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ACCELERATED TESTS AND PREDICTED CAPACITOR LIFE

by

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FOREWORD

What is the life expectancy of a capacitor under conditions of rated voltage and temperature? What will the life expectancy be under any other specific combination of voltage and temperature? What is the reliability of a particular capacitor?

These questions, and the answers thereto, have been the subject of much consideration by engineers who are engaged in capacitor quality, reliability and application research. Possibly,because accurate methods of predicting capacitor life are not generally available, the engineer may purchase low cost units having high failure rates, and then derate the units in an attempt to obtain the desired level of reliability. This system has its disadvantages.

In order to overcome this questionable procedure, this paper will present information which may considerably improve the accuracy presently obtained when predicting the life of high reliability capacitors.

ACCELERATED TESTS AND PREDICTED CAPACITOR LIFE

ABSTRACT

Purchasing low cost capacitors and then derating them in order to obtain a particular level of reliability may result in the reliability being questionable, and the size and weight of the selected unit being too great. In the complex and miniaturized industrial and military electronic equipment of today, emphasis is placed upon size as well as reliability.

This paper will serve to bring to your attention the different types of failure rates or patterns and the type of pattern most desirable. Information will be presented on accelerated and long term tests and how they can be used to determine failure rates and the effect on these rates of voltage (Power Law) and temperature. Procedures for predicting the life expectancy of capacitors will be discussed, plus factors that are believed to play a predominant part in the manufacture of truly reliable capacitors.

1. Reliability Criteria.

This paper is primarily concerned with the prediction of the life of high-reliability paper or paper-film capacitors, plus some of the accelerated tests that may be used to reach this end. The data presented has been derived from actual tests made on Hyrel Q* capacitors. The history, construction, and reliability of this capacitor are described in a separate paper.[1]

What criteria are necessary to determine whether a standard or a high reliability capacitor should be used for a particular application? A list of elementary considerations could be as follows:

1.1 The degree of reliability that the finished equipment must possess.

1.2 The complexity of the equipment, ie: the number of components that could fail and cause the equipment to cease functioning.

1.3 The cost resulting from equipment failure and the cost involved in equipment repair.

1.4 The component size and weight limitations.

1.5 The environmental, chemical, mechanical and electrical stress factors to which the components will be subjected.

1.6 The failure rate of the component and its variation with time.

1.7 The degree of accuracy necessary for the prediction of life at various conditions of voltage and temperature.

2. Failure Rates.

One of the most important factors to consider when determining capacitor reliability, or the degree of accuracy that can be obtained when predicting the life of a particular capacitor, is its failure rate and how this rate will vary with time. This is termed the failure rate pattern. The complete failure rate pattern is normally composed of two modes of failure; random failure and wear-out failure.

2.1 Random Failure. Random failures are early breakdowns caused by inherent weaknesses in the materials and/or by damage incurred during the manufacture process. The random failure rate pattern is characterized by a high initial failure rate followed by a leveling-off period. This is illustrated graphically in Figure 1.

2.2 Wear-Out Failure. This type of failure in capacitors is believed to be caused principally by the slow electrochemical deterioration of the dielectric. The presence of contaminants within the capacitor have been shown to accelerate this deterioration.[2] The wear-out failure rate pattern is usually bell-shaped and is often normal. Figure 1 illustrates this pattern.

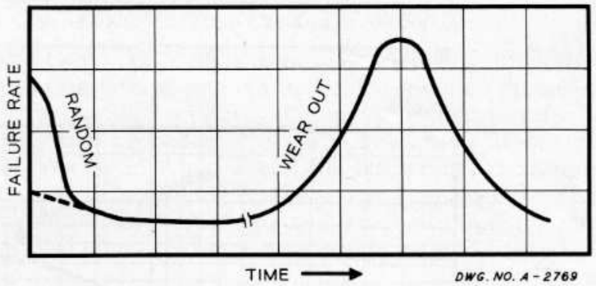

FIGURE 1
Random Failure Rate Pattern

2.3 Actual Failure Frequency. Pierushka[3] points out that actual failure frequency distributions are caused by both wear-out and random failures. Therefore, they have a characteristic shape as illustrated in Figure 1. This curve has the following characteristics: It will usually begin with a first peak or mode, at zero time, and may then be followed by a negative concave slope, indicating that during the first period of operation failures are predominantly by chance (random failures). After reaching a minimum, the curve rises again, reaches a second mode and drops again, approaching the abscissa asymptotically.

It is interesting to note that if this combined failure rate pattern curve is re-plotted as cumulative per-cent failures vs. time, the familiar "S"-type failure rate pattern for standard capacitors is obtained. Figure 2 illustrates this plot.

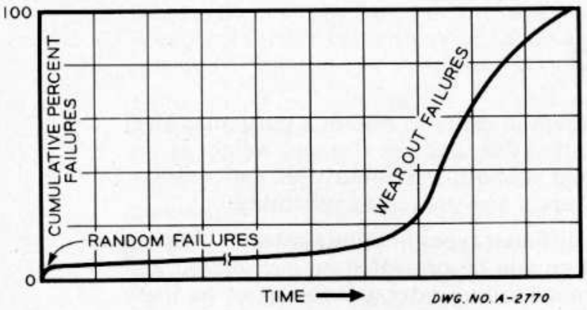

FIGURE 2
S-Type Failure Rate Pattern for Standard Capacitors

2.4 "S" Type Failure Rate Pattern. The "S" type failure rate pattern is very difficult to use when predicting the life expectancy of a capacitor. This fact has been admitted many times in the past by those who have had to work with this type of curve and its radical changes in failure rate. It becomes evident that an important and desirable characteristic for the life prediction of any particular capacitor type would be a constant failure rate. This is an ideal condition however, and as is often the case, some compromise must be made.

2.5 Capacitor Failure Mode Changes. In 1951, Weibull introduced a statistical distribution function of wide applicability[4]. This distribution provides a sensitive test for detecting changes in the mode of failure of a particular component. An example of this plot for a group of capacitors is presented in Figure 3. Note that this plot is made on special graph paper, wherein a plot having a resultant slope of 1.0 indicates a constant failure rate, whereas a slope greater than or less than 1.0 indicates increasing or decreasing failure rates respectively. The slope can be determined by drawing a line parallel to the plot through the given point and by extending this line until it intersects the vertical line 0. The slope can then be read at this point of intersection on the 'm' scale at the right.

It was found that the high initial failure rate of the random failure rate pattern of a capacitor can be eliminated if extreme care is used in the selection of raw materials and during the manufacturing processes. Elimination of this high initial failure rate will result in a failure rate pattern similar to that shown by the broken line in Figure 1.

Considerable information has been collected during the last few years from accelerated life tests on Hyrel Q® capacitors. On the basis of several 5000 hour, 125C life tests at from 50% to 250% of rated voltage, and many shorter life tests at 400% to 700% of rated voltage, it has been observed that the failure rate pattern up until 25% to 40% failures is slowly decreasing. This can be approximated by a straight line as shown in Figure 4. The data shown is for the 2X and 6X rated voltage plots. (Data for other plots is also available). This low, decreasing failure rate, which approximates the highly desirable constant failure rate previously discussed, was found to be characteristic of the Hyrel Q® capacitors.

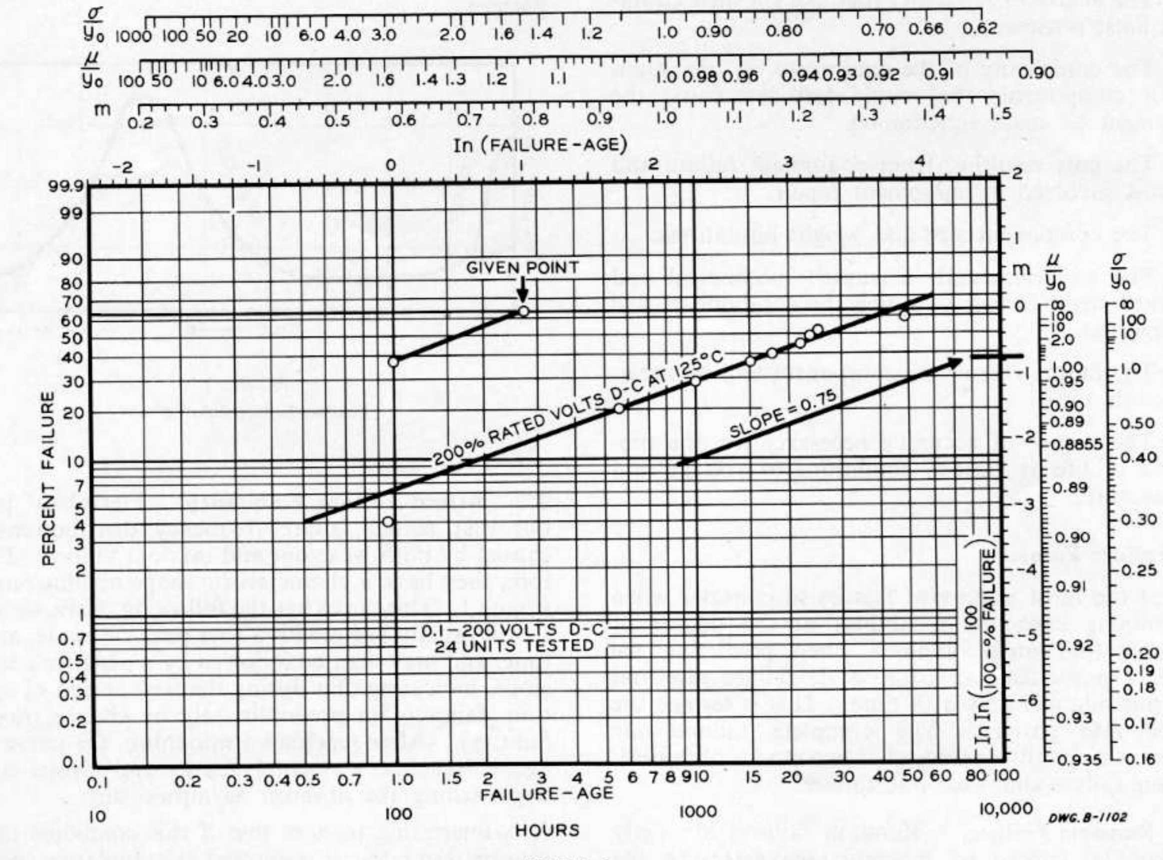

FIGURE 3
Examples of Failure Modes for a Group of Capacitors

3. Effects of Voltage on Capacitor Life.

Life test data for 85C oil impregnated paper capacitors was obtained a number of years ago. At that time, Brotherton[5] determined that the life of a capacitor was inversely proportional to some power "N" of the applied voltage. Note also that the failure rate and power law of voltage that a group of capacitors follow are dependent on the dielectric system, impregnant, raw materials, degree of contamination, and the manufacturing processes. Variations in power law for a given capacitor type are probably due to a combination of all these factors.

The range of "N" for the oil impregnated paper capacitors (85C) tested by Brotherton was from four to six. Hence, the fifth power law, (which states that the d-c life of a capacitor is inversely proportional to the fifth power of the applied voltage), was established and has been used as a guide for some time, for calculating the relative life of a capacitor at different voltages. In fact, the fifth power law has become so standardized that many manufacturers and engineers may use this figure without discretion and without due regard to the construction and reliability of the units under construction. Evidence now exists that capacitors of various constructions can exhibit a power law of two to a power law exceeding ten.

3.1 Life Prediction Accuracy. It can be seen by this variation in power law, that in order to predict the life of a capacitor used in any critical application (at a given temperature), maximum accuracy can be obtained only when the power law that a particular capacitor type follows is accurately known, and when there are no radical changes in the failure rate pattern of the capacitors during the predicted operating time. Probably the most accurate method of determining the failure rate pattern of a particular capacitor type, is by the extensive life testing (millions of unit hours) of several ratings of units utilizing the particular construction in question. Figure 4 illustrates this.

Most capacitor manufacturers make use of some form of life test that runs simultaneously with a statistical analysis to predict or guarantee the customer a certain failure rate over a fixed period of time. The most accurate single life test would be to test a group of capacitors at rated temperature and voltage for the guaranteed life of the unit. This method is not practical because of the time involved. Many leading manufacturers are approaching this accuracy however, by running slightly accelerated life tests for a shorter period of time. These tests are in the order of 1.5 times the rated voltage at the rated temperature.

3.2 Power Law Determination. For a given operating temperature, the life of a capacitor is known to be inversely proportional to some power "N" of the applied voltage. Accelerated life tests, to avoid consuming excess time, are based on this relationship. Consequently, the power law that a capacitor type follows can be quickly determined graphically by dividing a sample group of capacitors into minimum groups of five pieces each and life testing these at various multiples of rated voltage (4x, 5x, 6x, 7x, rated voltage). The average life of each group is then plotted against voltage on log-log paper and the slope of the resultant line calculated in order to obtain a representative power law. Figure 5 illustrates this. A second graphical method of obtaining "N", would be to plot failure rate against voltage on log-log paper. The slope of the resultant line will be equal to the power law. This is shown in Figure 6. An alternate method of obtaining "N", would be taking data at any two voltages from the plot in Figure 5, and calculating "N" from the following formula:

$$\left(\frac{V_2}{V_1}\right)^N x L_2 = L_1$$

where

V_1 = voltage at point 1
V_2 = voltage at point 2
L_1 = life at point 1
L_2 = life at point 2
N = Power Law

The power law "N" can now be used in conjunction with the failure rate to accurately predict capacitor life at various voltages, at a given temperature for a particular capacitor type. The evaluation of capacitor lots by plotting several life test points at various degrees of accelerated voltage has been found to be the most comprehensive and most accurate of any method conducted in a comparable length of time.

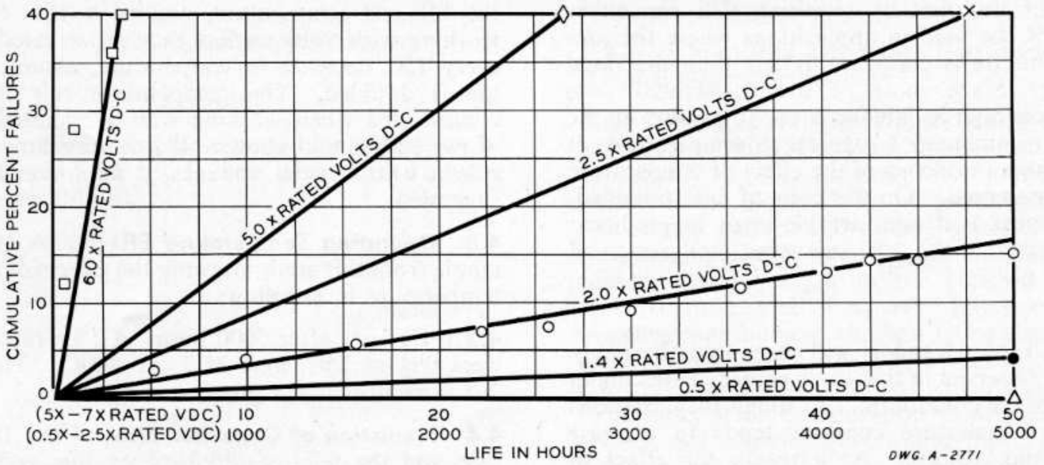

FIGURE 4

Failure Rate Characteristics of Hyrel Q Capacitors

The degree of acceleration used when conducting an accelerated life test is dependent on the capacitor dielectric. For example, paper-film capacitors may be tested at 6 to 7 times the rated voltage, whereas paper capacitors may be accelerated only 3 to 4 times the rated voltage. It is recommended that four accelerated life test points be taken for each plot, if possible.

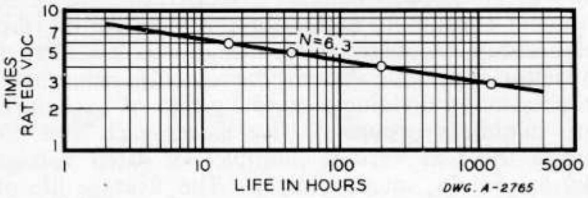

FIGURE 5

Capacitor Power Law Life vs Voltage Determination

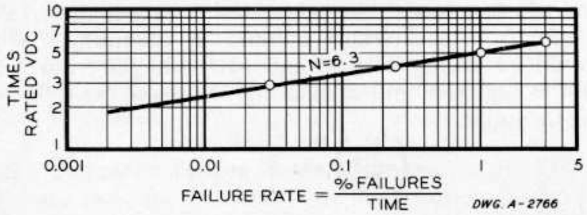

FIGURE 6

Capacitor Power Law Failure Rate vs Voltage Determination

4. Effects of Temperature on Capacitor Life.

Some years ago life tests were conducted on 85C oil impregnated paper capacitors at various temperatures. These tests show that capacitor life decreases as the ambient temperature increases. On the basis of these tests, the 10C rule was established. This rule states that for every 10C increase in ambient temperature (within the recommended operating range) the capacitor life is decreased by 50 percent. Conversely, for each 10C decrease in ambient temperature, the life of the capacitor is doubled. Design engineers often take advantage of this fact by requiring that capacitors rated at 125C be used in applications where the ambient temperature is considerably less than the rated temperature. Since most of the accelerated tests conducted on high reliability capacitors were at the maximum recommended operating temperature of 125C, conclusive evidence of the effect of temperature cannot be presented. On the basis of data obtained, it would appear that considerable error in predicted life would result if the 10C rule were used under all conditions.

A study of Tables I and II will show that the temperature rule observed in this study exceeded 10C under a majority of the conditions. At times they exceeded 25C. The temperature constant tends to increase with increasing voltage. As a result, the effect of small temperature changes becomes negligible when life testing at high degrees of accelerated voltage. At low voltage (rated or less), the effect of these small temperature changes can readily be observed and must be taken into consideration when predicting capacitor life expectancy. At higher voltages, the effect of temperature, unless it is extreme, is observed to a lesser extent, with the voltage appearing to be the dominating factor. Although this data is somewhat limited, the following rules are recommended for conservative iife expectancy predictions.

TABLE I

LIFE - TEMPERATURE RELATIONSHIP

$$L_1 = L_2 \; x \; 2 \left(\frac{T_2 - T_1}{K} \right)$$

Percent Failures During 1000 Hours Life,
264 Capacitors/Group; Rated 200-600 V.D.C.

% Rated Voltage	*100 C*	*125 C*	*k(°C)*
140	0	0	—
200	1.5	4.2	17
250	7.6	18	20

TABLE II

Percent Failures During 5000 Hours Life at 200% Rated Voltage; 72-96 Capacitors/Group

Voltage Rating	*100C*	*125C*	*k*
200	4.2	21	11
400	9.4	22	20
600	4.2	5.2	81

4.1 Predictions Above Life Test Temperatures. When predicting the life of a capacitor at temperatures above the life test temperature, assume a 10C rule, i.e., for every 10C increase in temperature, assume a 50% decrease in capacitor life.

4.2 Predictions Below Life Test Temperatures. When predicting the life of a capacitor at temperatures below the life test temperature, assume a 15C rule when working with voltages less than twice rated, i.e., for every 15C decrease in temperature, assume that the life is doubled. This temperature rule is not recommended when working with accelerated voltages of twice rated and above. If it is imperative that this rule be used at such voltages, a minimum of 20C is suggested.

4.3 Operating Temperature Effects. A typical example from this study showing the effects of operating temperature is as follows:

4.3.1 Failures after 5000 hours at 2.5 x rated voltage were 0% at 25C, and 25% at 100C. There were 264 capacitors in the group under test.

4.4 Prediction of Capacitor Life. Once the failure rate and the relationship between life, voltage, and temperature have been established for a particular type of capacitor, it is possible to accurately predict the life expectancy for this type of capacitor under other reasonable conditions of voltage and temperature.

4.4.1 The basic relationship for predicting capacitor life is as follows:

$$\frac{L_1}{L_2} = \frac{R_1}{R_2} \, x \left(\frac{V_2}{V_1}\right)^n x \; 2^{\left(\frac{T_2 - T_1}{k}\right)}$$

L = time to a given % failures
R = % failures on which L is based
V = d.c. voltage
T = temperature (°C)
n = power law exponent
k = temperature rule constant

4.4.1.1 Examples showing the application of this system of capacitor life prediction are as follows:

Example 1

In a piece of equipment operating at 400 volts d-c and 125 C, using 1000 capacitors of a particular type, what will be the expected time to 1% failures. It is known from accelerated tests that the time to 1% failures at 800 volts d-c (2 x rated voltage) and 125C is 225 hours.

Determine L_1

Known: L_0 = 225 hours
R_0 = 1% R_1 = 1% n = 5
V_0 = 800 vdc V_1 = 400 vdc k = 20°C
$T^0 = T^1 = 125C$

$$L_1 = L_0 \, x \, \frac{R_1}{R_0} \, x \left(\frac{V_0}{V_1}\right)^n x \; 2^{\left(\frac{T_0 - T_1}{k}\right)}$$

$L_1 = 225 \; x \; 1 \; x \; 2^5 \; x \; 2^0$

L_1 = *7,200 hours to 1% failure*

Example 2

Under the same conditions as in example 1, how many failures would be expected after 3000 hours of operation?

$$R_2 = R_1 \; x \; \frac{L_2}{L_1}$$

$R_2 = 1\% \; x \; 0.42$

$R_2 = 0.42\%$ failures after 3000 hours

Example 3

To what voltage must these particular capacitors be derated to obtain 0.1% failures after 2000 hours at the same conditions?

$$\left(\frac{V_0}{V_3}\right)^n = \frac{L_3 \, x \, R_0}{L_0 \;\; R_3}$$

$$\left(\frac{800}{V_3}\right)^5 = 8.9 \; x \; 10$$

V_3 = *325 vdc maximum allowable voltage*

Example 4

What would be the expected time to 0.1% failures if the conditions as in Example I are maintained, except for the ambient temperature being reduced from 125°C to 65°C?

$$L_4 = L_1 \, x \, \frac{R_4}{R_1} \, x \; 2^{\left(\frac{T_1 - T_4}{k}\right)}$$

$L_4 = 7200 \; x \; 0.1 \; x \; 2^3$

L_4 = *5760 hours to 0.1% failure at 65°C.*

5. Factors Affecting Reliability.

Probably the best way to consider the factors affecting capacitor reliability, is a comparison of the life characteristics of a standard capacitor with those of a high reliability capacitor, and emphasize what must be done to the standard capacitor to increase its reliability. A good, overall comparison can be made by examining the failure rate patterns for each of these units, as illustrated in Figure 1.

5.1 Standard Capacitors. Standard units have a high, initial failure rate because of inherent weaknesses in the dielectric, and because of damage incurred during manufacturing.

5.2 High Reliability Capacitors. The low, initial failure rate of high reliability capacitors decreases slowly until the wear-out portion of the curve is reached.

5.3 Standard Capacitor Failure Reduction. It is believed that the high initial failure rate of standard capacitors can be substantially reduced by observing the following rules.

5.3.1 Set up stringent specifications for raw materials to insure that only select materials are purchased.

5.3.2 Provide rigid inspection of the quality of incoming materials to insure continuous high quality.

5.3.3 Provide optimum storage conditions for all raw materials.

5.3.4 Keep work areas clean. Provide suitable clothing for persons working on the units.

5.3.5 Use whatever special handling is necessary during processing to avoid damage to the units.

5.3.6 Set up a rigid inspection program during all phases of manufacture and provide a constant feedback of information.

5.3.7 Use quality acceptance tests during and after the manufacturing processes.

5.4 Other Factors Affecting Reliability. In addition to reducing the high initial failure rate of standard capacitors, if the previous recommendations are followed, the slope of the wear-out portion of the failure rate pattern shown in Figure 1 will become considerably flatter because of the lesser degree of contamination present in the finished units. The most common cause of capacitor failure under normal working conditions is thought to be electro-chemical deterioration. This is usually observed under normal d-c stress, as a slow process, which ultimately leads to failure. This deterioration is accelerated by the presence of contaminants within the capacitor[2].

Additional factors affecting the reliability of a capacitor are its ability to withstand high G shock, vibration, temperature cycling and corrosion. These factors are dependent for the most part on the mechanical construction of the unit.

To supplement the information presented in this paper, actual performance data has been included on Sprague Type 195P, 125C subminiature metal-clad Hyrel Q capacitors and Sprague Vitamin Q small metal-clad tubular capacitors. See Figures 7 and 8 respectively, for this data.

6. Conclusion

This paper has dealt with failure rate patterns, the effects of voltage (Power Law), temperature, and factors that affect the reliability of oil impregnated capacitors. Tests have been discussed which must be performed to obtain at minimum cost and time, information necessary for the prediction of capacitor life, and how this information may be applied.

The evaluation of capacitors by the use of accelerated life tests has been found to be the most comprehensive and most accurate of any method that has been used heretofore, with the outstanding advantage that the overall quality of the capacitors can be evaluated. It has been pointed out that if proper precautions are taken, the quality and reliability of a capacitor can be increased to the point where it is reasonable to assume a constant failure rate for the conservative prediction of capacitor life. Once this constant failure rate is assumed, it is believed that with the aid of information obtained from the accelerated life tests (effect of temperature and voltage), the life of other capacitors of the same construction, but operating under different conditions, can be predicted with the highest degree of accuracy. The information gathered from accelerated life tests has been found to be of enormous value. The writers are certain that these same tests will aid reliability and quality control engineers in the evaluation of capacitors, and that the increased accuracy in predicting capacitor life expectancy, based on information from these tests, will be of invaluable aid whenever critical design applications must be met.

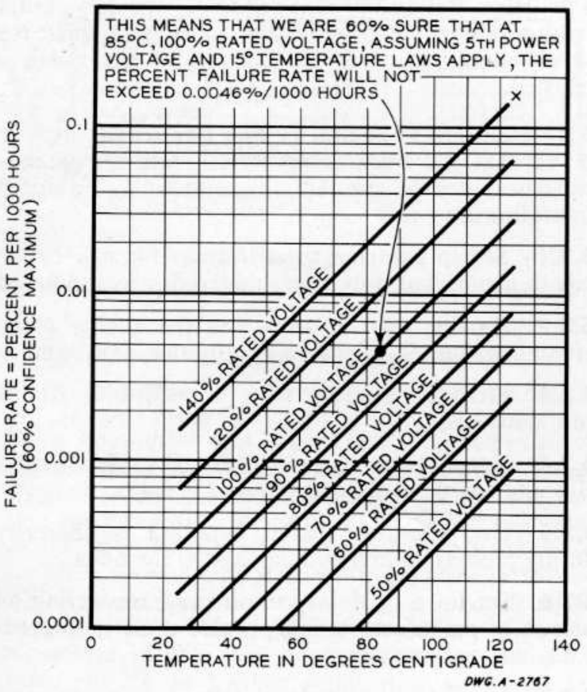

FIGURE 7

Performance Curves for Sprague Type 195P Hyrel Q Capacitors

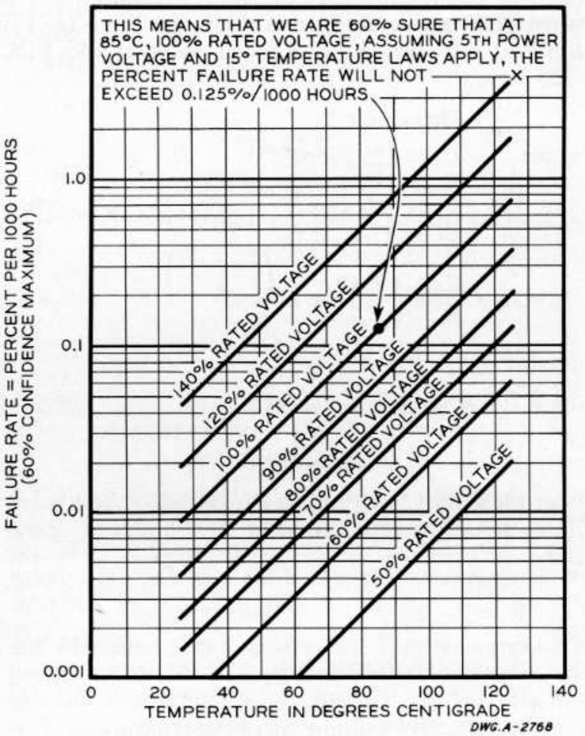

FIGURE 8

Performance Curves for Sprague Vitamin Q Capacitors

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