DETERMINATION OF THE SHELF LIFE OF ALUMINUM ELECTROLYTIC CAPACITORS

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The aluminum electrolytic capacitor is used extensively in the electric utility industry. A factor limiting the storage of spare capacitors is the integrity of the aluminum oxide dielectric, which over time breaks down contributing to a shelf life currently estimated at one nuclear power electric generating station to be approximately five years.

This project examined the electrical characteristics of naturally aged capacitors of several different styles to determine if design parameters were still within limits. Additionally, the effectiveness of a technique known as "Reforming" was examined to determine its impact on those characteristics.

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INTRODUCTION

Capacitors are either electrostatic or electrochemical devices that are made up of various materials that will exhibit certain electrical behavior when exposed to external stimuli (Kogler, 1999). They are energy storage devices and that energy can be dissipated over a short or long period of time depending upon the application. Capacitors are used to filter, couple, tune, block direct current, pass alternating current, power correction, and electric motor starting (Dorf, 1997; Kogler, 1999). These passive components are grouped according to their dielectric material and mechanical configuration (Dorf, 1997).

Commercially available capacitors come in a wide variety of types and values. Electrolytic capacitors generally have the largest value of capacitance and are commonly used in power supply filtering applications (Slaughter, 1996). As can be seen in figure 1, aluminum electrolytic capacitors use aluminum as the base material (Dorf, 1997), and a thin oxide layer on the order of 0.01 micron as the dielectric (Phillips Components, 1994). Because of their large capacitance values relative to size, aluminum electrolytic capacitors are the most widely; used electrolytic capacitors in the electronics industry (Electric Power Research Institute, 2000).

Nuclear power utilities have, as part of their operating license, limits imposed upon the period of time certain systems and components may be out of service or in a reduced reliability state before positive actions must be taken to place the plant into inherently safer condition. These limits suggest an economic incentive to maintain a

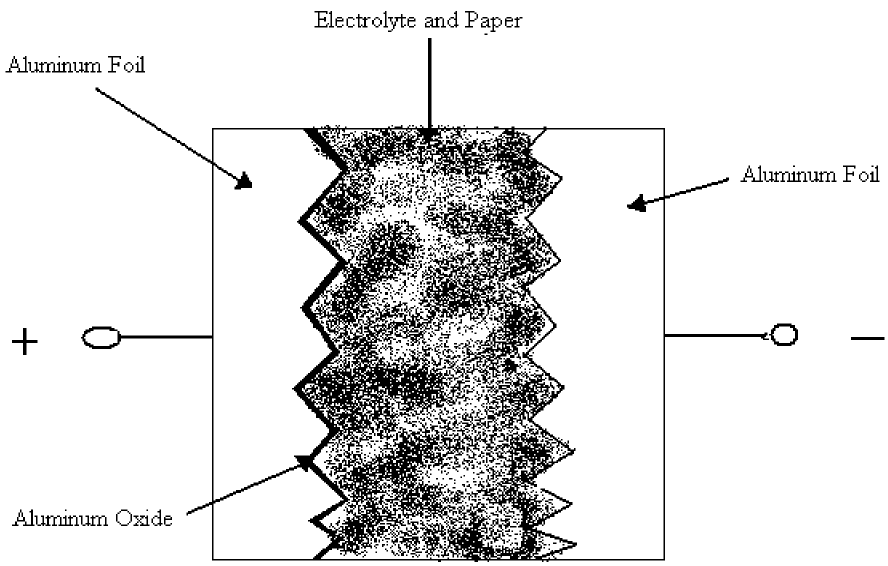


Figure 1, Structure of electrolytic capacitors

ready supply of spare parts. Due to the wide use of aluminum electrolytic capacitors of various styles and values in multiple systems and components, a large number of capacitors are maintained at the various nuclear generating stations in the United States and the world.

Aluminum electrolytic capacitors have a limited shelf life. The aluminum oxide dielectric is not stable. When a capacitor is in use (voltage applied) the dielectric is continuously being produced (healing). Because no healing takes place during storage, the dielectric strength will deplete due to dielectric polarization caused by impurities which exist in the material from manufacturing (American Society for Testing and Materials, 1978). The predominant effect on capacitors of this decrease in dielectric strength is a large increase in the DC leakage current (DCL) (Greason & Critchley, 1986), the theory of which I have explained in chapter two.

There is not a set shelf life beyond which an electrolytic capacitor is guaranteed to fail (Slaughter, 1996). Many manufacturers specify a typical shelf life for a capacitor or an assembly containing capacitors. The manufacture's stated shelf life for an aluminum electrolytic capacitor can range from 2 to 10 years, depending on the quality of the component (Kogler, 1999). Such a variation in shelf life can not be attributed only to design and application variations. Instead, it is believed that the variations are based on very conservative estimates of product life while in storage. The manufacturer will typically specify time intervals that should be conservative under all normal conditions (Davis & Funk, 1996). TXU Electric Comanche Peak Steam Electric Station established a shelf life of five years on all aluminum electrolytic capacitors unless periodically reformed (TXU Electric Comanche Peak SES, 1998).

The effect of aging on capacitors while in storage may be reduced or reversed by performing periodic reconditioning (more commonly referred to as reforming) to restore a capacitor's internal properties (Davis & Funk, 1996). Different methods have been described for reforming electrolytic capacitors. In general the process consists of applying voltage to the capacitor without exceeding the specified leakage current. The voltage is increased up to the rated value. This application of voltage tends to produce aluminum oxide thereby restoring the dielectric layer (Davis & Funk, 1996).

Problem Statement

The problem addressed in this research is the cost associated with the scrapping of capacitors that have reached the limit of five years storage and subsequent reorder cost.

The capacitors used in this research are standard commercial products commonly used at TXU Comanche Peak Steam Electric Station and other nuclear plants worldwide. The values for the electrical characteristic are the published values for the capacitors chosen. The capacitors were all naturally aged in the TXU warehouse systems, under conditions that exceed the requirements for ANSI level "B" storage. Testing performed was accomplished at Comanche Peak Steam Electric Station using standard readily available test equipment and TXU personnel. This research provided data to determine if the shelf life for capacitors could be lengthened, saving on scrapping and restocking cost.

Purpose

The purpose of this research was to determine for each style of aluminum electrolytic capacitors if they can be stored for periods longer than five years without deterioration of electrical characteristics below acceptable limits, and if reforming could successfully restore characteristic which have fallen below those limits.

Research Questions

There were two research questions addressed by this thesis. The first research question deals with the shelf life of unused aluminum electrolytic capacitors:

1. Is the shelf life of the various types of aluminum electrolytic capacitors 60 months?

This question has a corresponding null hypothesis 1 $(H_0)_1$: the shelf life of aluminum electrolytic capacitors is 60 months. As previously stated, the primary result of exceeding shelf life of capacitors is a large increase in the DC leakage current (Greason & Critchley, 1986) so the null hypothesis for all aluminum electrolytic capacitors is represented by equation (1) below where μ is the population average DC leakage rate for the capacitor.

$$\mu_{\text{Aged capacitor}} \geq \mu_{\text{Design capacitor}} \tag{1}$$

However, since there are three different styles of capacitors that may have different shelf lives the null hypothesis will be represented by three separate equations, one for each style of capacitor examined.

$$\mu_{\text{Aged can capacitor}} \geq \mathbf{DCL}_{\text{design can capacitor}} \tag{1a}$$

$$\mu_{\text{Aged axial capacitor}} \geq \mathbf{DCL}_{\text{Design axial capacitor}} \tag{1b}$$

$$\mu_{\text{Aged radial capacitor}} \geq \mathbf{DCL}_{\text{Design radial capacitor}} \tag{1c}$$

This research question also has an associated alternate hypothesis 1 $(H_a)_1$: the shelf life of aluminum electrolytic capacitors is some value greater than 60 months. As with the null hypothesis, there are three separate equations for the alternate hypothesis, one for each of the styles of capacitors. Reflecting the DC leakage current as the measurement of expiration of shelf life, the alternate hypothesis is represented by equation (2) below.

$$\mu_{\text{Aged capacitor}} < \mathbf{DCL}_{\text{Design capacitor}} \tag{2}$$

And expanding that equation for the different styles of capacitors result in the three equations below

$$\mu_{\text{Aged can capacitor}} < \mathbf{DCL}_{\text{Design can capacitor}} \tag{2a}$$

$$\mu_{\text{Aged axial capacitor}} < \mathbf{DCL}_{\text{Design axial capacitor}} \tag{2b}$$

$$\mu_{\text{Aged radial capacitor}} < \mathbf{DCL}_{\text{Design radial capacitor}} \tag{2c}$$

The second research question deals with the use of reforming to restore the electrical characteristic of aged capacitors. Research question 2 was:

2. Will the reforming process on capacitors that have been aged past five years improve their electrical characteristics?

The corresponding null hypothesis 2 $(H_o)_2$ can be stated as follows: there is no improvement in DC leakage due to the reforming process. This is represented by equation (3) below:

$$\mu_{Aged} - \mu_{Reformed} = 0 \tag{3}$$

Likewise, alternate hypothesis 2 $(H_a)_2$ can be stated as follows: there is less DC leakage after capacitors have been reformed. This is represented as equation (4) below:

$$\mu_{Aged} - \mu_{Reformed} > 0 \tag{4}$$

Unlike research question 1, there are not multiple equations representing research question 2. The capacitor response to reforming will be evaluated as it affects all styles.

Assumptions

The following assumptions applied to the research performed in this thesis:

1. Measuring and test equipment used in this research was assumed to provide accurate measurements because all measuring and test equipment was calibrated by TXU's calibration laboratory.
2. Capacitors used in this research were assumed to be homogeneous by style and date manufactured and representative samples of capacitors used in power supplies throughout the industry. This was assumed as the capacitors were selected from spare stock maintained by TXU for replacement of installed capacitors in power supplies common to multiple power plants (Electric Power Research Institute, 2000).

3. Samples selected for testing were unused and naturally aged under typical warehouse conditions during the period of their aging. This was assumed based upon the required periodic surveillance of the TXU Comanche Peak warehouse system.

Limitations

This research had the following limitations:

1. Style and ratings of capacitors limited to available stock of aged capacitors.
2. No effect of condition of storage of capacitors prior to receipt at Comanche Peak were included in the research.
3. Reforming technique used complied with Military Standard (U.S. Department of Defense, 1979) and did not always exactly follow manufacture's suggested technique.
4. Measurement of DC leakage applies a voltage to the test sample, which may result in some reforming of dielectric.
5. Testing was performed only at TXU's Procurement Overview testing facility.

Overview of the Remainder of the Research

Chapter 2 provides a review of literature related to the thesis. Specifically discussed are aluminum electrolytic capacitor theory and design and the effects of natural aging on capacitors. Chapter 2 also provides a discussion of reforming and the actions of the applied voltage to the deteriorated aluminum oxide dielectric layer of the capacitors.

Chapter 3 provides the details of the research including research design, control of variables, sample selection, test equipment and testing methodology. The statistical basis for this research including sample size and objective criteria is provided as well.

Chapter 4 contains the testing results and analysis as well as observations made during the testing. The conclusions reached from this research are discussed in chapter 5, and Chapter 6 contains recommendations for further research in this area.

CHAPTER 2

REVIEW OF LITERATURE

The aluminum electrolytic capacitor is used extensively in the electric utility industry. The need to maintain a supply of useful capacitors to replace failed components in the generating plants requires knowledge of the practical shelf life of this type of capacitor. A thorough understanding of capacitor theory as well as the effects of aging on the electrical properties of the capacitor is necessary to correctly assign shelf life.

The nature of the electrical utility industry is changing. Traditionally, a regulated monopoly, the industry is rapidly transitioning into a non-regulated competition arena. There is an acknowledged need to minimize operational and maintenance cost to remain competitive (TXU Corporation, 2000). The high cost of purchasing and testing the required replacements parts, when coupled with the increased incidences of obsolescence necessitating equivalency evaluation of proposed replacements mandates attempts to extend shelf lives.

A review of literature was conducted in the following areas: Aluminum electrolytic capacitor theory and design, effects of aging on capacitors, methods of shelf life evaluations, recent studies on capacitor performance and reformation of capacitors.

Theory and Design

A capacitor consists basically of two conductors separated by a dielectric so as to store an electric charge in a small volume. The capacitance is expressed as a ratio of electric charge to the voltage applied. According to the Electric Power Research Institute Capacitor Guide (Kogler, 1999) "… capacitance is dependent on 1) the dielectric constant of the medium between the plates, (2) the surface area, of one plate, and 3) the distance between the plates. (p.1)." Commercially available capacitors come in a wide variety of types and values. Electrolytic capacitors generally have the largest value of capacitance and are commonly used in power supply filtering applications (Slaughter, 1996).

The electrolytic capacitor was developed about 85 years ago and essentially consists of an aluminum foil ribbon, on the surface of which is a thin film of aluminum oxide formed electro-chemically, and a water-based electrolyte fluid which acts as the opposing plate (Phillips Components, 1994). Over the years since their inception, there have been continuous improvements in electrolytic capacitor design, and advancements in their technology. One of the most significant was that of etching the anode plate (Kaiser, 1995). In the modern capacitors, to reduce the size and increase the capacitance, the surfaces of the aluminum foil with greater than 99.9 per cent purity is etched and the electrode surface area is increased so that the foil can be used as the anode (Komatsu & Shimizu, 1991). The oxide dielectric has a thickness on the order of 0.01 micron (Phillips Components, 1994) and the electrolyte, usually a solution of ethylene glycol and adipic or boric acid is the cathode. Since the cathode is a liquid, and electricity cannot be conducted directly from it, an aluminum foil is used to play the role of the cathode. To avoid contact between the electrodes, an electrolytic sheet is included. To prevent loss of the electrolytic solution, capacitors are sealed in cases, usually of aluminum, with seals of rubber (Komatsu & Shimizu, 1991) and (Phillips Components, 1994).

Since the aluminum oxide film acts as the dielectric, the configuration and integrity of the film directly affects the performance of the capacitor. Formation of the film on the foil…

> Requires a continuous application of DC voltage at 140% to 200% of the rated voltage for the capacitor being manufactured. The dielectric thickness of this aluminum oxide film is approximately 15 angstroms/volt (United Chemi-Con Inc, 1995)

During operation, the applied voltage tends to produce a dielectric oxide that maintains the capacitor's characteristics. Spare capacitors are not energized therefor the dielectric oxide layer is not maintained and the capacitor electrical characteristics will tend to slowly change (Davis & Funk, 1996).

Practical capacitors are modeled and analyzed using equivalent circuits with distributed parameters. Due to the design elements and construction, not only does a capacitor have capacitance, but it also has a series resistance and inductance as well as a parallel resistance allowing the flow of current (United Chemi-Con Inc, 1995). As a result of these elements, at the terminals of a capacitor we see resistance that declines with frequency. Because it is really not a pure resistance, it is called ESR or "Equivalent Series Resistance (Kaiser, 1995). A useful diagram of this equivalent circuit, (figure 2) allows the modeling of aluminum electrolytic capacitors and should be referred to understand the effects of changes in the capacitors electrical characteristics. The characteristics of interest are Equivalent Series Resistance, DC Leakage Current, Capacitance, and Equivalent Series Inductance (Slaughter, 1996)and (United Chemi-Con Inc, 1995).

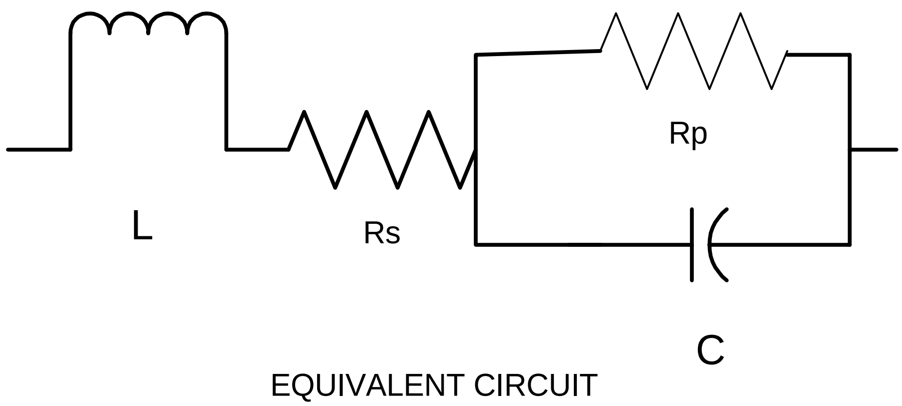


Figure 2

Equivalent Series Resistance (ESR) is made up of three basic constituents. These are the resistance due to aluminum oxide thickness, due to the electrolyte/spacer combination, and that due to the materials of construction e.g., the foil length, tabbing, lead wires and ohmic contact resistance (United Chemi-Con Inc, 1995). ESR can be calculated by measuring the initial dissipation factor (DF) at different frequencies and using the relationship of equation (5) (Greason & Critchley, 1986)

$$ESR = DF/(2\pi fC) \tag{5}$$

The Rp resistance seen in the equivalent circuit is shunt resistance. This resistance is due to the resistivity of the dielectric and case materials and to dielectric losses (Slaughter, 1996). In an ideal capacitor, Rp would be infinitely high, as this high resistance would prevent the flow of DC current in a charged capacitor. Leakage Current

(DCL) is a measure of the small amount of current allowed to pass within the capacitor (United Chemi-Con Inc, 1995)

> … due to very small foil impurity sites which are not homogeneous, and the dielectric formed over these impurities does not create a strong bond. Leakage current is also determined by the following factors:
>
> 1. Capacitance value
> 2. Applied voltage versus rated voltage
> 3. Previous history.
>
> The leakage current is proportional to the capacitance and decreases as the applied voltage is reduced. (p. 2)

Due to the nonlinear V-I characteristics of aluminum electrolytic capacitors, leakage current will decrease at a greater than linear rate as the applied voltage is decreased from the capacitor's rated voltage (Greason & Critchley, 1986).

As previously mentioned on page 3, capacitance is determined by effective plate area and dielectric constant. Variances in either of those factors will generally be small over capacitor life with the exception of the effects of electrolyte loss, since the electrolyte acts as the cathode, one of the plates, in electrolytic capacitors (Kogler, 1999).

> Gradually, during storage and/or operation, the electrolyte in an aluminum electrolytic capacitor is lost by means of vapor transmission through the end seals. The rate of loss is directly dependent on the composition of the electrolyte, the effectiveness of the end-seal, and the operating and/or storage temperatures…. Electrolyte loss can be measured as weight loss. … after about 40% of the electrolyte has been lost… the ESR increased rapidly, the capacitance decreased (p.37).

Therefore, the limiting factor determining the maximum possible capacitor life is the evaporation through the seals that dries the electrolyte solution (Komatsu & Shimizu, 1991).

The last of the components in the equivalent circuit is Equivalent Series Inductance (ESL). The inductance of a capacitor is a constant and is due primarily to the capacitor terminal spacing. Since this factor is unchanging and a function of the configuration of the capacitor, it is not a major component in any variations in electrical function of the capacitor. Generally speaking, the inductance does not affect the overall impedance unless the capacitor is operating at extremely high frequencies (United Chemi-Con Inc, 1995).

Effects of Aging

The effect of aging on capacitors is generally studied from the perspective of aging in use, that is, in an energized application (Denson & Domingos, 1996). From a shelf life perspective, the concern is the effects of long term storage in an non-energized state. Accelerated aging tests have shown that capacitors show a small decrease in capacitance but proportionately larger increases in ESR and DC leakage current (Greason & Critchley, 1986). The variation in capacitance is on the order of 10% and generally is more than made up by the wide tolerances in the manufacturers rating of the capacitors. The increase in ESR was on the order of 65% and DC leakage a magnitude of over 400% (Greason & Critchley, 1986). The effect of these elevated values for ESR and DCL has been shown to be a decrease in service life. As ESR goes up, the resistive heating of the capacitor in service increases. The effect of elevated temperatures is an increase in the rate of evaporation of the electrolyte, which in turns contributes to higher ESR values (Harada, Katsuki, & Fujiwara, 1993). The increase in DC leakage current also contributed to the effects of elevated temperature on the capacitor.

When an electrolytic capacitor is stored for an extended period of time, particularly at elevated temperatures, the internal resistance can drop to a level where the DC leakage current might exceed the rated value when initially energized. In many cases the leakage current will return to normal low levels after a short period of operation as the dielectric oxide layer is restored. However, in some cases when placed into service, the initially higher leakage current will generate excessive internal gas, resulting in a rupture of the rubber seals on the capacitor (Davis & Funk, 1996).

In the analysis of test results, (Greason & Critchley, 1986) concluded that the increased ESR in aged capacitors was due to the increased resistivity of the electrolyte, probably due to dryout. Improvements in the seals used by manufacturers have reduced the vapor loss in capacitors (Komatsu & Shimizu, 1991) and other than tightly controlling the environmental conditions of the storage of spare capacitors; little can be done to reduce electrolyte loss in storage.

A capacitor performance project completed in 2000 found that normal aging from time and temperature have little effect on filter capacitor's behavior in linear power supplies(Electric Power Research Institute, 2000). For some capacitors as old as 28 years, there was some loss of electrolyte and capacitance decrease, especially in larger can style capacitors, but as long as there was enough electrolyte left in the capacitor, the capacitor would reform itself, either in the application circuit or by reforming outside of the circuit (Electric Power Research Institute, 2000).

DC leakage current values can be reduced in stored capacitors by performing periodic reconditioning (more commonly referred to as reforming) to restore a capacitors internal properties (Davis & Funk, 1996).

… thereby restoring the dielectric oxide layer (p.81). Different methods have been described for reforming electrolytic capacitors. In general, the reforming process consists of applying voltage to the capacitor without exceeding the specified leakage current. The voltage is increased up to the rated value… the application of voltage tends to produce dielectric oxide

MIL-STD-1131B provides guidance and a typical circuit (figure 3) for reforming (U.S. Department of Defense, 1979).

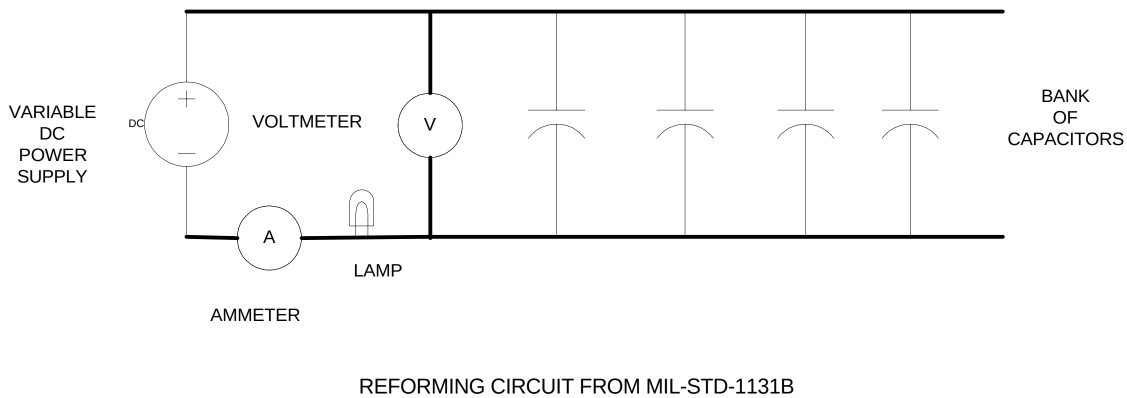


Figure 3.

Current Shelf Life Methods

There is not a set shelf life beyond which an electrolytic capacitor is guaranteed to fail. In one study, electrolytic capacitors were verified to perform adequately after 30 years of storage (Davis & Funk, 1996). Capacitor manufacturers tend to establish conservative shelf life limits for their electrolytic capacitors. Published shelf lives can range from as low as two years to greater than ten years (Slaughter, 1996). Texas Utilities Comanche Peak Steam Electric Station (TXU Electric Comanche Peak SES, 1998) established:

> Shelf Life is 16yrs with periodic reforming in accordance with manufacturers' standards, otherwise 5yrs or manufacturer's recommended shelf life. (p. 8.B)

Such a variation in shelf life can not be attributed only to design and application variations. Instead, it is believed that the variations are based on very conservative estimates of product life while in storage and assumed storage at the most extreme temperatures. From plant experience and limited studies, it appears that even the shelf life of aluminum electrolytic capacitors may not be as limited as previously thought (Kogler, 1999).

Styles of Capacitors.

Capacitors are grouped according both to their dielectric material and their mechanical configuration (Dorf, 1997). There are three major styles or types of these capacitors; radial lead, axial lead, and cylindrical or can. There is a distinction between the axial and radial lead-type and can-type aluminum capacitors (Kogler, 1999).

Axial and radial lead capacitors are those typically used on printed circuit boards where space is at a premium. The sealing mechanism of these types of aluminum electrolytic capacitors is also different than the can style and better prevents evaporation of the electrolyte (Kogler, 1999). Manufacturer’s data indicates that the oxide film of these style capacitors is quite stable at no load conditions (Vishay Sprague, 1995), and these capacitors do not “deform”. This stability is credited to good anodizing techniques that result in a superior oxide film (Kogler, 1999).

Can-type aluminum electrolytic capacitors are used in power supplies, converters and inverters are typically of higher capacitance and have diameters greater than one inch (Kogler, 1999). Typically can capacitors, especially the larger sizes have screw terminals and vent plugs to act as relief of the electrolyte if excessive pressure builds up due to heating, either ambient temperature or as a result of excessive current. Safe operating voltages of can style capacitors can exceed 450 volt, but the construction has certain inherent limitations that affect the use and performance of these capacitors (Phillips Components, 1994). The larger plate areas of these capacitors make for appreciable leakage currents.

Based on the differences between the styles and some anecdotal information provided by various utilities, EPRI in the Capacitor Maintenance and Application Guide (Kogler, 1999) has suggested that:

> Can electrolytic capacitors, typically greater than 1 inch in length and diameter and used in power supplies, converters and inverters, should have a shelf life of about 20 years, based upon storage temperatures.
>
> Radial and axial lead electrolytic capacitors of the type used on printed circuit boards should have a shelf life greater than the can electrolytic capacitors. Radial and axial lead capacitors tend to have smaller volumes and better sealing mechanisms. (p. 2-6)

CHAPTER 3

METHODS AND MATERIALS

The review of literature in chapter 2 demonstrated the need to determine the shelf lives of the different styles of aluminum electrolytic capacitors. The review further indicated that, for those capacitors aged past their actual shelf life, the DC leakage current may has risen to the point that failure will occur when energized or shortly after being placed into service. Reforming is a method to reduce the DC leakage current of aged capacitors to extend their shelf life. This research focused on determining if aluminum electrolytic capacitors have a longer shelf life than previously assigned and if the reforming technique does reduce the aged capacitors' DC leakage current values.

The approach used in this research was to select unused capacitors that had been naturally aged, as opposed to artificially accelerated aging, and that were representative of capacitors used in power supply circuits at utility power plants and elsewhere in industry. The capacitors were obtained from warehouse inventory at TXU's Comanche Peak Steam Electric Station and had been in storage under normal storage conditions for periods of time greater than 5 years. Each capacitor was tested and the electrical characteristics measured and compared to the published design characteristics of new capacitors. A reforming process was performed and the testing and measurement repeated. The post reforming values were then compared to the unreformed capacitor values and the design values of new capacitors.

Research Design

This research was conducted in two steps, which corresponded to the two research questions. The first part of the research addressing the question of shelf life used a post-test only experimental design with a comparison to published design values. No pretest measurements of values were possible in that the "test" was the natural aging of the capacitors, and as such the test duration was as a minimum 5 years and in the case of one style of capacitors 19 years. The selection of this experimental design was made as it most closely matched the research question, "Is the shelf life of capacitors five years?"

The second research question dealing with the reforming process was modeled with a pretest, test, post-test experimental design, in which the pretest measurements of that experiment were the post-test measurement of the first experimental design. The electrical characteristics of the aged capacitors measured in the first experiment were compared to the values measured after those capacitors had been reformed. The result of these comparative experiments allows the conclusions to be drawn that I discuss in chapter 5 (Diamond, 1989). This research was designed to control those variables that could be controlled and that would affect the capacitors electrical characteristics. Variables that were not expected to affect the results or were uncontrollable (intervening variable) were not controlled.

Controlled Variables

The independent variable or factor that was the primary interest of this research was the age of the capacitor. This capacitor aging occurred during normal storage at TXU's Comanche Peak warehouses. Conditions during that storage were controlled and monitored (TXU Electric Comanche Peak SES, 1999). The selection of the capacitors to be aged occurred as a natural result of inventory stocking activities during the construction phase of the two unit nuclear pressurized water reactor generating station. The aged capacitors were examined for manufacturing dates to ensure that no possible confusion with new or more recently manufactured samples occurred. For those capacitors with no manufacturing dates marked on the case, a review of purchase and issue history was performed to confirm date of receipt and verify no commingling of variously aged pieces.

The reforming process effect on the capacitor was the other factor of primary interest in this research and thus the other independent variable or factor. The military standard (U.S. Department of Defense, 1979) and as well as manufacturers of capacitors (Phillips Components, 1994) provided information on reformation circuits and controls to prevent damage to the capacitors. The circuit used in this research to reform capacitors was designed to closely match the diagrams shown in the manufacture's literature and military specification. The circuit set up was used on all capacitors reformed, with the only variations being the values of the current limiting resistors and the voltage settings used on the power supply. The rating of the capacitors reformed drove the selected parameters.

The capacitor style and electrical ratings were the moderating variables associated with the capacitors. As reviewed in Chapter 2, the shelf life of different styles of capacitors was believed to vary, with cylindrical can capacitors having shorter shelf lives than the radial or axial lead capacitors (Kogler, 1999). Capacitors selected to be tested were of each of the three different styles. Capacitors used in this research were of standard grades and common commercial ratings.

The moderating variable associated with the reforming process that could affect the capacitors was regulation of the power supplies used to reform the capacitors. Monitoring of the current and voltage output of the supplies using calibrated meters ensured no variation in regulation. Additionally, all testing was performed using the same meters during one cycle of normal calibration.

Uncontrolled Variables

The extraneous variables that were not expected to confound the results were not controlled in this research nor were the intervening variables. Variations in the storage environment of the capacitors during the many years of storage were not controlled any tighter than the requirement of “Level B” storage. The warehouse storage procedures required the temperature to be maintained between 40 and 140 degrees Fahrenheit (TXU Electric Comanche Peak SES, 1999). A long-term variation of storage temperature of 100 degrees could possible affect the chemical breakdown of the dielectric film layer (Slaughter, 1996). TXU warehouse procedures require notification and documentation of the dates and duration of periods when the temperature in the warehouse exceeds 100 degrees. A review of non-conformance reports for TXU shows that the temperature excursions over 100 degrees occur infrequently and usually last for less than 6 hours (Simmon, 1999).

Control variations in manufacture of the capacitors was an intervening variable that could have affected the results of the testing. Variations in the weld characteristics of the lead to foil connection have been shown to result in differences in electrical characteristics that may have impacted test results (Slaughter, 2001). ESR measurements were recorded for all test specimens to identify any significant variations.

Required Sample Sizes

In every experiment, there is a risk that the experimenter will infer the wrong decision from the test data. However, the amount of risk can be controlled by selecting the proper sample size to use in the experiment (Diamond, 1989). The two different research questions could have possibly required different sample sizes. The first question dealing with the shelf life of the capacitors could be described as a comparison of means. That is, the mean value of the DC leakage current for aged capacitors was compared to a design maximum value. The determination of sample size for this question followed the approach described as "Case 4" by Diamond (1989). In that case, the alpha and beta risks were first chosen. A value for the desired minimum difference, δ, between the mean of the aged capacitors' DC leakage current and the design number chosen to accept that there is a difference at those risk levels was then determined. The sample size was then calculated for a normal distribution as a first approximation. The size of the sample was then calculated using a student t distribution based on the preliminary normal distribution sample size.

The second research question dealing with the effectiveness of the reforming process is an example of a pair-comparison experiment (Diamond, 1989). In a pair-comparison experiment, the experimenter is interested in determining the effect of a process on a part. This method is to measure the trait of interest on a sample, in this case the DC leakage current. The reform process is then performed on the sample and the DC leakage re-measured. The difference between leakage currents before and after reforming is the effect of reforming on the capacitor. The differences for all the capacitors tested then become the data, which is analyzed to make the decision as to which hypothesis to accept. The sample size for the pair-comparison test is made by letting the desired improvement, δ, be equal to the standard deviation, σ, of the mean of the differences measured. The required sample size is then calculated in the same manner as in the first research question.

Alpha (α), Beta (β), and Delta (δ)

The assignment of values for the probabilities of committing type I (α) or type II (β) errors was made based upon the consequences of committing those errors. Rejecting the null hypothesis, H_0, when it is true would, in the case of the first research question result in allowing capacitors to be stored or used passed their allowed shelf life. Committing a type II error, rejecting H_1 when it was in fact true, would result in disposing of spare parts that were still acceptable for use.

In the second research question, the consequence of committing a type I error would mean that it would have been claimed that reforming capacitors restored the desired lower DC leakage current levels when, in fact, it did not. This would result in increases in labor cost to perform the process with no improvements gained. A type II error would claim that reforming made no difference when, in fact, there was an improvement. The type II error would have resulted in a missed opportunity to reduce inventory and restocking cost associated with replacing aged unused capacitors.

It appears that the consequence of committing a type I error is greater that for type II errors, at least in the first research question, in that unacceptable capacitors may be retained. The pre-installation testing that occurs at nuclear facilities mitigates this consequence making it unlikely that nuclear safety would be impacted. Because the consequences of committing both types of errors were otherwise similar, the significance of both types of errors were treated the same in this research. The probability of committing a type I error, α, is generally chosen to be in the range of .01 to .1 (Kvanli, Guynes, & Pavur, 1996b). For my research, I chose to minimize the probability of errors to 1% and therefore chose the value of .01 for both α and β.

The term δ is the other factor necessary to determine the sample size. δ is the difference between μ_0 and the potential value of μ_1 at which the β risk applies and is termed delta. δ is the Greek letter delta (Diamond, 1989). The larger the amount of difference, or improvement, the smaller the sample size at the same risk. Since no information on the value of the DC leakage current for the aged capacitors was available until they could be tested, delta as a function of population variance was chosen as the approach used to deal with determination of sample size. A value of δ equal to one standard deviation σ was specified for the second research question and that value was also used for the first question. A larger value of delta would have allowed a smaller sample size, but may have rejected H_1 unnecessarily. The selection of one standard deviation will result in approximately 68% of the measured values for the aged capacitors being within plus or minus one sample standard deviation of the measured mean of the samples (Kvanli, Guynes, & Pavur, 1996a).

<u>First Approximation of Sample Size</u>

For both research questions, the value of the population variance, σ^2, is unknown and only an estimate of σ^2 could be obtained from the experiment; that estimate is S^2. Using an estimate of σ^2 introduces an additional element of uncertainty into the experiment and the decision making process. This additional uncertainty is taken into account by using what is called the *t* distribution in place of the normal distribution when the variance (σ^2) is only estimated (Diamond, 1989). When calculating the sample size using the *t* distribution, a first approximation is made using the normal distribution (figure). For this case, the sample size for a normal distribution at a specified α, β, and δ is given by the equation (6) (Diamond, 1989):

$$N = (U_\alpha + U_\beta)^2\, \sigma^2/\delta^2 \qquad (6)$$

For a single sided test with α and β chosen as 0.01, $U_\alpha = U_\beta = 2.326$. This results in a normal distribution sample size of N = 21.641.

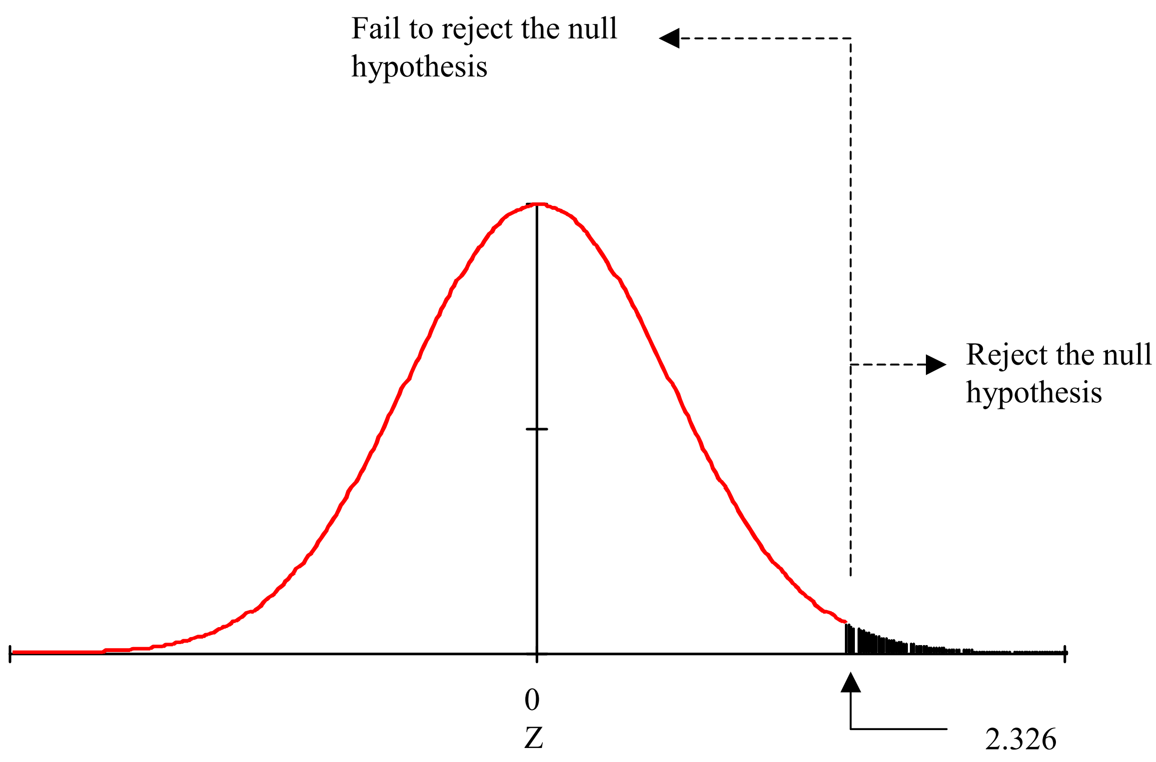


Figure 4. Normal distribution one tail plotted with Matlab.

Refined *t* Distribution Sample Size

The estimate of N obtained above is too low since the decision-making criterion should be based on the *t* distribution instead of the normal distribution. Following the guidance given by Diamond (1989), values for t_α and t_β are obtained from table 3 with ϕ, the degrees of freedom, set at N-1 = 20.641. The value obtained for t_α and t_β, 2.53, was substituted into the equation for sample size using *t* distribution:

$$N_t = (t_\alpha + t_\beta)^2\ \sigma^2/\delta^2 \qquad (7)$$

$$N_t = (2.53 + 2.53)^2\ \sigma^2/\delta^2 = 25.6 \qquad (8)$$

Rounding up, the required sample size for both of the research questions were determined to be 26.

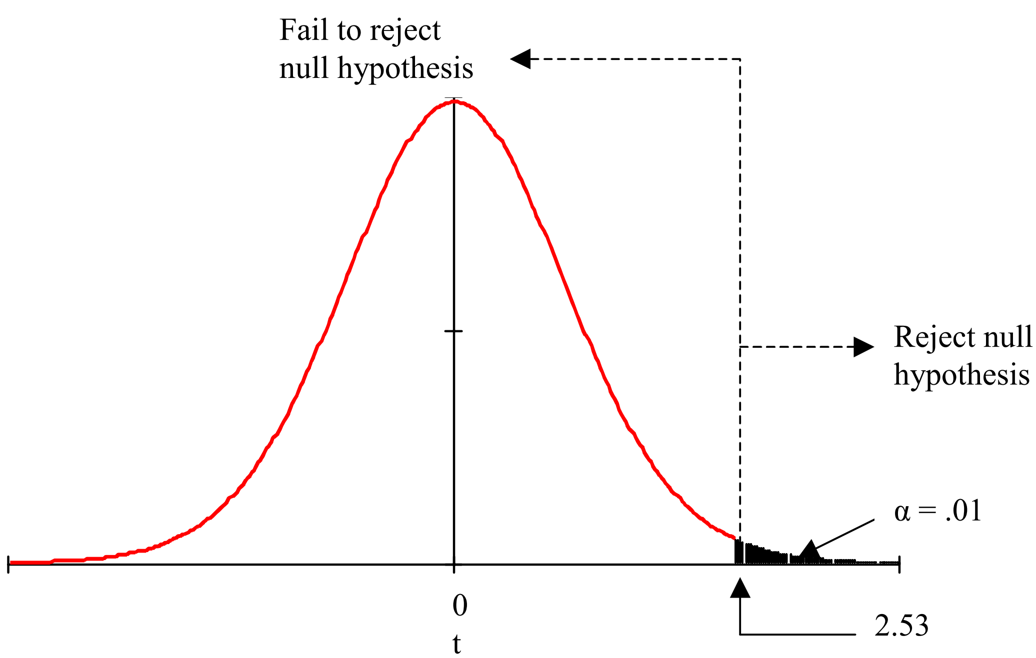


Figure 5. Student t distribution with 25 degrees of freedom, one tail test, plotted with Matlab.

Objective Criteria

The objective criteria provides the measure by which the test results can be compared to the design criteria to determine if sufficient differences between the estimate of population mean and the design value exist to reject the null hypothesis. The one-population-sample situation arises when the experimenter wishes to compare a population with a fixed number (μ_0) (Diamond, 1989). The research questions dealing with the shelf life of the capacitors is such a one-population-sample situation. If the observed means of the test samples was less than the criteria value determined by equation X, than the null hypothesis is rejected and the alternate accepted.

$$X^* = \mu_0 - t_\alpha S / (N_t)^{1/2} \qquad (9)$$

The research question dealing with the reforming process was addressed using a pair-comparison technique. To evaluate the effectiveness of reforming, a comparison of the DC leakage current of an aged sample was made to the same parameter after reforming. The mean of the differences for all of the samples process for a given population was then compared to the objective criterion determined by equation X (Diamond, 1989).

$$X^* = t_\alpha S / (N_t)^{1/2} \qquad (10)$$

In this evaluation, if the observed mean of the difference was greater than the criterion value X* $H_{0,}$ the null hypothesis is rejected and the alternate, H_1 accepted.

Test Capacitors

As previously stated, the capacitors which were used in this research were obtained from the stock of the Comanche Peak Generation Station and had been naturally aged for more than five years. With a required sample size of 26, the population from which to select was limited to capacitor styles and ratings with existing quantities greater than 26. An additional limiting criterion was the requirement of common date of manufacture. Factoring all these requirements, and selecting one of each style of capacitor; radial, axial and can, resulted in the selection of following capacitors.

<u>Radial Lead Capacitor</u>

The capacitor selected as the example of radial lead style was the XICON™ XRL series 220 MFD 50 VDC (see figure 5). The warehouse inventory for this part revealed 127 on hand; all of which were procured on the same purchase order and received in 1991. This capacitor has no date code markings, but labels received with the capacitors

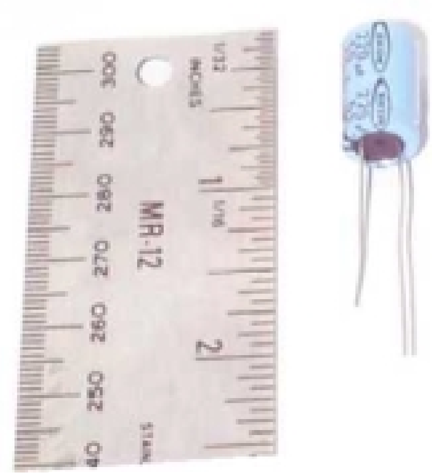


Figure 6, Radial lead capacitor

showed the date of July 1991. Information from the product catalog was extracted to determine the design DC Leakage using the following formula (Xicon Capacitors, 1993).

I = 0.02CV or 3 (μA) whichever is greater (after 5 minutes) applying the rated DC working voltage at 20˚ C)

Where: C = rated Capacitance in μF.

V + rated DC working voltage.

Using this equation and 220 μF and 50 VDC gives the following:

$$I = 0.02\ (220)\ (50) = 220\ \mu A \qquad (11)$$

This style of capacitors is a commonly used printed circuit board mounted component.

Axial Lead Capacitors

The capacitor selected as the example of radial lead style was the SPRAGUE™ Type TE, Littl-Lytic® TE1307, 50 MFD 50 VDC (figure 6). The warehouse inventory for this part revealed 35 on hand; all with the same manufacturer date code of "9147" which corresponded to the 47 week of 1991. The maximum design leakage current for all type TE capacitors at + 25°C is 15μA except for case code "DD" which is 15.8μA. The TE1307 is a case code "DD"(Vishay Sprague, 1995). These axial lead capacitors are widely used in the power supplies in the nuclear instrumentation cabinets at Comanche Peak and other nuclear utilities that use Westinghouse supplied nuclear instruments (TXU Electric Comanche Peak SES, 2001).

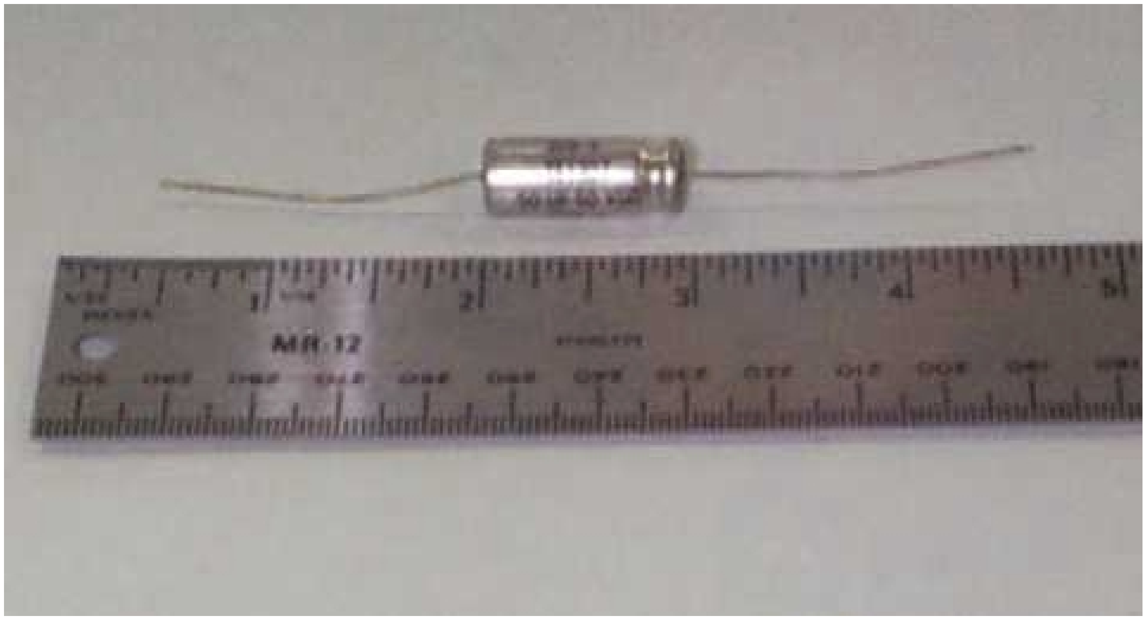


Figure 7, Axial lead capacitor

Can Style Capacitors

The capacitor selected as the example of canister or “Can” style capacitors is a Sprague Powerlytic® 36D model 530-250 DC. This capacitor has a rating of 530 MFD at 250 VDC (figure). The inventory of these capacitors included 40 with date codes of “8226” and 29 with date codes of “8747”. Samples of 26 of each of these date codes were selected for the testing which was performed. The maximum DC Leakage current for these capacitors is calculated by the following formula (Vishay Sprague, 1995):

$$I_{microamps} = K(CV)^{1/2} \quad \text{where } K = 4 \text{ @ } 25°C$$

$$I = 4 * (530 * 250)^{1/2} = 1456\ \mu A = 1.456\ mA \qquad (12)$$

These can style capacitors are commonly used in power supplies as output filtering devices.

Figure 8, Can style capacitor

Test Sequence

The test sequence followed for all the samples tested were similar. The samples of the population were randomly selected from all of the available capacitors of the same date code. In the case of the radial and axial lead capacitors, this random sample technique consisted of a "grab bag" in that all of the samples were collected loosely in a large bag and the required sample size of 26 were chosen by reaching into the bag and removing that number, one at a time. For the can styles, since the total population from which to chose was much smaller, the technique here differed in that instead of selecting the samples to be tested, I selected the samples which were not to be tested. The selection process was conducted the same, otherwise.

Once the samples were selected, the testing proceeded in the following order. First, for a sample type and style, the capacitors were all tested for capacitance and ESR values using a Keithley® model 3330 LCZ meter (Keithley Instruments Inc, 1991). After those measurements were obtained, a DC leakage test was performed on the sample at the rated voltage and duration specified by the manufacturers' data sheets. Following the DC leakage testing, the samples were reformed using the circuit diagramed in figure 2, with the modification of the use of a current limiting resistor in place of the lamp shown on the figure. The resistor was chosen to limit the current to not exceed the rated allowed DC leakage current. Post reforming, all the initial testing was repeated after a minimum wait of at least 24 hours. The results of the testing are documented in the appendixes and discussed in chapter 4.

Figure 9, Keithley 3300 LCZ meter

Figure 10, DC leakage testing of can capacitors

Figure 11, Reforming a group of 13 can style capacitors

CHAPTER 4

RESULTS AND ANALYSIS

All testing of capacitors and reforming processes were conducted at TXU's Procurement Overview test facility. The temperature was maintained at 25 degrees Celsius and all test equipment and power supplies were observed to be in calibration and operated per established procedures. The results of the testing were recorded manually on data sheets and later entered into Microsoft® Excel spreadsheet. The equations for testing objective criterion as explained in chapter 3, were the primary test method employed to analyze the test data. Additionally, observation of the samples appearances and evaluation of capacitance and ESR was performed to identify any possible extreme outlying results.

Tests of Objective Criteria

Tables 1 and 2 are based on the observed test data sheets (Appendix A) and show the results of the testing of each of the sample populations compared to the objective criteria. The tables show the sample population means, standard deviation and test criterion.

Table 1 addresses the first research questions: Is the shelf life of the various styles of aluminum electrolytic capacitors five years? For each of the styles and sample groups, the objective criteria was computed using equation 9. As can be seen in Table 1, for each sample population, the mean value of DC Leakage was less than the objective criteria and resulted in the rejection of the null hypothesis and accepting the alternate hypothesis with at least 99 per cent confidence.

Table 1. Test of null hypothesis for shelf life

Capacitor Style	DC Leakage Sample Mean	Sample Std. Deviation	Test Criterion	Null Hypothesis
Radial Lead	40.14 µamps	29.83 µamps	205.2 µamps	Reject H_0
Axial Lead	11.22 µamps	4.13 µamps	13.75µamps	Reject H_0
Can, 14 year	148 µamps	66 µamps	1423 µamps	Reject H_0
Can, 19 year	1340 µamps	192 µamps	1361 µamps	Reject H_0

Table 2 corresponds to the research question 2: Will the reforming process on capacitors that have been aged past five years improve their electrical characteristics? The objective criteria for this question were computed using equation 10. Table 2 shows that for each of the styles tested, the comparison of the mean of the difference between the reformed and unreformed DC leakage values to the criteria for that style resulted in rejection of the null and accepting the alternate hypothesis with a greater than 99 per cent confidence.

Table 2. Test of null hypothesis for reforming process

Capacitor Style	Mean of Difference in DCL	Standard Deviation	Test Criterion	Null Hypothesis
Radial Lead	29.95 µamps	27.32 µamps	13.55 µamps	Reject H_0
Axial Lead	3.97 µamps	3.69 µamps	1.83 µamps	Reject H_0
Can, 14 year	79 µamps	55 µamps	27 µamps	Reject H_0
Can, 19 year	1089 µamps	162 µamps	80 µamps	Reject H_0

ESR and Capacitance Observations

As explained in Chapter 2, the correlation between ESR and DC leakage current is normally an inverse relationship. Additionally, ESR is a parameter that also indicates the homogeneity of a lot or population of capacitors (Slaughter, 2001). Appendix B contains plots of the ESR and Capacitance of each of the aged samples to allow a visual analysis of variations in ESR from sample to sample and the relationship to measured capacitance. The appendix also contains plots of ESR and Capacitance, before and after reforming. This graphical indication clearly shows the inverse relationship between the reforming processes improvement of DC leakage and the increase in ESR. The only noticeable exceptions were several samples of the oldest, most aged can style capacitors. Of those capacitors, several showed reductions in ESR post reforming. This reduction was accompanied by the expected improvement in capacitance and would seem to be contrary to expected increases in resistance due to electrolyte changes or the increased thickness of the aluminum oxide layer, post reform (Harada et al., 1993). A possible explanation was derived from a visual examination of the samples. The older can capacitors use a screw terminal that had the appearance of light oxidation, not unexpected after 19 years of storage. The initial pre-reforming testing of the capacitance and ESR was the first time the screws and lugs were installed. The removal of the screws, installation again for reforming circuitry, and the final installation for post reform testing may have sufficiently worn away the light surface corrosion previously present, thus reducing the resistance of the connection.

The effect on capacitance of the reforming process was observed to be negligible. The aged capacitors did have an increase in mean capacitance from 535.9 MFD to 541.1 MFD. That increase of approximately 1 per cent, was not statistically significant, and further supports the alternate hypothesis of the first research question that the shelf life of the capacitors is greater than five years.

Visual Examination

Since a suggested area of concern for long term storage of aluminum electrolytic capacitors is electrolyte leakage and loss through the seal (Electric Power Research Institute, 2000), the samples were examined for signs of electrolyte loss. The can capacitors have a rubber seal, or blow out, in the top of the capacitor, (figure 12). None of the can capacitors showed any signs of failure or leakage at that seal plug. The axial and radial capacitors were hermetically sealed and also were examined for any sign of leakage. No evidence of any electrolyte loss was found.

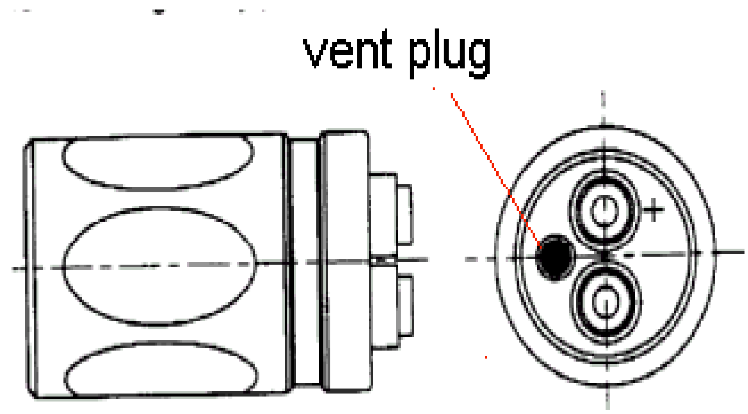


Figure 12, Can capacitor showing vent plug. (Phillips Components, 1994)

As previously stated, some evidence of light oxide buildup on the terminals of the oldest can capacitors was found (figure 13), but other than a slightly dull appearance of the leads to the axial and radial capacitors no visual evidence of aging of these capacitors was detected. In all cases, all of the surface changes due to aging could be easily addressed during normal installation activities.

Figure 13, Can capacitor with slight terminal oxidation.

CHAPTER 5

CONCLUSION

The purpose of this research was to determine if the shelf life of aluminum electrolytic capacitors was five years. An additional purpose of the research was to determine if reforming aged aluminum electrolytic capacitors restored the aluminum oxide dielectric film and in so doing reduced the DC leakage current.

Analysis of the test data resulted in the rejection of the null hypothesis and the acceptance of the alternate hypothesis in both research questions for all sample populations. It was concluded from this analysis, that this research clearly supports the claim that the shelf life of aluminum electrolytic capacitors is some period in excess of the five years currently assigned by TXU's Comanche Peak Steam Electric Station procedures. The claim that reforming of aged capacitors improved the DC leakage characteristics of the capacitors was also proven.

The observed mean DC leakage currents of the aged unreformed capacitors, while still within specification, did exhibit an increase that could be shown to be directly associated with the duration of storage. For the longest aged can style capacitors, some individual samples did have measured leakage currents slightly in excess of the design values. Measurement of capacitance and ESR while not directly associated with the research questions and hypotheses also supported the conclusion that the shelf life of the capacitors is longer than five years.

The reforming process was shown to reduce the DC leakage current for all populations sampled. Although none of the sample populations had pre-reforming DC leakage values which were in excess of the design values, all populations show improvement in this criteria. The process of applying voltage at rated voltage or slightly above on a periodic basis can be associated with improvement to aged capacitors and could be a basis for extended storage.

CHAPTER 6

RECOMMENDATIONS

The conclusion drawn from this research is that the shelf life of aluminum electrolytic capacitors stored in a level “B” controlled environment is greater than five years and exceeds the established limits currently in place at TXU’s Comanche Peak Steam Electric Station. Changes to site procedures should be initiated to change the assigned shelf life to a longer period, possible to 16 years from date of manufacture, a period previously used based upon accelerated aging test. Assignment of an even longer shelf life to aluminum electrolytic capacitors of the radial or axial style may be evaluated upon further research. Additionally, the use of reforming techniques or periodic application at rated voltage to extend storage and restore capacitors is warranted and recommended.

APPENDIX A

CAPACITOR TEST DATA SHEETS

	CAPACITANCE MicroFarads	ESR Ohms	DC LEAKAGE Microamps
1	213.4	0.402	10.6
2	213.8	0.452	11.5
3	215	0.387	11.5
4	226	0.227	68.9
5	213.9	0.372	11.2
6	224.3	0.238	72.1
7	224.5	0.238	62.7
8	214.8	0.381	10.8
9	215	0.375	10.6
10	213.4	0.355	10.3
11	224.4	0.224	67.4
12	212.9	0.402	11.3
13	215.1	0.392	11.2
14	226.3	0.223	71.9
15	224.5	0.221	78.5
16	227.4	0.226	66
17	224.5	0.238	64.9
18	212	0.415	11.9
19	214.4	0.395	12.5
20	225.6	0.22	64.6
21	224.4	0.232	72.4
22	224.6	0.227	68.2
23	222.2	0.246	9.4
24	233.8	0.23	72.7
25	225	0.233	69.8
26	215.5	0.365	10.7
Mean	220.25	0.304	40.14
std. Deviation	6.16	0.084	29.83

Radial Lead Style
220 MFD 50 VDC
Aged 10 Years
XICON™ XRL Series

	CAPACITANCE MicroFarads	ESR Ohms	DC LEAKAGE Microamps
1	213.9	0.418	7.5
2	213.6	0.466	7.4
3	213.5	0.403	7.1
4	225.7	0.236	5
5	214.4	0.383	7.3
6	224	0.245	13.4
7	224.1	0.249	5
8	214.9	0.4	7.8
9	215.2	0.393	7.5
10	213.9	0.366	7.5
11	223.9	0.232	13.5
12	212.9	0.42	7.9
13	215	0.416	7.9
14	226.1	0.227	14.3
15	224.1	0.229	14.1
16	227	0.234	13.1
17	224.3	0.244	14.2
18	212.2	0.433	8.4
19	214.5	0.414	8.9
20	225.1	0.229	13.6
21	224	0.24	14.9
22	224.3	0.234	13.8
23	222.9	0.255	7.3
24	224.8	0.241	14.9
25	223.5	0.235	14.8
26	215.8	0.384	7.8
Mean	219.75	0.316	10.19
std. Deviation	5.39	0.088	3.49

Radial Lead Style
220 MFD 50 VDC
Aged 10 Years
XICON$_{TM}$ XRL Series
Post Reforming

	CAPACITANCE MicroFarads	ESR Ohms	DC LEAKAGE Microamps
1	53.03	0.519	9.7
2	55.11	0.532	9.35
3	49.89	0.535	9.01
4	50.02	0.54	8.15
5	49.27	0.553	15.39
6	49.17	0.537	18.08
7	56.47	0.533	13.01
8	53.5	0.548	5.57
9	55.96	0.538	20.53
10	55.38	0.532	8.14
11	50.65	0.548	9.59
12	51.38	0.516	9.89
13	50.54	0.528	10.06
14	51.4	0.522	10.65
15	51.05	0.517	10.04
16	50.97	0.522	19.55
17	50.07	0.52	7.94
18	50.98	0.527	16.66
19	50.09	0.52	9.79
20	49.4	0.54	7.94
21	49.7	0.539	10.49
22	55.48	0.553	14.16
23	49.5	0.549	8.29
24	50.22	0.536	8.43
25	50.54	0.522	7.72
26	57.43	0.526	16.52
Mean	51.82	0.53	11.22
Std. Deviation	2.556	0.011	4.131

Axial Lead Style
50 MFD 50 VDC
Aged 10 Years
Model TE-1307

	CAPACITANCE MicroFarads	ESR Ohms	DC LEAKAGE Microamps
1	53.01	0.538	8.3
2	55.07	0.556	7.4
3	49.87	0.556	7
4	50	0.561	6.5
5	49.27	0.572	7.4
6	49.16	0.557	7.5
7	56.45	0.552	8.4
8	53.49	0.569	6.5
9	56.01	0.545	8.2
10	55.38	0.552	7.1
11	50.63	0.567	6.9
12	51.36	0.543	7.5
13	50.53	0.549	7.6
14	51.4	0.546	7.1
15	51.06	0.532	7.5
16	50.92	0.545	7.5
17	50.07	0.543	6.9
18	50.97	0.549	7.6
19	50.1	0.54	7.6
20	49.41	0.559	7.2
21	49.69	0.557	7.3
22	55.51	0.567	8.2
23	49.56	0.57	6.5
24	50.25	0.548	6.6
25	50.56	0.538	6.4
26	57.47	0.538	8.8
Mean	51.81	0.55	7.37
Std. Deviation	2.556	0.011	0.637

Axial Lead Style
50 MFD 50 VDC
Aged 10 Years
Model TE-1307
Post Reforming

	CAPACITANCE MicroFarads	ESR Ohms	DC LEAKAGE Milliamps
1	547.9	27.4	0.152
2	525.5	27.7	0.127
3	503.5	26.9	0.126
4	534.7	26.7	0.125
5	536.3	27.2	0.142
6	530.9	27.6	0.127
7	529.7	26.9	0.132
8	524.7	26.4	0.164
9	524	26.2	0.122
10	505.8	26.5	0.15
11	498.1	27.1	0.16
12	492.3	26.6	0.16
13	529	26.8	0.462
14	528	26.5	0.127
15	533.8	25.3	0.14
16	538.8	27	0.155
17	519.9	27	0.128
18	547.9	25.9	0.117
19	524.2	26.7	0.16
20	527.3	27.6	0.119
21	524	27	0.124
22	527.9	26.8	0.125
23	496.3	26.6	0.128
24	529.9	27.3	0.129
25	524.1	26.8	0.124
26	522.3	27	0.126
Mean	524.1	26.8	0.148
Std Deviation	14.3	0.528	0.066

Can Style
530 MFD 250 VDC
Aged 14 Years
Sprague Model 36D

	CAPACITANCE MicroFarads	ESR Ohms	DC LEAKAGE Milliamps
1	550.2	29.2	0.072
2	527.2	36.6	0.064
3	505.1	29.5	0.062
4	536.8	37.3	0.062
5	538.2	28.5	0.073
6	532.7	27.7	0.063
7	531.9	27.7	0.074
8	526.6	27.7	0.099
9	525.7	26.9	0.062
10	507.4	27.5	0.076
11	499.6	28	0.059
12	493.8	27.9	0.085
13	530.7	28.7	0.116
14	529.9	27.4	0.063
15	535.5	26.4	0.062
16	540.9	27.6	0.071
17	521.6	28.3	0.06
18	529.6	26.6	0.06
19	526.1	28.1	0.076
20	529.1	27.7	0.06
21	525.8	27.3	0.059
22	529.7	29	0.063
23	497.9	27.6	0.06
24	531.6	28.4	0.061
25	525.8	27.5	0.062
26	524	28.4	0.061
Mean	525.1	28.6	0.069
Std Deviation	13.65	2.57	0.013

Can Style
530 MFD 250 VDC
Aged 14 Years
Sprague Model 36D
Post Reformed Data

	CAPACITANCE MicroFarads	ESR Ohms	DC LEAKAGE Milliamps
1	531.7	48.7	1.55
2	543.2	43.1	1.23
3	548.7	49.5	1.01
4	543.6	43.5	1.13
5	528.9	50.6	1.34
6	545.4	56.7	1.37
7	535.1	62.8	1.29
8	539	40.3	1.18
9	531.7	44.3	1.62
10	546.5	53.2	1.27
11	524.8	52.9	1.17
12	539.7	51.1	1.12
13	546.7	60.3	1.55
14	536.2	46.5	1.64
15	539.2	46.9	1.69
16	543.3	47.8	1.47
17	532.9	45.4	1.35
18	535.5	42.4	1.5
19	537.1	47.5	1.23
20	532.1	45.3	1.29
21	529.7	49.8	1.49
22	527.3	53.3	1.1
23	523.2	46.1	1.43
24	523.4	53.5	1.14
25	533.9	51.4	1.15
Mean	535.9	49.1	1.34
Std Deviation	7.35	5.43	0.192

Can Style
530 MFD 250 VDC
Aged 19 Years
Sprague Model 36D

	CAPACITANCE MicroFarads	ESR Ohms	DC LEAKAGE Milliamps
1	540.1	44.7	0.338
2	551.5	38.4	0.24
3	557.7	42.9	0.23
4	550.3	39.7	0.215
5	535.5	45	0.247
6	551.8	51.7	0.212
7	540.5	58	0.259
8	544.6	40	0.216
9	537.8	42.4	0.374
10	552.6	51.4	0.252
11	527.3	57.8	0.243
12	542.6	51.2	0.231
13	549.6	65.2	0.265
14	539.9	48.3	0.285
15	543.1	53.7	0.281
16	547.1	54.5	0.272
17	536.7	46	0.281
18	539.6	45.2	0.204
19	551.1	52.5	0.206
20	536.1	47.7	0.276
21	533.7	49.3	0.283
22	531.2	52.2	0.184
23	525.8	54.8	0.257
24	526.3	52.6	0.204
25	536.6	58.9	0.17
26	539.8	48.3	0.314
Mean	541.1	49.7	0.252
Std Deviation	8.61	6.53	0.047

Can Style
530 MFD 250 VDC
Aged 19 Years
Sprague Model 36D
Post Reformed Data

	DC LEAKAGE Aged in Microamps	DC LEAKAGE Reformed in Microamps	Difference Aged - reformed
1	10.6	7.5	3.1
2	11.5	7.4	4.1
3	11.5	7.1	4.4
4	68.9	5	63.9
5	11.2	7.3	3.9
6	72.1	13.4	58.7
7	62.7	5	57.7
8	10.8	7.8	3
9	10.6	7.5	3.1
10	10.3	7.5	2.8
11	67.4	13.5	53.9
12	11.3	7.9	3.4
13	11.2	7.9	3.3
14	71.9	14.3	57.6
15	78.5	14.1	64.4
16	66	13.1	52.9
17	64.9	14.2	50.7
18	11.9	8.4	3.5
19	12.5	8.9	3.6
20	64.6	13.6	51
21	72.4	14.9	57.5
22	68.2	13.8	54.4
23	9.4	7.3	2.1
24	72.7	14.9	57.8
25	69.8	14.8	55
26	10.7	7.8	2.9
Mean	40.14	10.19	29.95
Std. Deviation	29.83	3.49	27.32

Radial Lead Style 220 MFD 50 VDC
Aged 10 Years
XICON™ XRL Series
Aged - Reformed DC Leakage

	DC LEAKAGE Aged in Microamps	DC LEAKAGE Reformed in Microamps	Difference Aged - Reformed
1	9.7	8.3	1.4
2	9.35	7.4	1.95
3	9.01	7	2.01
4	8.15	6.5	1.65
5	15.39	7.4	7.99
6	18.08	7.5	10.58
7	13.01	8.4	4.61
8	5.57	6.5	-0.93
9	20.53	8.2	12.33
10	8.14	7.1	1.04
11	9.59	6.9	2.69
12	9.89	7.5	2.39
13	10.06	7.6	2.46
14	10.65	7.1	3.55
15	10.04	7.5	2.54
16	19.55	7.5	12.05
17	7.94	6.9	1.04
18	16.66	7.6	9.06
19	9.79	7.6	2.19
20	7.94	7.2	0.74
21	10.49	7.3	3.19
22	14.16	8.2	5.96
23	8.29	6.5	1.79
24	8.43	6.6	1.83
25	7.72	6.4	1.32
26	16.52	8.8	7.72
Mean	11.33	7.37	3.97
Std. Deviation	4.06	0.64	3.69

Axial Lead Style
Model TE-1307
Aged 10 Years
Aged - Reformed DC Leakage

	DC LEAKAGE Aged in Milliamps	DC LEAKAGE Reformed in Milliamps	Difference Aged - Reformed
1	0.152	0.072	0.08
2	0.127	0.064	0.063
3	0.126	0.062	0.064
4	0.125	0.062	0.063
5	0.142	0.073	0.069
6	0.127	0.063	0.064
7	0.132	0.074	0.058
8	0.164	0.099	0.065
9	0.122	0.062	0.06
10	0.15	0.076	0.074
11	0.16	0.059	0.101
12	0.16	0.085	0.075
13	0.462	0.116	0.346
14	0.127	0.063	0.064
15	0.14	0.062	0.078
16	0.155	0.071	0.084
17	0.128	0.06	0.068
18	0.117	0.06	0.057
19	0.16	0.076	0.084
20	0.119	0.06	0.059
21	0.124	0.059	0.065
22	0.125	0.063	0.062
23	0.128	0.06	0.068
24	0.129	0.061	0.068
25	0.124	0.062	0.062
26	0.126	0.061	0.065
Mean	0.148	0.069	0.079
Std. Deviation	0.066	0.013	0.055

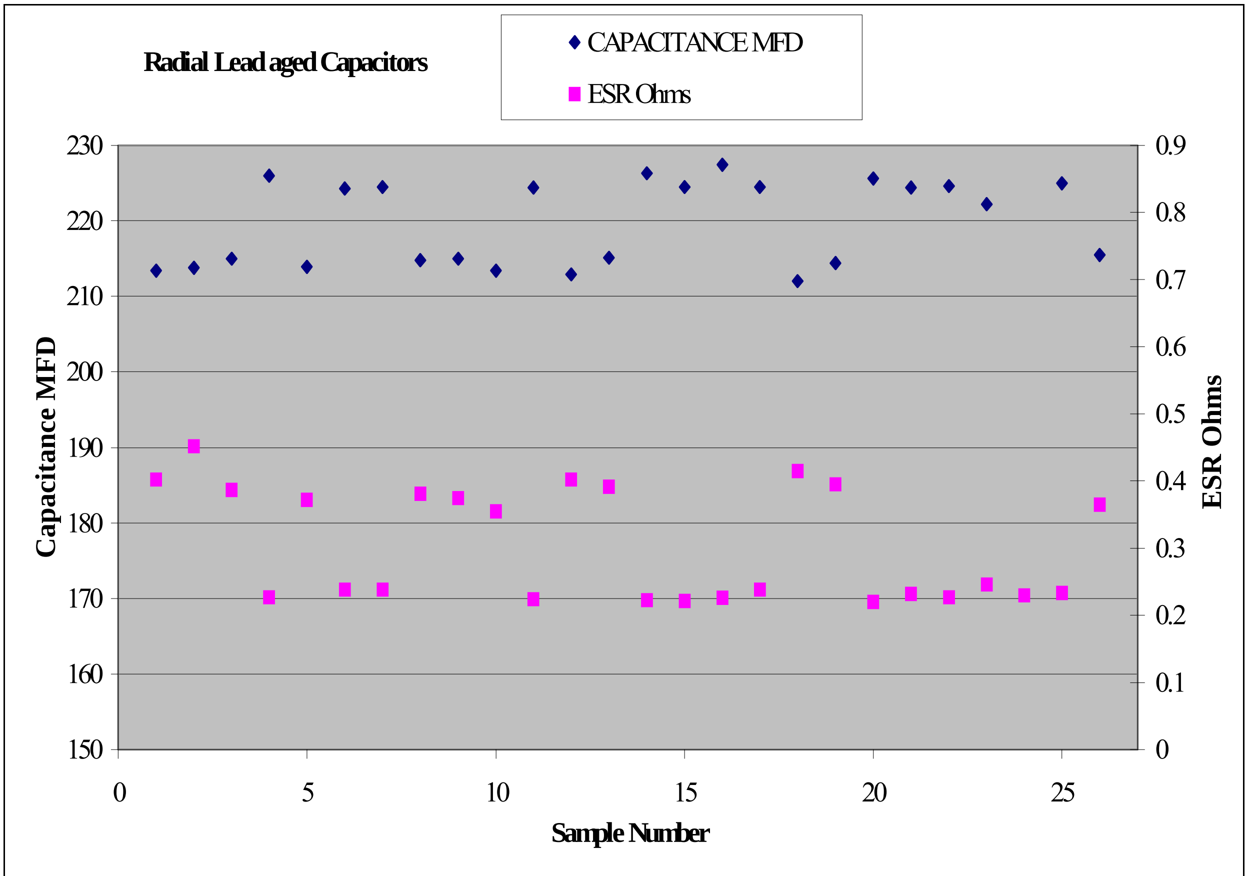
Can Style 530 MFD
250 VDC
Aged 14 Years
Sprague Model 36D
Aged - Reformed
DC Leakage

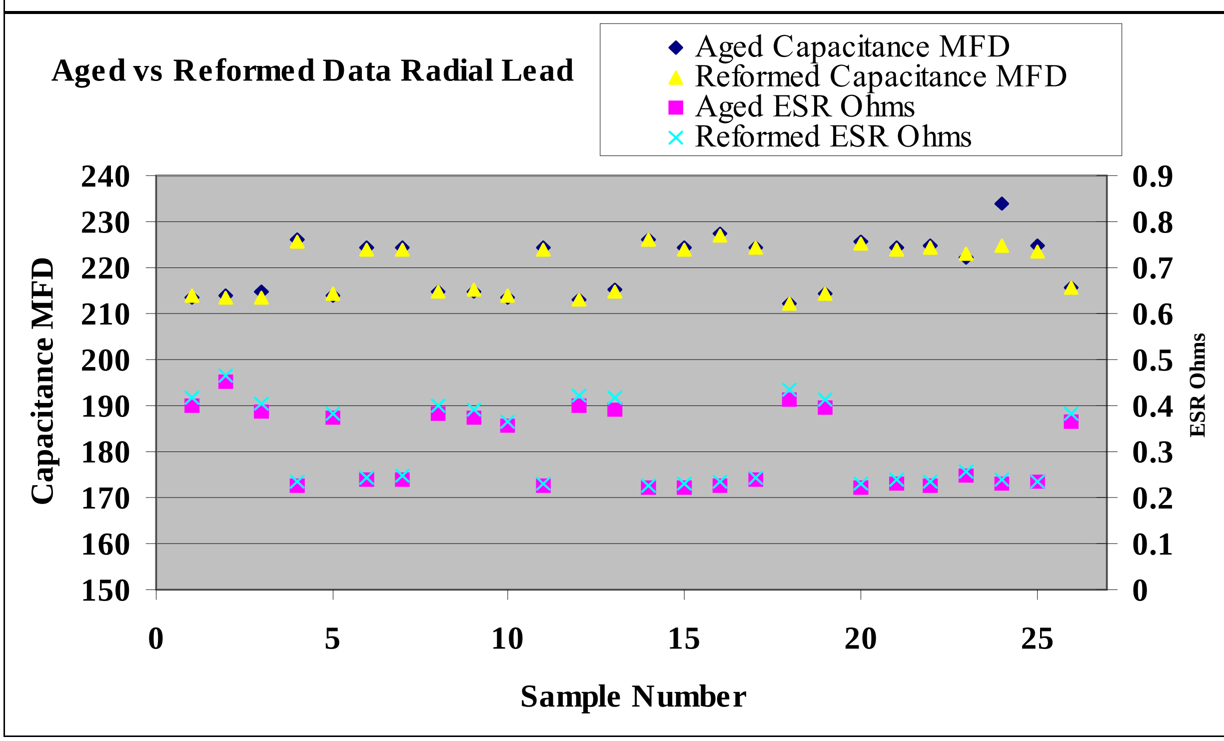
	DC LEAKAGE Aged in Milliamps	DC LEAKAGE Reformed in Milliamps	Difference Aged - Reformed
1	1.55	0.338	1.212
2	1.23	0.24	0.99
3	1.01	0.23	0.78
4	1.13	0.215	0.915
5	1.34	0.247	1.093
6	1.37	0.212	1.158
7	1.29	0.259	1.031
8	1.18	0.216	0.964
9	1.62	0.374	1.246
10	1.27	0.252	1.018
11	1.17	0.243	0.927
12	1.12	0.231	0.889
13	1.55	0.265	1.285
14	1.64	0.285	1.355
15	1.69	0.281	1.409
16	1.47	0.272	1.198
17	1.35	0.281	1.069
18	1.5	0.204	1.296
19	1.23	0.206	1.024
20	1.29	0.276	1.014
21	1.49	0.283	1.207
22	1.1	0.184	0.916
23	1.43	0.257	1.173
24	1.14	0.204	0.936
25	1.15	0.17	0.98
26	1.55	0.314	1.236
Mean	1.341	0.252	1.089
Std. Deviation	0.192	0.047	0.162

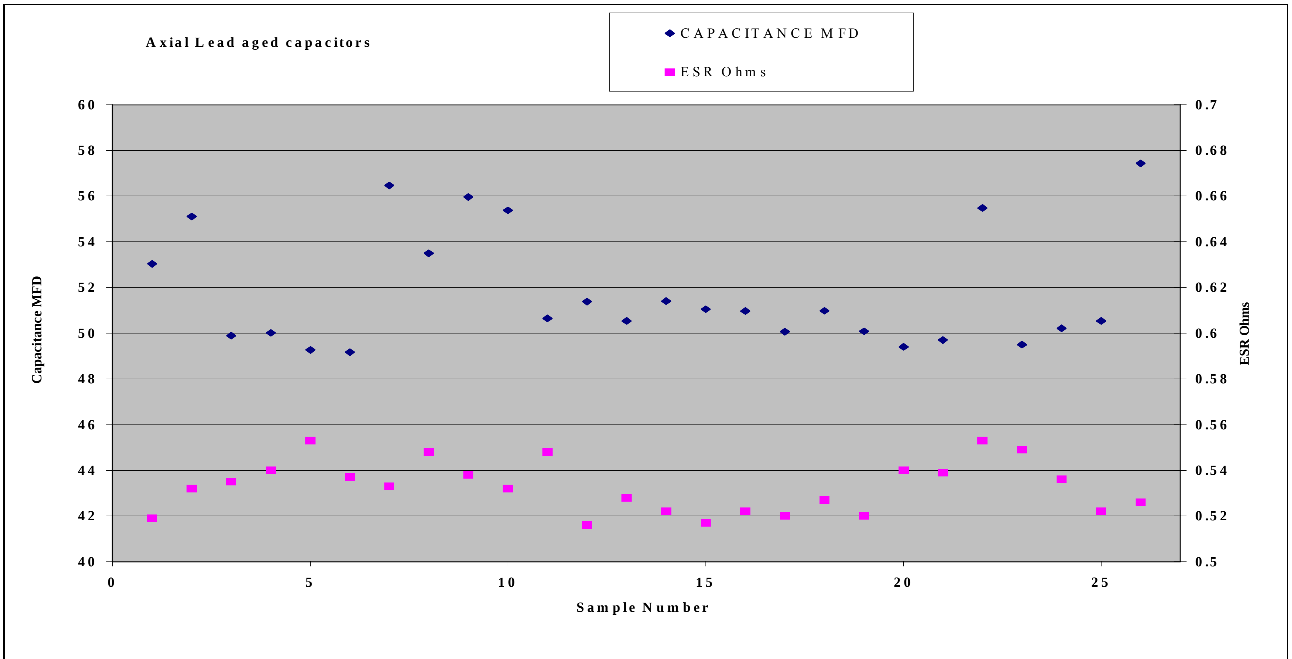
Can Style 530 MFD
250 VDC Aged 19 Years
Sprague Model 36D
Aged - Reformed DC
Leakage

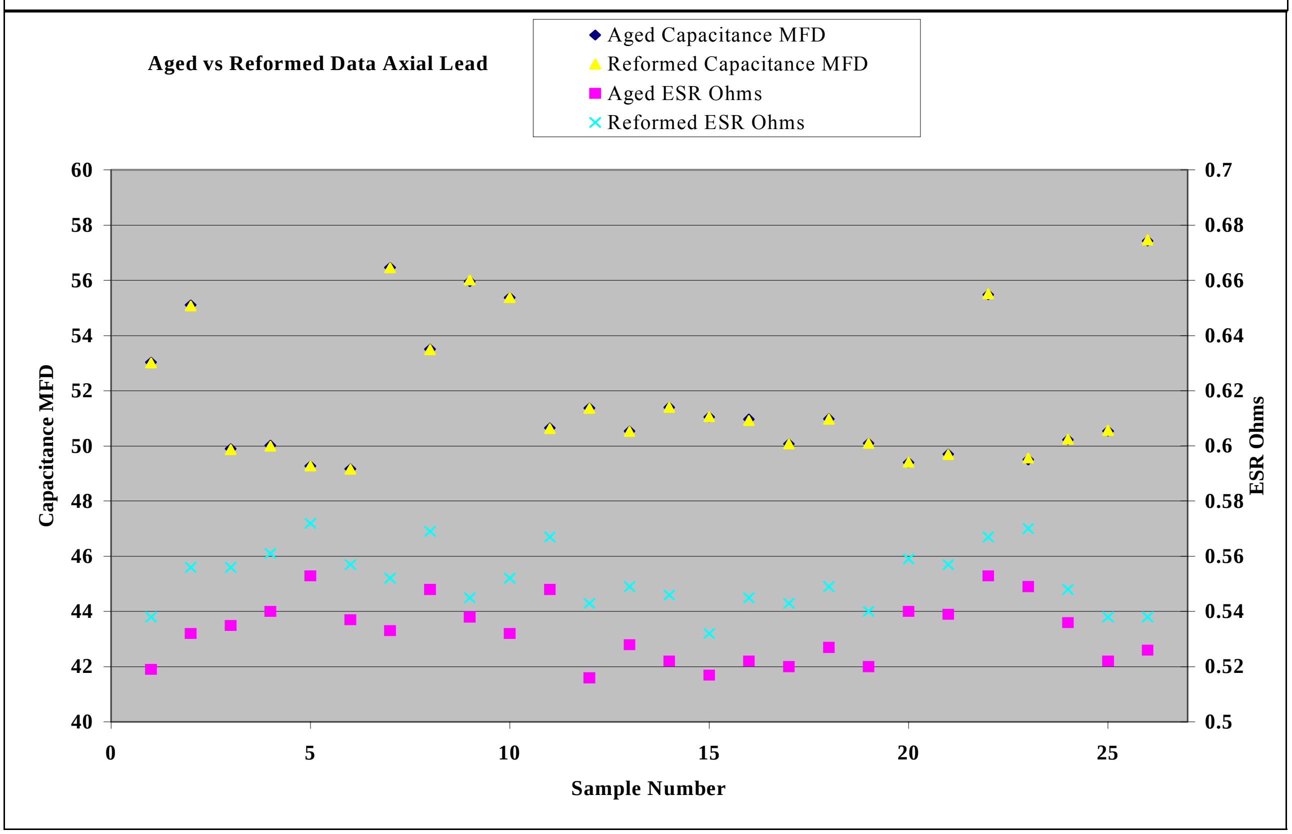
APPENDIX B

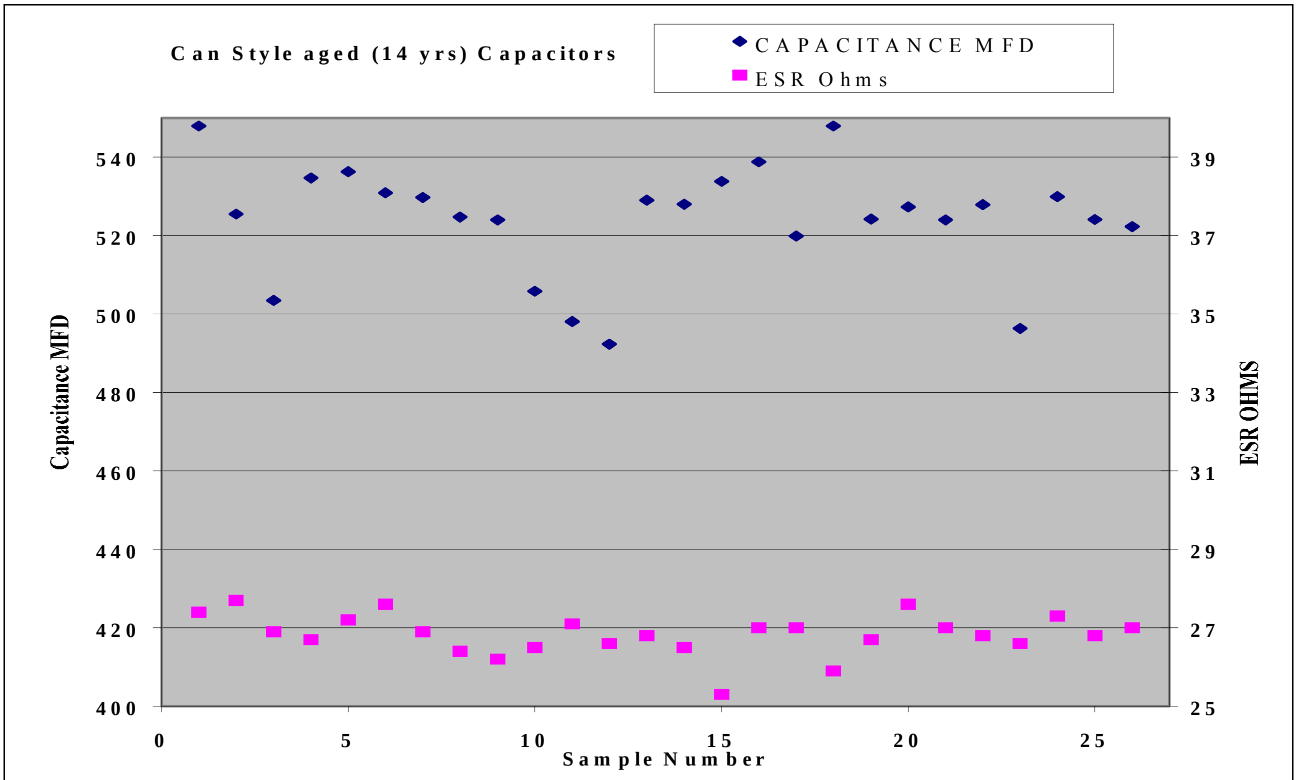
CAPACITANCE AND ESR PLOTS

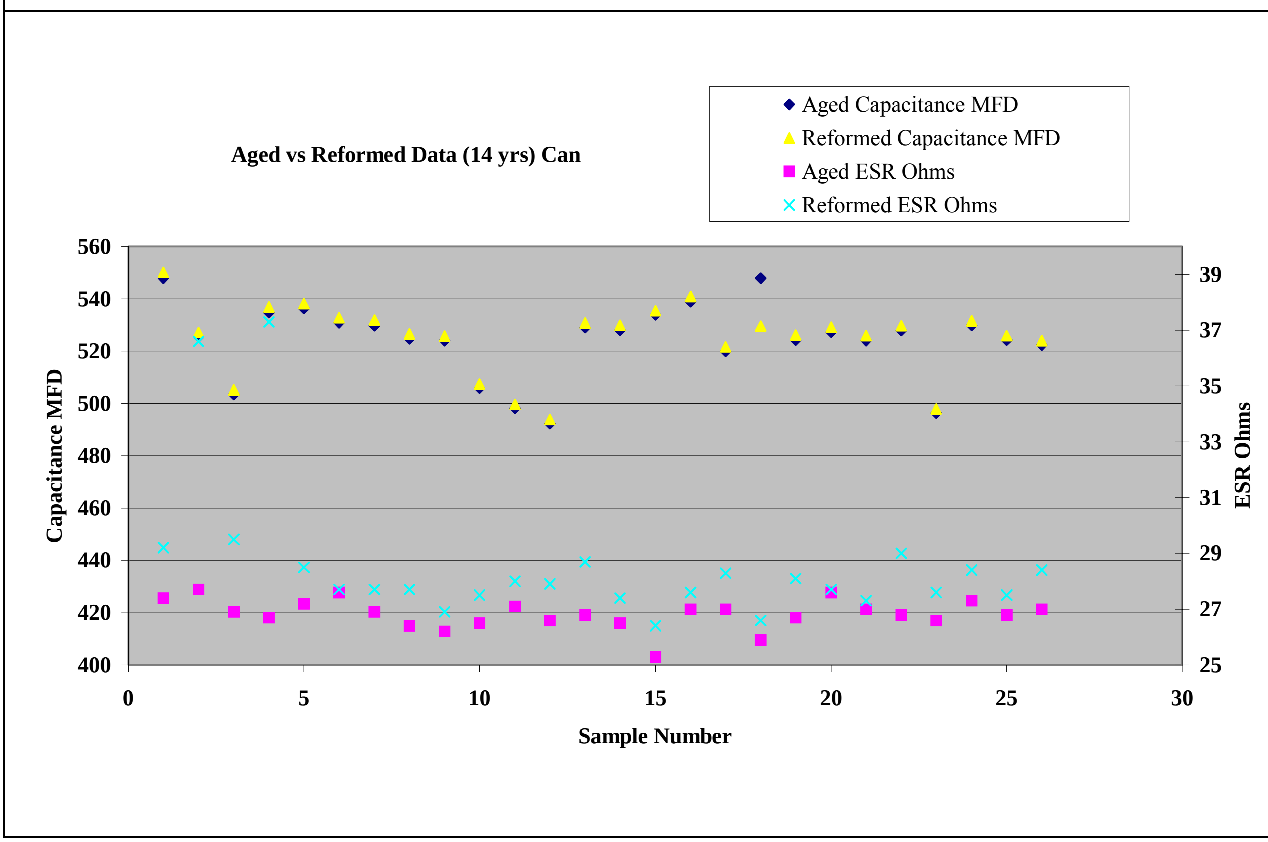

Radial Lead aged Capacitors
CAPACITANCE MFD
ESR Ohms
Capacitance MFD
ESR Ohms
230
220
210
200
190
180
170
160
150
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
Sample Number

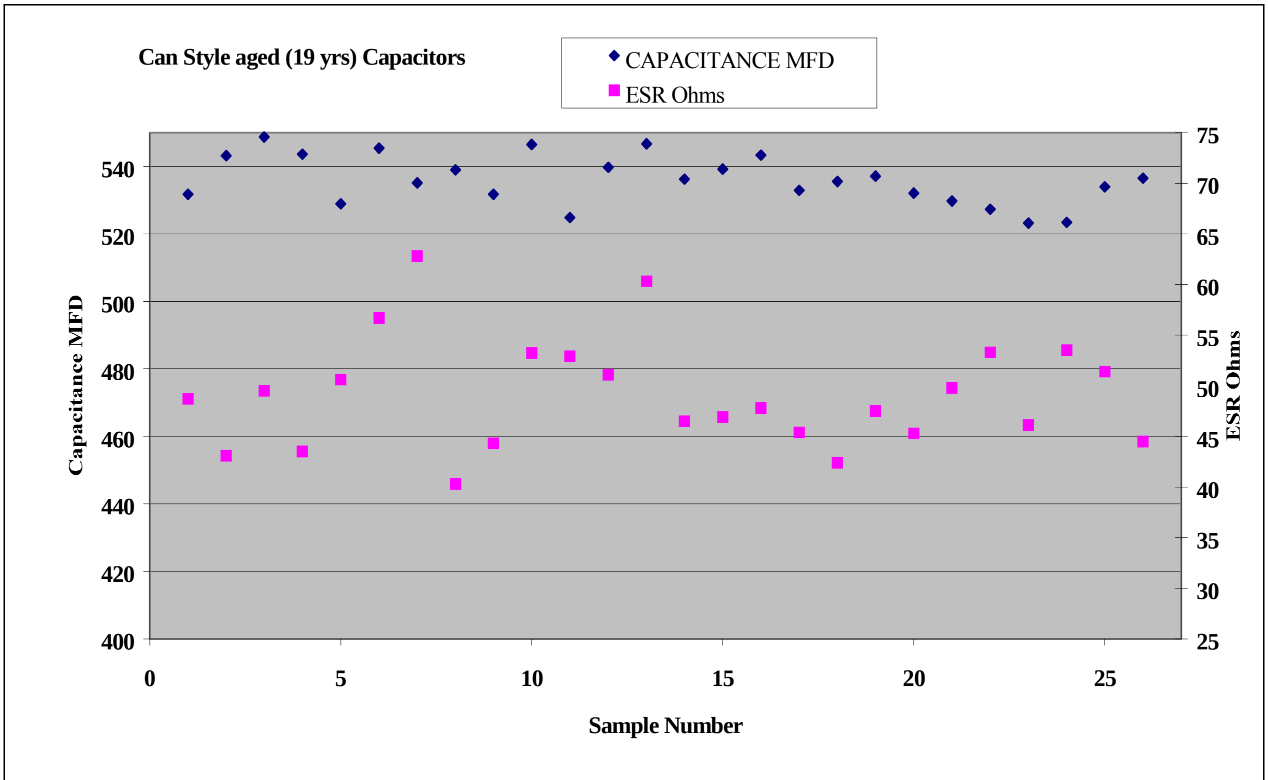

Aged vs Reformed Data Radial Lead
Aged Capacitance MFD
Reformed Capacitance MFD
Aged ESR Ohms
Reformed ESR Ohms
Capacitance MFD
ESR Ohms
240
230
220
210
200
190
180
170
160
150
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
Sample Number

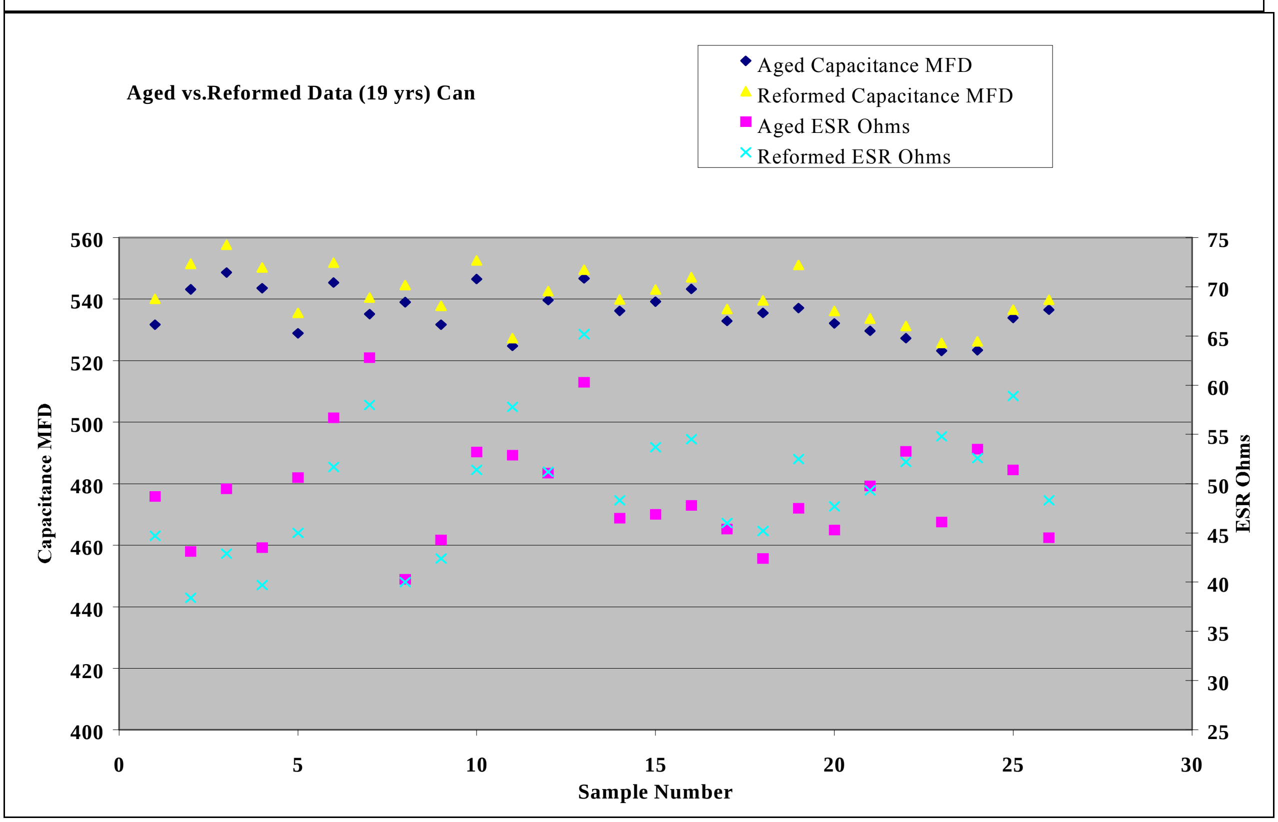

Axial Lead aged capacitors
CAPACITANCE MFD
ESR Ohms
Capacitance MFD
ESR Ohms
Sample Number
60
58
56
54
52
50
48
46
44
42
40
0.7
0.68
0.66
0.64
0.62
0.6
0.58
0.56
0.54
0.52
0.5
0
5
10
15
20
25


Aged vs Reformed Data Axial Lead
Aged Capacitance MFD
Reformed Capacitance MFD
Aged ESR Ohms
Reformed ESR Ohms
Capacitance MFD
ESR Ohms
Sample Number
60
58
56
54
52
50
48
46
44
42
40
0.7
0.68
0.66
0.64
0.62
0.6
0.58
0.56
0.54
0.52
0.5
0
5
10
15
20
25


Can Style aged (14 yrs) Capacitors
CAPACITANCE MFD
ESR Ohms
Capacitance MFD
ESR OHMS
540
520
500
480
460
440
420
400
39
37
35
33
31
29
27
25
0
5
10
15
20
25
Sample Number


Aged vs Reformed Data (14 yrs) Can
Aged Capacitance MFD
Reformed Capacitance MFD
Aged ESR Ohms
Reformed ESR Ohms
Capacitance MFD
ESR Ohms
560
540
520
500
480
460
440
420
400
39
37
35
33
31
29
27
25
0
5
10
15
20
25
30
Sample Number


Can Style aged (19 yrs) Capacitors
CAPACITANCE MFD
ESR Ohms
Capacitance MFD
ESR Ohms
Sample Number
400
420
440
460
480
500
520
540
25
30
35
40
45
50
55
60
65
70
75
0
5
10
15
20
25


Aged vs.Reformed Data (19 yrs) Can
Aged Capacitance MFD
Reformed Capacitance MFD
Aged ESR Ohms
Reformed ESR Ohms
Capacitance MFD
ESR Ohms
Sample Number
400
420
440
460
480
500
520
540
560
25
30
35
40
45
50
55
60
65
70
75
0
5
10
15
20
25
30

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