fig. 6). The component that survived the off period and failed long after it, after 1,840 h, failed in the same way as those that failed before the off period (Fig. 7).

Tantalum capacitor failures were much more dramatic immediately after the off period. These capacitors cracked in the middle and their molding compound turned black, blackening the nearby components as well (Fig. 8). Compared with the failures before and long after the off period, which showed only some redness in one corner, these failed capacitors were all black on the inside.

In Test 3, no failures occurred right after the power was turned on (failure times shown in Table IV). All three failures occurred in a constant manner and failed in the same way as those before and long after the off period in Test 2, showing redness in pellet corners. After 2,500 h of testing, there were still four display units working.

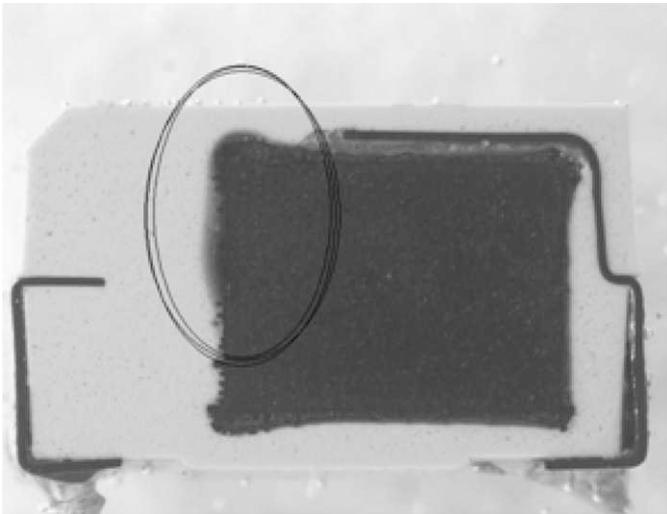


Fig. 6. Tantalum capacitor failing after 1,450 h in Test 2.

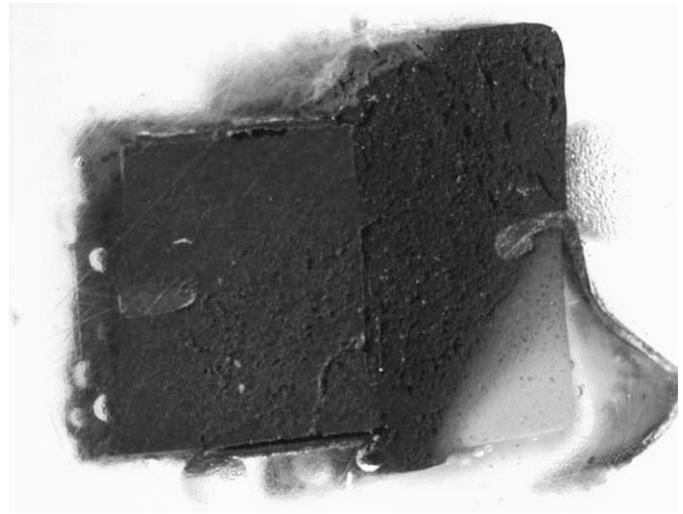


Fig. 8. Tantalum capacitor failing after the off period, when the power was turned back on, in Test 2.

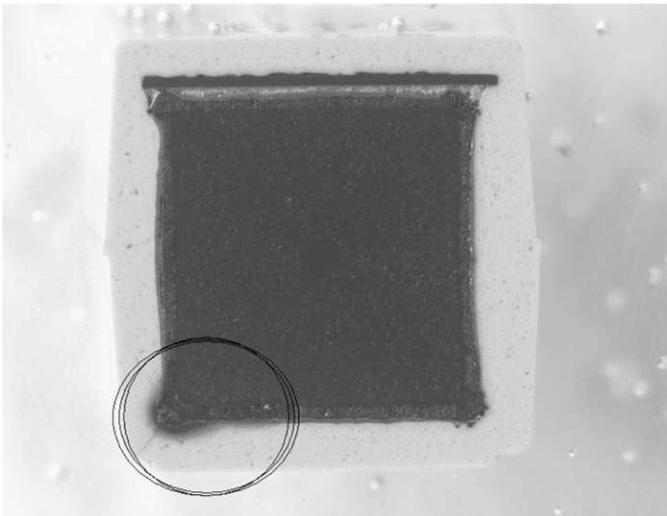


Fig. 7. Tantalum capacitor failing after 1,840 h in Test 2.

C. Discussion

The results suggest that humidity is absorbed during a high humidity test, especially during the power off period, and catastrophic failures occur when devices are turned on afterward. Moisture may have a bigger effect inside the capacitor when the power is turned off because of the lower temperature inside the capacitor. Thus a lot of testing time could be saved if the initial 1620-h operation were omitted. However, because no failures occurred in Test 3 right after the power break, that is, no increased stress effect was discovered: the simpler test cannot replace the earlier power cycling test. The capacitor package was obviously thick enough for moisture not to diffuse to the tantalum electrodes in the first 70 h of no power in Test 3. Based on these results, some new tests could be proposed:

- A test similar to Test 3 should be tried, with a longer initial off time, in order to achieve a higher degree of moisture absorption before the power is turned on. A test with 168 or

Table IV
Times to Failure in Test 3

| N | TTF (h) | |
|---|-------------|-----------------------|
| 1 | 1,300-1,400 | Long after off period |
| 1 | 1,400-1,500 | |
| 1 | 1,870 | |
| 4 | 2,500 | Not failed |

240 h initial off time followed by power turn on could be tried.

- Tests similar to Test 2 should be tried, with less on time at the beginning in order to save a lot of testing time. An initial on time of 250 h, before the off period of 70 h could be tried.
- If the on and off times would be selected such that the device reaches a state of equilibrium moisture absorption before changing the on/off state, the time axis of the accelerated tests could be further scaled down.

CONCLUSIONS

Power cycling may occur in electrical devices used in the field, and an off period may often occur in a humid environment with high temperature, further accelerating stress effects. The results showed that humidity is absorbed during a power off period, and catastrophic failures occur when devices are turned on afterward. New kinds of reliability tests were developed on the basis of the standard 85/85 test. These developed tests could be efficiently used for examining the effects of power cycling in a humid environment.

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