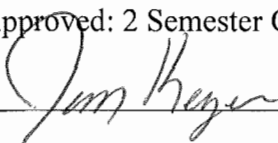Evaluation of Supercapacitor Electrolyte Leakage Life

by

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A Research Paper
Submitted in Partial Fulfillment of the
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Abstract

The objective of this research project was to assess the reliability of a supercapacitor that was to be used as a replacement for supercapacitors of recalled products. The supercapacitors used in company XYZ's medical device products had considerable quality problems which caused them to leak electrolyte over time onto surrounding electronic circuitry. The electrolyte leakage problem grew to affect 5% of the company's installed base. This study addressed the plan to use newer versions of the same device as recall replacements – trusting that the manufacturer had solved its quality problems. The focus of the study was accelerated life testing using elevated temperature and electrical stresses. The accelerated life test goal was to demonstrate the newer supercapacitors had a less than 2% probability of leaking electrolyte over the useful life of the product. The research explored accelerated life test approaches and models that were employed successfully to achieve the project objective. Accelerated life test results and reliability/probability calculations base on the test results are presented and explained. Company

XYZ successfully implemented the product recall of leaky supercapacitors. This field action minimized future field failures and patient risk, while protecting the corporate quality reputation.

Keywords: supercapacitor, electrolyte leak, reliability, accelerated life test, product recall

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Chapter I: The Leaky Supercapacitor

Company XYZ makes a medical device product that has mechanical and electromechanical components and several electronic assemblies. The electronics provide the power and control intelligence of the system. Company XYZ produces approximately 5,000 of these products per year. These products help sustain the lives of tens of thousands of people throughout the world. However, Company XYZ has been plagued with a quality problem over the last few years.

This chapter provides a description of Company XYZ's problem and its magnitude. The magnitude illuminates the significance of resolving the problem. A formal problem statement is given, followed by the objectives of the research project. Additionally, project limitations, assumptions, and definitions are presented.

Problem Description: Leaky Supercapacitors

Company XYZ has had a history of latent field failures due to supercapacitors leaking electrolyte onto nearby electronic circuitry. Supercapacitors are electrochemical capacitors that are used for energy storage (Miller, Goltser, & Butler, 2006). The trends and frequency of supercapacitor leakage have been monitored and reported monthly within company XYZ for over two years. The rate of reported defects has steadily risen during that time. Currently 5% of the products built within a certain date range have experienced electrolyte leakage from the supercapacitor. The author of this paper has been responsible for collecting field data and trending these issues, and through this research, has helped identify a solution. The cause of the electrolyte leakage is primarily attributable to quality issues on the part of the supercapacitor manufacturer (referred to in this paper as Manufacturer ABC).

The magnitude of this problem is large. It affects over 13,000 products currently in the field. The failures in Company XYZ's products resulting from leaking supercapacitors range from no functional impact to a complete shutdown of the unit. Another critical effect of electrolyte leakage is that the alert or warning mechanism can be disabled. The ramifications are great in terms of cost of repair, Company XYZ's reputation, and potential risk to the product users. Therefore, there is great significance associated with resolving this problem.

Problem Statement

Replacing potentially leaky supercapacitors with newer versions from the same manufacturer will result in improved field performance, such that less than 2% of XYZ's products, over the course of a 30,000 hour usage life, experience a failure due to a supercapacitor that leaks electrolyte.

Description of Supercapacitor and Electrolyte Leakage

Two supercapacitors are used in one of the electronic assemblies of Company XYZ's product. Due to quality defects by Manufacturer ABC, the supercapacitors have potential to leak electrolyte. The electrolyte that leaks from them migrates onto the circuit board, or in some cases other physically nearby circuit boards, resulting in an electrical malfunction of the affected circuit board.

The supercapacitors are high capacitance devices manufactured by Manufacturer ABC. As shown in Figure 1, each supercapacitor actually consists of a dual supercapacitor subassembly, in which two 2.2 farad (F) supercapacitors are mounted (in series) on a small circuit board. This results in a device with a capacitance of approximately 1.1 F. This dual supercapacitor "subassembly" is then shrink wrapped and sold by Manufacturer ABC as a single device. These supercapacitors, by design, are not hermetically sealed. Either of the individual

supercapacitors in the subassembly has the potential to leak electrolyte. Company XYZ's design actually uses two of these supercapacitor subassemblies in parallel, for a total of four individual supercapacitors per unit.
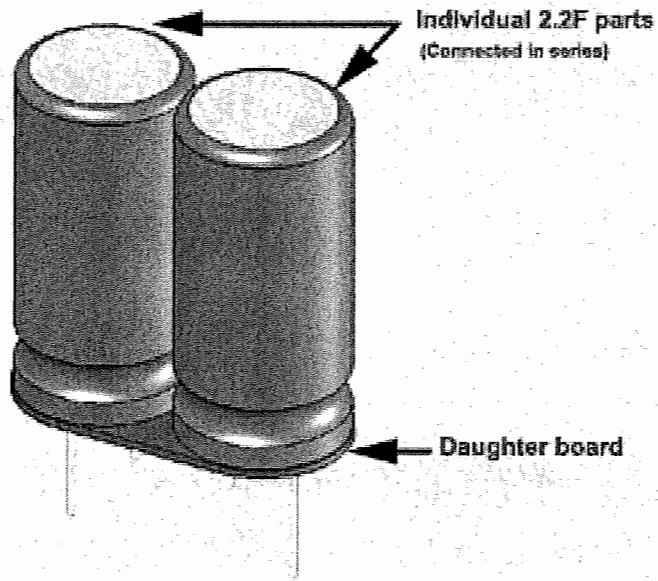
Figure 1. *Pictorial representation of the dual supercapacitor subassembly*

Research Objectives

The main objective of this project determine if the current version of supercapacitor made by Manufacturer ABC meets the reliability goal identified in the problem statement. This objective is assessed through performing accelerated life testing combined with analysis of field performance data. Research was performed and provided on methods of conducting accelerated life test of supercapacitors.

Project Overview

Company XYZ has been moving closer toward taking action to remove potentially affected assemblies from products in the field. This action is classified as a product recall. In the arena of the medical device industry, product recalls require notification to the Food and Drug Administration (FDA). These decisions are very critical for the company involved. There are regulatory obligations to present the FDA with the analysis of field performance data, health risk assessments, and the prescribed corrective actions. Therefore a number of number of questions needed to be answered. What are the most likely or most common system failures and their probabilities of occurrence? What are the most severe system failures and their probabilities of occurrence?

If the fielded assemblies are replaced, with what should they be replaced?

- A similar component from a different supplier (involving some amount of redesign of the circuit board).

- A redesign to get rid of these supercapacitors altogether – from any supplier.

- Replace old supercapacitors with newer versions of the same supercapacitor – trusting that the supercapacitor manufacturer has made the necessary quality improvements.

How aggressively should company XYZ pursue a field action?

- Can Company XYZ wait for normal maintenance cycles?

- Does XYZ need to formally recall the units? A recall may be mandated if there is a significant safety or health risk to the user. Even if there is no risk to the user, a recall may be warranted for the sake of reputation and customer satisfaction.

Limitations

The costs associated with any amount of redesign or re-layout to correct the problem is significant. But more prohibitive is the time it would take to engineer and validate a new design to eliminate the problem. In this time, even more field failures will occur, and the probability of patient harm increases the longer these potentially leaky supercapacitors are in the field. This fact led company XYZ into the approach of relying on the quality improvements implemented by Manufacturer ABC.

Assumptions

The ultimate decision as to whether to pursue a field action (recall the existing product in the field) is beyond the researcher's control. The researcher did, however, perform and communicate the analysis of the failure data to senior management of company XYZ. This study assumed that a field action would take place. This study also assumed, as indicated in the problem statement, that the replacement assemblies would be made with the current version of the supercapacitor from Manufacturer ABC.

Definition of Terms

Accelerated testing – "Accelerated testing consists of a variety of test methods for shortening the life of products or hastening the degradation of their performance." (Nelson, 1997, p. 3).

Derating – "Using an item in a way that applied stresses are below rated values." (Rome Laboratory and Reliability Analysis Center, n. d., p. 35).

Reliability – "The probability that an item will perform its intended function for a specified interval under stated conditions." (Rome Laboratory and Reliability Analysis Center, n. d., p. 36).

Supercapacitor – "A static and passive electrical energy storage device." (Kim, 2002, p. 59).

Chapter II: Literature Review

The literature review for this project focused on three areas. The first was the circuit design application factors that affect life. The second was researching other documented problems of capacitor electrolyte leakage. The final aspect of the literature review studied methods for performing accelerated life tests to demonstrate reliability goals.

Application Factors that Affect Capacitor Life

Supercapacitor application literature from five different supercapacitors manufacturers was reviewed. These manufacturers included Panasonic, Nesscap, Cooper, Maxwell, and Cap-XX. Application guidelines from these supercapacitor manufacturers all address three factors that are relevant to the problem of electrolyte leakage. These relevant factors are life, stress, and voltage balancing. All three of these factors are interrelated. Electrolyte leakage obviously affects the life of the supercapacitor. Electrical and temperature stresses also affect the life of the device, but also are contributors to the internal chemical reaction that results in electrolyte leakage. Voltage balancing is a way of equalizing the voltage stress across two capacitors connected in series.

Life

The life of the supercapacitor is typically identified as a percentage decrease in capacitance or an increase in Equivalent Series Resistance (ESR) capacitance (Cooper Electronic Technologies, 2007), (Maxwell Technologies, 2007), (Nesscap 2008). The amount of decrease in capacitance or increase in ESR that defines end-of-life is application specific. Electrolytic supercapacitors have a liquid electrolyte inside an aluminum can which is sealed with a rubber bung. Prolonged exposure to high applied voltage, elevated temperatures or excessive current will lead to increased ESR and reduced capacitance. Also over many years the electrolyte in the

supercapacitor can dry out causing high ESR and end of life. Miller, et al. (2006) states that life

can also be defined as the time until the supercapacitor exhibits an explicit failure such as

electrolyte leakage or an internal short.

Supercapacitor manufacturers have performed tests to characterize the life of the device.

Figure 2 that follows shows life versus operating temperature in three different applications.

Based on this life chart, an application where the applied voltage per supercapacitor is 2.5 volts,

and the operating temperature is 40 degrees C, the expected life of the a supercapacitor is nearly

400,000 hours given the design can withstand a 50% decrease in capacitance. The specific

manufacturer that published the chart in figure 2 is not cited for reasons of protecting anonymity.
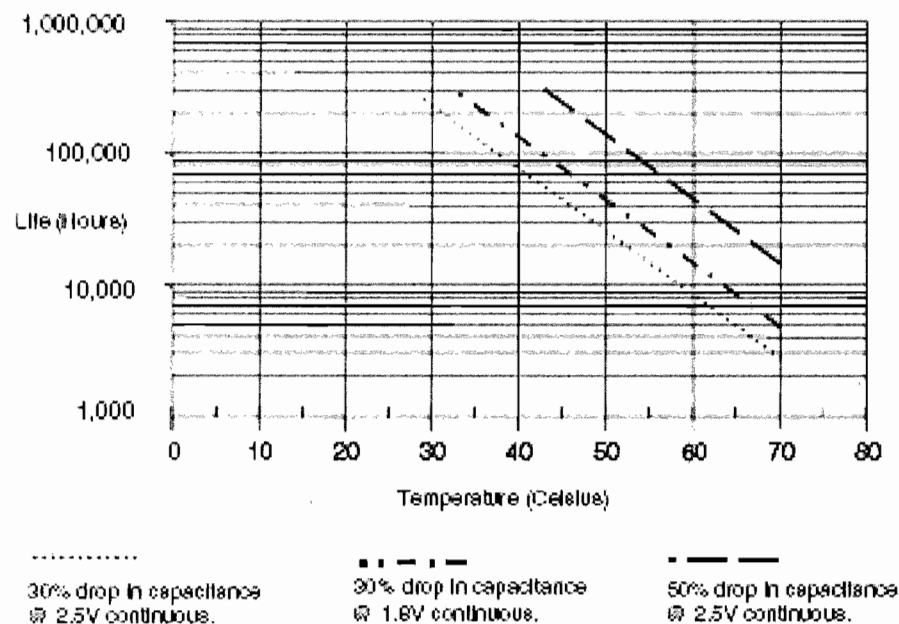
Figure 2. *Supercapacitor life curves from a manufacturer*

Stress and Derating

Derating is a common term related to applied stress on an electrical, mechanical, or

electromechanical device. Derating is the practice of limiting the stress applied to a component

to levels below the specified maximum (O'Connor, 1992). The goal of derating is to improve reliability, extending the useful life of a product or device, by designing it to operate at low stress conditions.

The life critical stresses for the supercapacitor are temperature and voltage, if the applied voltage exceeds the maximum rated voltage the result will be reduced lifetime. If the voltage is excessive for a prolonged time period, gas generation will occur inside the supercapacitor causing internal pressure to build which may result in leakage (Cooper, 2007). O'Connor (1992) recommends derating supercapacitor voltage to 80% of the devices rated maximum voltage. The recommended temperature derating is 20°C below the devices rated maximum temperature. For high reliability applications, the recommended derating is 50% of the maximum rated voltage and 40°C from the maximum rated temperature. The supercapacitors in company XYZ's application are rated for 2.5 volts and 70°C. The XYZ design application applies five volts across two supercapacitors in series. This results in 2.5 volts across each supercapacitor. Therefore, there is no voltage derating in company XYZ's design. The supercapacitor operates at approximately 40°C, in the XYZ application. Therefore, temperature is derated by 30°C in the XYZ design.

Voltage Balance

Voltage balance is another factor when two supercapacitors are used in series. If the two supercapacitors have exactly the same capacitance, the applied voltage will be equally distributed across the two. If one has a slightly higher capacitance than the other that it is in series with, the one with the lower capacitance will be subjected to proportionately more voltage across it. The supercapacitor manufacturers recommend a voltage balancing scheme to control the voltage across each supercapacitor connected in series (Cooper Electronic Technologies,

2007), (Maxwell Technologies, 2007), (Nesscap 2008) (Panasonic, 2006). Since there is no voltage derating in company XYZ's application, if the two series supercapacitors are not equal, one of the two will exceed its rated voltage. The simplest way to achieve voltage balance is to include a balancing resistor between the two series supercapacitors. This forces the voltage across both supercapacitors to be equal. However, this voltage balancing scheme can add leakage current to the circuit. This leakage current may be problematic for some designs.

Supercapacitor manufacturer ABC sells the dual supercapacitor subassembly shown in figure 1. It is two supercapacitors in series without voltage balancing, even though their own literature recommends voltage balancing. Research has discovered that manufacturer ABC does not include a balance resistor because large customers could not tolerate the loss in performance resulting from the extra leakage current. Manufacturer ABC pairs up supercapacitors from the same manufacturing lot in order to minimize variability between the two supercapacitors that make up the dual supercapacitor subassembly. This helps compensate for the lack of voltage balancing.

Other Publicized Occurrences of Leaking Supercapacitors

In general very little documented evidence of other cases could be found. However, in articles that were found, the problem of electrolyte leakage from supercapacitors appears to have been widespread. In 2001 to 2003 the electronics industry became plagued with problems cause by electrolyte leakage from similar capacitors. In their February 2003 issue, the IEEE Spectrum ran an article titled "Leaking Capacitors Muck up Motherboards" (Chiu, Moore, 2003). This article identifies the problem as faulty electrolyte and attempts to identify the source of the problem. It alleges that an incomplete electrolyte formula or recipe was stolen from a plant in Japan, and was then used in other capacitor and electrolyte plants in Taiwan. By interviewing

sources that repair computers, the article reported the problem was not only large in magnitude but could not be isolated to even a small number of suppliers. A photo from this article is shown in figure 3. Figure 4 shows an example of electrolyte leakage on one of company XYZ's products. One can see the corrosive effects on the adjacent circuitry.
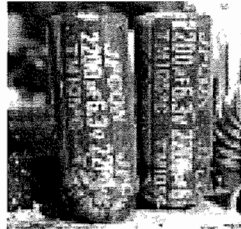
Figure 3. *Photo showing electrolyte leakage from supercapacitors (Chiu, Moore, 2003)*

Figure 4. *Photo showing supercapacitors electrolyte leakage on company XYZ's product*

An earlier article from Electronic News (Sperling, October, 2002) also reports on the same problem of capacitor's electrolyte leakage. This article states that the scope of the problem extended beyond just the computer industry. The problem also affected televisions and camcorders. This problem has caused a large ripple effect throughout the supply chain of and commercial electronics.

Test Methods to Demonstrate Reliability

This section describes approaches to demonstrating that a product meets a desired reliability. It examines accelerated life test approaches, and how to determine acceleration factors, sample sizes, and test times. Reliability can be defined as the probability of having no failures for a given time period. Accelerating life tests is accomplished by performing tests at higher than normal stress levels or cycle rates. Test acceleration is important, because it is how product behavior over a long period of time (such as reliability) can be observed in a relatively short time period. Knowing the acceleration factor of a test is critical to determining the equivalent operating life at normal usage conditions. It is also necessary for calculating reliability at normal usage conditions from the test results at accelerated conditions.

Accelerated Life Tests

There are two approaches to accelerated life testing. Life tests can be planned based on generally accepted theoretical acceleration models such as the Arrhenius reaction model. Accelerated life tests can also be designed such that the test results reveal the acceleration factors of the test. In practice, accelerated life tests can be initially planned using theoretical models, then as test data becomes available for analysis, the true acceleration factors can be calculated from the empirical data.

The Arrhenius reaction model is based on the rate of chemical reaction that occurs in components due to temperature and changes in temperature. Dovich (1990) states that the Arrhenius reaction model is often simplified by the rule of thumb that for every 10°C increase in operating temperature the life of a device is decreased by 50%. Likewise, for every 10°C decrease in operating temperature, the life of a device is doubled.

Another method of conducting an accelerated life test involves planning the test using multiple stress levels, for example a test may be performed at 3 or 4 different temperatures. Therefore, when failure data becomes available during the test, the data can be analyzed to determine the life characteristics at each stress level. In this way, the relationship between life and stress levels can be determined directly from the test data, rather than based on a theoretical model. However, one must begin a test with some general idea of the relationship between stress level and life time. Therefore, predictive models such as the Arrhenius model are used initially to plan the test.

Acceleration Factors

The stresses that affect the life of supercapacitors are temperature, voltage and current. Current is not a significant issue for company XYZ in the design application. Therefore, the test methodology considered primarily temperature and voltage as the life-dependent stress factors to accelerate. Three methods of determining acceleration factors for accelerated life tests are detailed in this section. These three methods are the Arrhenius model, a reliability prediction model, and an empirical approach.

The Arrhenius equation. The Arrhenius model was referred to earlier. The Arrhenius model applies primarily to temperature acceleration. The formula for the Arrhenius acceleration factor provided by Nelson (1990) is:

$$AccelerationFactor = \tau / \tau' = e^{\left(\left(\frac{Ea}{k}\right)\cdot\left(\frac{1}{T}-\frac{1}{T'}\right)\right)}$$

Where: τ is the life at normal operating temperature T,

τ' is the life at accelerated temperature T',

Ea is the activation energy,

K is Boltzmann's constant ($= 8.671 \times 10^{-5}$)

T is the normal operating temperature in degrees Kelvin

T' is the accelerated test temperature in degrees Kelvin.

All of these factors are known prior to performing the test except τ (this is what the test will determine) and activation energy (Ea). Activation energy typically takes on a value between 0.3 and 1.0 (Nelson, 1990). Its units are in electron-volts. Unless Ea is known from previous tests on similar products, an assumption may have to be made as to what the Ea value should be. The range between 0.3 and 1.0 can make a big difference in the results calculated for τ. The Bellcore reliability prediction procedures (1992) use an Ea value of 0.15 to account for temperature related stresses for non-solid tantalum capacitors. This is not a perfect match for the electrolytic supercapacitor, but it is the most applicable choice from the Bellcore prediction procedures. In an IEEE article regarding aluminum electrolytic capacitors, Zanobini, Iuculano, & Falciani (2006, April) cited the use of 0.405 for Ea. This is the value used for the analyses of this project. It is the most applicable to the electrolytic capacitors that make up the subject supercapacitors. However, the value assumed for use as activation energy adds a factor of uncertainty to using strictly theoretical models for conducting accelerated life tests.

Empirical approach. Supercapacitor consultant John Miller (2006) has published an accelerated life test approach that includes both temperature and voltage stresses. Figure 5 shows a pictorial view of this test design. In this test approach, supercapacitors were tested at four different temperatures and four different voltages. There were a total of ten voltage-temperature combinations represented in the test design.
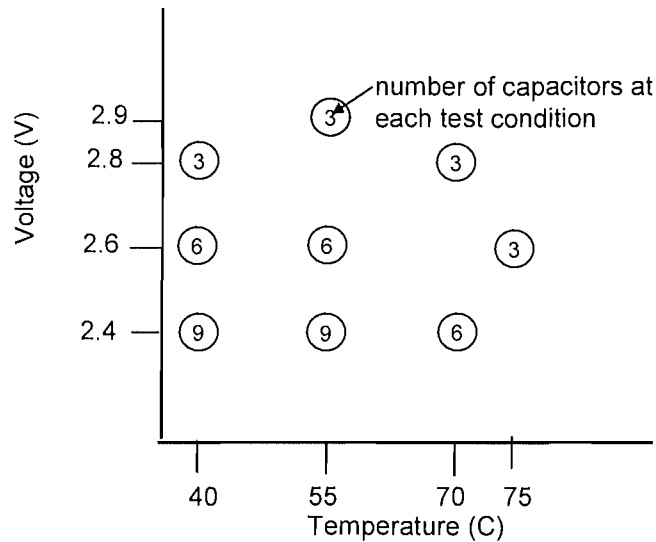
Figure 5. *Example test approach used by Miller, et al.*

Analysis of the test results allowed for the affects of temperature on life to be determined from the tests that samples that were at the same voltage conditions. Likewise, the affects of voltage on supercapacitor life could be determined from the samples that were tested at the same temperatures. Once the test was complete, a dual regression algorithm was derived by Miller, et al. (2006) from the test results that could estimate the life of a supercapacitor for any given combination of operating temperature and voltage.

Reliability prediction models. There are several resources that provide life reliability prediction models for electronic devices. One such resource is the Bellcore reliability prediction procedures (1992). These prediction methods are based on empirically derived stress-life relationships that account for electrical and thermal stress factors. These models represent the relationship between stress factors and electrical component life. Therefore, the reliability prediction models can be used to calculate the expected reduction in component life due to operation at various elevated stress levels. The result becomes the acceleration factor of the test. In fact the temperature factors from the prediction procedures are based on the Arrhenius

reaction model. However, Bellcore uses other models to calculate the affects of electrical stresses.

Sample Sizes and Test Times

In his book, Reliability Statistics, Dovich (1990) provides a method for determine sample sizes for zero-failure test plans. The sample sizes are based on achieving a desired reliability, at a given confidence level. The formula is:

$$n = \frac{\ln(1 - confidence)}{\ln(reliability)}, \text{ or } 1 - confidence = (reliability)^n \qquad \text{Formula 2.1}$$

Where: n equals the sample size, and

ln is the natural log.

The reliability function was determined, through previous analysis of field data, to follow a Weibull distribution with a shape parameter, β equal to 1.37. The formula for the Weibull distribution is:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad \text{Reliability Statistics, Dovich (1990),} \qquad \text{Formula 2.2}$$

Where: t equals the time over which the reliability is calculated,

β equals the Weibull shape parameter,

η equals the Weibull scale parameter, also known as the characteristic life, and

e is Euler's constant 2.71828.

This reliability formula (Formula 2.2) was substituted into the previous zero-failure test plan formula (Formula 2.1). Representing "confidence" with the letter C, the entire formula above can be written as:

$$1 - C = e^{-n\left(\frac{t}{\eta}\right)^{\beta}}$$
Formula 2.3

With a little algebra, this formula was used to assess tradeoffs between sample sizes and test times for a desired reliability, at a given confidence level.

Literature Review Summary

The literature research reviewed design application factors and how they relate to the life and reliability of supercapacitors. Temperature and electrical (applied voltage) stresses have a direct relationship to the useful life duration of supercapacitors. Reliable circuit designs derate or limit these stresses in order to prolong the life of products. These same factors, however, can also be used to accelerate life testing by operating devices at stress levels much higher than normal usage conditions. Other publicized incidences of electrolyte leakage were discussed. The commercial electronics industry was plagued by electrolyte leakage problems in the early years of the twenty first century. Additionally, accelerated life test models and test methods were explored. The mathematical formulas for calculating reliability and computing test times and sample quantities were presented. This research laid the groundwork for the remainder of this field project.

Chapter III: Methodology

This study endeavors to determine if the quality improvements implemented by supercapacitor manufacturer ABC exceed the reliability demonstrated by the lots that exhibited electrolyte leakage. This chapter details the approach taken to achieve this goal. The methodology includes analysis of field performance data, and accelerated life test planning. It also includes analyzing the results of accelerated life testing of the current supercapacitor.

Analysis of field performance data

The problem statement asserts that 5% of the products built within a certain date range have experienced electrolyte leakage from the supercapacitor. This was determined by evaluating available data. The data for the population of products included in this analysis has been acquired from data tables in company XYZ's enterprise resource planning (ERP) system. Ship dates, serial numbers, total quantities, and usage hours were derived from this data base.

Acquire failure, usage hour and ship date data. Quantities of failures – supercapacitors that have leaked - were taken from the monthly tracking data. Each failure record also includes the usage hours for the product at the time the failure was reported. These usage hour data are helpful; but in order to use it to calculate the probability of failure over time, the usage hours on the population that has not failed must also be known. However, this data can only be obtained when the product is returned to a service center for repair or maintenance. Therefore, a point estimate of the supercapacitor's reliability was calculated.

Calculate reliability based on available field data. The percent failure associated with electrolyte leakage was calculated by the number of failures (leakers) in the population, divided by the total number of products in the population. The percent failure can also be viewed as the probability of failure. The compliment of (one minus) the probability of failure is the probability

of success. The probability of success is, by definition, reliability. Therefore, a point estimate of reliability can be calculated as 1 – (number of failures / total population).

Reliability can also be determined from this time to failure data in combination with the usage hours on the entire population. In this way a reliability distribution can be determined which correlates the probability of success (or failure) to a given time (usage hours) in the field. But in this case, usage hours on the entire population were not available; therefore a point estimate of reliability was used.

Accelerated life Test

An accelerated life test was planned in order to demonstrate that the current version of the supercapacitor has a higher reliability than then lots more prone to leakage. An accelerated test method similar to the one discussed in chapter 2 was employed (see figure 3.).

Test setup and description. The accelerated life test was performed on six groups of supercapacitors. There were thirty supercapacitor samples in each test group. Each group was tested with a different combination of temperature and voltage stress conditions. The six groups of thirty supercapacitors were exposed to the following test conditions:

Individual supercapacitors (single component)

- 2.9 Volts DC (VDC) at 70 degrees Celsius

- 2.6 VDC at 70°C

- 2.9 VDC at 40°C

- 2.6 VDC at 40°C

- 2.75 VDC at 55°C

Dual Package (paired supercapacitors)

- 5.8 VDC at 70°C (This is equivalent to the samples at 2.9 VDC and

  70°C, since the voltage divides across the two supercapacitors in

  series.) This group is the control sample since these are the packaged

  parts used in the end product.

Acceleration factors. The acceleration factors for the above test conditions are based on

the difference from the nominal usage conditions, which are 2.5 VDC at 40°C. The Arrhenius

model, Nelson (1990), was used to determine the acceleration factors for temperature. The

Bellcore reliability prediction procedures (1992), were used to determine the acceleration factors

for voltage. Tables 1, 2 and 3 show the acceleration factors calculated for the test levels planned

for the supercapacitors.

Table 1:

Temperature Acceleration Factors

Test Temperature	Acceleration Factor
40°C	1.0
55°C	2.0
70°C	3.7

Table 2:

Voltage Acceleration Factors

Test Voltage	Acceleration Factor
2.6 VDC	6.6
2.75 VDC	8.2
2.9 VDC	10.1

Table 3:

Combined Voltage and Temperature Acceleration Factors

Test Configurations (Voltage and Temperature)	Acceleration Factor
2.6 VDC at 40°C	6.6
2.6 VDC at 70°C	24.6
2.75 VDC at 55°C	16.4
2.9 VDC at 40°C	10.1
2.9 VDC at 70°C	37.4

Test duration. The test was initially planned for 2300 hours. Based on the test quantities, 2300 hours at the accelerated test conditions is equivalent to total cumulative test time of 11,200,000 hours at nominal usage condition in the XYZ's product. chapter 4 shows how this was derived based on the test quantities, acceleration factors, sample sizes, and confidence level. If no failures (electrolyte leakage) are observed in this time frame, the product under test has demonstrated the acceptable reliability goal of 0.98 with 90% confidence.

Leakage determination. Test samples were inspected periodically to check for electrolyte leakage. They were checked daily in the beginning of the test, then gradually at longer intervals as the total test time increased.

Test results and data analysis. Ideally the acceleration factors could be determined directly from the test results. Time-to-failure data at 70°C can be used to determine the acceleration factor for the voltage stress (2.6VDC versus 2.9VDC). Likewise, time-to-failure data at 2.9VDC can be used to determine the acceleration factor for the temperature stress (40°C versus 70°C). This method requires that a minimum of 3 failures occur at each temperature and voltage combination in order to determine the life distribution at each stress level. If no failures occur, then the acceleration factors assumed in the test setup are used.

The reliability demonstrated by this test can be calculated from the cumulative test hours and the number of leakers found in the test. If all test samples complete this 2300 hour test under the electrical and thermal stresses without electrolyte leakage, they will have demonstrated a reliability of 0.98 with 90% confidence. Another way to state this is that there is 90% confidence that the probability of electrolyte leakage is less than 2%.

Methodology Summary

The accelerated life testing methodology was detailed in this chapter. Both temperature and applied voltage stresses were elevated simultaneously on supercapacitor test samples. Devices were exposed to five combinations of temperature and voltage in a design of experiments approach. The acceleration factors are listed for each of the three temperature and voltage stress levels. The number of test devices planned at each of the five combinations of accelerated stress levels dictated that the total test time must be 2,300 hours in order demonstrate the project objective was met. If no failures occur during the accelerated life, then there is 90% confidence that the probability of electrolyte leakage is less than 2% for the products 30,000 hour life.

Chapter IV: Results

This chapter presents the results of the supercapacitor reliability assessment project. The initial analysis of field performance data is shown, which led to the decision to initiate a product recall. Accelerated life testing was performed as described in chapter 3, Methodology. Additionally, field data from product in use in the field was used to provide additional support to the accelerated life test results.

Analysis of Field Performance Data

In the problem description in chapter 1, it was stated that the leaking supercapacitor issue has affected 5% of the company XYZ's products. This was determined by dividing the number of observed malfunctions by the total quantity of products potentially affected. The manufacturer of the supercapacitor (Manufacturer ABC) had implemented several quality and process improvements that have reduced the occurrence of electrolyte leakage. Communication with Manufacturer ABC identified the lot code of their final improvement. This lot code is identified (for the purposes of this report) as lot code 6222. With this information Company XYZ was able to determine how many of their products contained supercapacitors with lot codes earlier than 6222. Research of Company XYZ's shipments and finished goods found that approximately 13,000 products have been shipped to customers that have supercapacitors with lot codes earlier than 6222. Company XYZ has recorded 640 field issues of electrolyte leakage from this population of products. The quantities of failures – supercapacitors that have leaked - were taken from the monthly tracking data.

Calculate reliability based on field data. The percent failure associated with electrolyte leakage was calculated by dividing the number of failures (leakers) reported, by the total number of products in the population. The 5% defect number was derived by dividing 640 recorded

defects by the population 13,000 products containing the affected lots. The percentage of

failures can also be viewed as the probability of failure (probability of failure is 0.05). The

compliment of (one minus) the probability of failure is the probability of success. The

probability of success is, by definition, reliability. Therefore, a point estimate of reliability was

calculated as 1 – (number of failures / total population), which equals 0.95.

Accelerated Life Test

The accelerated life test was performed as defined in chapter 3. No electrolyte leakage

was observed from any test sample at the conclusion of the test duration – approximately 2300

hours. Test samples were inspected periodically to check for electrolyte leakage. They were

checked daily in the early stages of the test, then gradually to longer intervals as the total test

time increased. Appendix A contains a log of the observations and data collected from the

periodic inspections of the test samples. The following table shows the test results including the

test configuration and acceleration factors for each sample set.

Table 4:

Results of Accelerated Life Testing

Test Temperature	Test Voltage	Test Quantity (N)	Test Failures	Test Time (hours)	Total Device Hours	Acceleration Factors	Equivalent Hours
70	2.9	60	0	2,448	146,880	37.4	5,493,441
70	2.9	30	0	2,352	70,560	37.4	2,639,006
70	2.6	30	0	2,352	70,560	24.6	1,733,950
55	2.75	30	0	2,304	69,120	16.2	1,120,657
40	2.9	30	0	2,304	69,120	10.1	696,344
40	2.6	30	0	2,304	69,120	6.6	457,531
		Total	Total	Average	Total	Test	Total
		210	0	2,344	495,360	24.5	12,140,930

The absence of test failures did not allow an analysis of the time-to failure distribution.

Therefore, the results were analyzed using the same models and assumptions used to set up the

test. In other words, without failure data to analyze, the best method with which to analyze the results was the theoretical models – the same one used to design the test initially.

Reliability Calculations

Table 4 above shows the test results including total equivalent operating hours, taking into account the test accelerating factors of the test. The object of this research project was to demonstrate that the replacement supercapacitors will have no more than a 2% chance of failure throughout the 30,000 hour intended usage life. Another way to state this is that the reliability of the replacement supercapacitors will be at least 0.98 for 30,000 hours. The following calculations demonstrate how this objective was met based on the test results.

First, the average equivalent operating hours per test device were calculated by dividing the total equivalent hours (12,140,930 hours) by the total number of test samples (210 test devices). The result is 57,814 average hours per tested device. This number is denoted as tt, for test time. Next, formula 2.3 was used to solve for eta (η), the scale parameter of the weibull distribution, also known as the characteristic life. Formula 2.3 is repeated here.

$$1 - C = e^{-n\left(\frac{t}{\eta}\right)^{\beta}} \qquad \text{Formula 2.3}$$

All parameters of this formula have been identified except eta (η).

C = confidence level, 90% (0.90)

n = the number of test samples, 210.

β = the weibull shape parameter has been previously identified as 1.37

t = the time over which the reliability is calculated. tt will substituted for time, 57,814.

Using algebra to solve for eta (η), formula 2.3 is reconfigured as follows:

$$\eta = \frac{tt}{\sqrt[\beta]{\ln(1 - C)/(-n)}} \qquad \text{Formula 4.1}$$

Inserting the known values into formula 4.1 yields the following expression and result:

$$\eta = \frac{57,814}{\sqrt[1.37]{\ln(1-0.90)/(-210)}} = 1,574,315$$

Thus, the characteristic life parameter has been calculated which corresponds to having zero

failures when testing 210 devices for 57,814 hours. The test has demonstrated with 90%

confidence that the supercapacitor leakage life distribution (with a β of 1.37) will have a

minimum characteristic life of 1,574,315 hours.

Now that the weibull distribution parameters of shape (β), and minimum characteristic

life (η) are known for supercapacitor leakage life, the reliability of the supercapacitors can be

calculated for the 30,000 hour expected field life of company XYZ's products. Formula 2.2 was

used with the known β, the η parameter that has just been derived (above), and 30,000 hours

substituted for time, t.

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$
<div style="text-align:right">Formula 2.2</div>

The reliability, R(t), is computed as follows:

$$R(t) = e^{-\left(\frac{30,000}{1,574,315}\right)^{1.37}} = 0.996$$

This represents the probability of a single capacitor surviving 30,000 operating hours.

Recall that each capacitor is paired with another to create a 1uF device; and company XYZ's

product uses two of these dual capacitor devices. Therefore, there are actually four

supercapacitor devices in each of company XYZ's products. Hence, there are four opportunities

for a leaky supercapacitor per product. To account for this additional probability of failure, the

calculated reliability is raised to the 4th power (the reliability of the individual devices are

multiplied together).

$$0.996 \times 0.996 \times 0.996 \times 0.996 = 0.996^4 = 0.982$$

Thus, company XYZ's supercapacitor leakage reliability has been demonstrated with 90% confidence to be at least 0.982. Conversely, the probability of a product failing during its life time due to supercapacitor electrolyte leakage is at most 0.018, or a 1.8% chance of failure.

Combine Field Performance Analysis Results with Accelerated Life Test Results

The accelerated life test has demonstrated a reliability of at least 0.98. Additional confidence in the newest version of the supercapacitor was gained from the fact that no devices in the field with lot codes later than 6222 had yet failed due to electrolyte leakage. This was significant because of the latent nature of the electrolyte leakage failure mechanism. Due to this latency, at the time the decision was made to recall the supercapacitors, the devices of lot codes later than 6222 had been in fielded products for over 2 years. Previously, electrolyte leakage had been observed in the lots that were recalled, as early 3 months and out to 3 years in the field, and beyond. However, not one supercapacitor built after lot 6222, had leaked electrolyte in products that had been in the field for up to two years.

The fact that no failures were found during accelerated life test is a double edged sword. On one hand, there are not enough failures to actually identify the life distribution of the electrolyte leakage failure mechanism. One the other hand, since there were no failures the test devices are presumed to have a longer life, or better reliability, than the test was planned for. In the absence of test failures, the theoretical models with which the life test was planned are the best method available for analyzing the results. However, the test results were bolstered and supported by the failure-free results of field performance.

Total failures. There were no failures in the accelerated life test. There were also no failures experienced in the field at the time the life test was completed.

Total cumulative usage hours. There were 12,000,000 equivalent operational hours accumulated during the accelerated life test. At the time the accelerated life test was completed, there were approximately 19,000 units in the field that already had the newer supercapacitors in them. They had been built and shipped to the field over the preceding two and a half years. Each of these units has 4 individual capacitors in them, for a total of 76,000 devices in the field. A conservative estimate of their average accumulated operating time was 5,000 hours. Thus the total time on capacitors in the field, at the time the life test was completed was 380,000,000 hours.

The usage hours from the accelerated life test may look insignificant compared to the field operating hours, but it is very significant considering the time-to-failure aspect of the electrolyte leakage failure mode. The accelerated life test has represented up to ten and a half (10.5) years of operating time.

Results Summary

The recalled supercapacitor defect rate of 5% was shown in this chapter. The accelerated life test was executed per the plan defined in chapter 3. No failures occurred. The test log data was provided in appendix A. The reliability calculations were shown which explain how the test results were used to show the project goals were accomplished. In parallel to the accelerated life testing, the performance of supercapacitors in fielded products was monitored. No field failures occurred either. This positive field performance lent practical confidence to the accelerated life test results. The testing successfully demonstrated the project objectives were met.

Chapter V: Conclusion

Company XYZ had a problem with their medical device products that approached five percent of their total installed base. The problem, which was electrolyte leakage from supercapacitors, was caused by poor quality control by the manufacturer of supercapacitor. Company XYZ's design application did not allow for derating which also exacerbated the problem.

Company XYZ made the decision to recall products from the field and replace the electronics assembly that contained the potentially leaky supercapacitors. What was the appropriate replacement device? How could company XYZ be assured that this problem will eliminated or significantly minimized? The test plans and analysis presented in this paper answer these questions.

Objective

The objective of this project was to determine if the current version of supercapacitor made by Manufacturer ABC meets the reliability goal identified in the problem statement, which was:

"…less than 2% of XYZ's products, over the course of a 30,000 hour usage life, will experience a failure due to a supercapacitor that leaks electrolyte."

This objective was assessed through performing accelerated life testing combined with analysis of field performance data. Research was performed and provided on methods of conducting accelerated life test of supercapacitors.

Limitations

The absence of test failures made it necessary to rely on theoretical models with which to analyze the test results. However, the test results were validated by the positive results of field performance.

Conclusion

The objectives of this research project were successfully achieved. An accelerated life test method was researched, planned and executed. The results reported in chapter IV demonstrate with 90% confidence that the reliability goal was met. The goal was that less than 2% of company XYZ's products will fail due to supercapacitor electrolyte leakage over the 30,000 hour product life.

The author of this paper identified the scope and magnitude of the problem, and reported trend updates monthly to senior management. Company XYZ used this data to support the difficult corporate decision to recall fielded products with supercapacitors that had potential to leak electrolyte. The author also planned and executed the accelerated life that identified the solution that replaced the recalled product. The accelerated life test demonstrated, with 90% confidence, that newer lots of the supercapacitor had less than a 2% probability of electrolyte leakage failures.

Additionally, company XYZ had products that had been in use in the field with supercapacitors of the newer lot codes. None of these newer supercapacitors had leaked electrolyte. This empirical evidence supported the accelerated life test results. It also added confidence to the decision to replaced the potentially leaky supercapacitors (from lots 6222 and older) with newer supercapacitors of the same type (from lots greater that 6222).

Recommendation

Based on the results of this research project, it is recommended that company XYZ replace the assemblies of recalled products with assemblies containing newer supercapacitors that are much less likely to leak electrolyte.

The product recall effort was navigated successfully by company XYZ. It ultimately minimized future field failures and patient risk, while protecting the corporate quality reputation.

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Appendix A: *Log of Results from Periodic Test Sample Inspections*

This is the test log data kept throughout the accelerated life test. It identifies the test time (in hours on test) and the number of observed failures at each inspection point. There was no electrolyte leakage observed on any of the test samples throughout the planned duration of test.

70C Hours on Test	2.9V 70C	2.6V 70C	55C & 40C Hours on Test	2.75V 55C	2.9V 40C	2.6V 40C	5.8V @70C Hours on Test	5.8V 70C
360	0	0	312	0	0	0	456	0
384	0	0	336	0	0	0	480	0
408	0	0	360	0	0	0	504	0
432	0	0	384	0	0	0	528	0
504	0	0	456	0	0	0	600	0
528	0	0	480	0	0	0	624	0
552	0	0	504	0	0	0	648	0
576	0	0	528	0	0	0	672	0
600	0	0	552	0	0	0	696	0
672	0	0	624	0	0	0	768	0
696	0	0	648	0	0	0	792	0
720	0	0	672	0	0	0	816	0
744	0	0	696	0	0	0	840	0
768	0	0	720	0	0	0	864	0
840	0	0	792	0	0	0	936	0
864	0	0	816	0	0	0	960	0
888	0	0	840	0	0	0	984	0
912	0	0	864	0	0	0	1008	0
936	0	0	888	0	0	0	1032	0
1056	0	0	1008	0	0	0	1152	0
1080	0	0	1032	0	0	0	1176	0
1104	0	0	1056	0	0	0	1200	0
1224	0	0	1176	0	0	0	1320	0
1248	0	0	1200	0	0	0	1344	0
1272	0	0	1224	0	0	0	1368	0
1344	0	0	1296	0	0	0	1440	0
1368	0	0	1320	0	0	0	1464	0
1392	0	0	1344	0	0	0	1488	0
1416	0	0	1368	0	0	0	1512	0
1440	0	0	1392	0	0	0	1536	0
1512	0	0	1464	0	0	0	1608	0
1536	0	0	1488	0	0	0	1632	0
1560	0	0	1512	0	0	0	1656	0
1584	0	0	1536	0	0	0	1680	0
1608	0	0	1560	0	0	0	1704	0

70C Hours on Test	2.9 70C	2.6 70C	55C & 40C Hours on Test	2.75 55C	2.9 40C	2.6 40C	5.8V @70C Hours on Test	5.8V @70C
1680	0	0	1632	0	0	0	1776	0
1704	0	0	1656	0	0	0	1800	0
1728	0	0	1680	0	0	0	1824	0
1752	0	0	1704	0	0	0	1848	0
1776	0	0	1728	0	0	0	1872	0
1848	0	0	1800	0	0	0	1944	0
1872	0	0	1824	0	0	0	1968	0
1896	0	0	1848	0	0	0	1992	0
1920	0	0	1872	0	0	0	2016	0
1944	0	0	1896	0	0	0	2040	0
2016	0	0	1968	0	0	0	2112	0
2040	0	0	1992	0	0	0	2136	0
2112	0	0	2064	0	0	0	2208	0
2208	0	0	2160	0	0	0	2304	0
2352	0	0	2304	0	0	0	2448	0