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DESIGN AND APPLICATION OF POLYCARBONATE CAPACITORS IN AEROSPACE AC POWER SYSTEMS

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16. Abstract

Aerospace quality, hermetically sealed, wound, ac polycarbonate capacitors of metallized and film-foil construction were designed and subjected to a 5000-hour, 400-Hz life test. Temperature and voltage conditions for the life test were selected to force failures. Analysis of failed capacitors established failure causes. Recommendations have been made for improvements in the design and processing of polycarbonate capacitors for ac application in aerospace power systems.

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FOREWORD

The research described in this report was conducted by TRW under NASA contract NAS 3-11834. Mr. Richard R. Secunde of the Lewis Research Center Space Power Systems Division was the NASA Project Manager.

CONTENTS

SUMMARY

Capacitors which employ polycarbonate film as the dielectric have advantages for ac power applications in the aerospace industry because of low dissipation factor, excellent stability, and potential temperature capability of 125°C. Little application data was available on how to design and rate this type of capacitor for reliable, long term, 400-Hertz aerospace operation.

A specification which detailed the requirements for typical aerospace ac fixed capacitors was prepared. Wound capacitors in both metallized film and film-foil type construction were designed and supplied by two independent manufacturers in accordance with this specification. These capacitors were then subjected to a 5,000-hour, 400-Hz sinewave, ac life test at test conditions designed to force failures so that failure modes and causes could be established. The objectives were to generate life and failure information, study failures, learn how to properly design and rate these capacitors for aerospace ac electrical systems, and to recommend changes for capacitor improvement.

In the test program, no failures occurred at 65°C or 85°C, regardless of voltage applied. Of a total of 128 capacitors tested at 105°C, 13 failed during the test period. Of 128 capacitors tested at 125°C, 42 failures occurred consisting of 31 capacitors which failed during the test and 11 which were out-of-limits electrically or were open at the end of the test program.

Observing the fact that there was no correlation of increasing failures with increase in voltage at temperatures up to 125°C, a 400-Hz sinewave ac voltage stress of 300 volts rms/mil (.0254 mm) should be a reasonable design operating level. A derating of voltage at 125°C, based on these findings, would not improve confidence of successful operation at 125°C.

Two capacitor designs experienced no failures at all at any test condition to which they were subjected. Of the designs which did experience failures, the failure causes were traced to workmanship, material defects, corona, and contamination. Recommendations have been made for design improvements and process changes which will reduce the probability of these causes and allow improved performance at the higher temperature levels for all types of polycarbonate ac capacitors. The capability of polycarbonate ac capacitors to operate at temperatures up to 125°C has been demonstrated by two designs which experienced no failures.

INTRODUCTION

Capacitors using polycarbonate film as the dielectric material have advantages for use in aerospace ac power conditioning systems. They have a low dissipation factor along with good stability and a potential temperature capability of 125°C.

Considerable application data is available on the use of these capacitors in dc circuits. However, there is little such information for rating them for long term 400-Hertz application which is the most commonly used aerospace power frequency. Proper application of capacitors in power conditioning systems is essential to minimum system weight and reliable electrical service.

The purposes of this program were to learn how to properly design and rate wound polycarbonate film capacitors for aerospace ac electrical system uses and to recommend ways of improving this type of capacitor to make it better suited for such uses. Both the metallized film and the film-and-foil types of construction were studied.

The approach used to explore and evaluate polycarbonate capacitor performance in ac power circuits was to test a quantity of samples at 400-Hertz voltages over a range of voltage and temperature conditions for an extended period of time. The test capacitors were designed and built by two independent manufacturers to meet aerospace requirements for performance, reliability, and long life. The best available state-of-the-art design techniques were used without resorting to heavy over-design. All were metal encased and hermetically sealed. In order to obtain a diversity of types, the samples of metallized and film-foil type construction were evenly distributed between voltage ratings of 200 volts peak at 1 microfarad and 400 volts peak at 0.25 microfarad, and between two manufacturers. Thus, a total of eight designs were acquired for use in a matrix type life test of 5,000 hours duration. The two voltage ratings provided samples with and without the probability of corona. The combinations of voltage ratings and capacitance values were selected so that all samples would have the same nominal volt-ampere rating, and therefore be of similar physical size. This minimized the influence of size on the test results so that more meaningful conclusions might be drawn.

A total of 512 capacitors were endurance tested for 5,000 hours at four case temperatures ranging from 65°C to 125°C with four sine-wave, 400-Hertz, voltages ranging from 70 to 130 percent of each of the peak rated values. A previous program (Reference 1) determined the voltage and temperature levels that polycarbonate capacitors may be expected to withstand. The results of this earlier program were used in establishing the test voltage and temperature levels used in this 5,000-hour test in order to experience forced failure patterns designed to provide the most meaningful experimental results. The results that were achieved have been analyzed and are discussed in this report. Where failures occurred, the causes were determined and design or process modifications to minimize or eliminate the failures are recommended.

By studying performance of polycarbonate over a 5,000-hour test period, designs have been evaluated, improvements recommended, and a better understanding of how to rate polycarbonate capacitors for 400-Hertz aerospace applications has resulted.

EXPLANATION OF TERMS

To aid understanding of the results of this program as presented in this report, terms which are commonly used in the capacitor industry are explained below.

Clearing. This is the term applied to the process whereby shorts within a capacitor are burned clear without further damage to the capacitor. This occurs quite commonly in metallized types when the current at a pin-hole short is sufficient to vaporize the metallized film around the pin hole without further damage.

Core. A core is used in some designs. This is a rigid insulating material which is left in the center of the winding after removal from the winding machines. It is used to prevent collapse of winding material into the hole which would otherwise occur when the completed winding was removed from the winding machine.

Corona. This is a type of discharge in the dielectric of an insulation system caused by an electric field and characterized by the rapid development of an ionized channel which does not completely bridge the electrodes. Corona occurs when a voltage gradient around a conductor exceeds a critical value for the insulating medium surrounding the conductor and ionization results.

Corona Onset Voltage. The voltage level at which corona is first detected when raising the voltage from a lower level.

Corona Offset Voltage. The level of voltage at which corona will cease when lowering the voltage after corona has started.

Dielectric Strength. In this report, it describes the ability of the capacitors to withstand dc potentials applied from terminal to terminal and terminal to case and ac potentials applied terminal to terminal.

Dissipation Factor (DF). This is the ratio of effective resistance in ohms to the capacitive reactance in ohms. This term is associated only with a sine wave of alternating voltage applied at some frequency and is a measure of the dielectric quality and of the imperfections of a capacitor, such as the resistance of internal connections. It can also be represented by a ratio of real power lost per cycle to reactive power stored per cycle. Measurements are often expressed in % which is DF x 100.

Impregnation. This is the process by which the air in the capacitor winding is removed and replaced by an insulating material such as oil. The elimination of air and its replacement with an impregnating oil reduces the possibility of corona and aids heat transfer.

Insulation Resistance (IR). This is the dc equivalent resistance between the two terminals of a capacitor. IR_{T-T} indicates terminal-to-terminal insulation resistance and IR_{T-C} represents terminal-to-case insulation resistance. This is measured with a dc voltage and is one of the important quality measurements of a capacitor. A very high IR is desirable and all measurements in this report are in units of megohms.

Lead Head. A lead head is formed in the wire lead at the end where connection is made to the wound capacitor element. It is a single spiral loop, the plane of which is perpendicular to the lead axis.

Margin. A margin can be described as physical spacing existing at the edge of the surface of the dielectric which separates one conducting plate from another conducting plate. On metallized dielectric type construction, the margin is formed during manufacture of the raw material by masking off a certain width along the edge of the dielectric material to prevent deposition of metal on that portion of the surface. Shorts on a capacitor between two conducting plates can occur across the surface of the dielectric if the margin is not adequate for the voltage impressed. On the film-foil type construction, the margin is again that edge area on the surface of the dielectric separating one conducting plate from another conducting plate, but is formed by an offset of foil from the dielectric and also by choice of foil and dielectric widths.

Padding. Padding as mentioned within this report consists of additional plain dielectric which is wound around the winding core to protect the winding from possible rough edges on the core.

Schooping. Schooping refers to a metal spray process. The metal spray on axial end of winding for all designs using metallized dielectric provides the means for making the electrical connection to the very thin metallized plates.

Stability. Stability refers to the amount of drift or change in capacitance as a function of time. A minimum amount of capacitance change is desirable. The symbol $\%\Delta C$ is sometimes used to designate the percent change in capacitance.

Swedging. Swedging is a method of applying solder to the edges of the foil conducting plates after the capacitor element is wound. It generally consists of applying solder with a hot iron in pressing and wiping strokes.

Termination. The termination in a wound capacitor consists of the lead, lead head, and the means of connection of the lead to the capacitor plate. A wound capacitor has two terminations, one for each conducting plate.

DESCRIPTION OF CAPACITORS TESTED

A procurement specification was written (reference Appendix A) to assure that the capacitors tested under this program represented the best available design practice applicable to aerospace use. Capacitors in sufficient quantity for this program were obtained to this specification from two independent manufacturers. A total of eight designs were used, four from each manufacturer.

The general ratings and descriptions of the capacitors obtained are given in Tables I and II.

TABLE I

CAPACITOR DESIGNS ACQUIRED FOR TEST

Designs[a]	400 Hz ac Peak[b] Voltage Rating (Volts)	Cap. (uF)	Tolerance (Percent)	Construction
A-1 & B-1	200	1.0	±5	Metallized Polycarbonate
A-2 & B-2	200	1.0	±5	Polycarbonate Film with Aluminum Foil
A-3 & B-3	400	0.25	±5	Metallized Polycarbonate
A-4 & B-4	400	0.25	±5	Polycarbonate Film with Aluminum Foil

[a] Letters designate manufacturers A and B, each of which furnished their own design.

[b] Zero-to-peak voltage.

TABLE II

PHYSICAL PROPERTIES OF CAPACITORS TESTED

Design	Outside Body Dimensions Diameter		Outside Body Dimensions Length	Winding Dimensions Diameter		Winding Dimensions Length	Liquid Impregnant[a]	Liquid Fill[b]
A-1	.775" (1.969 cm)	x	2.156" (5.476 cm)	.560" (1.422 cm)	x	1.812" (4.602 cm)	Silicone Oil	Silicone[c] Compound
B-1	1.0" (2.540 cm)	x	2.406" (6.111 cm)	.670" (1.702 cm)	x	1.812" (4.602 cm)	Polybutene	Polybutene
A-2[d]	1.125" (2.857 cm)	x	3.00" (7.620 cm)	.966" (2.453 cm)	x	2.625" (6.667 cm)	None	Silicone Compound
B-2	1.0" (2.540 cm)	x	2.687" (6.825 cm)	.855" (2.172 cm)	x	2.250" (5.715 cm)	Polybutene	Polybutene
A-3[d]	.775" (1.969 cm)	x	2.156" (5.476 cm)	.550" (1.397 cm)	x	1.812" (4.602 cm)	Silicone Oil	Silicone Oil
B-3	1.0" (2.540 cm)	x	1.875" (4.762 cm)	.706" (1.793 cm)	x	1.375" (3.492 cm)	Polybutene	Polybutene
A-4	1.0" (2.540 cm)	x	2.250" (5.715 cm)	.775" (1.969 cm)	x	2.00" (5.080 cm)	Silicone Oil	Silicone Oil
B-4	1.0" (2.540 cm)	x	2.156" (5.476 cm)	.800" (2.032 cm)	x	1.625" (4.128 cm)	Polybutene	Polybutene

(a) Impregnant is the material used for filling all air voids in the winding itself.

(b) Liquid Fill refers to the insulation oil or other material which fills the space between the winding and the outer metal encasement.

(c) The silicone compound is a black rubbery compound used as a fill in 2 designs furnished by Manufacturer A. Exact composition of silicone compound considered proprietary by Manufacturer A.

(d) Designs A-2 and A-3 exceed the maximum dimensions given in the procurement specification, but were accepted for this program.

All capacitors were of extended foil construction and were hermetically sealed in tin-plated brass cases. Traceability records for all parts were a requirement. The design life goal was 50,000 hours at rated peak 400-hertz voltage rating at 125° C with 95% survival. Designs were to minimize possibility of corona at test conditions being considered. Leakage rates for hermetic seals were specified to be less than 1×10^{-8} atm cc/sec when tested to Method 112A of MIL-STD-202, Test Condition C, Procedure IIIa. Requirements for shock, vibration, acceleration, gravity, and radiation were part of the procurement specification to describe potential space environment, but these environmental tests were not actually performed on the test parts.

Additional description of the designs tested follows:

In discussing film-foil or metallized dielectric construction, the dielectric thickness refers to the thickness of dielectric between any 2 conducting plates. It should be understood that with cylindrically wound type capacitor construction, if the dielectric is described as having one sheet of thickness dielectric and one sheet of another thickness dielectric or 2 sheets of dielectric of a certain thickness, the complete capacitor winding contains twice the number of sheets described as dielectric. The specified dielectric thickness exists on both sides of each conducting plate.

Design A-1 utilized 1 sheet of .00024" (.0061 mm) thick aluminum metallized polycarbonate and 1 sheet of .00024" (.0061 mm) clear polycarbonate as dielectric with a total of 2 clear sheets and 2 metallized sheets in the winding. The axial ends of the windings were sprayed with metal for making electrical contact to the metallized plates, and 18 gage (.102 cm) leads soldered to the metal spray, were used for termination. Margins on design A-1 were 1/16 inch (.159 cm). This design did not use a core.

Design B-1 utilized 1 sheet .00040" (.0102 mm) thick and 1 sheet .00020" (.0051 mm) thick aluminum metallized polycarbonate as dielectric. A total of 2 sheets of .00040" (.0102 mm) metallized polycarbonate and 2 sheets of .00020" (.0051 mm) metallized polycarbonate were used in the winding. The winding was wound on a hollow core. Winding ends were sprayed with metal for contact to metallized plates, and 18 gage (.102 cm) leads with metal screen contact washers, soldered to the metal spray, were used for terminations. Margins were 1/8 inch (.317 cm). The design used a back-to-back assembly technique in which each conducting plate is made up of the metallized surface of 2 sheets of dielectric. Use of the back-to-back assembly technique allows the 2 sheet dielectric thickness desirable and increases by a factor of 2 the effective thickness of the conducting plate which is important for carring currents associated with ac operation. This design has a patent pending.

Design A-2 used 2 layers of .00040" (.0102 mm) thick plain polycarbonate as dielectric with a total of 4 sheets in the winding. Two aluminum foils each .00025" (.0063 mm) thick were used as the capacitor plates. Leads of 18 gage (.102 cm) wire were soldered directly to the foils for terminations. Margins were 1/8 inch (.317 cm). This was a coreless design.

Design B-2 made use of 1 layer of .00024" (.0061 mm) thick and 1 layer of .00032" (.0081 mm) thick plain polycarbonate and aluminum foil which was .00025" (.0063 mm) thick. A total of 2 polycarbonate sheets each .00024" (.0061 mm) thick, 2 sheets of polycarbonate each .00032" (.0081 mm) thick, and 2 aluminum foils each .00025" (.0063 mm) thick made up the winding. The winding was wound on a rigid hollow core. The terminations consisted of leads of 18 gage (.102 cm) soldered to a screen-type metal contact washer which was soldered to the foil edges. Margins were 1/8 inch (.317 cm).

Design A-3 had 1 layer of .00040" (.0102 mm) thick aluminum metallized polycarbonate plus 1 layer of .00050" (.0127 mm) thick plain polycarbonate as dielectric. Total layers of material making up the winding were 4, consisting of 2 of each of the above sheets. Terminations to the metal sprayed axial ends of the winding were made with 18 gage (.102 cm) leads soldered as in design A-1. Margins were 1/8 inch. This design did not use a winding core.

Design B-3 included a total of 4 layers of .00050" (.0127 mm) thick aluminum metallized polycarbonate in back-to-back design so that between metallized plates dielectric thickness was .001" (.0254 mm). The winding was wound on a rigid hollow core and 18 gage (.102 cm) leads with metal screen-type contact washers were used for terminations to the metal sprayed axial end of the winding, soldered as in design B-1. Margins were 1/8 inch (.317 cm).

Design A-4. The dielectric consisted of 3 layers each .00040" (.0102 mm) thickness plain polycarbonate. Total dielectric sheets in the winding were six. The plates were .00025" (.0063 mm) aluminum foil. Margins were 3/16 inch (.476 cm). Terminations consisted of 18 gage (.102 cm) leads soldered directly to the foil edges. This design had no winding core.

Design B-4. This winding utilized 2 layers of plain polycarbonate each .00050" (.0127 mm) thick. Plates were aluminum foil, .00025" (.0063 mm) thick. A total of 4 sheets of dielectric and 2 aluminum foils made up the winding. The winding was wound on a rigid hollow core and terminations consisted of 18 gage (.102 cm) leads with screen-type metal contact washers soldered as in design B-2. Margins were 1/8 inch (.317 cm).

Figure 1 is a photograph that illustrates the physical sizes and configurations of all designs tested.

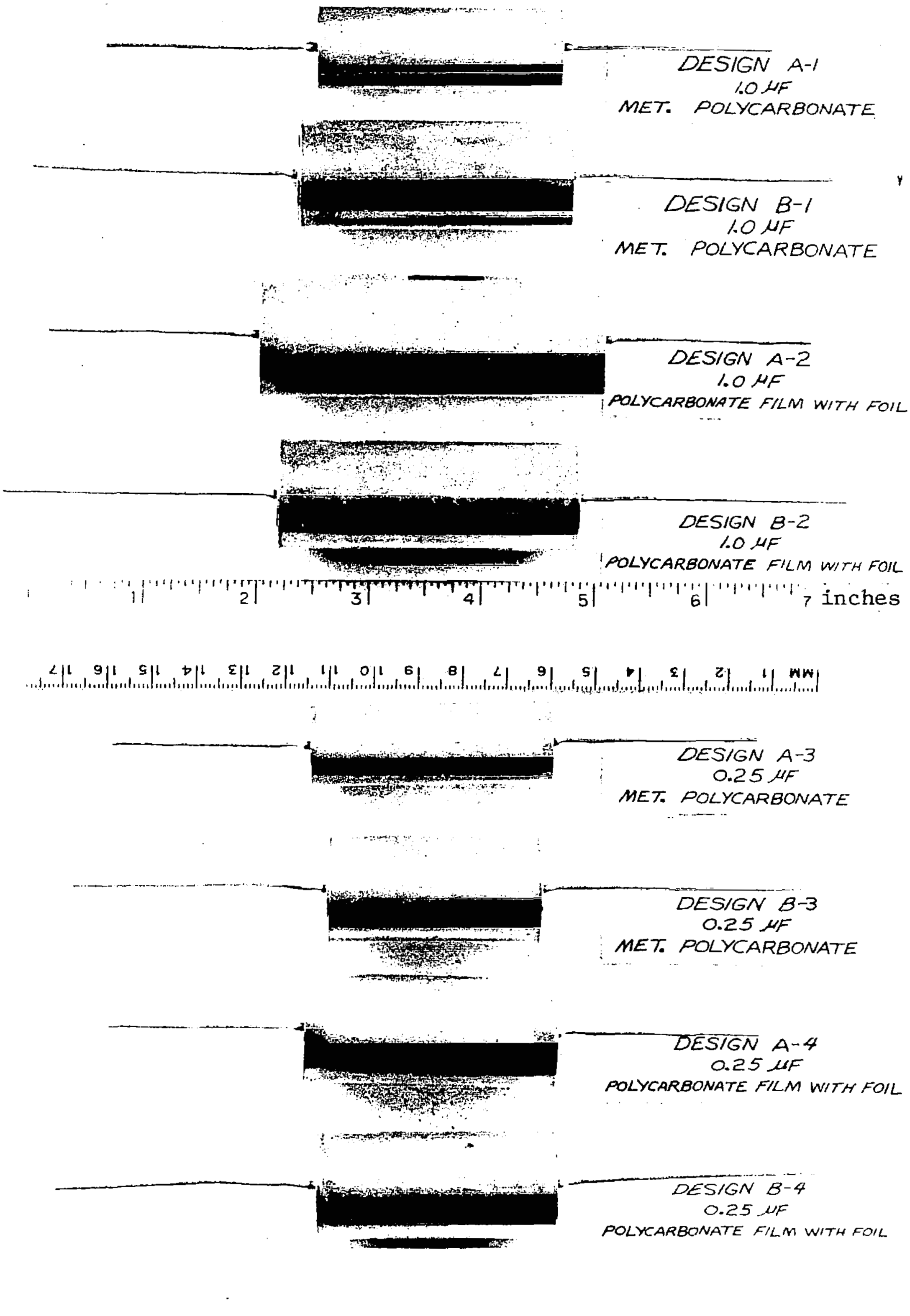


FIGURE 1. Representative Samples of all Test Capacitor Designs

TEST PROCEDURE

All capacitors were inspected to assure their meeting the electrical and physical requirements of the procurement specification. Body length and diameter, lead length and diameter, marking, workmanship, seal leakage, capacitance, dissipation factor, insulation resistance from terminal-to-terminal and terminal-to-case, and ac dielectric strength from terminal-to-terminal were measured as a part of receiving inspection.

Of each design, 64 pieces were scheduled and serialized to go into the 5,000-hour ac life test. One capacitor of each design was dismantled for internal inspection.

Equipment used for receiving inspection is outlined below.

Capacitance (C) and Dissipation Factor (DF)	Micro Instrument Digital Readout Bridge Model 5320D, for 400 Hz - utilizes 4 terminal Kelvin type measurement.
Insulation Resistance (IR)	Beckman Model L-8 Megohmmeter. Voltage variable from 10 to 1000 volts dc modified by TRWC to include timing devices, signal indicators, and shielding.
Seal Leakage	Veeco Mass Spectrometer Model MS-9AB, Standard Veeco leak calibrator, and pressurizing chamber for helium gas.
Dielectric Strength (DC)	TRW Variable Power Supply Model 1100H2, Includes timing devices and short indicators.
Dielectric Strength (AC)	TRW AC equipment P-88 consisting of variacs and transformers to elevate 60-Hz, AC line power to desired voltage levels. A Fluke Voltmeter Model 931P was used to monitor voltage level.

Upon completion of receiving inspection, capacitors were placed into test trays in 4 different ovens (each oven operated at a different temperature) for conducting the life test. Metal body clamps riveted to metal heat sink bars held each capacitor metal case. This type mounting maintained the case temperatures of all capacitors essentially at the oven ambient temperature. See Figure 2 which illustrates a typical test tray. Each oven consisted of 8 test trays of 16 test positions per tray.

Capacitor case temperatures selected for the life test were 65°C, 85°C, 105°C, and 125°C. Test voltage peak values were set at 70%, 90%, 110%, and 130% of the capacitor ac peak voltage ratings. These test conditions were selected based on findings reported in an earlier test program (Reference 1).

Four sample capacitors of each of the eight designs were subjected to each combination of temperature and percent rated voltage for 5,000 hours. Thus, in this test there were a total of 512 capacitors on test. Each group of four capacitors of the same design on test at a particular temperature-voltage condition is considered a test cell.

For capacitors rated at 200 volts ac peak, the ac peak test voltages were 140, 180, 220, and 260. For capacitors rated at 400 volts ac peak, the ac peak test voltages were 280, 360, 440, and 520.

A requirement of the test procedure was that capacitor case temperatures be maintained within ±3°C of specified test temperature. Another requirement of the life test was that voltage levels be maintained within ±2% of specifed levels and that total harmonics were not to exceed 3 percent.

Corona onset and offset voltage levels were measured on 10 spare capacitors of each design to determine whether corona might occur at voltage levels below some of the life test voltage levels to be used. The 200-volt, 400-Hz, ac peak rated capacitors scheduled for life test up to 260 volts ac peak (184 volts rms) were tested for corona up to 300 volts rms at 60 Hz. Those parts rated 400 volts ac peak at 400 Hz and life tested at up to 520 volts ac peak (367 volts rms) were checked for corona at voltages up to 500 volts rms at 60 Hz. Previous test experience at TRWC has demonstrated negligible change in corona starting voltages at frequencies from 60 Hz to considerably above 400 Hz.

Initial electrical measurements on life test capacitors of capacitance, dissipation factor, insulation resistance between terminals and between terminals and case were recorded at test temperature and then measurements were repeated at 1,000, 2,000, 3,000, 4,000, and 5,000-hour points at test temperature. The power to the capacitors was removed during these measurements. Any parts which were noted to have failed due to a short or open condition were not removed until the following power shutdown for electrical measurements. At that time, if spare parts were available, they were placed into test.

At the end of the 5,000-hour test, all remaining capacitors were returned to room ambient (25°C) and the electrical measurements mentioned above plus the helium leak detection test were performed on them.

A failure analysis was performed on those capacitors that developed shorts, opens, intermittent connections during the test or that exceeded a dissipation factor limit of 0.50% or a change in capacitance of more than ±10% at the end of the test. Photographs were taken of many of the failures where it was useful in describing the cause of failure.

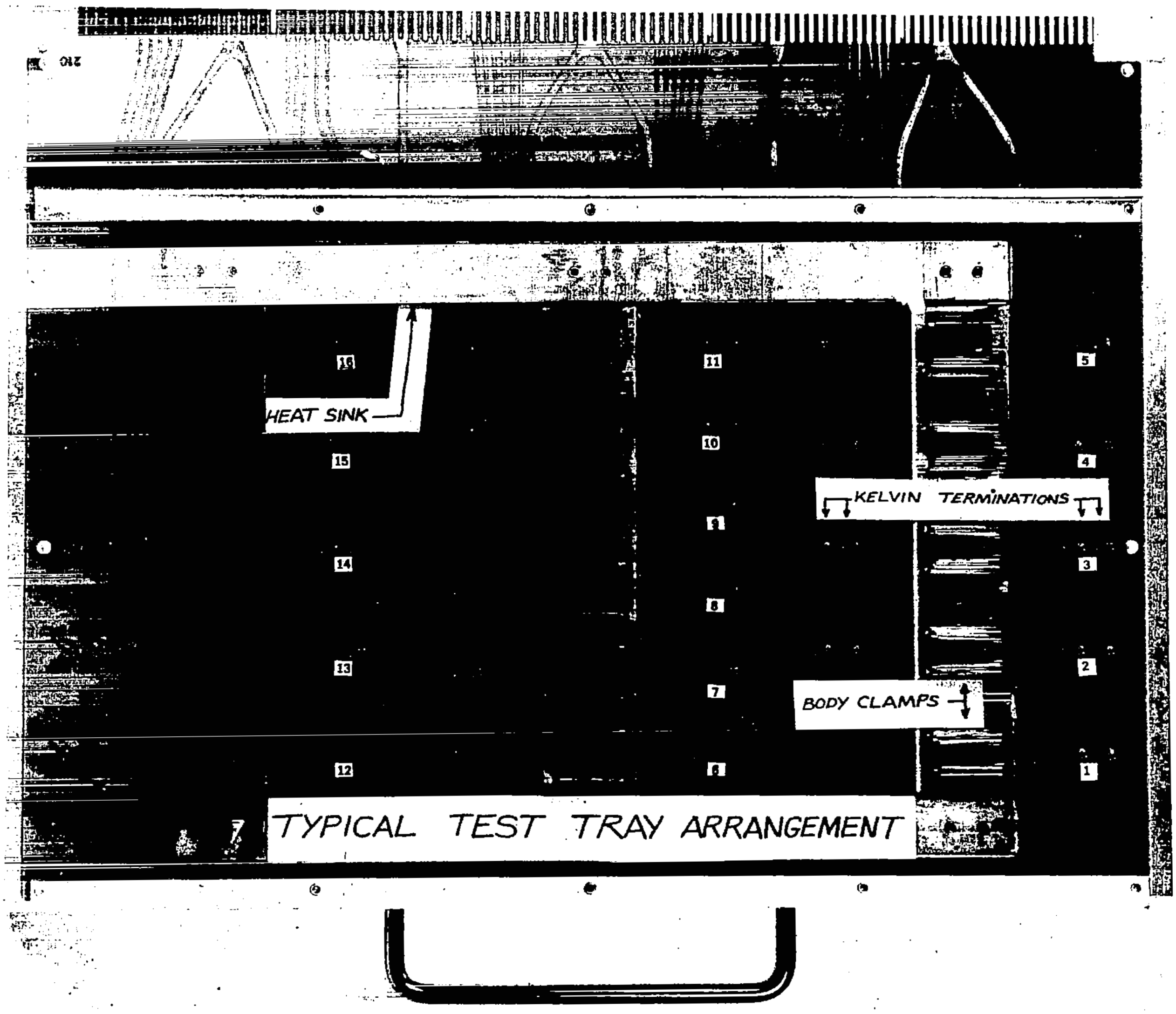


FIGURE 2. Typical Printed Circuit Type Test Tray Illustrating Heat Sinks and Body Clamps for Aid in Control of Capacitor Case Temperature.

Every group of capacitors at a particular temperature and voltage had its own continuous strip-chart current recorder, capable of displaying total current in the test tray plus the resolution to display an increment of current equivalent to that drawn by an individual test capacitor. A total of 32 current recorders were used.

Scanning type, 8-channel, strip-chart voltage recorders were used to monitor the 8 voltage levels entering each life test oven. Total time for one cycle of the scanner was 12 seconds. A total of 4 voltage recorders was used. Each recorder included a signal conditioning network for converting the 400-Hz sinewave voltages to dc voltages for the measuring element.

Two 24-channel temperature recorders were used to monitor the case temperature of 1 capacitor in each of the 8 test trays in each of the 4 ovens. The thermocouples were cemented to the capacitor cases. Several thermocouples were used in each oven to record ambient temperature. Some dummy thermocouples provided adequate time for the balancing mechanism to move from measuring temperature in one oven to a different position on the chart for temperature of another oven. Each 24-channel temperature recorder served 2 ovens.

Shorts, intermittent connections, or opens during test were detected by the continuous strip-chart current recorders. In addition, shorts were detected by an arrangement of fuses, resistors, and neon bulbs. Each test capacitor had a fuse external to the heated chamber and in series with the test capacitor. The fuse was paralleled by a resistor in series with a neon bulb. The bulb iginited when the fuse opened to give visual indication that a short had occurred.

A portable power plant was rigged to insure maintenance of oven temperature and chart drives on voltage and temperature recorders in case of power failure. The timed strip charts on the voltage recorders would give evidence of duration of power failure and operation of temperature recorders would give proof that oven temperature was maintained. Purpose for this procedure was to assure that, should commercial power fail, temperature would not decrease.

A manual scanner designed as an integral part of the capacitance bridge enabled 4-terminal Kelvin type measurements of capacitors while in the test ovens.

A description of additional equipment used to conduct the life test and perform failure analysis is given below.

Life Test Systems (Ovens)	Micro Instrument Model 1025 with special load trays including fuses and special test trays.
Current Recorders	Esterline Angus Model 601C.
Voltage Recorders	Esterline Angus Model E1124E with special transducers for signal conditioning type TB-501.

Temperature Recorders	Honeywell Recorders, Model No's Y153X85-(C)-II-III-51-A8 (P13) and Y153X80-(C)-II-III-31-F4.
Auxiliary Power Plant	Kohler Model 5 RM62.
Microphotography	Bausch & Lomb Microscope with Polaroid Camera.
Voltmeter (rms)	John Fluke Model 931P
Oscilloscope	Tektronix Model 531, with Plug-in 53/54K.
Motor Generators	Kato Engineering, 3KW, #64025-1, -2, -3, and -4.
Motor Generators	Kato Engineering, 5KW, #64027-1, -2, -3, and -4.

Equipment used for the corona check consisted of the following:

Pulse Calibrator	HiPotronics Model CDPC68B-1.
AC Dielectric Test Set	HiPotronics Model 72.5-5.
Corona Detector	HiPotronics Model CDO-3-68.

RESULTS AND DISCUSSION

Initial Measurements

Initial room temperature electrical measurements and hermetic seal leakage rate comparisons for the eight designs tested under this program are tabulated in Table III as an average of all parts that were measured for each design. Initial dissipation factor and terminal-to-terminal insulation resistance were comparable for designs A & B of each type and capacitance value. Slightly lower average leakage rates were observed on designs with prefix letters of B, indicating better hermetic seals.

The initial corona test was performed on 10 samples of each design. The results shown in Table IV indicate that design B-2 was on the borderline of exhibiting corona. Designs A-3 and B-3 demonstrate a susceptibility to corona at voltages below those used in the test. However, only one capacitor failure, design A-3, was attributed to the effect of corona.

Temperature & Voltage Effects

There were no failures during the 5000-hour life test at 65°C or 85°C. However, 13 failures (all catastrophic shorts or opens) were recorded at 105°C and 42 failures (31 catastrophic shorts during operational life and 11 out-of-limits or opens) were recorded at 125°C. Tables V and VI show the distribution of failures within test cells at 105°C and 125°C respectively. These findings demonstrate the affect of temperature. Tables VII and VIII present the 1.0 u F and 0.25 u F failures respectively in a way that illustrates the effect of temperature for the designs tested at a given voltage. A review of these tables shows little or no correlation between the number of failures and the level of test voltages used in this program. This indicates that temperature is more of a limiting environmental condition for the capacitors. Voltage derating to as low as 70% of rated condition would not give assurance of failure-free operation at 125°C.

Parameter Variations

To describe the performance of these polycarbonate capacitors with various temperature and voltage operating conditions as a function of time, plots of capacitance change, dissipation factor, and insulation resistance are shown for temperatures of 65°C, 85°C, and 105°C in figures 3 through 20. Any one figure will specify a particular capacitance value and temperature and the legend on that figure relates a plotted curve to a specific design.

The capacitance change in percent as a function of operating hours and referred to as stability characteristics was plotted for each design at temperatures of 65°C, 85°C and 105°C.* Values are algebraic averages of all good parts within all 4 voltage cells at time of measurement. Figures 3 through 8 illustrate stability characteristics for the 3 lower temperatures.

* Note: Characteristics @ 125°C are shown separately and are presented differently.

TABLE III

INITIAL ROOM TEMPERATURE ELECTRICAL PARAMETER
AND HERMETIC SEAL LEAKAGE RATE COMPARISONS

DESCRIPTION	DESIGN	AVERAGE % DF (a)	AVERAGE IR T-T(b) (Megohms)	AVERAGE IR T-C(c) (Megohms)	AVERAGE LEAKAGE RATE (atm cc/sec)
1.0 u F, Metallized Polycarbonate	A-1	.10	285K	44,346K	$.61 \times 10^{-8}$
1.0 u F, Metallized Polycarbonate	B-1	.12	205K	114,192K	$.45 \times 10^{-8}$
1.0 u F, Polycarbonate Film-foil	A-2	.14	136K	8,947K	$.62 \times 10^{-8}$
1.0 u F, Polycarbonate Film-foil	B-2	.09	195K	15,328K	$.25 \times 10^{-8}$
0.25 uF, Metallized Polycarbonate	A-3	.15	609K	3,363K	$.33 \times 10^{-8}$
0.25 uF, Metallized Polycarbonate	B-3	.12	1,012K	218,974K	$.19 \times 10^{-8}$
0.25 uF, Polycarbonate Film-foil	A-4	.09	974K	1,449K	$.41 \times 10^{-8}$
0.25 uF, Polycarbonate Film-foil	B-4	.10	931K	74,897K	$.35 \times 10^{-8}$

Notes: (a) DF--Dissipation Factor
(b) Insulation Resistance, Terminal-to-Terminal
(c) Insulation Resistance, Terminal-to-Case

TABLE IV

INITIAL CORONA TEST RESULTS

Description	Design	Onset* Voltage Level Max.	Min.	Ave.	Offset** Voltage Level Max.	Min.	Ave.	Quantity Exhibiting Corona
		(--------------rms	volts				----)	
1.0 u F, Metallized Polycarbonate	A-1	300	235	263	290	220	247	8
1.0 u F, Metallized Polycarbonate	B-1	---	---	---	---	---	---	0
1.0 u F, Polycarbonate Film-Foil	A-2	300	260	279	280	245	264	6
1.0 u F, Polycarbonate Film-Foil	B-2	245	195	222	230	180	205	2
0.25 u F, Metallized Polycarbonate	A-3	400	290	351	380	270	332	6
0.25 u F, Metallized Polycarbonate	B-3	500	350	443	480	330	420	3
0.25 u F, Polycarbonate Film-Foil	A-4	---	---	---	---	---	---	0
0.25 u F, Polycarbonate Film-Foil	B-4	---	---	---	---	---	---	0

Notes: Ten samples of each capacitor design were tested.
All 1.0 u F. capacitors were tested for corona using a maximum of 300V rms @ 60 Hz. Similar parts to these were placed in the 400-Hz AC life test @ a maximum of 184V rms.

All 0.25 u F. capacitors were tested for corona using a maximum of 500V rms @ 60 Hz. Similar parts to these were placed in the 400-Hz AC life test @ a maximum of 368V rms.

*Onset is the voltage level at which corona starts as voltage is increased.
**Offset is the voltage level at which corona is extinguished after it has started and when voltage level is decreased.

TABLE V - CAPACITOR FAILURES @ 105°C

Catastrophic* & Out-of-Limits
From
5000 Hour AC Life Test @ 400 HZ

CELLS	99		127		156		184		198		255		311		368	
FB																
	1008	3002	1001		0999		0997								4229	
XB																
FA																
XA																
															0114	
											0999				0038	
									0999		0999		0999		0038	

RMS VOLTAGE LEVELS

← 1.0 μF CAPACITORS → | ← 0.25 μF CAPACITORS →

Note: Cells are denoted by letters. The letter "F" designates polycarbonate film with aluminum foil. The letter "X" designates metallized polycarbonate. The second letter designates design prefix.

Each number within a box represents the life hours of the capacitor @ the time of failure. The left group of four boxes represent cell position for original test parts and the right group of four boxes represents replacements and their failures.

* Catastrophic defined as opens or shorts.

TABLE VI - CAPACITOR FAILURES @ 125°C

Catastrophic* & Out-of-Limits
From
5000 Hour AC Life Test @ 400 HZ

CELLS	Box	99	99	127	127	156	156	184	184	198	198	255	255	311	311	368	368
		Original	Replacement	Original	Replacement	Original	Replacement	Original	Replacement	Original	Replacement	Original	Replacement	Original	Replacement	Original	Replacement
FB	1																
FB	2																
FB	3					0705											
FB	4			0000		0002		0101				0444		0961		0399	0000
XB	1			5000 ⊙		5000 ⊙											
XB	2			5000 ⊙		3250		5000 ⊙									
XB	3	5000 ⊙		3954		3093		1987									
XB	4	5000 ⊙		0723		2503		0882	2123								
FA	1																
FA	2																
FA	3																
FA	4	5000 ⊙		1950		0052		5000 ⊙									
XA	1									0999							
XA	2									0999						0038	
XA	3	5000 ⊙				5000 ⊙				0999				0993		0038	
XA	4	3004		5000 ⊙		4355				0760		0000		0058		0038	0276

RMS VOLTAGE LEVELS

← 1.0 μF CAPACITORS → | ← 0.25 μF CAPACITORS →

Note: Cells are denoted by letters. The letter "F" designates Polycarbonate film with aluminum foil. The letter "X" designates metallized polycarbonate. The second letter designates design prefix.

Each number within a box represents the life hours of the capacitor @ the time of failure. The left group of four boxes represents cell position for original test parts and the right group of four boxes represents replacements and their failures.

* Catastrophic defined as opens or shorts.

⊙ Designates out-of-limits

TABLE VII - CAPACITOR FAILURES VS TEMPERATURE, 1.0uF DESIGNS
Catastrophic* & Out-of-Limit

RMS VOLTAGE @ 400 HZ 99

CELLS		65°C		85°C		105°C		125°C	
FB									
						1008	3002		
XB									
								5000 ⊙	
								5000 ⊙	
FA									
								5000 ⊙	
XA									
								5000 ⊙	
								3002	

RMS VOLTAGE @ 400 HZ 127

CELLS		65°C		85°C		105°C		125°C	
FB									
						1001		0000	
XB								5000 ⊙	
								5000 ⊙	
								3954	
								0723	
FA									
								1950	
XA									
								5000 ⊙	

RMS VOLTAGE @ 400 HZ 156

CELLS		65°C		85°C		105°C		125°C	
FB									
								0705	
						0999		0002	
XB								5000 ⊙	
								3250	
								3093	
								2503	
FA									
								0052	
XA									
								5000 ⊙	
								4355	

RMS VOLTAGE @ 400 HZ 184

CELLS		65°C		85°C		105°C		125°C	
FB									
						0997		0101	
XB									
								5000 ⊙	
								1987	
								0882	2123
FA									
								5000 ⊙	
XA									

Note: Cells are denoted by letters. The letter "F" designates polycarbonate film with aluminum foil. The letter "X" designates metallized polycarbonate. The second letter designates design prefix.

Each number within a box represents the Life Hours of the capacitor @ the time of failure. The left group of four boxes represents cell position for original test parts and the right group of four boxes represents replacements and their failures.

* Catastrophic defined as opens or shorts. ⊙ designates out-of-limits.

TABLE VIII - CAPACITOR FAILURES VS TEMPERATURE, 0.25uF DESIGNS

Catastrophic* & Out-of-Limits

RMS VOLTAGE @ 400 HZ 198

CELLS	65°C		85°C		105°C		125°C	
FB								
XB								
FA								
XA							0999	
							0999	
							0999	
					0999		0760	

RMS VOLTAGE @ 400 HZ 255

CELLS	65°C		85°C		105°C		125°C	
FB								
							0444	
XB								
FA								
XA								
					0999			
					0999		0000	

RMS VOLTAGE @ 400 HZ 311

CELLS	65°C		85°C		105°C		125°C	
FB								
							0961	
XB								
FA								
XA								
							0993	
					0999		0057	

RMS VOLTAGE @ 400 HZ 368

CELLS	65°C		85°C		105°C		125°C	
FB								
					4229		0399	0000
XB								
FA								
XA								
					0114		0038	
					0038		0038	
					0038		0038	0276

Note: Cells are denoted by letters. The letter "F" designates polycarbonate film with aluminum foil. The letter "X" designates metallized polycarbonate. The second letter designates design prefix.

Each number within a box represents the Life Hours of the capacitor @ the time of failure. The left group of four boxes represents cell position for original test parts and the right group of four boxes replacements and their failures.

* Catastrophic defined as opens or shorts. @ designates out-of-limits

Plots of dissipation factor as a function of operating hours show the effect of time on terminations and internal losses. For each specific design, the average dissipation factor for all good capacitors in all 4 voltage cells at 65°C, 85°C, and 105°C is shown in Figures 9 thru 14.

Figures 15 through 20 illustrate the terminal-to-terminal insulation resistance as a function of time. Insulation resistance is a quality measure of the capacitor dielectric and other insulating materials existing between terminals. The average values plotted were calculated using all good parts of a specific design from all 4 voltage cells at a specific temperature.

At 65°C, all 1.0uF designs remained stable to within -0.6% of the original reference measurement throughout the test. The 0.25uF designs remained stable to within +0.1 to -1.0% throughout the test duration. The tendency for slight negative change with most of the change taking place by the 2000-hour point in time could be due to gradual relaxation of winding materials with the added possibility of clearing on metallized types. Figures 3 and 4 illustrate this stability. The dissipation factor of all designs had a slight tendency to decrease (improve) with time as illustrated in Figures 9 and 10. The variations between designs on either Figure 9 or 10 were due mostly to winding terminations, and some possibly to winding design. The insulation resistance of all designs remained constant or improved slightly with time as shown in Figures 15 and 16. At 65°C, the temperature had little affect and the slight improvement is possible due to improvement of impregnant penetration.

At 85°C, the capacitance stability of all designs as plotted in Figure 5 and 6 remained close to that experienced at 65°C. Reasons for the slight negative shift as explained for the 65°C temperature are applicable. Dissipation factor decreased slightly on all designs except A-2 which was consistently higher. Improvement of the termination process and better end seals would contribute to lower DF, particularly noticeable with the large capacitance value involved. Curves of DF for both the 1.0uF and 0.25uF designs are shown in Figures 11 and 12 respectively. Terminal-to-terminal insulation resistance improved on all designs except A-3 which decreased slightly. However, all capacitors met performance requirements at this test temperature. Results of measurement are plotted in Figures 17 and 18.

At 105°C, the capacitance stability compared closely to that found at the 2 lower temperatures, with less than +0.15% to -0.90% shift for the test duration as shown in Figures 7 and 8. Reasons for the slight negative change observed occurring by the end of 2000 hours is as outlined for the 65°C temperature. The dissipation factor for design A-2 was a factor of 4 to 5 times higher than the DF of the other 1.0uF designs but remained within limits (0.5% max.) established for test. A termination problem was found on this design and is discussed in the Failure Analysis section of this report. This explains in part the higher dissipation factor of one design found in Figure 13. Figure 14 displays a very low DF level versus time for the 0.25uF designs. The terminal-to-terminal insulation resistance varied considerably between designs (Figures 19 and 20). Contributing factors to variations in insulation resistance are thoroughness of impregnation cycles, purity of impregnants, dielectric and foil material purity and quality, amount of clearing that has taken place in metallized dielectric designs, method of winding construction, and methods of termination and purity of solders used. Close control of materials and processes can result in higher terminal-to-terminal insulation resistance.

At 125°C, the amount of variation in electrical parameters and the increased number of forced failures created difficulty in presenting data as averages of all operating capacitors in the 4 voltage cells for specific designs. To provide a more meaningful presentation of 125°C test results, the variation of electrical parameters of individual capacitors prior to failure are presented. The significance of these variations as well as the causes of failure are discussed. Figures 21 through 49 are a selection of performance curves and photographs which are useful in illustrating and discussing some causes of failure. A discussion follows in the Failure Analysis section of this report.

Failure Analysis

Representative capacitors of those which failed were selected so that graphs of parameter variation preceding failure could be shown. Photographs are used in discussing failures.

Definitions

Types of Failure

a. Infantile - Failure which occurred in less than 1 week of operation (168 hours).

b. Long Term - Failures which occurred after operating more than a week (operating hours greater than 168 hours).

Note: Failures are discussed in general here with respect to causes. Copies of representative failure analysis reports are included in Appendix B of this report.

Causes of Failure

a. Workmanship or Process Defects - These consist of problems in termination, such as cold or poor solder joints, leading to increase in dissipation factor with associated increase in heating and eventual failure. Included also are construction defects such as poor hermetic seals allowing loss of impregnant, wrinkles and other manufacturing or process defects.

b. Material Defects - These are any defect attributed to the raw material itself. In the case of metallized dielectrics, pinholes in the dielectric material may result in excessive clearing at numerous locations. On plain polycarbonate, clean dielectric punctures with no other contributing factors to cause of failure are considered due to weak material when total dielectric thickness is more than adequate for the voltage impressed.

c. Corona - Corona is unwanted ionization of an insulating medium (usually air) when a voltage gradient exceeds a critical value for the insulating medium. Corona is associated with minute arcing or tracking which eventually erodes the dielectric and results in failure.

d. Contamination - Foreign material such as dust or oils from machinery or from handling which are present and contribute to degradation or dielectric puncture.

Failures Caused by Workmanship or Process Defects

Twenty-seven capacitor failures have been placed in this group and involve 8 parts tested @ 105°C and 19 parts tested @ 125°C. Representative failures are discussed as follows:

Inadequate Termination

a. Design B-1 See performance curves in Figures 21, 22, and 23, photograph Figure 24 and refer to Failure Analysis 41 in Appendix B. The increase in DF with time is apparent when reviewing the curve of Figure 22. This was caused by a deteriorating termination which resulted in excess heat at the termination and led to eventual failure.

b. Design A-1 See performance curves in Figures 25, 26, and 27, photograph Figure 28 and Failure Analysis 48 in Appendix B. A review of Figure 26 illustrates a continually increasing DF after 1000 hours on test. The part was considered a failure due to exceeding the 0.5% maximum DF allowable and though it made it through 5000 hours without shorting, would have eventually failed. Reason for the curious and short lived low DF at the 1000-hour point in time could have been due to some physical changes in progress due to the termination problem which gave a temporary improvement in DF.

c. Design A-2 See performance curves in Figures 29, 30, and 31, photograph Figure 32 and Failure Analysis 46 in Appendix B. This capacitor was still operating at the end of the 5000 hour test but is considered a failure since the 0.5% maximum DF was exceeded. As evidenced by Figure 30, the DF was increasing with time and the resulting heat losses would have caused failure.

Poor Eyelet Seal and Inadequate Termination

a. Design A-1 The performance curves applicable are shown in Figures 33, 34, and 35 with photograph Figure 36 and Failure Analysis 42 in Appendix B. Review of the performance curves indicates a gradual deterioration of the capacitor. The photograph of Figure 36 illustrates the raised eyelet indicating a broken eyelet rim-to-can solder seal.

Wrinkles in Winding Material

a. Design B-2 This capacitor was an infantile failure since it shorted after 1.5 hours and consequently, no performance curves could be drawn. Figure 37 illustrates photographically the wrinkle found at the point of failure and Failure Analysis 3 in Appendix B describes findings in detail.

b. Design A-3 This capacitor failed after 760 hours of operation which was too soon to establish performance curves. The wrinkle is shown photographically in Figure 38 and additional details can be found in Failure Analysis 16 of Appendix B.

Drilled Holes in Core and Construction Error

a. Design B-1 Photographs of Figures 39 and 40 and details of Failure Analyses 23 and 36 in Appendix B illustrate and discuss this problem. Purpose of the small hole drilled at right angles to the winding core axis was to allow improved heat transfer from inner surface of winding through oil and to external area of winding. Also, an error was found in that dielectric padding specified at the beginning of the winding was not present.

Manufacturing Equipment Defective

a. Design A-3 Photograph Figure 41 illustrates a gouge found in the winding material. Failure Analysis 35 in Appendix B details reasons for a decision that the damage was done by the winding machine during capacitor manufacture.

Failures Caused by Material Defects

Twenty-four capacitor failures have been placed in this group and involve 4 capacitors @ 105°C and 20 capacitors @ 125°C. Photographs and representative Failure Analyses are placed in this report to aid in discussion of raw material defects as a cause of failure.

a. Design B-2 See photograph Figure 42 and Failure Analysis 1 in Appendix B. This capacitor was an infantile failure since it occurred immediately upon application of the 400-Hz test voltage. Since no construction error was found and no other contributing factors found, the clean dielectric puncture is evidence of weak material and inability to withstand the 127 VRMS applied to this part.

b. Design A-2 See photograph Figure 43 and Failure Analysis 6 in Appendix B. This capacitor is considered an infantile failure since it shorted within 52 hours of life test start. No contributing circumstances were found that would have caused the failure. The clean dielectric puncture occurring early in the test gives evidence that the material was weak.

c. Design A-3 Photograph Figures 44 and 45 illustrate a pinhole which successfully cleared and one which didn't, respectively. Both photographs are taken of material found in the one capacitor. Metallized dielectric material which has a number of pinholes in it is susceptible to some lowering of insulation resistance if not adequately cleared. During measurement of IR with a low energy power source, the failure was created. Failure Analysis 25 in Appendix B covers details.

d. Design B-2 Photograph Figure 46 illustrates the point of failure and Failure Analysis 14 in Appendix B gives some details on the capacitor. A pure dielectric puncture such as occurred on this film-foil design in which no other cause of failure is evident is regarded as indicative of weak areas in the dielectric material.

Failure Caused by Corona

Only 1 capacitor failure was attributed to the effects of corona. Involved was Design A-3. Photograph Figure 47 illustrates a transfer of metal from the metallized surface of one dielectric onto the face of an adjacent plain sheet of dielectric. Failure Analysis 7 in Appendix B mentions other areas where carbon deposits were found.

Failures Caused by or Involving Contamination

Three capacitor failures were found in which contamination was involved.

a. Design A-3 Photograph Figure 48 gives evidence of some contamination found in a part which failed. Contamination can lead to general degradation of the dielectric in time and eventual failure. Though contamination was found in the capacitor involved here, failure occurred during IR measurements at the 1000-hour point and material quality was a factor in the failure. See Failure Analysis 27 in Appendix B.

b. Design A-2 Photograph Figure 49 illustrates a flaky condition found in a few outside turns of the winding. The contamination was determined to be the cause of failure with this capacitor. Failure Analysis 22 in Appendix B gives details. Failure did not occur until the capacitor operated almost 2000 hours. This illustrates the gradual deteriorating affect that contamination can cause.

Summary of Failures

In addition to discussion of representative failures and their causes, a summary by design of the failures at temperatures of 105°C and 125°C is given as follows:

Thirteen (13) failures @ 105°C consisted of the following:

Three (3) capacitors, design A-3, were considered infantile failures since failure occurred on 2 in less than 40 hours and on the other capacitor in less than 115 hours. These capacitors gave evidence that pinholes existed in the material, weakening the dielectric strength with clearing occurring and eventual failure.

Four (4) capacitors, design A-3, in which failure occurred while taking IR measurements at 500 volts, dc. As a result of pinholes, the material did not clear sufficiently while measuring IR with a low energy power supply and a permanent breakdown resulted. The dc voltage was higher than the peak ac operating voltages that had been applied to these 4 capacitors prior to failure, but was within the dc voltage rating assigned to the capacitors.

Four (4) capacitors, design B-2, in which failure occurred during IR measurement at the 1000-hour point while under stress of 300 volts, dc. Some slight wrinkles were found. The dc measuring voltage was higher than the peak ac life test voltage the parts had experienced. After some initial failures had occurred while measuring insulation resistance at rated dc voltage, all subsequent insulation resistance measuring voltage was reduced to one-half (½) the rated dc working voltage on all designs.

One (1) capacitor, design B-4, shorted after 4,229 hours of operation at the highest test voltage of 368 VRMS. A small wrinkle was found at point of failure.

One (1) capacitor, design B-2, shorted as a result of dielectric puncture after 3,002 hours in test. Dissipation factor may have contributed to heating.

Forty-two (42) failures at 125°C consisted of the following:

Number of Failures	Design	Construction
5*	A-1	1.0 uF metallized polycarbonate
14*	B-1	1.0 uF metallized polycarbonate
4*	A-2	1.0 uF polycarbonate film and aluminum foil
4	B-2	1.0 uF polycarbonate film and aluminum foil
11	A-3	0.25uF metallized polycarbonate
0	B-3	0.25uF metallized polycarbonate
0	A-4	0.25uF polycarbonate film and aluminum foil
4	B-4	0.25uF polycarbonate film and aluminum foil

*Note: Included in quantity of failures are three capacitors (design A-1) which had high DF, six capacitors of design B-1 as out-of-limit on DF at end of test @ 125°C but good at 25°C, and two capacitors of design A-2 which were open at room temperature at end of test.

It is known from failure analysis that solder joints between the eyelet rim and the tube need to be improved on designs having a prefix of "A" to prevent loss of impregnant and liquid fill at high temperature.

Terminations were a major problem observed on design B-1 and to a lesser extent on several other designs. The recommendations for correction have been outlined in the next section of this report.

Many of the problems found which contributed to failure at higher temperatures can be eliminated or minimized by design and/or process improvement to give considerably better performance at 125°C, which is the potential temperature capability of polycarbonate dielectric. Of particular interest were the reasonably few failures of designs A-1, A-2, B-2, and B-4 and no failures at all for designs B-3 and A-4 at 125°C. Some of these designs met and exceeded the performance goals.

Capacitor Improvement Recommendations

Voltage Stress - Maximum stress placed on the capacitor designs at the highest ac test voltage level in terms of volts (rms) per mil (.0254 mm) dielectric were as follows:

Design A-1	383 volts/mil (.0254 mm)
B-1	307 volts/mil (.0254 mm)
A-2	230 volts/mil (.0254 mm)
B-2	329 volts/mil (.0254 mm)
A-3	409 volts/mil (.0254 mm)
B-3	368 volts/mil (.0254 mm)
A-4	307 volts/mil (.0254 mm)
B-4	368 volts/mil (.0254 mm)

Observing the fact that there was no correlation of increasing failures with increase in voltage at temperatures up to 125°C, a 400- Hz sinewave ac voltage stress of 300 volts rms/mil (.0254 mm) should be a reasonable operating level. A derating of voltage at 125°C, based on these findings, would not improve confidence of successful operation at 125°C. Initiation of recommended changes to minimize problems from failure causes outlined will allow improved performance for all types of polycarbonate capacitors at temperatures up to 125°C.

Termination Improvement - In the case of the metallized polycarbonate, there was evidence on some designs that the metal end spray did not adhere well to the metallized plate on the surface of the dielectric. The adhesion and contact can be improved by using a slight offset in the winding layers, by careful process control of the spraying operation in terms of angle, amount of heat, type of metal used, and by making sure that the axial end of the winding is well coated with an adequate amount of metal spray, (schooping). For improved connection between the lead head and the metal spray, it is recommended that after the initial soldering of lead head to the schooping, the leads be protected and additional metal spray be added to fill in around the surface of the lead head and the first metal spray. This procedure is recommended for any of the metallized designs and thus would be preferred instead of the metal screen type contact washers used on designs B-1 and B-3.

In the case where eyelet seals broke, impregnant escaped and termination deteriorated, the solder bond can be improved by using cans that have bright tin plating and are free of oxidation. X-rays can be helpful in examination of adequacy of solder seals. Addition of sufficient amounts of solder and application of heat long enough to get good flow of solder between eyelet rim and the can is required.

For film-foil designs, termination can be improved by swedging the lead head into the axial end of the winding and adding enough molten solder to cover the lead head well or by use of metal screen-type washers such as used on designs B-2 and B-4. The dissipation factor of these designs was excellent and remained very low throughout the test.

Minimizing Wrinkles - Wrinkles can be minimized though not eliminated through the use of cores to prevent collapse of winding material into mandrel holes and the use of wrinkle removing devices on winding machines. Wrinkles are also affected by type of impregnant and process temperatures used. Some impregnants have a tendency to lubricate and thus allow easier movement of dielectric sheets should they attempt to slide during thermal processing of the winding. If the impregnant does not allow easy slippage of dielectric materials, more tendency to wrinkle exists.

The drilled hole in the winding core could either be eliminated or padding included to prevent stress on the dielectric as it passes over the hole.

Equipment Maintenance - The gouge in the dielectric found in Failure Analysis 35 is an example of problems that can occur during manufacture. Maintenance of equipment to prevent formation of burrs on material guides or rollers and a burn-in at 1.25 times rated voltage at 125°C for 250 hours could minimize these failures.

Material Quality Improvement - Preclearing of the metallized polycarbonate raw material by the raw material manufacturer is recommended. Much of the quality of metallized polycarbonate and plain polycarbonate depends on processes and cleanliness at the raw material manufacturer's plant but is affected also by the capacitor manufacturer in processes used to complete the capacitor.

Reduction of Corona - Corona can be minimized by thorough evacuation of air from windings followed by long soak time for maximum impregnation. The writers consider long soak time to be 16 hours or longer. The design should minimize restrictions that might tend to entrap air. Making and breaking of vacuum or pressure shocks sometimes are helpful in moving entrapped air.

The presence of pinholes or air bubbles as well as sharp metal projections from the electrodes increases the chance of corona. Some impregnants offer advantages over others in minimizing corona. However, the 2 impregnants involved in this test program were similar in levels of corona noted. Specifications for capacitors used in ac aerospace power systems should include corona screening requirements.

Contamination - Process controls and handling techniques must minimize contamination. Polycarbonate capacitor windings should not be stored in the open for long periods of time. Storage in a clean dry atmosphere at 85°C to 100°C temperature is recommended for parts that might be delayed for any length of time during manufacture. The use of clean lint free gloves is recommended for production personnel to avoid direct contact of material with hands. For increased reliability important in ac aerospace application, the capacitors should be built in a "clean room" type production area with close process control.

Discussion of Designs and Recommendations

1.0 uF 200VAC Peak Rated, 400 Hz, Metallized Polycarbonate

For this capacitor, design B-1 is recommended after modifications in termination are made. The metal contact washer would be eliminated and the termination would be made as outlined above for termination improvements for metallized polycarbonate type construction. About the only problem with this design was the termination. This design uses the back-to-back metallized construction technique mentioned in a previous section of this report (Description of Capacitors Tested). It has twice the thickness of metallized conducting plate found on conventional type construction of metallized capacitors. The double metallized plate is important in that it has better current carrying capability important in ac applications and can do more toward carrying internal heat to external parts of the winding. This design technique has been in use for this type application for some time by one manufacturer and has a patent applied for. It is recommended that the core be used as originally designed and that the 1/32" (.0794 cm) holes at right angles to the core axis be covered with a padding. The above changes should be incorporated followed by a study to determine the most suitable impregnant. *

1.0 uF 200VAC Peak Rated, 400 Hz, Polycarbonate Film with Aluminum Foil

Design B-2 with improvements is recommended. This design and design A-2 each had 4 failures @ 125°C. Design B-2 is considerably smaller in physical size and the termination resulted in much lower DF which is important in ac applications. See Figures 11 and 13 as an example.

0.25 uF 400VAC Peak Rated, 400 Hz, Metallized Polycarbonate

Design B-3 is recommended with modifications of termination. This design experienced no failures at all. Though this design experienced no problem, it used the same termination technique as design B-1 which did experience problems due to termination. This design used the back-to-back metallized design as mentioned for the similar design B-1.

* Note: A comparison of impregnants was difficult to make since polybutene and silicone oil were involved in different designs and both of the impregnants were involved in designs which experienced no failures.

0.25 uF 400VAC Peak Rated, 400 Hz, Polycarbonate Film with Aluminum Foil

Design A-4 is recommended. This design experienced no failures. This was the only design which used 3 sheets of dielectric between foils. It used 1.2 mils (.0305 mm) dielectric thickness compared to 1.0 mils (.0254 mm) for design B-4 and is slightly larger. Though there were no failures, a core is recommended to prevent the possibility of collapse into the mandrel hole and resultant wrinkles. The termination could be improved as recommended since a similar design A-2 did experience termination problems.

CONCLUSION

Purpose of the 400 Hertz sinewave test of polycarbonate capacitors was to study performance of these capacitors under matrix type test conditions, and from the results of test and failure analysis, make recommendations for design improvements. A total of 8 designs incorporating metallized polycarbonate and plain polycarbonate film with aluminum foil in two capacitance values and two voltage ratings were subjected to test at 4 temperatures and 8 voltages.

All designs operated at 65°C and 85°C with no failures. Thirteen failures were recorded at 105°C and 42 at 125°C, all with no noticeable effect due to increasing voltage level. Two capacitor designs experienced no failures at any test condition to which they were subjected. Temperature had the most effect on performance.

The main causes of failure and recommended corrective measures are:

Workmanship or Process Defects. These involved inadequate termination, poor eyelet seals allowing escape of impregnant, wrinkles in winding material, core design or construction error and manufacturing equipment. All workmanship defects found can be minimized and in some cases eliminated through process change and control. An ac burn-in of 250 hours is recommended at 125°C and 125% rated peak voltage.

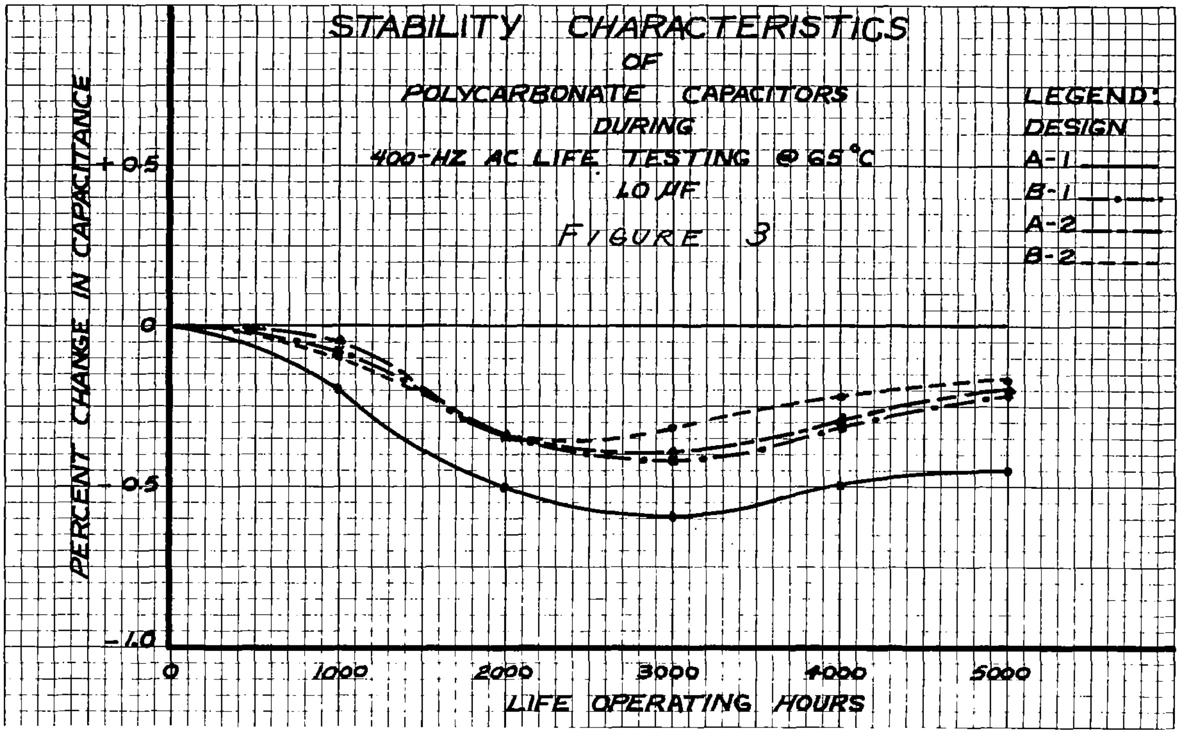
Material Quality. These involved weak dielectric with much evidence of clearing in some cases. Processes involved from manufacture of raw material to completion of capacitor can affect material quality. Burn-in as recommended above can minimize failures traceable to raw material.

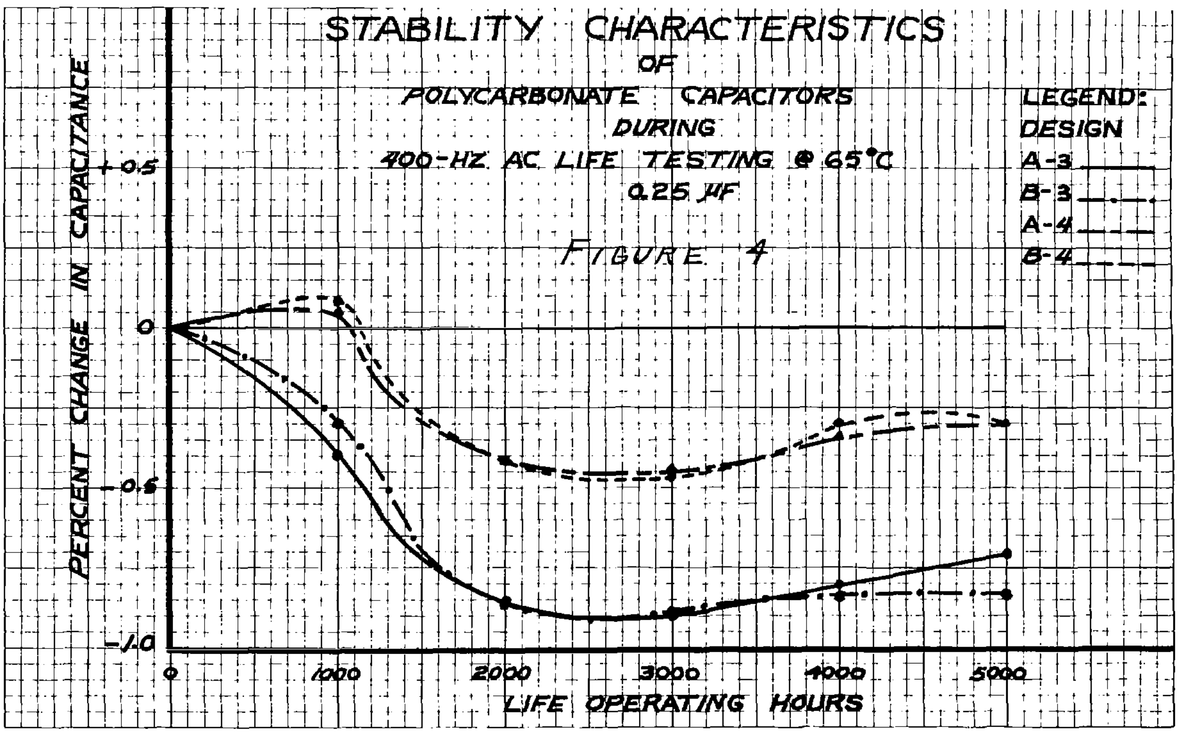
Corona. Capacitor manufacture must include process controls for maximum removal of air, thorough impregnation and elimination of sharp metal projections. Specifications for capacitors to be used in ac aerospace applications should include corona screening requirements at a level slightly higher than intended operational voltage level.

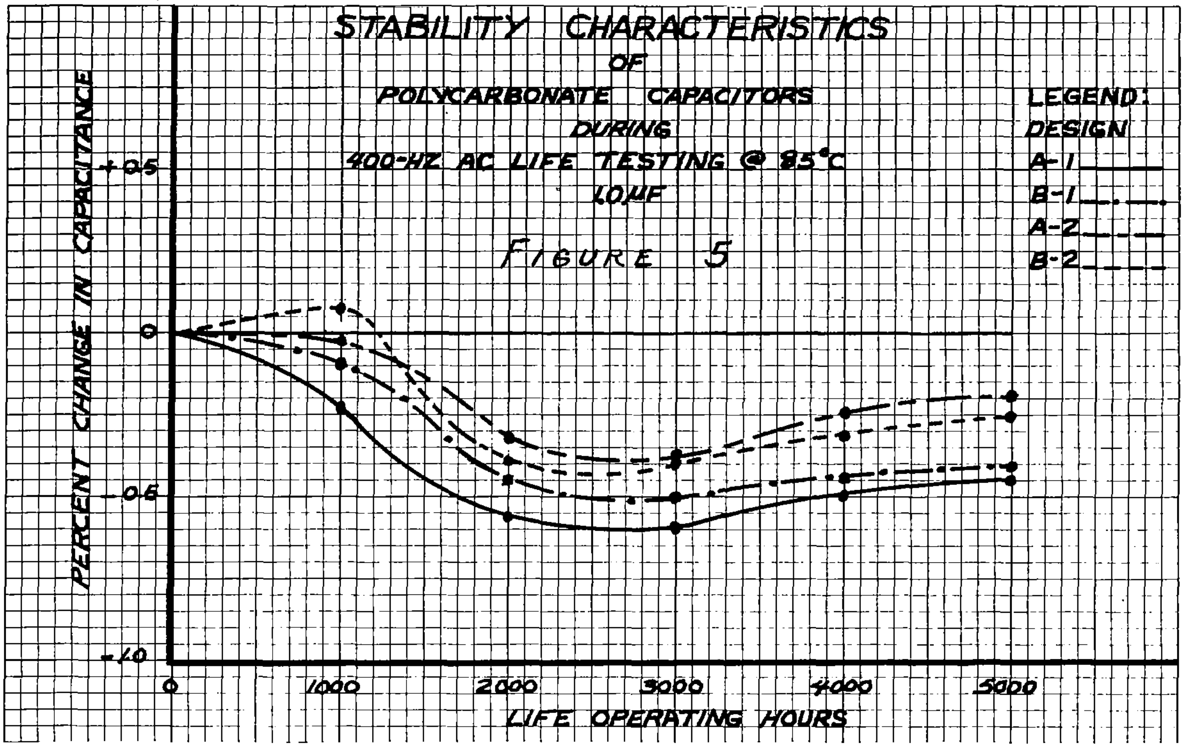
Contamination. Can be minimized by process controls to protect material during storage and also through manufacturing. A burn-in as recommended above will minimize this problem.

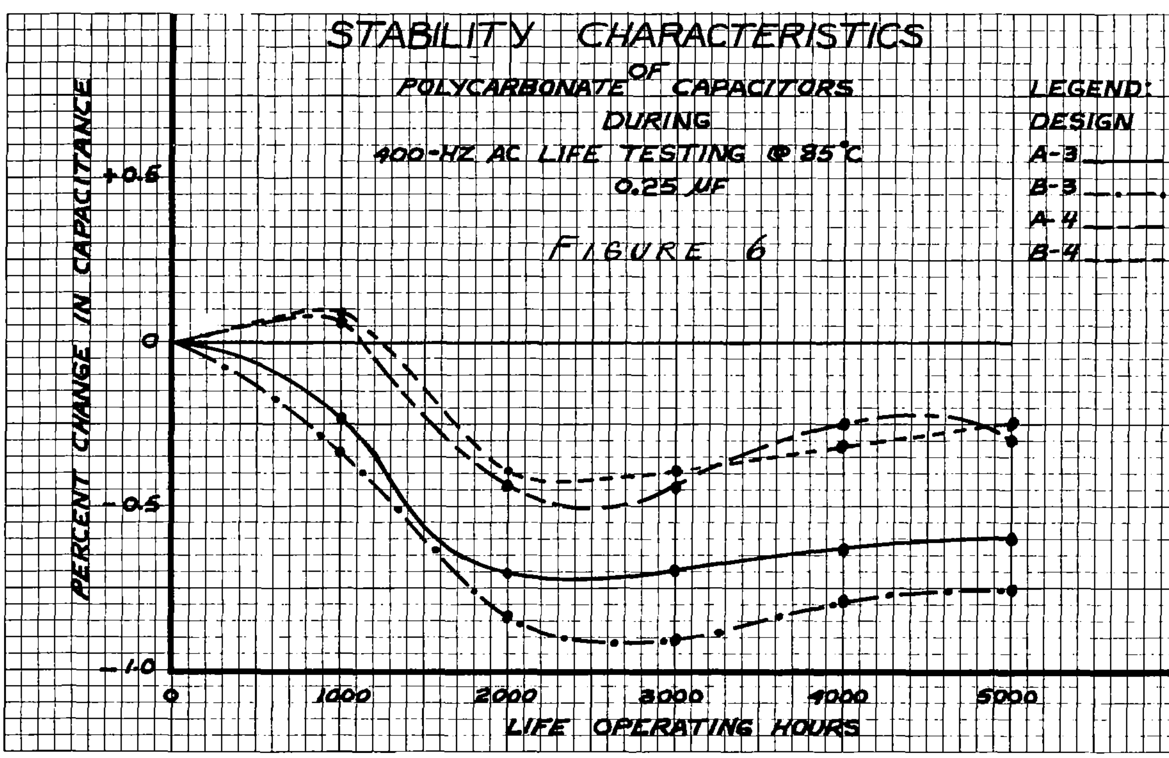
Observing the fact that there was no correlation of increasing failures with increase in voltage at temperatures up to 125°C, a 400Hz sinewave ac voltage stress of 300 volts rms/mil (.0254 mm) should be a reasonable operating level. A derating of voltage at 125°C, based on these findings, would not improve confidence of successful operation at 125°C. Initiation of recommended changes to minimize problems from failure causes outlined will allow improved performance for all types of polycarbonate capacitors at temperatures up to 125°C.

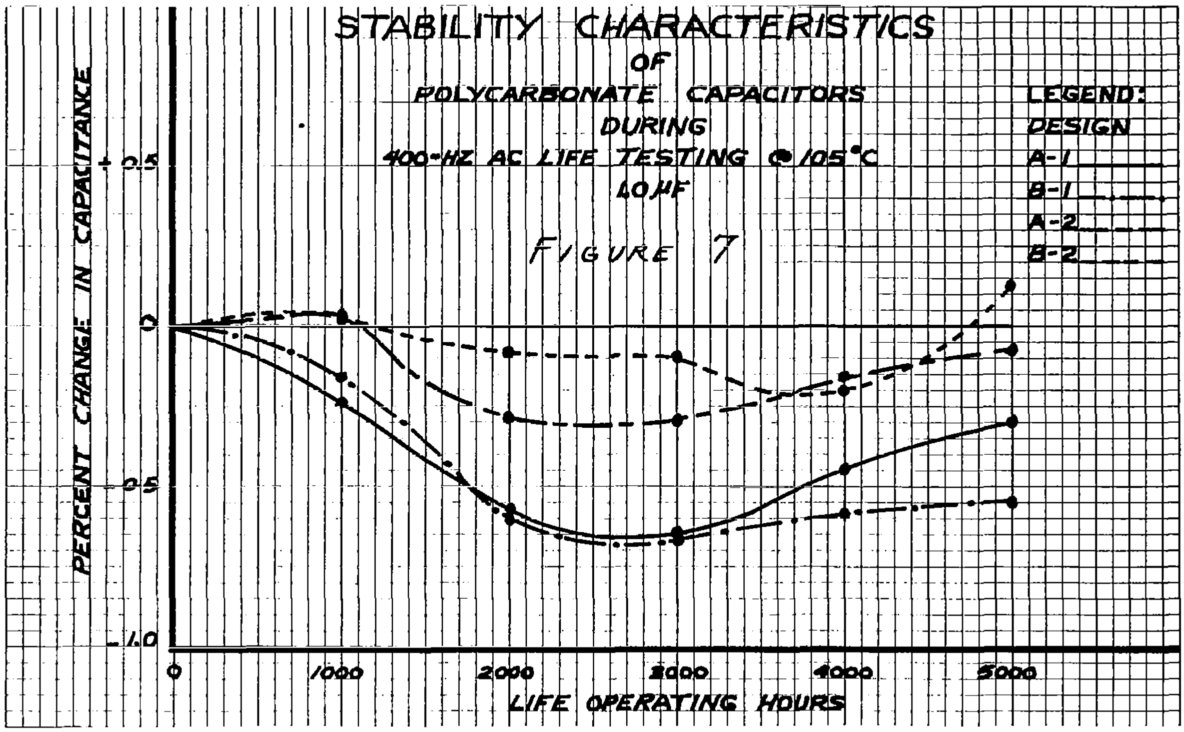
The capability of polycarbonate ac capacitors to operate at temperatures up to 125°C has been demonstrated by two designs which experienced no failures.

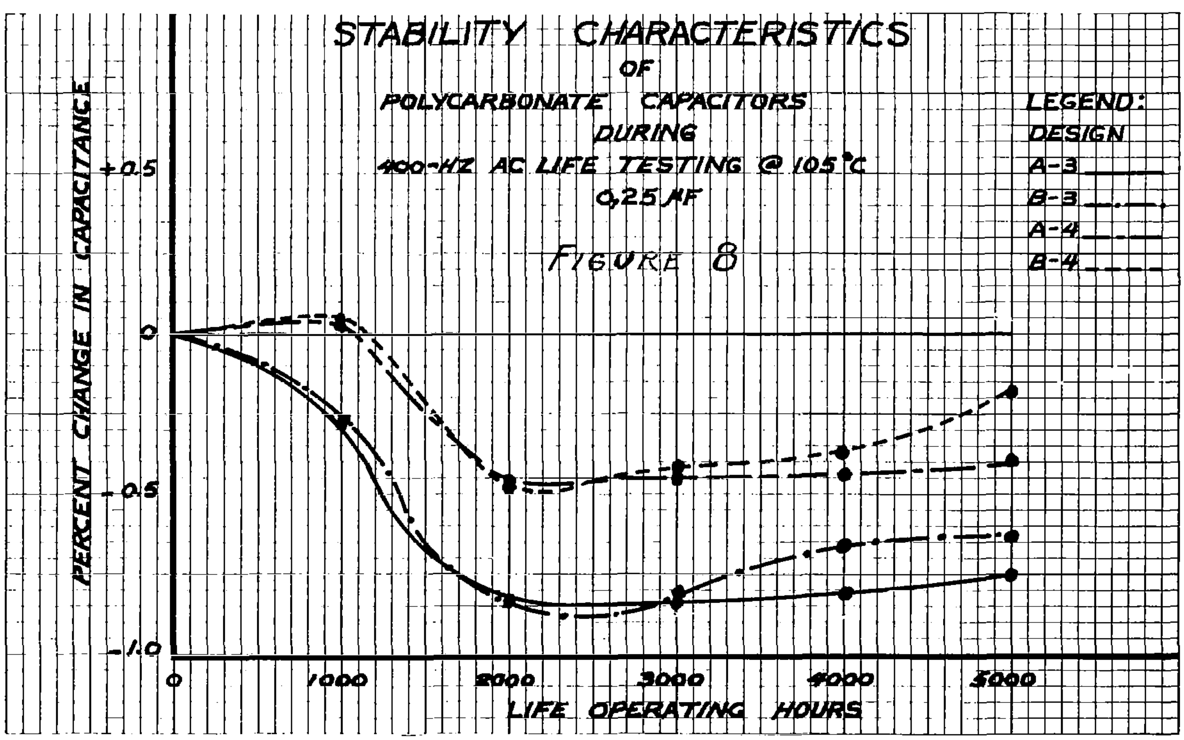

STABILITY CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 65°C
1.0 μF
FIGURE 3
LEGEND:
DESIGN
A-1
B-1
A-2
B-2
PERCENT CHANGE IN CAPACITANCE
+0.5
0
-0.5
-1.0
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

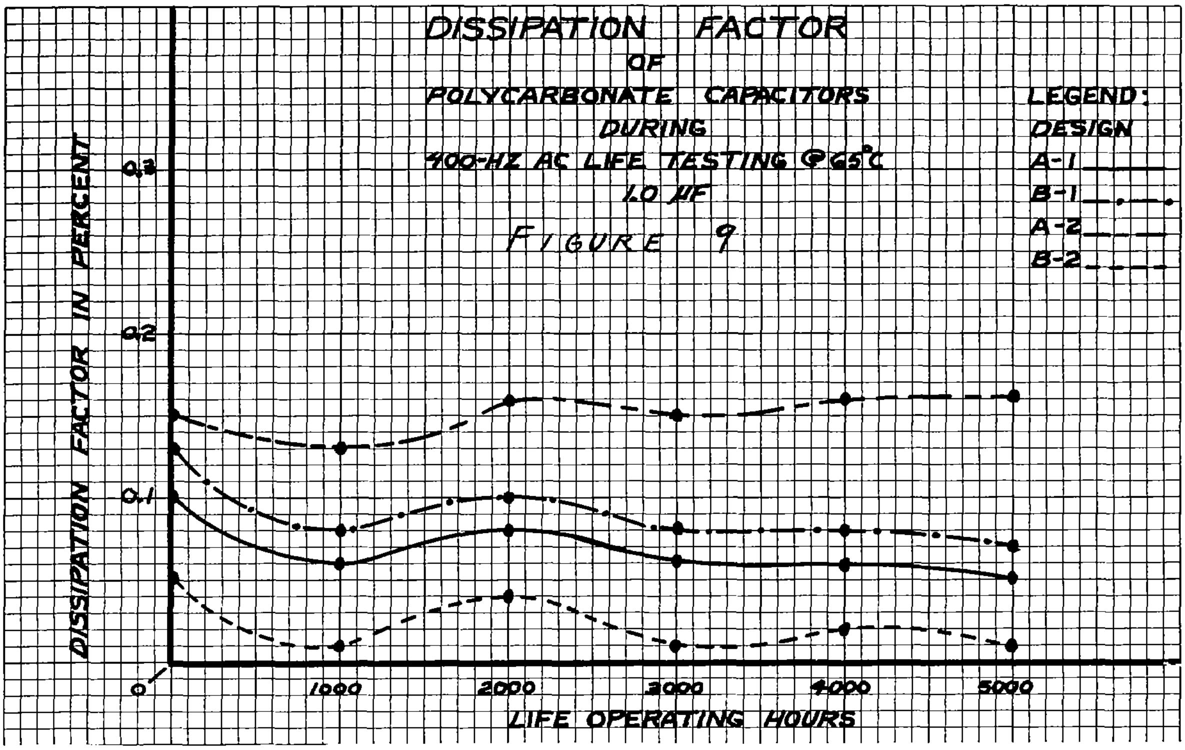

STABILITY CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 65°C
0.25 μF
FIGURE 4
LEGEND:
DESIGN
A-3
B-3
A-4
B-4
PERCENT CHANGE IN CAPACITANCE
+0.5
0
-0.5
-1.0
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

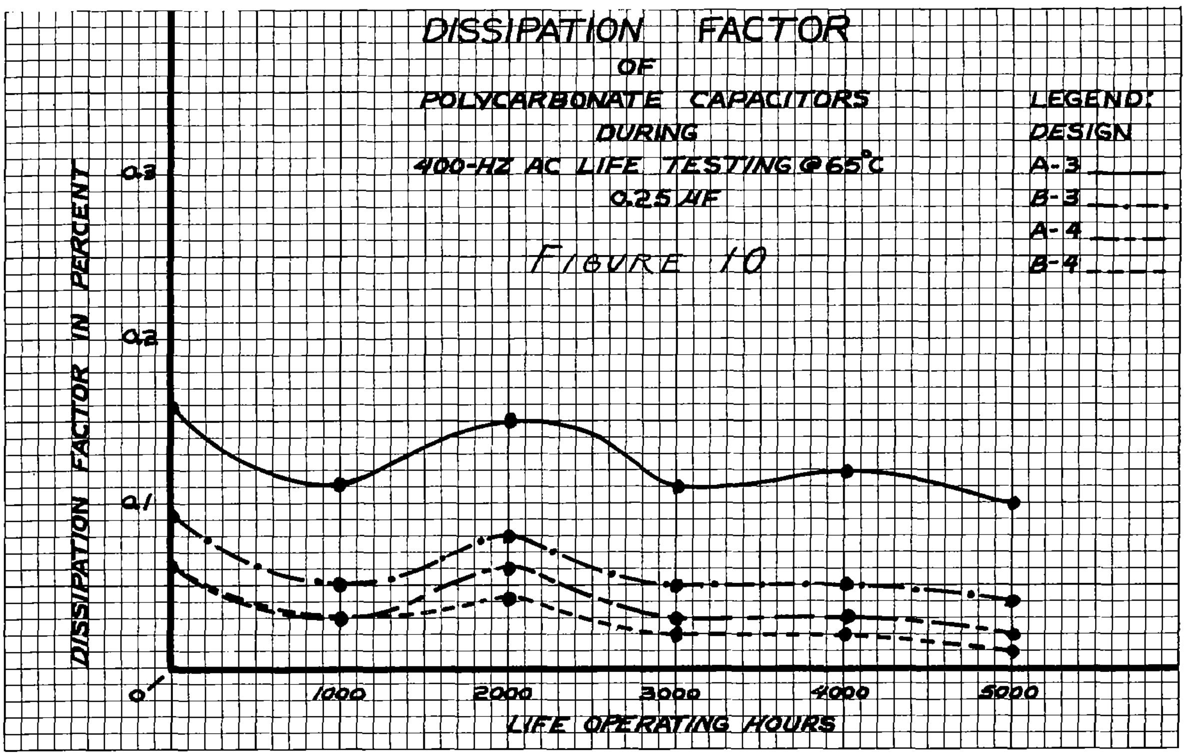

STABILITY CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 85°C
1.0 µF
FIGURE 5
LEGEND:
DESIGN
A-1
B-1
A-2
B-2
PERCENT CHANGE IN CAPACITANCE
+0.5
0
-0.5
-1.0
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS


STABILITY CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 85°C
0.25 µF
FIGURE 6
LEGEND:
DESIGN
A-3
B-3
A-4
B-4
PERCENT CHANGE IN CAPACITANCE
+0.5
0
-0.5
-1.0
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS


STABILITY CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 105°C
10 μF
FIGURE 7
LEGEND:
DESIGN
A-1
B-1
A-2
B-2
PERCENT CHANGE IN CAPACITANCE
+0.5
0
-0.5
-1.0
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS


STABILITY CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 105°C
0.25 μF
FIGURE 8
LEGEND:
DESIGN
A-3
B-3
A-4
B-4
PERCENT CHANGE IN CAPACITANCE
+0.5
0
-0.5
-1.0
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS


DISSIPATION FACTOR
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 65°C
1.0 μF
FIGURE 9
LEGEND:
DESIGN
A-1
B-1
A-2
B-2
DISSIPATION FACTOR IN PERCENT
0.3
0.2
0.1
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS


DISSIPATION FACTOR
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 65°C
0.25 μF
FIGURE 10
LEGEND:
DESIGN
A-3
B-3
A-4
B-4
DISSIPATION FACTOR IN PERCENT
0.3
0.2
0.1
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

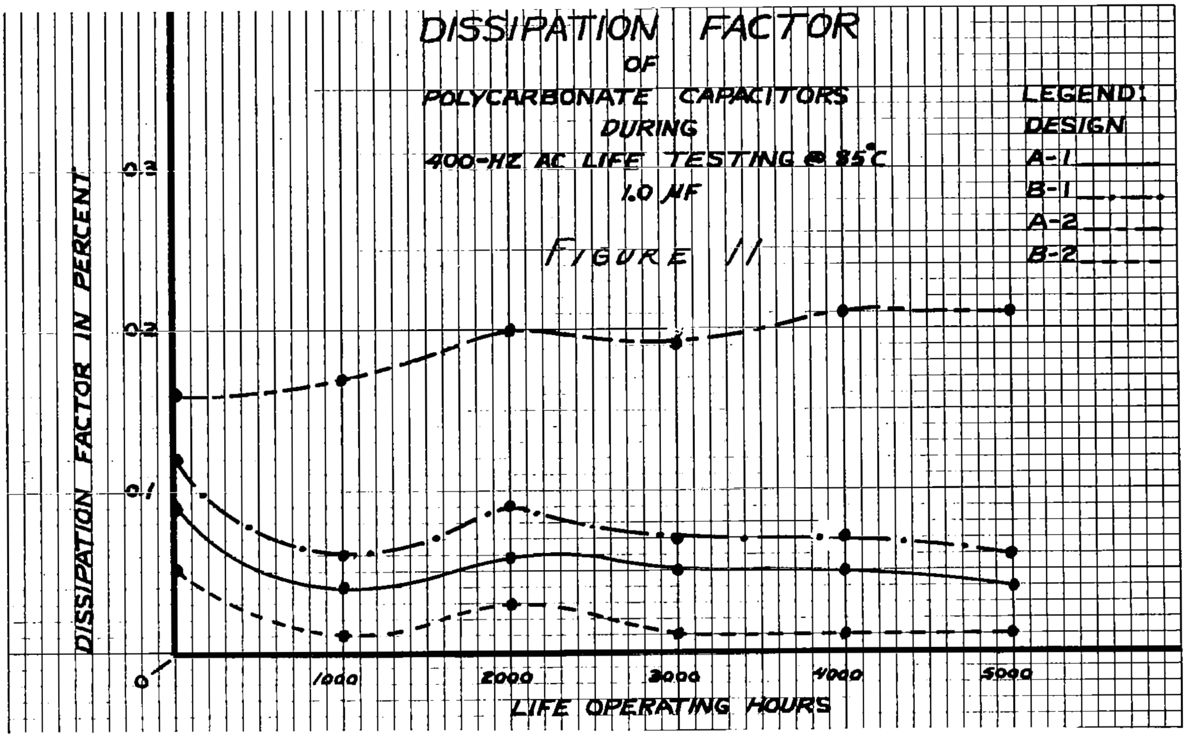


Figure 11

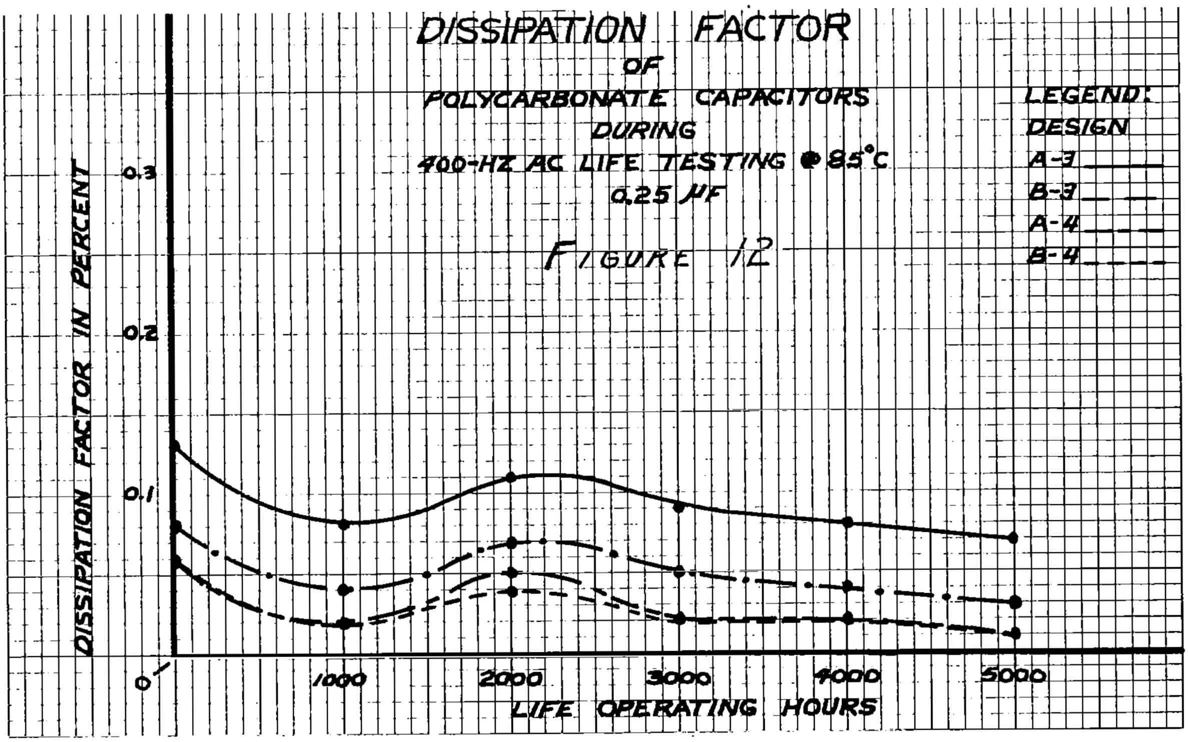
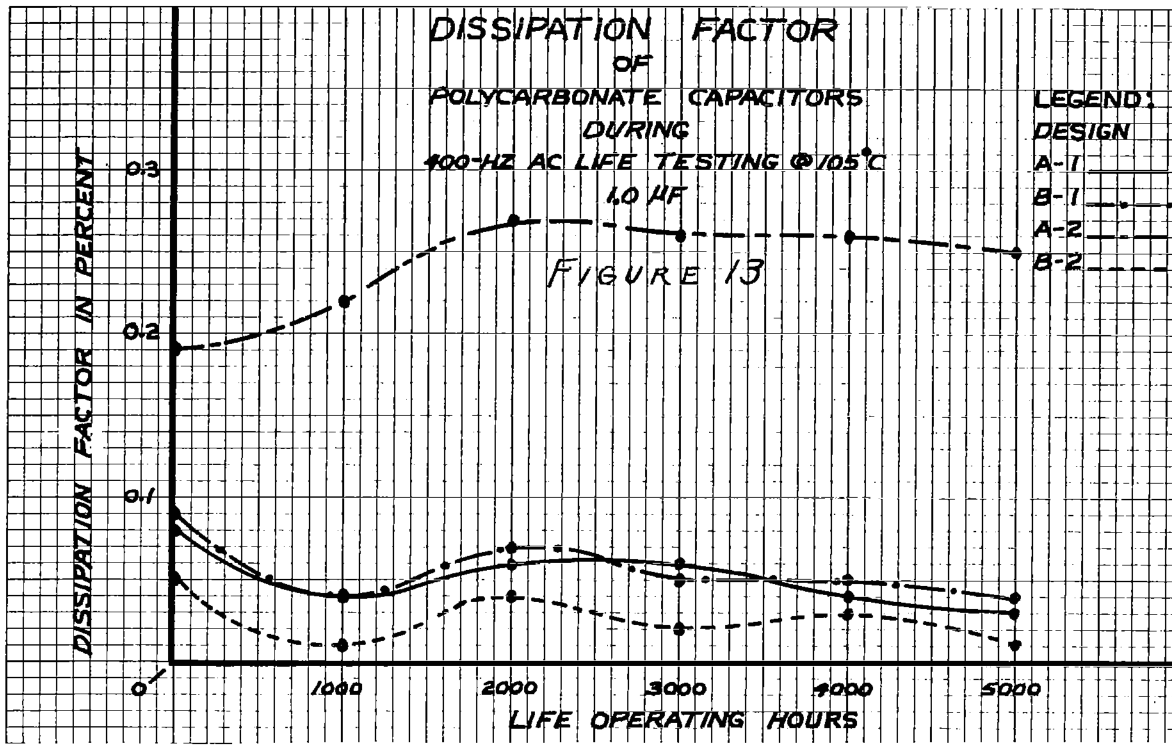
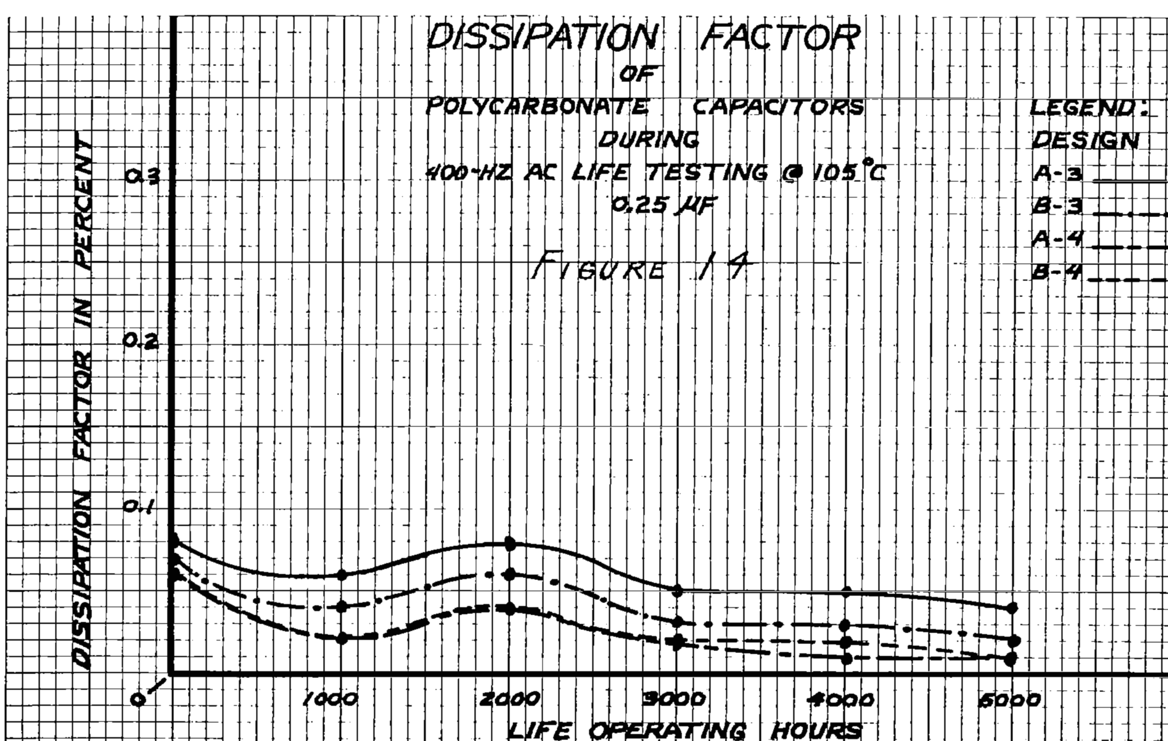
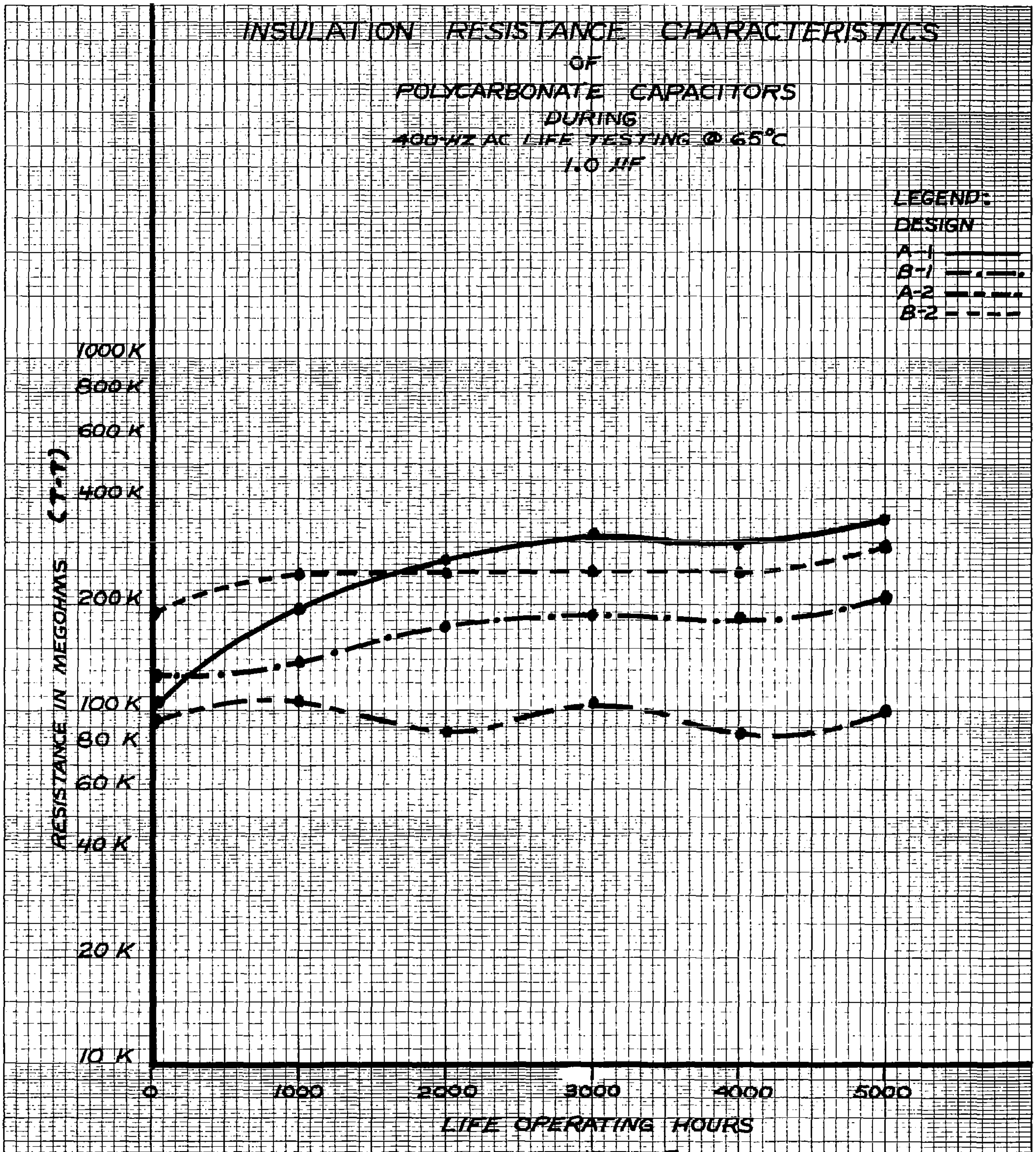


Figure 12


DISSIPATION FACTOR
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 105°C
1.0 μF
FIGURE 13
LEGEND:
DESIGN
A-1
B-1
A-2
B-2
DISSIPATION FACTOR IN PERCENT
0.3
0.2
0.1
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS


DISSIPATION FACTOR
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 105°C
0.25 μF
FIGURE 14
LEGEND:
DESIGN
A-3
B-3
A-4
B-4
DISSIPATION FACTOR IN PERCENT
0.3
0.2
0.1
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS



INSULATION RESISTANCE CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 65°C
1.0 µF
LEGEND:
DESIGN
A-1
B-1
A-2
B-2
1000 K
800 K
600 K
400 K
200 K
100 K
80 K
60 K
40 K
20 K
10 K
RESISTANCE IN MEGOHMS (T-T)
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 15

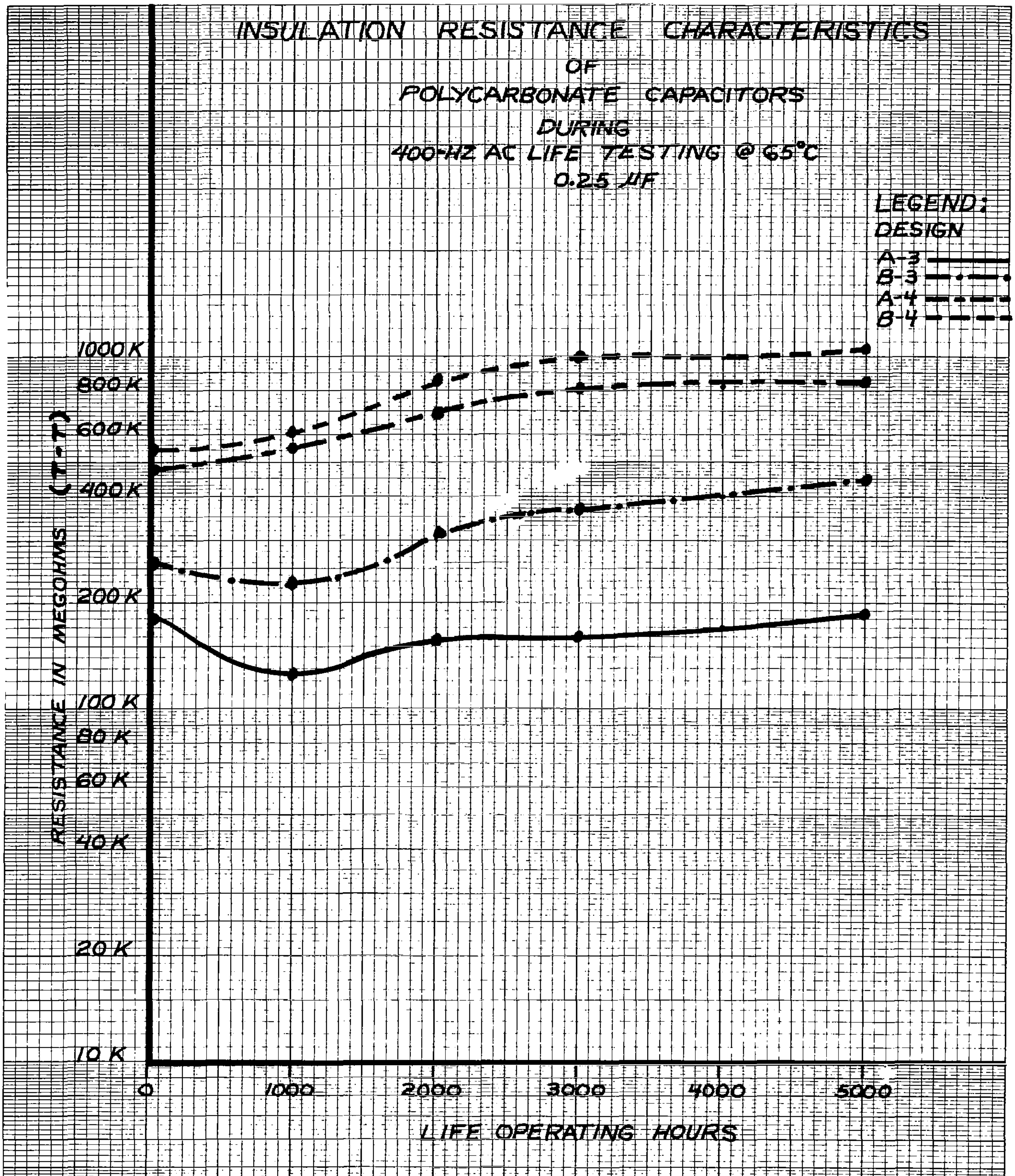

INSULATION RESISTANCE CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 65°C
0.25 μF
LEGEND:
DESIGN
A-3
B-3
A-4
B-4
1000 K
800 K
600 K
400 K
200 K
100 K
80 K
60 K
40 K
20 K
10 K
RESISTANCE IN MEGOHMS (T-T)
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 16

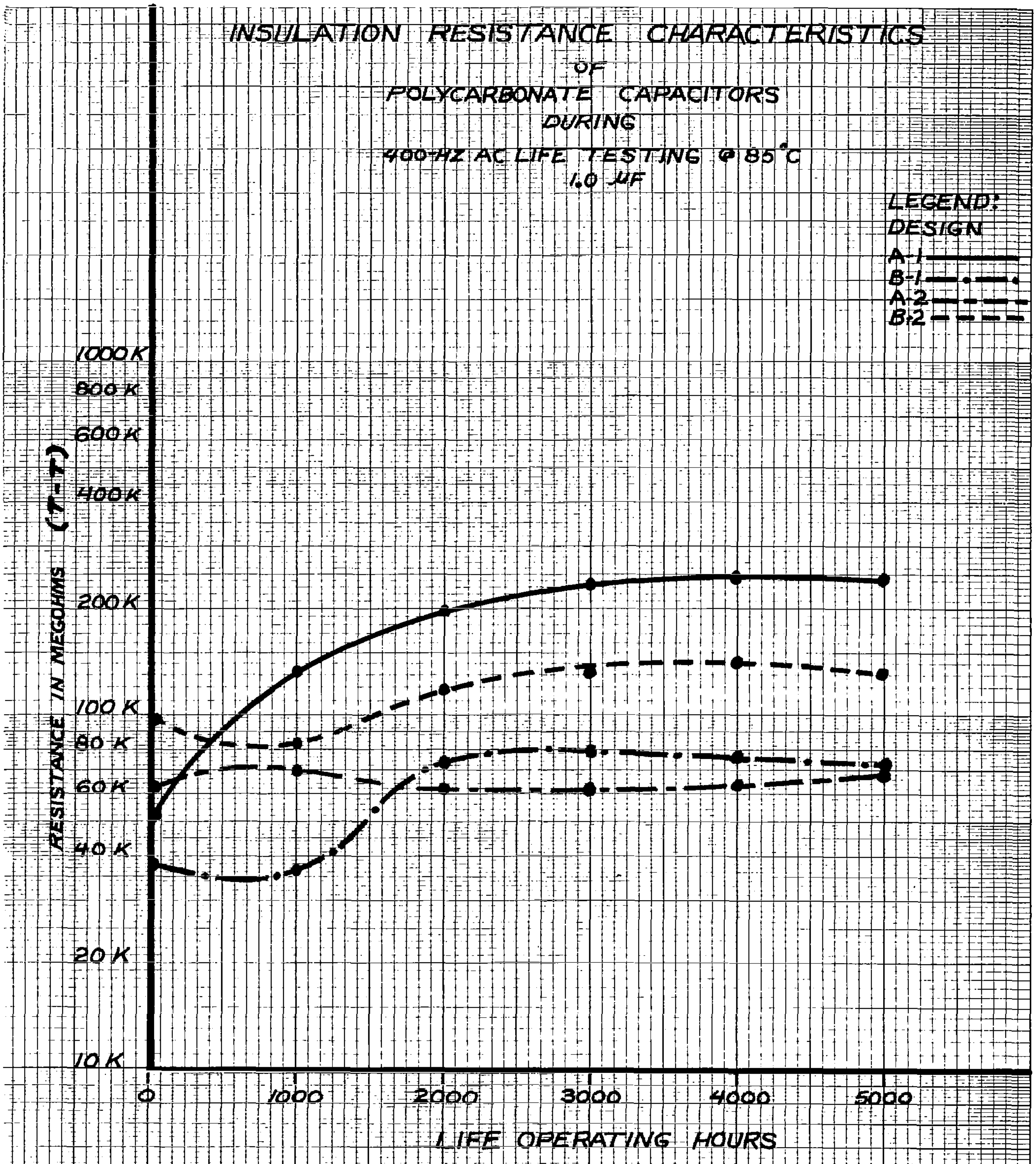

INSULATION RESISTANCE CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 85°C
1.0 µF
LEGEND:
DESIGN
A-1
B-1
A-2
B-2
RESISTANCE IN MEGOHMS (T-T)
1000 K
800 K
600 K
400 K
200 K
100 K
80 K
60 K
40 K
20 K
10 K
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 17

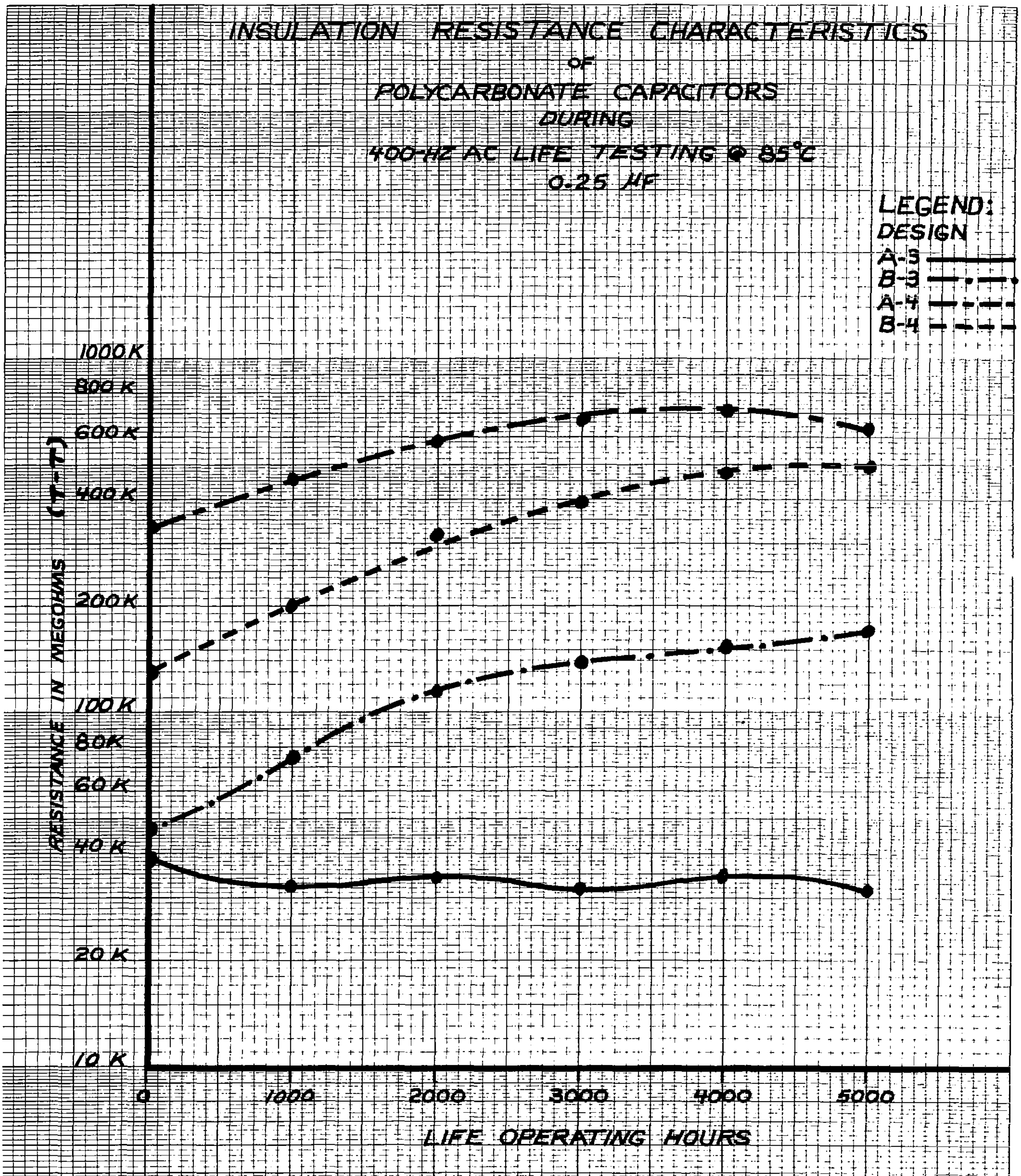

INSULATION RESISTANCE CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 85°C
0.25 µF
LEGEND:
DESIGN
A-3
B-3
A-4
B-4
1000 K
800 K
600 K
400 K
200 K
100 K
80 K
60 K
40 K
20 K
10 K
RESISTANCE IN MEGOHMS (T-T)
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 18

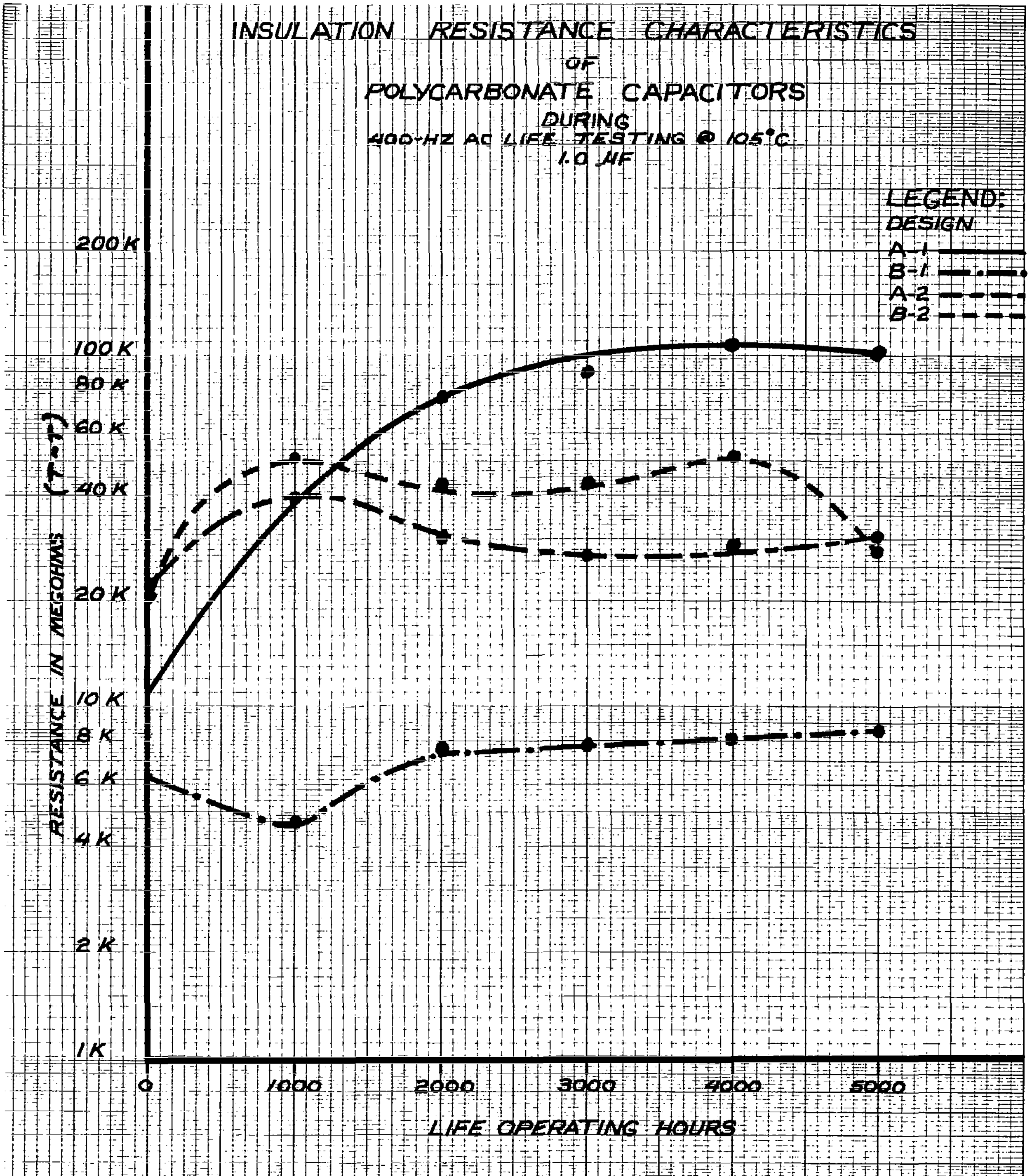

INSULATION RESISTANCE CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 105°C
1.0 µF
LEGEND:
DESIGN
A-1
B-1
A-2
B-2
RESISTANCE IN MEGOHMS (T-T)
200 K
100 K
80 K
60 K
40 K
20 K
10 K
8 K
6 K
4 K
2 K
1 K
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 19

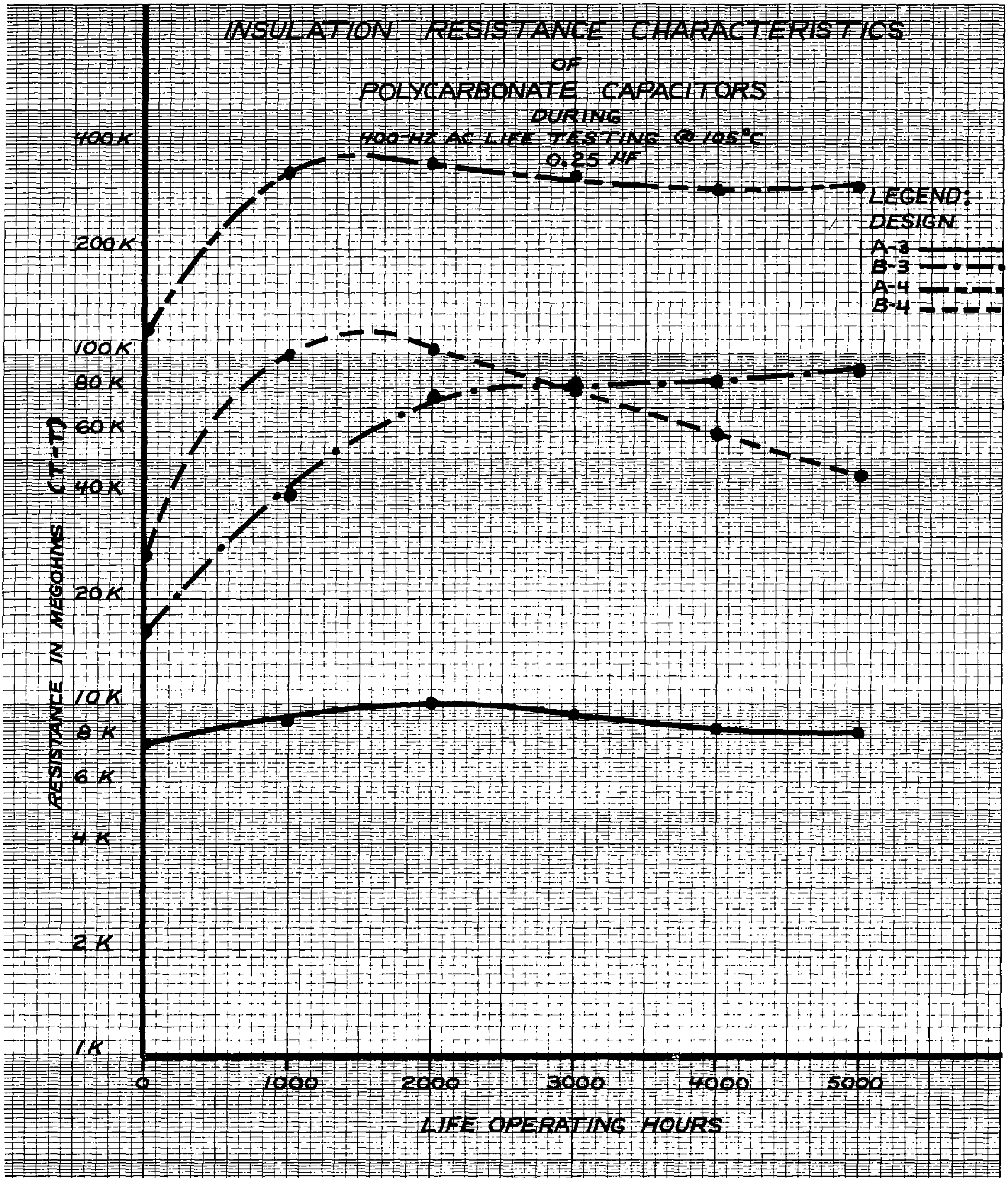

INSULATION RESISTANCE CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400-HZ AC LIFE TESTING @ 105°C
0.25 µF
LEGEND:
DESIGN
A-3
B-3
A-4
B-4
RESISTANCE IN MEGOHMS (T-T)
400 K
200 K
100 K
80 K
60 K
40 K
20 K
10 K
8 K
6 K
4 K
2 K
1 K
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 20

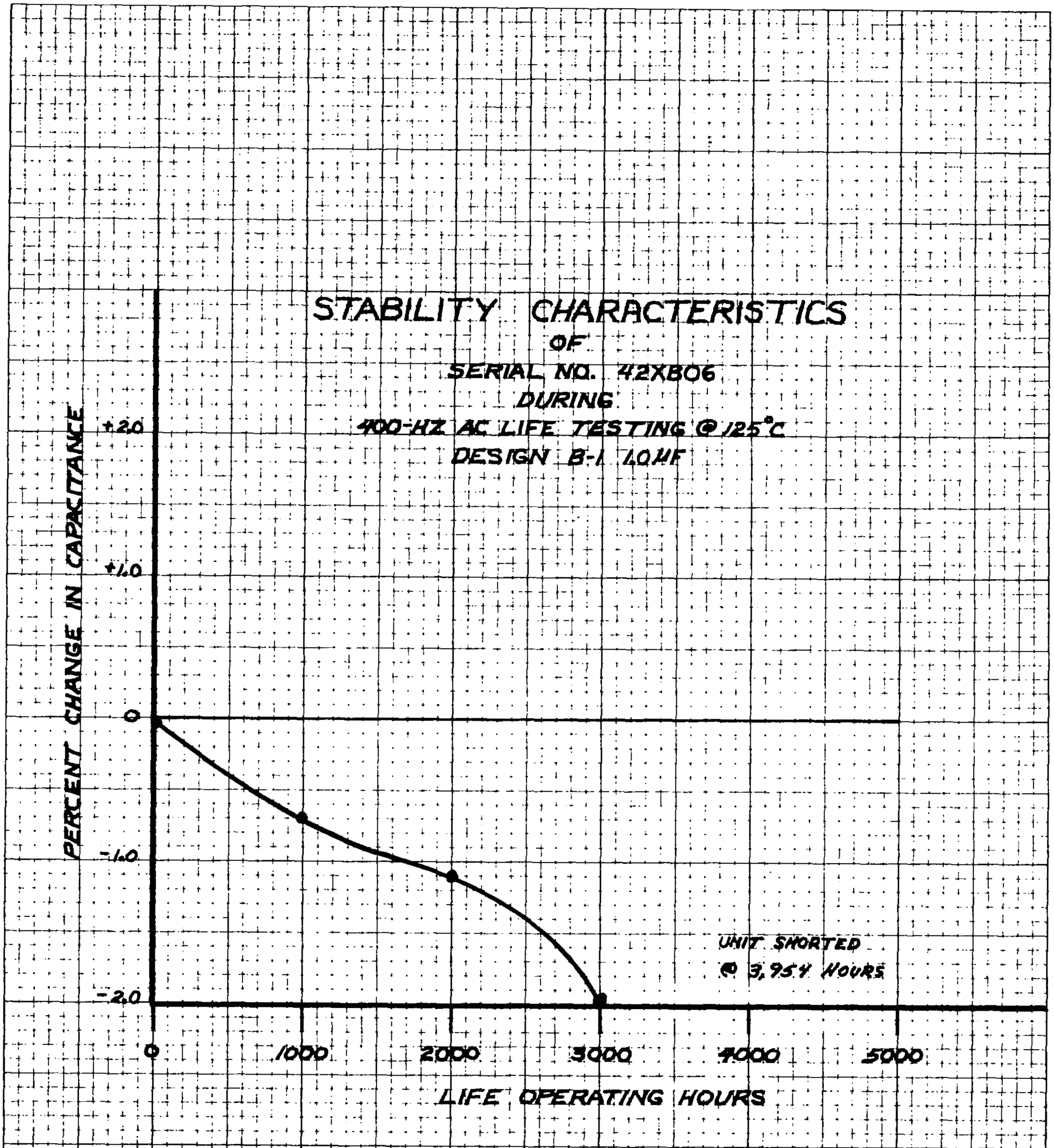
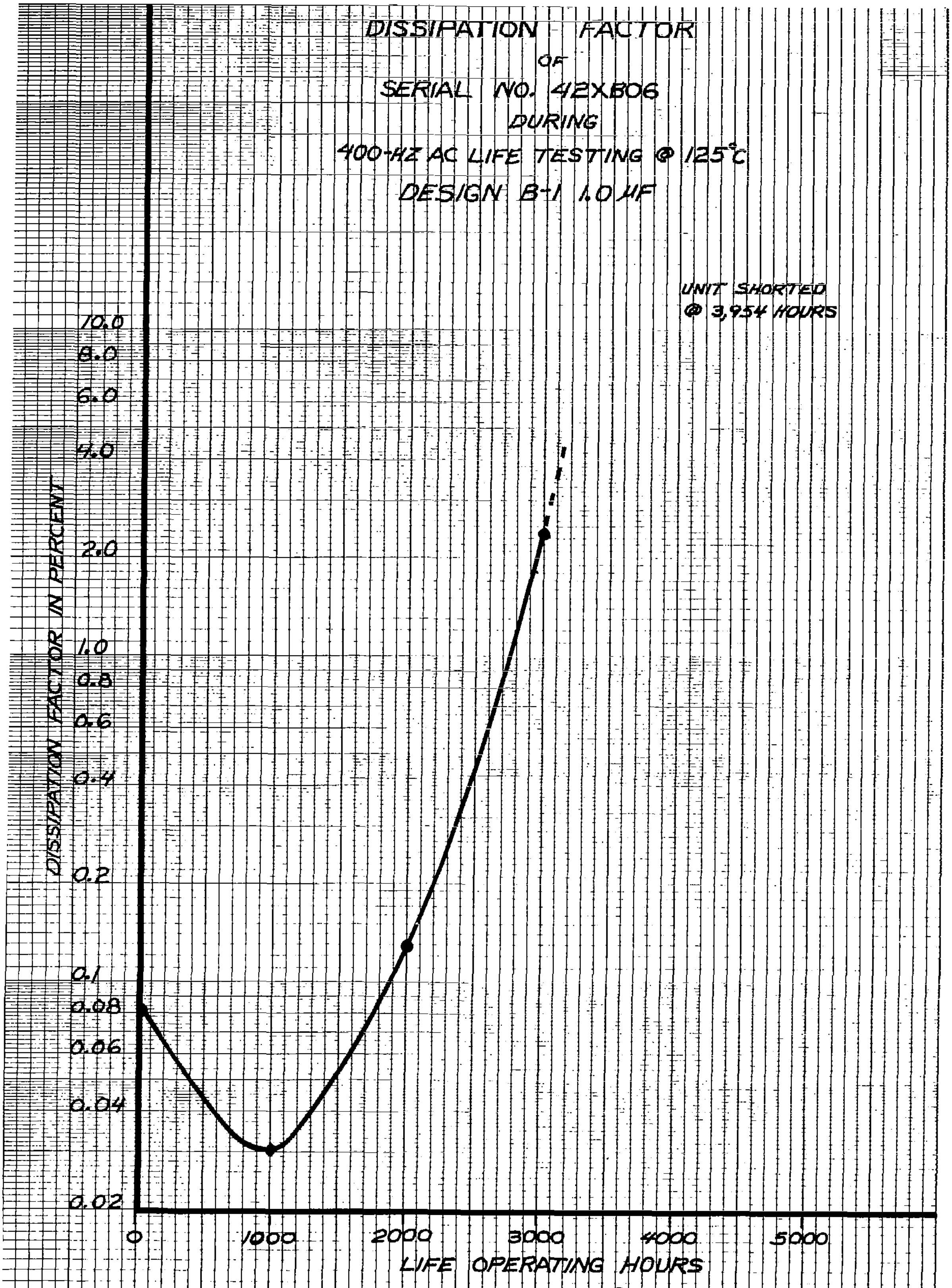

STABILITY CHARACTERISTICS
OF
SERIAL NO. 42XB06
DURING
400-HZ AC LIFE TESTING @ 125°C
DESIGN B-1 1.0 μF
PERCENT CHANGE IN CAPACITANCE
+2.0
+1.0
0
-1.0
-2.0
UNIT SHORTED
@ 3,954 HOURS
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 21


DISSIPATION FACTOR
OF
SERIAL NO. 42XB06
DURING
400-HZ AC LIFE TESTING @ 125°C
DESIGN B-1 1.0 µF
UNIT SHORTED
@ 3,954 HOURS
DISSIPATION FACTOR IN PERCENT
10.0
8.0
6.0
4.0
2.0
1.0
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS
FIGURE 22

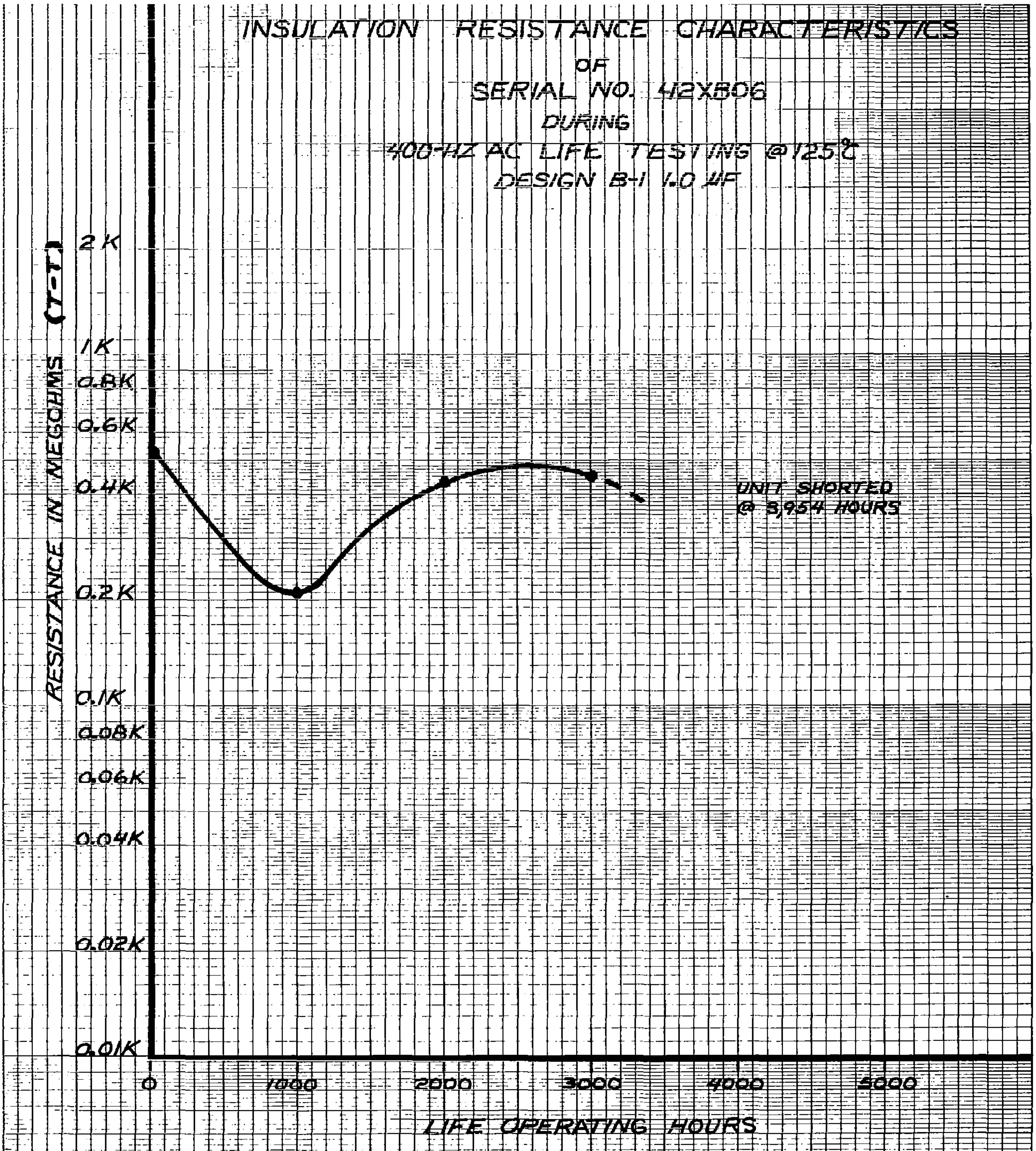
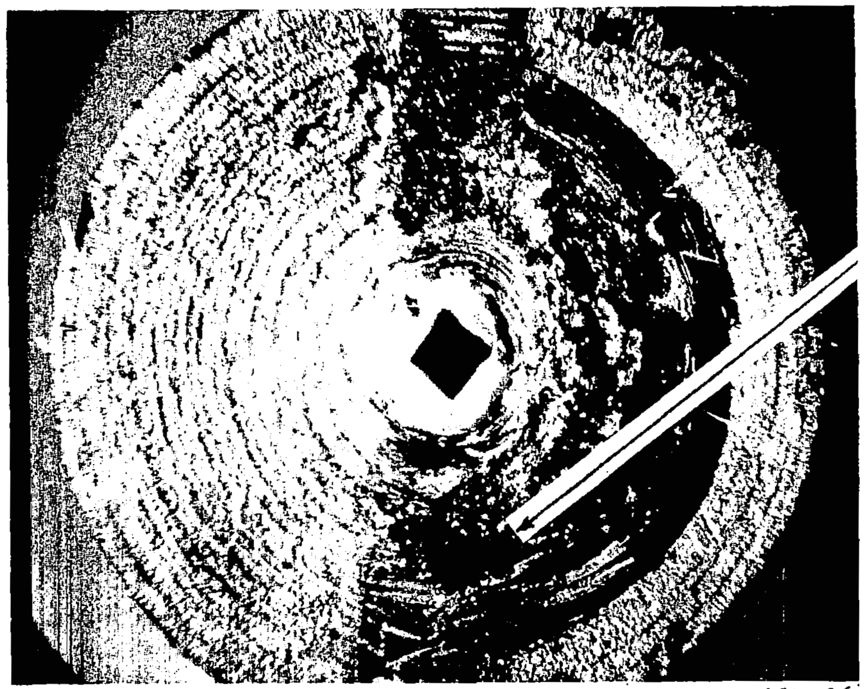

INSULATION RESISTANCE CHARACTERISTICS
OF
SERIAL NO. 412X806
DURING
400-HZ AC LIFE TESTING @125°C
DESIGN B-1 1.0 µF
RESISTANCE IN MEGOHMS (T-T)
2 K
1K
0.8K
0.6K
0.4K
0.2K
0.1K
0.08K
0.06K
0.04K
0.02K
0.01K
UNIT SHORTED
@ 3,954 HOURS
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 23



Note: Carbonization resulting from excess heat

Ser. No. 42XB06

FIGURE 24. Poor termination with increase in DF responsible for part failure (Design B-1). Refer to Failure Analysis #41 and to Figures 21, 22, and 23 for performance curves. Magnification is 6X.

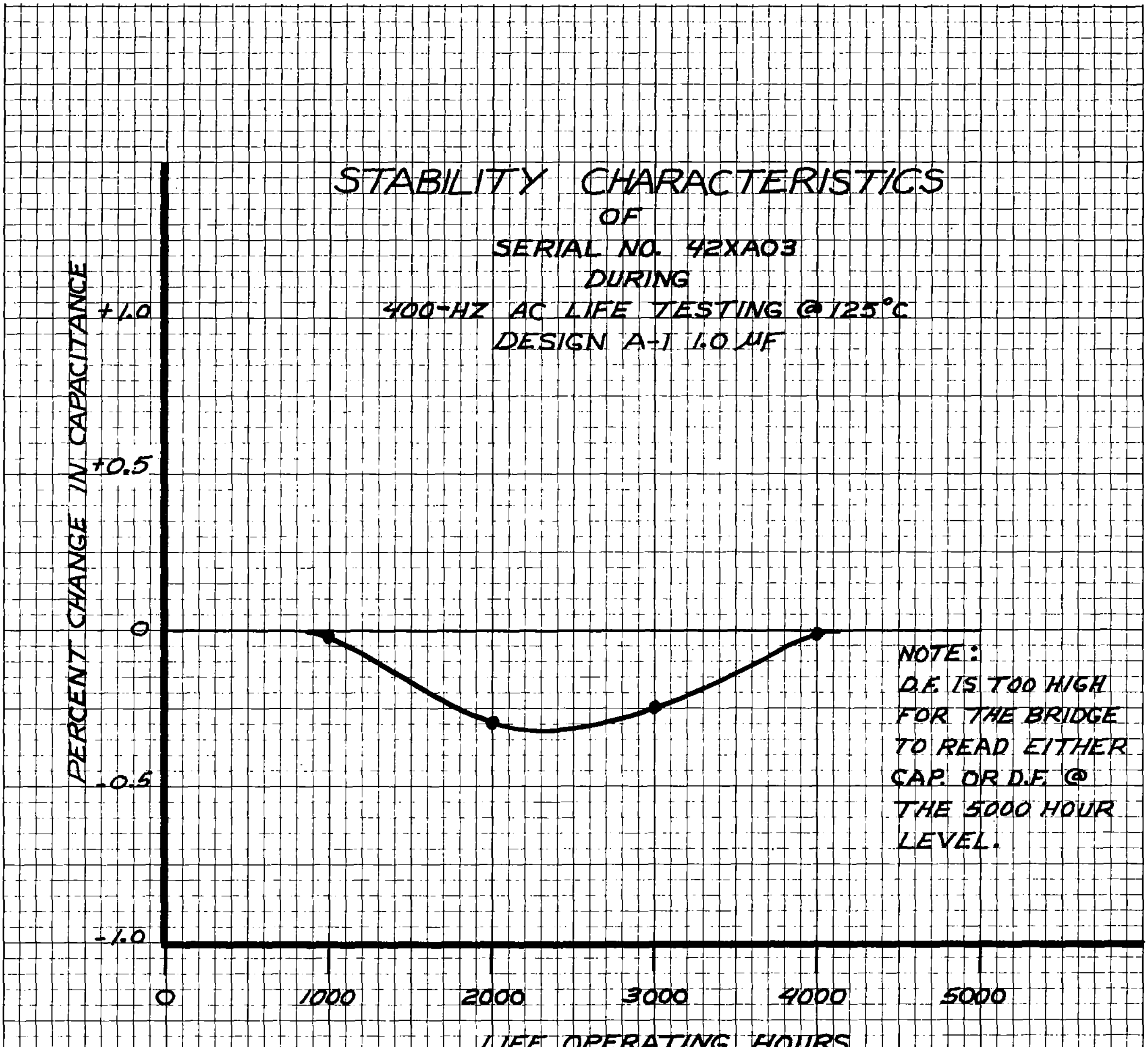

STABILITY CHARACTERISTICS
OF
SERIAL NO. 42XA03
DURING
400-HZ AC LIFE TESTING @ 125°C
DESIGN A-1 1.0 µF
PERCENT CHANGE IN CAPACITANCE
+1.0
+0.5
0
-0.5
-1.0
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS
NOTE:
D.F. IS TOO HIGH
FOR THE BRIDGE
TO READ EITHER
CAP. OR D.F. @
THE 5000 HOUR
LEVEL.

FIGURE 25

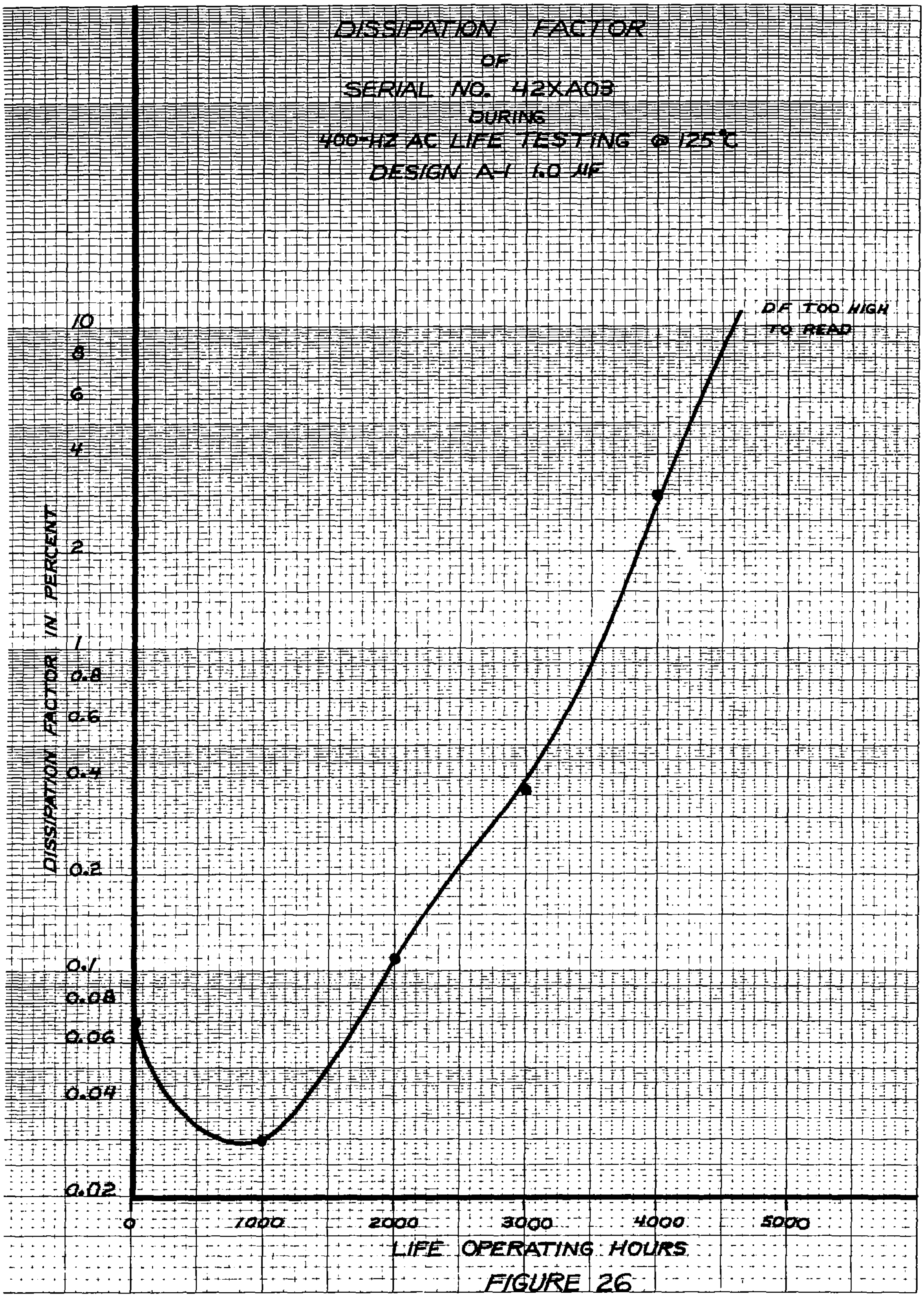

DISSIPATION FACTOR
OF
SERIAL NO. 42XA03
DURING
400-HZ AC LIFE TESTING @ 125°C
DESIGN A-1 1.0 μF
DF TOO HIGH
TO READ
10
8
6
4
2
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
DISSIPATION FACTOR IN PERCENT
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 26

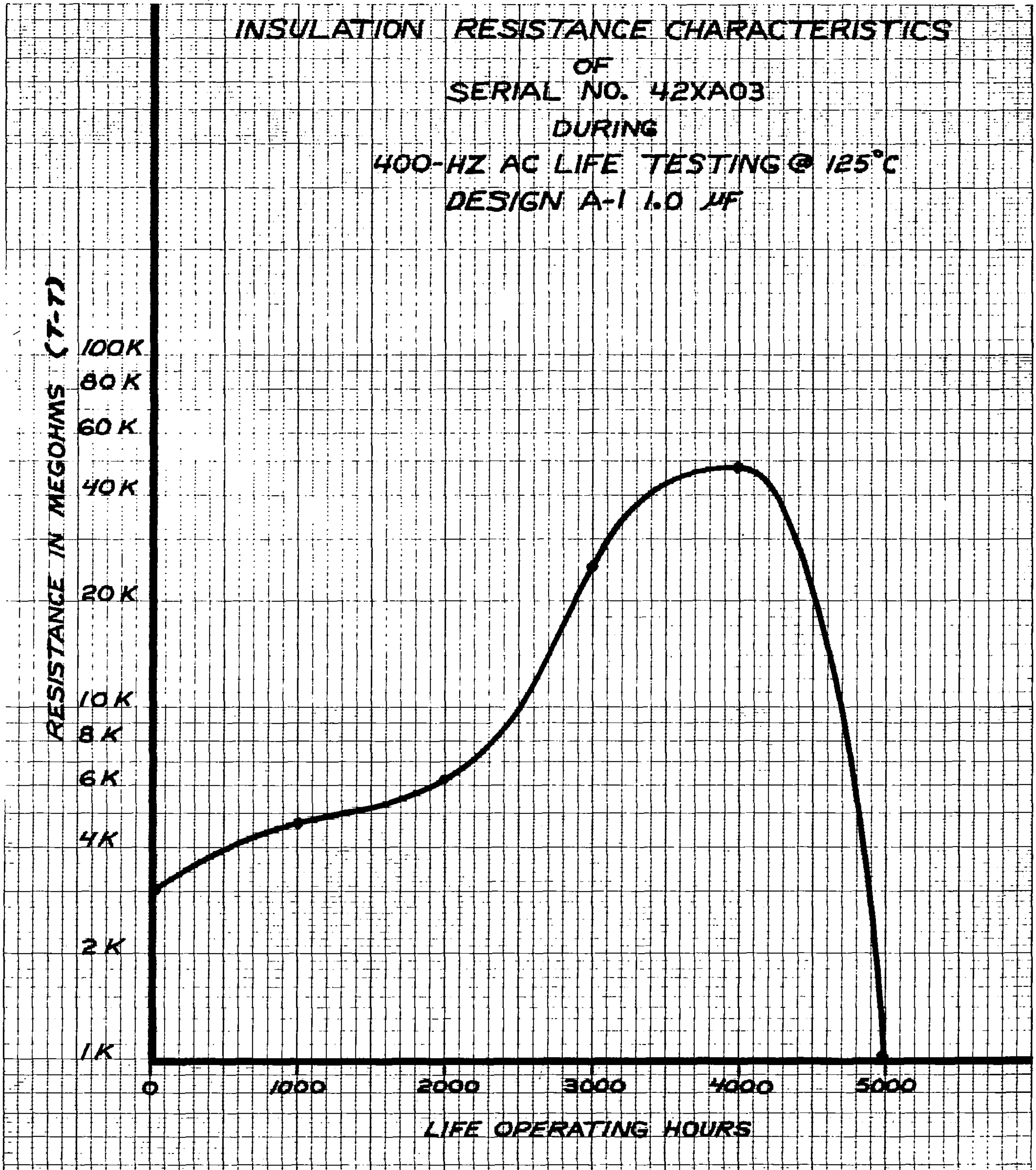
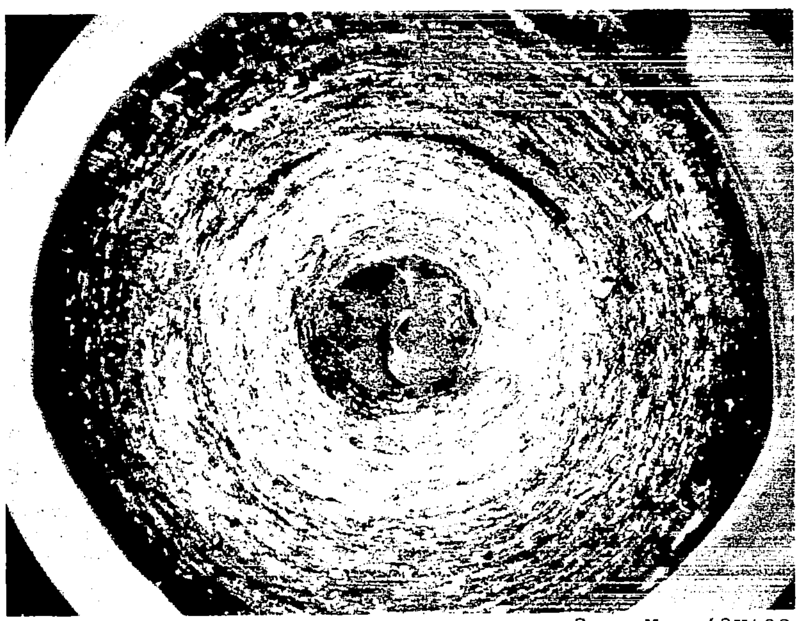

INSULATION RESISTANCE CHARACTERISTICS
OF
SERIAL NO. 42XA03
DURING
400-HZ AC LIFE TESTING @ 125°C
DESIGN A-1 1.0 μF
RESISTANCE IN MEGOHMS (T-T)
100K
80 K
60 K
40 K
20 K
10 K
8 K
6 K
4K
2 K
1 K
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 27



Note: Total carbonization resulting from excess heat

Ser. No. 42XA03

FIGURE 28. Poor termination with increase in DF responsible for part failure (Design A-1). Refer to Failure Analysis #48 and to Figures 25, 26, and 27 for performance curves. Magnification is 7X.

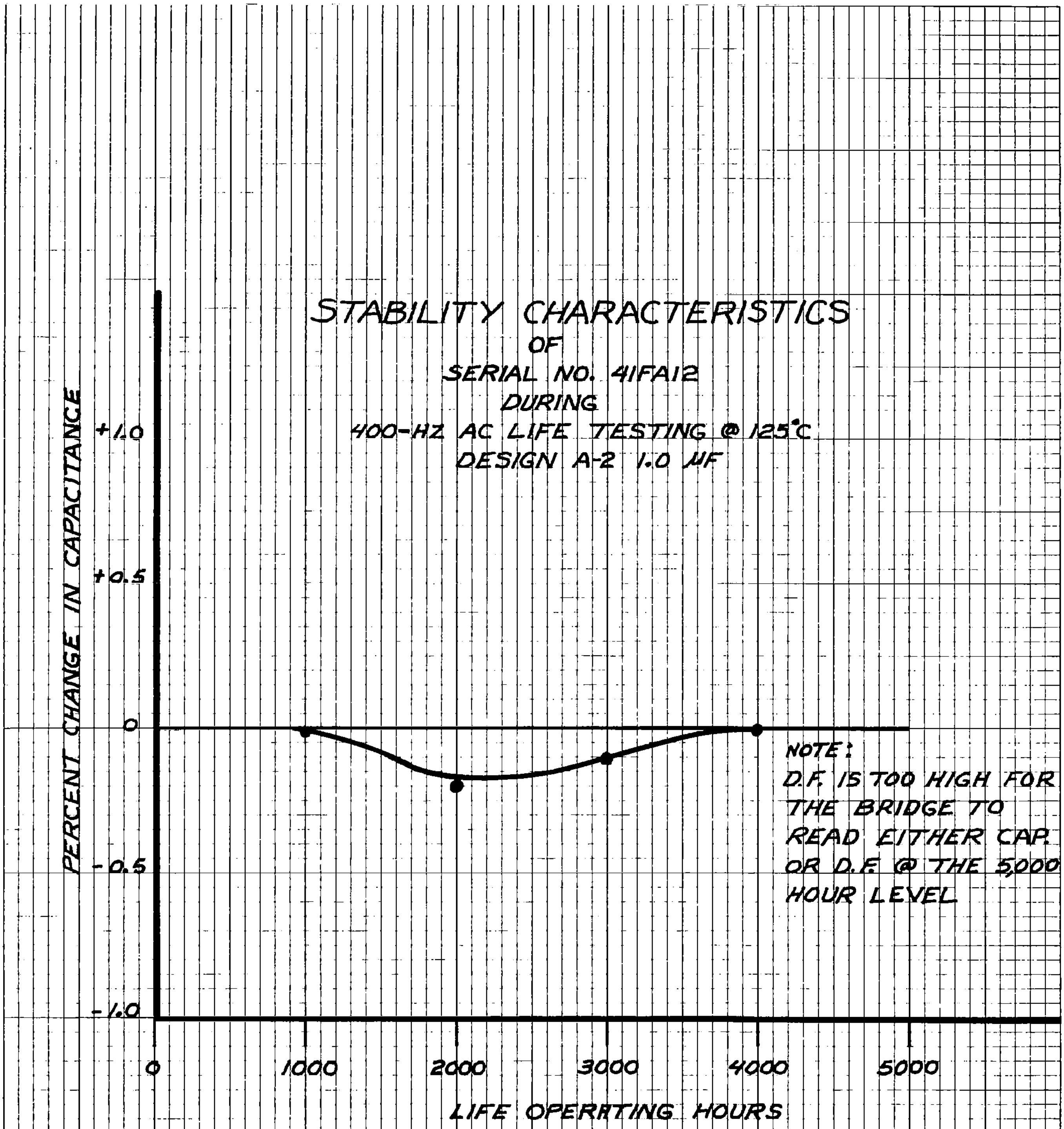

STABILITY CHARACTERISTICS
OF
SERIAL NO. 41FA12
DURING
400-HZ AC LIFE TESTING @ 125°C
DESIGN A-2 1.0 µF
PERCENT CHANGE IN CAPACITANCE
+1.0
+0.5
0
-0.5
-1.0
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS
NOTE:
D.F. IS TOO HIGH FOR
THE BRIDGE TO
READ EITHER CAP.
OR D.F. @ THE 5,000
HOUR LEVEL

FIGURE 29

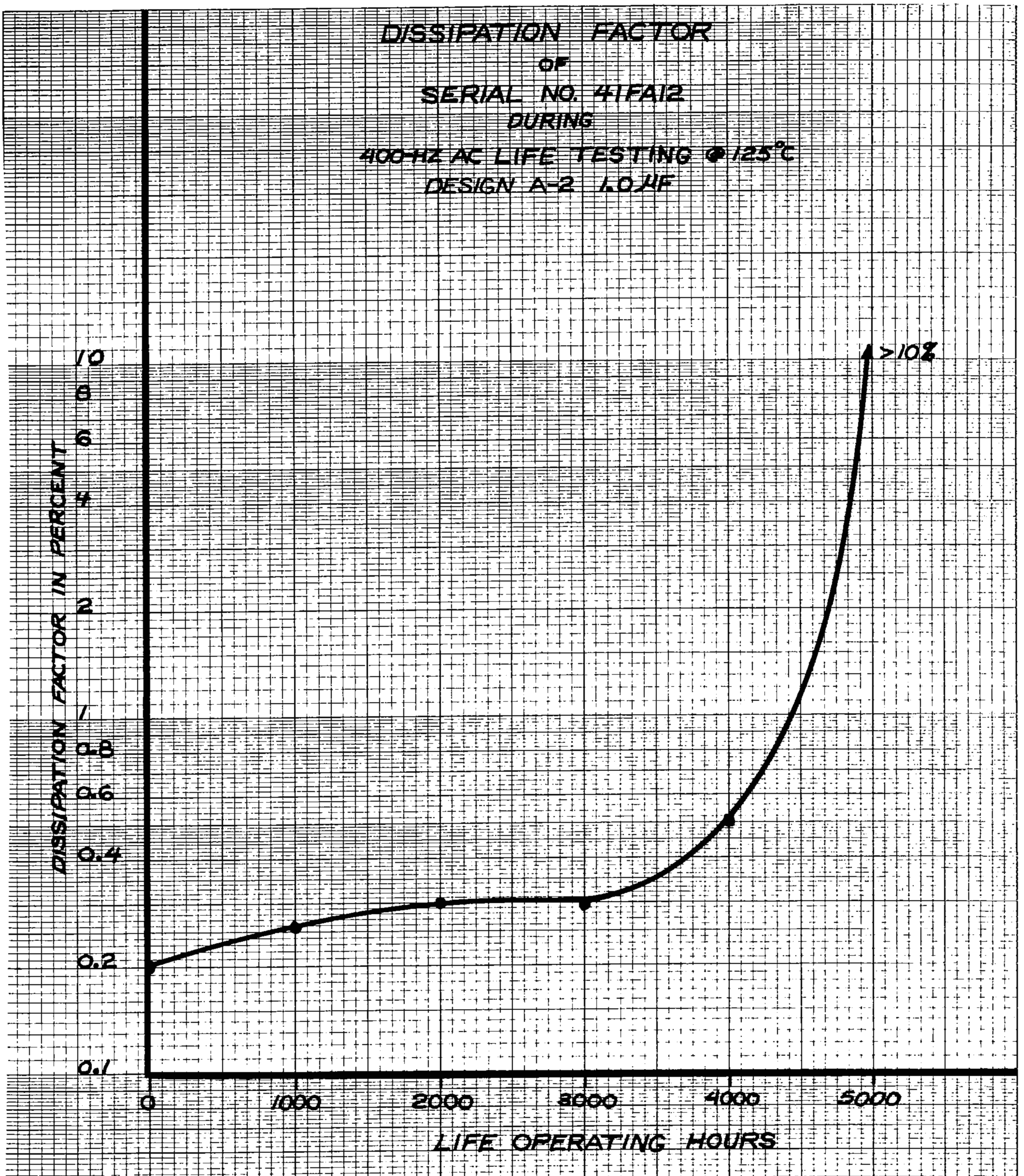

DISSIPATION FACTOR
OF
SERIAL NO. 41FA12
DURING
400-HZ AC LIFE TESTING @ 125°C
DESIGN A-2 1.0 μF
>10%
DISSIPATION FACTOR IN PERCENT
10
8
6
4
2
1
0.8
0.6
0.4
0.2
0.1
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 30

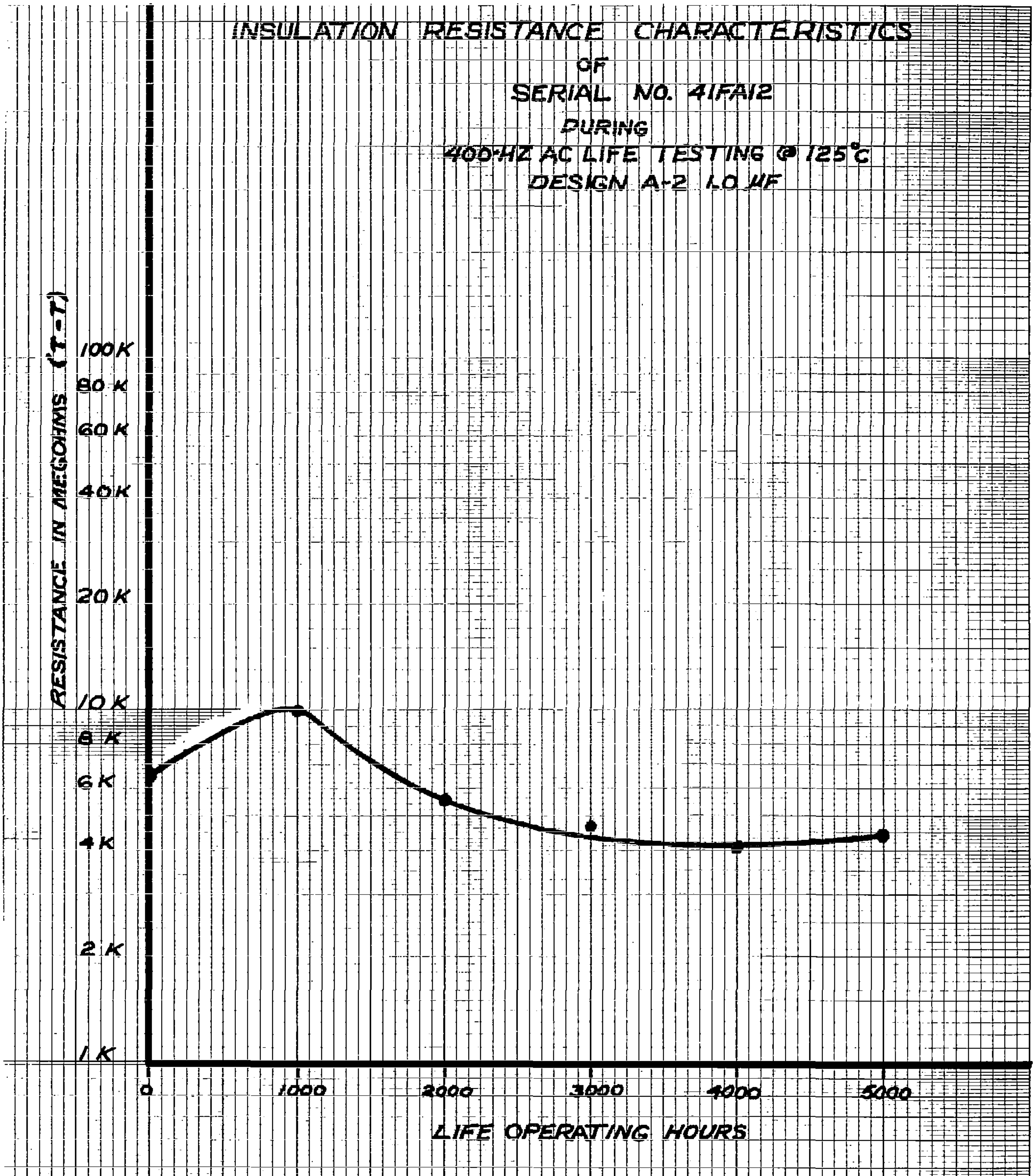
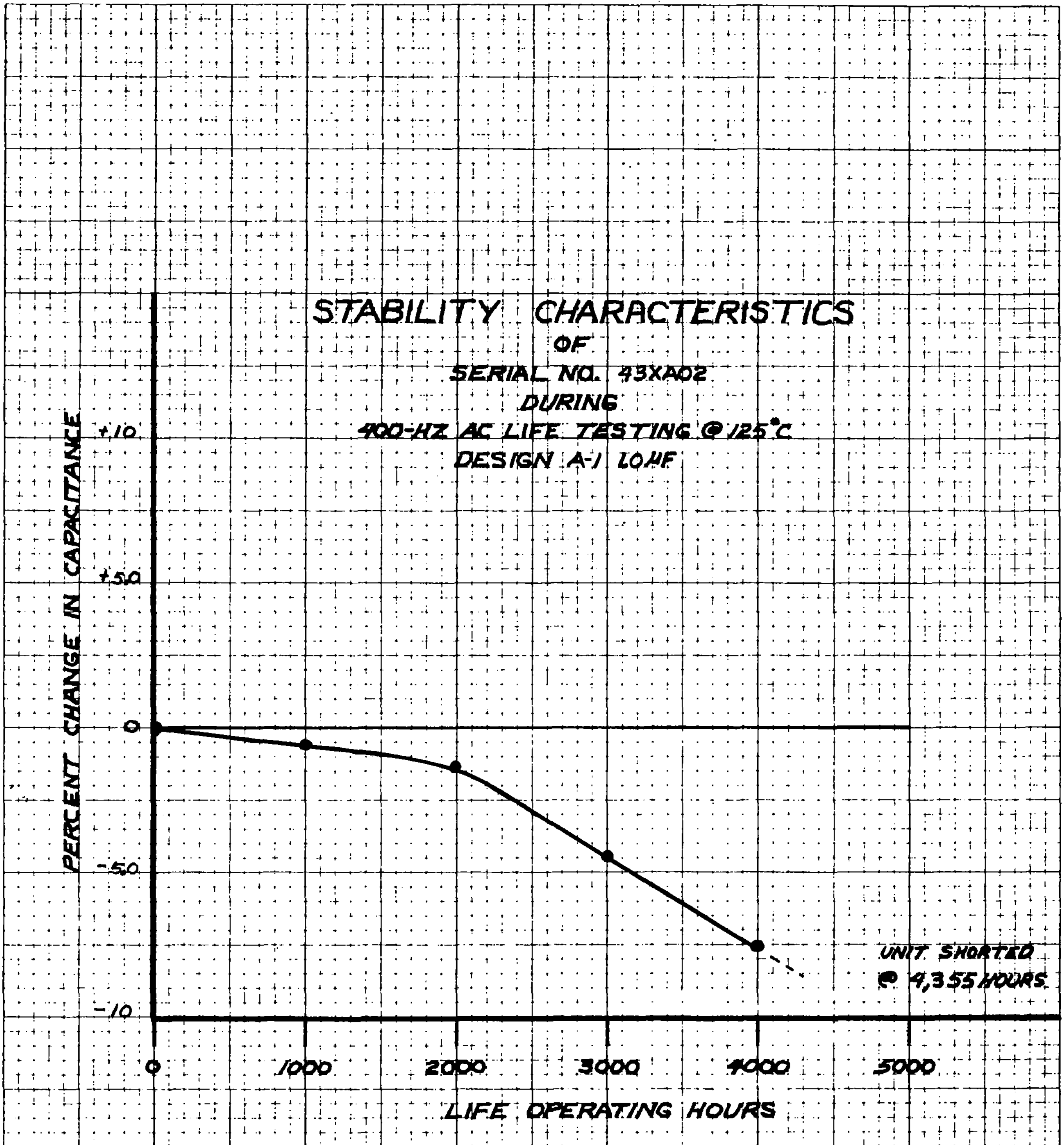

INSULATION RESISTANCE CHARACTERISTICS
OF
SERIAL NO. 41FA12
DURING
400-HZ AC LIFE TESTING @ 125°C
DESIGN A-2 1.0 µF
RESISTANCE IN MEGOHMS (T-T)
100 K
80 K
60 K
40 K
20 K
10 K
8 K
6 K
4 K
2 K
1 K
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS

FIGURE 31

Ser. No. 41FA12

Note: View is of end of winding after lead had been removed.

FIGURE 32. Poor termination resulting from cold solder joint is responsible for part failure (Design A-2). Refer to Failure Analysis #46 and to Figures 29, 30, and 31 for performance curves. Magnification is 5.2X.



STABILITY CHARACTERISTICS
OF
SERIAL NO. 43XA02
DURING
400-HZ AC LIFE TESTING @ 125°C
DESIGN A-1 10µF
PERCENT CHANGE IN CAPACITANCE
+10
+5.0
0
-5.0
-10
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS
UNIT SHORTED
@ 4,355 HOURS

FIGURE 33

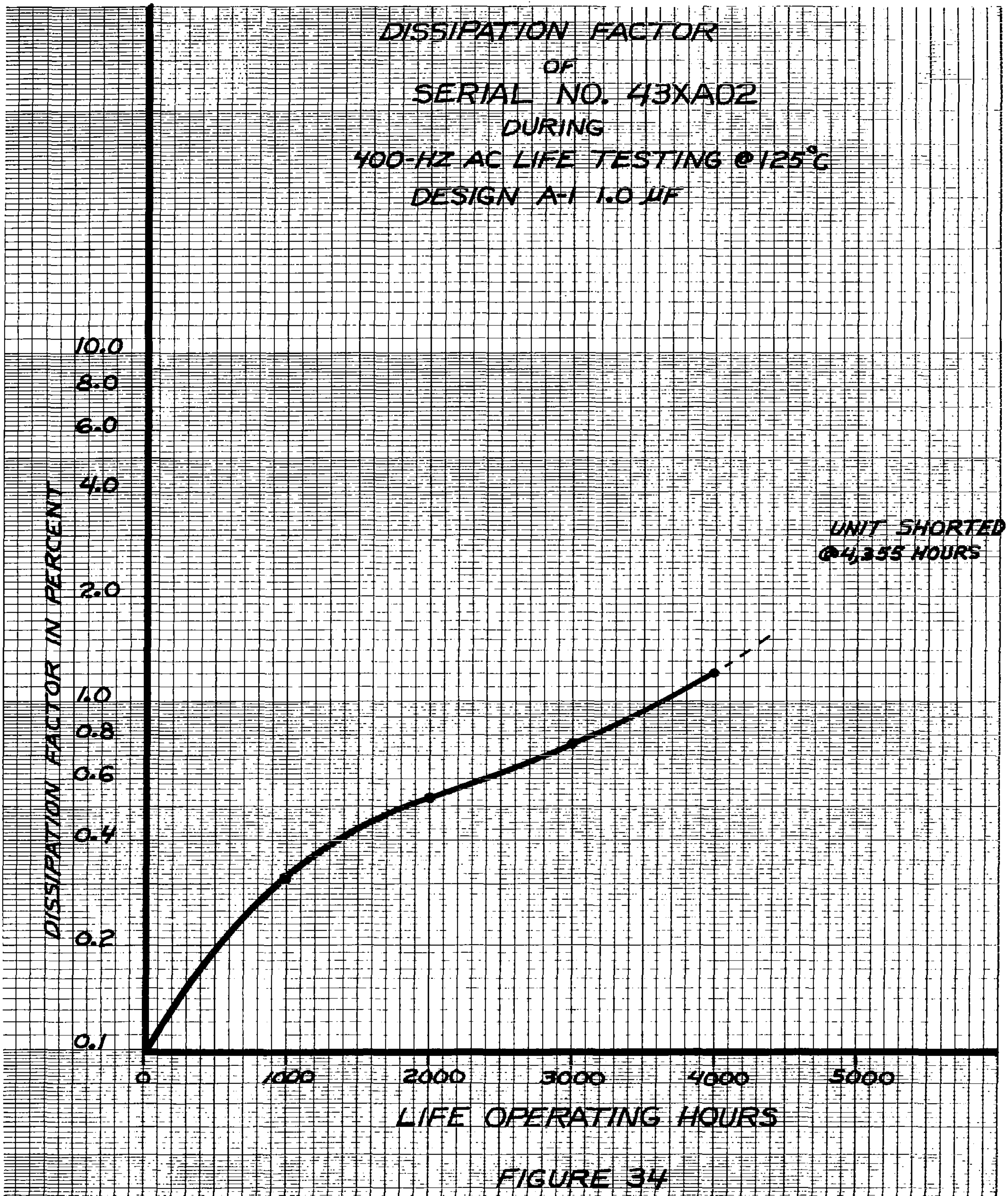
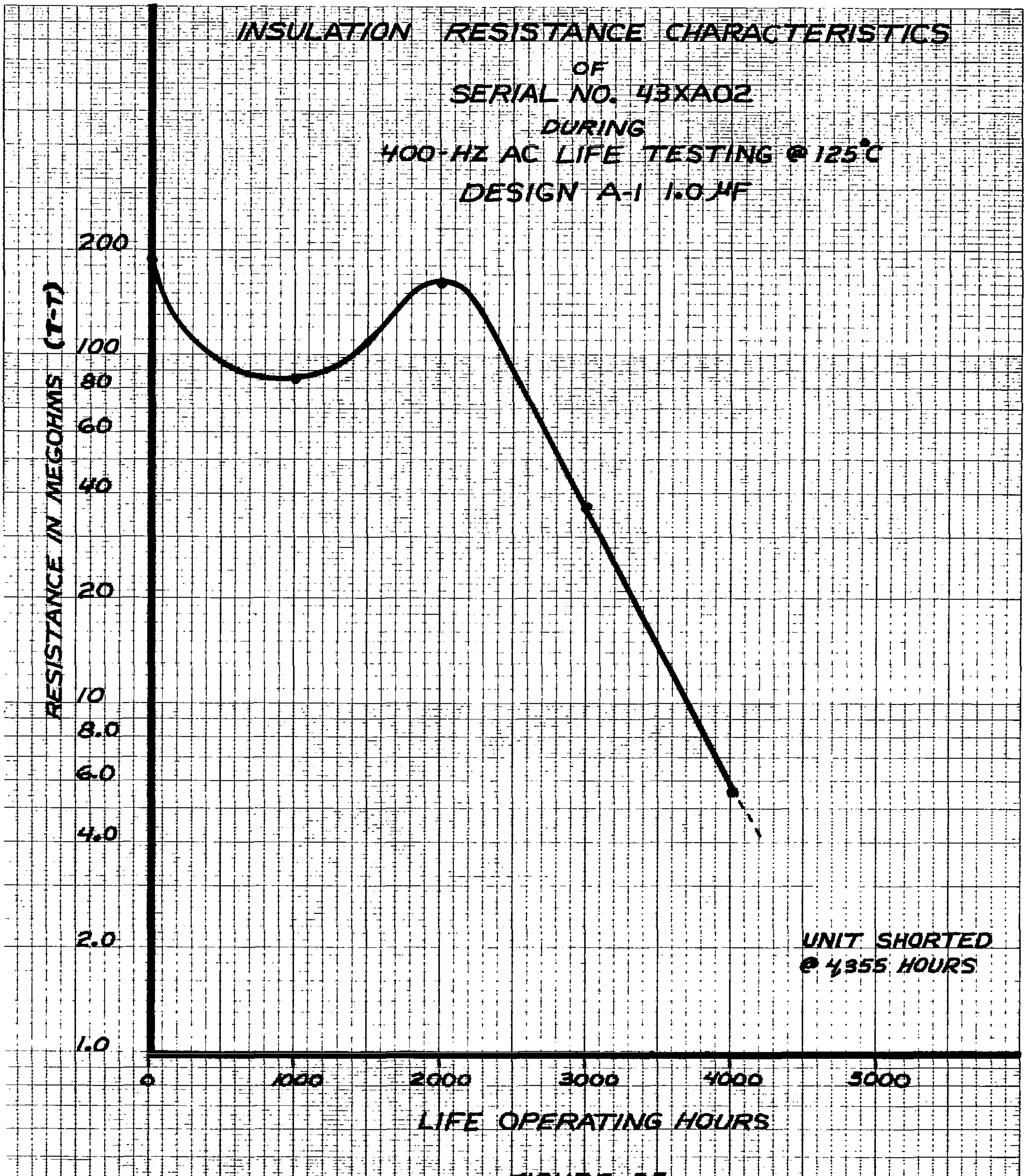

DISSIPATION FACTOR
OF
SERIAL NO. 43XA02
DURING
400-HZ AC LIFE TESTING @ 125°C
DESIGN A-1 1.0 µF
DISSIPATION FACTOR IN PERCENT
10.0
8.0
6.0
4.0
2.0
1.0
0.8
0.6
0.4
0.2
0.1
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS
UNIT SHORTED
@ 4,355 HOURS

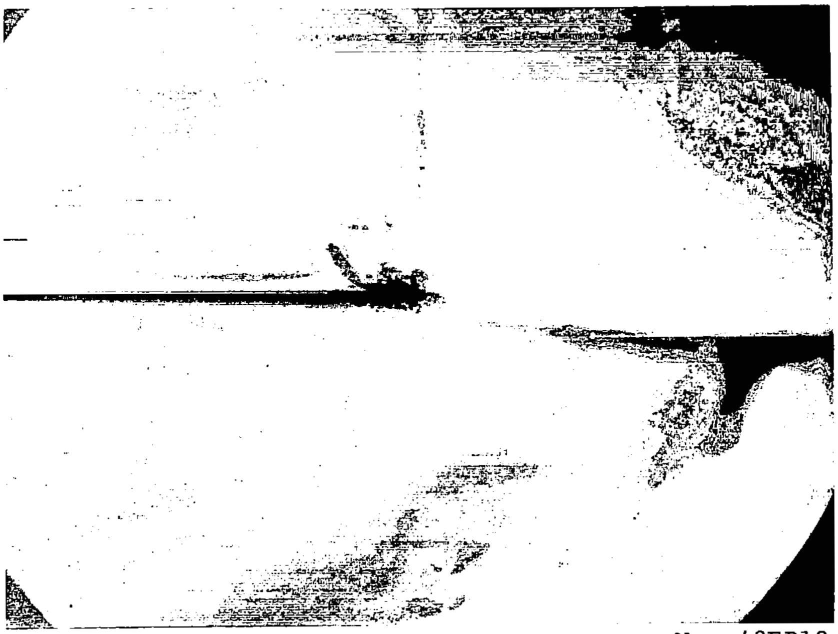
FIGURE 34


INSULATION RESISTANCE CHARACTERISTICS
OF
SERIAL NO. 43XA02
DURING
400-HZ AC LIFE TESTING @ 125°C
DESIGN A-1 1.0 μF
RESISTANCE IN MEGOHMS (T-T)
200
100
80
60
40
20
10
8.0
6.0
4.0
2.0
1.0
0
1000
2000
3000
4000
5000
LIFE OPERATING HOURS
UNIT SHORTED
@ 4355 HOURS
FIGURE 35

Note: Broken seal between eyelet rim and case.

Ser. No. 43XA02

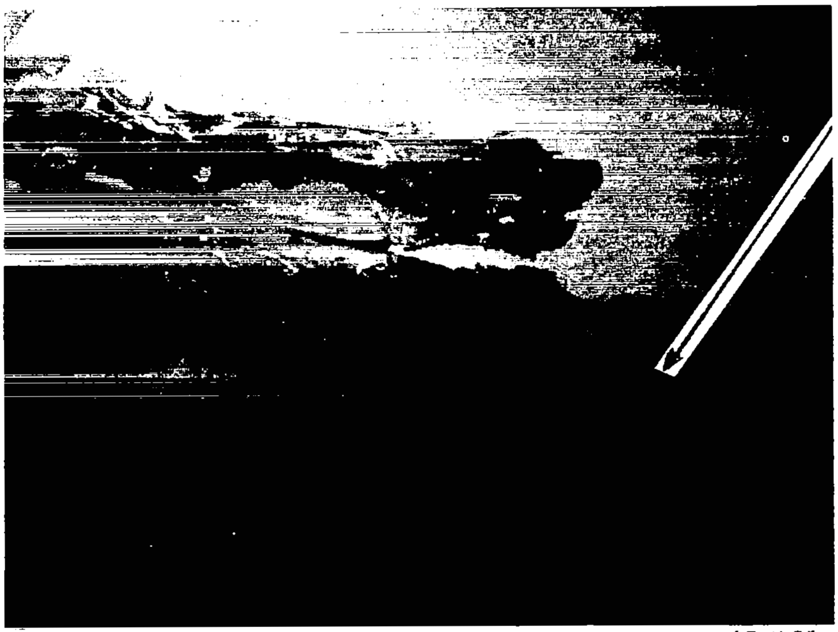
FIGURE 36. The solder joint between tube and eyelet seal was poor allowing the impregnant to escape and subsequent failure of part (Design A-1). Refer to Failure Analysis #42 and to Figures 33, 34, and 35 for performance curves. Magnification is 8.7X.



Ser. No. 43FB13

FIGURE 37. Wrinkle in dielectric responsible for failure of part (Design B-2). Refer to Failure Analysis #3. Magnification is 6X.

Note: Crease caused by winding collapsing into mandrel hole.



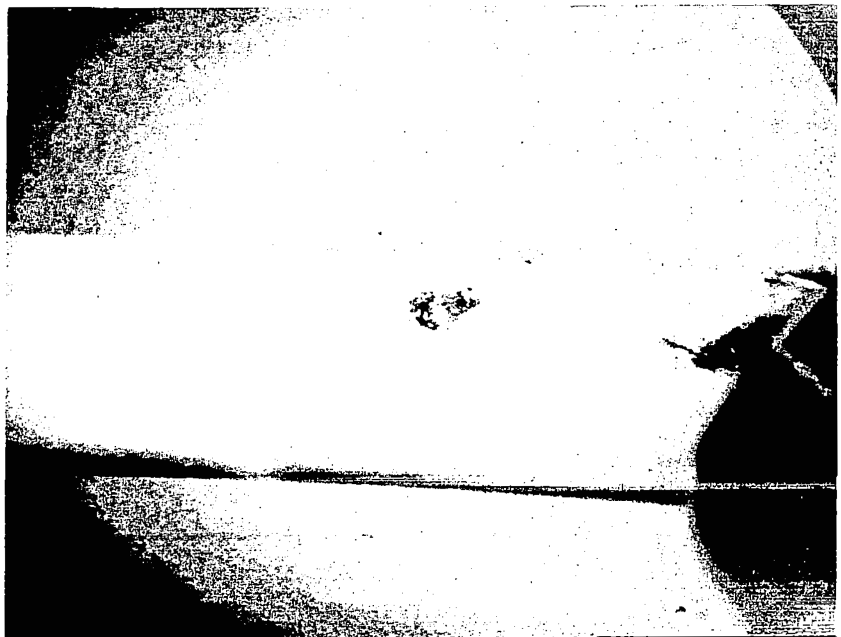
Ser. No. 45XA01

FIGURE 38. Wrinkle in dielectric responsible for failure of part (Design A-3). Refer to Failure Analysis #16. Magnification is 10X.

Note: The main puncture hole shown was found to be associated with hole in ceramic core.

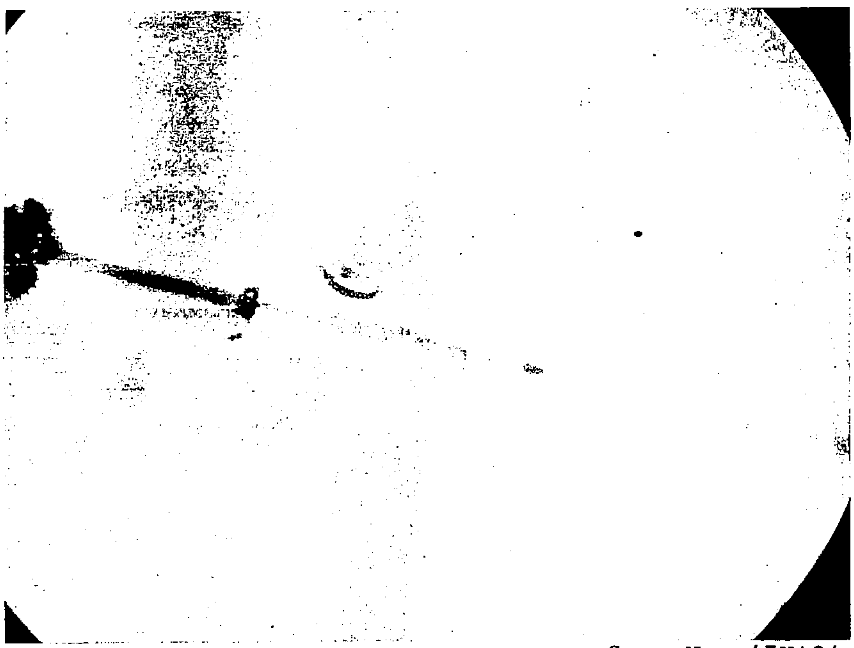
Ser. No. 44XB08

FIGURE 39. Stress created by the 1/32" hole in the ceramic core is responsible for failure of part (Design B-1). Refer to Failure Analysis #23. Magnification is 5.8X.



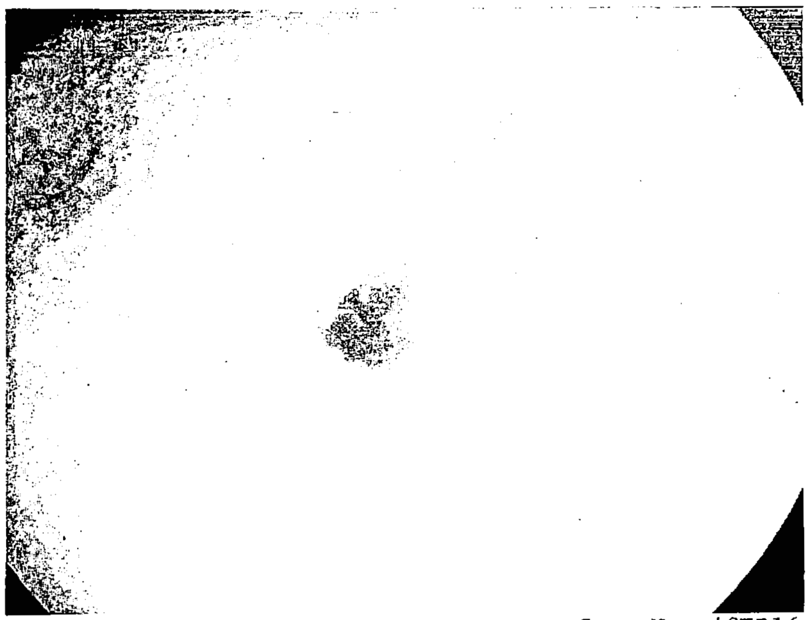
Ser. No. 43XB06

FIGURE 40. Winding machine operator error coupled with effect of drilled hole in core resulted in failure of part (Design B-1). Refer to Failure Analysis #36. Magnification is 5X.



Ser. No. 47XA04

FIGURE 41. The scratched and gouged surface of the dielectric caused the failure of part (Design A-3). Refer to Failure Analysis #35. Magnification is 45X.



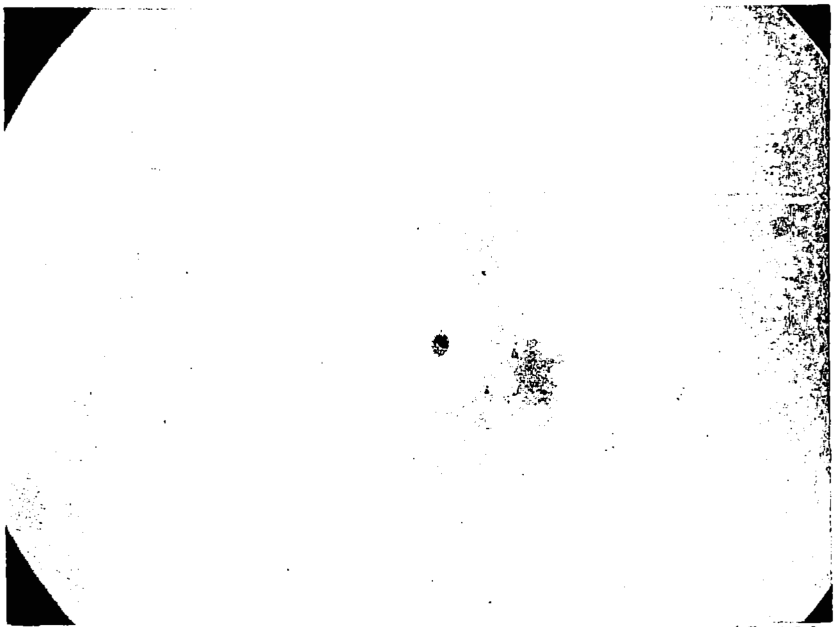
Ser. No. 42FB16

FIGURE 42. A weak spot in the dielectric caused the infantile failure of part (Design B-2). Refer to Failure Analysis #1. Magnification is 22X.

Note: White streak near failure is the result of a damaged photograph.

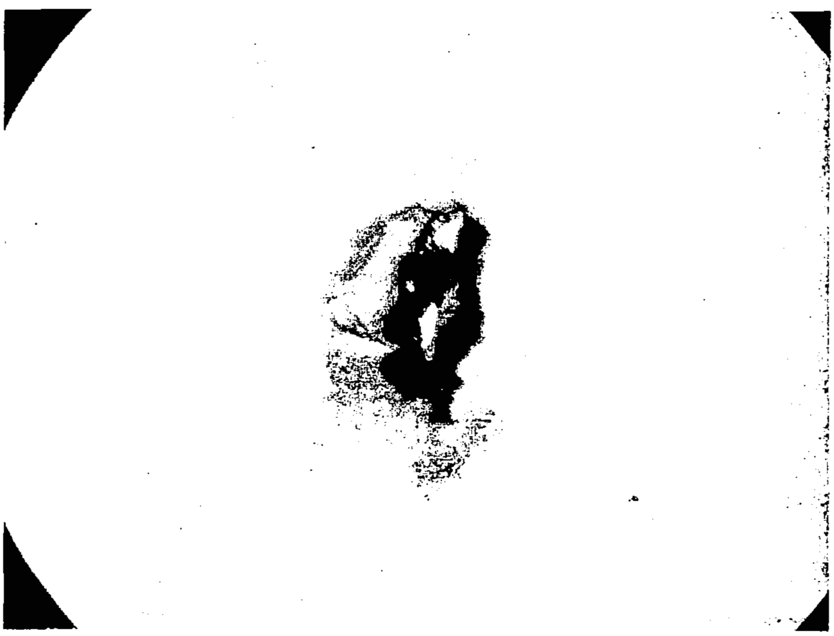
Ser. No. 43FA11

FIGURE 43. A weak spot in the dielectric caused the infantile failure of part (Design A-2). Refer to Failure Analysis #6. Magnification is 6.5X.



Ser. No. 45XA03

FIGURE 44. One of the many small pinholes found which had successfully been cleared. This is in contrast to Figure #45 below.

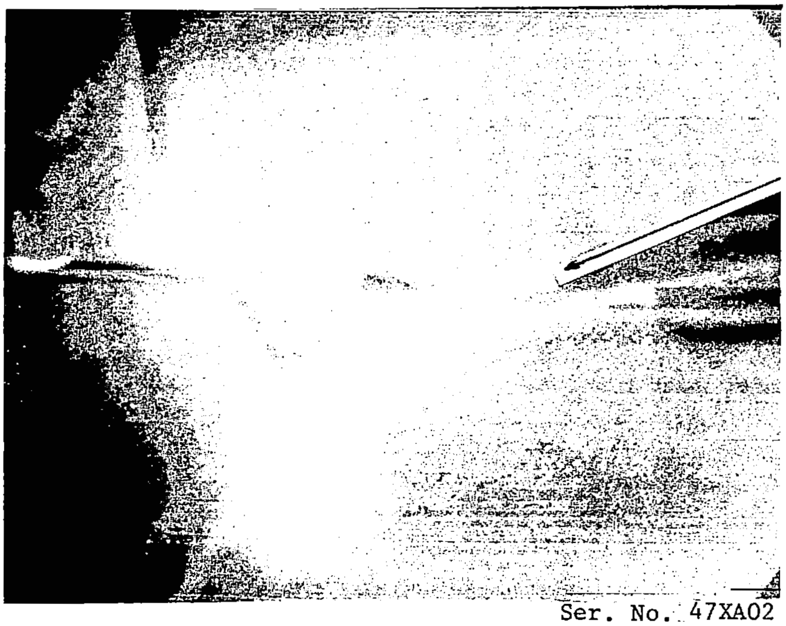


Ser. No. 45XA03

FIGURE 45. Dielectric failure of part (Design A-3). Same part shown in Figure 44 above. Refer to Failure Analysis #25. Magnification is 22X.

Ser. No. 43FB16

FIGURE 46. Dielectric failure of part (Design B-2). Refer to Failure Analysis #14. Magnification is 15X.



Note: Notice the deposit of metallizing on the layer of plain polycarbonate film.

Ser. No. 47XA02

FIGURE 47. Weakened dielectric due to the presence of corona is the cause for part failure (Design A-3). Refer to Failure Analysis #7. Magnification is 5.25X.

Ser. No. 35XA01

FIGURE 48. Some contamination found in the winding material of one capacitor (Design A-3). Refer to Failure Analysis #27. Magnification is 22.5X.

Ser. No. 42FA10

FIGURE 49. Crystallization of plain polycarbonate film caused by contamination resulting in failure of part (Design A-2). Refer to Failure Analysis #22. Magnification is 22.5X.

APPENDIX A

TRW PROCUREMENT SPECIFICATION 27A0087
CAPACITORS, FIXED, POLYCARBONATE

1. General Aspects

   1.1 This specification outlines requirements for hermetically sealed capacitors, both in polycarbonate film-foil and metallized polycarbonate construction.

   1.2 Capacitors furnished to this specification will be subjected to extensive life testing utilizing 400 Hz sinewave voltages at a variety of voltage levels and temperatures outlined in Para. 4.4.

   1.3 Objective of test program is to generate life and failure information for polycarbonate capacitors when used in 400 Hz AC applications found in the aerospace industry and from test results, make recommendations for improvements in capacitor design.

   1.4 The design life objective of the capacitors shall be 50,000 hours at rated conditions outlined in Table I.

   1.5 Only manufacturers capable of supplying both polycarbonate film-and-foil and metallized polycarbonate types are to be considered.

2. Applicable Documents

   2.1 MIL-STD-202C TEST METHODS FOR ELECTRONIC AND ELECTRICAL COMPONENT PARTS

3. Requirements

   3.1 Design and Construction

      3.1.1 Material: The capacitors shall be constructed using the highest quality materials obtainable, consistent with present state-of-the-art. When a definite material is not specified, a material shall be used which will meet the performance requirements of this specification.

      3.1.2 Capacitor Element: The capacitor elements must consist of conducting layers separated by layers of polycarbonate film. Both film and foil and metallized film capacitors will be required (see Table I). Extended foil type construction shall be used. Insulating, impregnating and filling compounds including oils or waxes shall be suitable for the AC application. Compounds used shall not at time of tests specified herein, or after aging in operation or storage conditions under environmental conditions specified, cause any chemical or adverse affect on the performance.

TABLE I

PART NO.	CAP (MFD)	TOL. %	CONSTRUCTION	400 Hz PEAK* AC VOLTAGE RATING	DIMENSIONS (Inches) See Figure 1	
					A MAX.	B MAX.
27A0087-1	1.0	±5	Metallized Polycarbonate	200	1 1/8"	2 1/2"
27A0087-2	1.0	±5	Polycarbonate Film-Foil	200	1 1/8"	2 3/4"
27A0087-3	0.25	±5	Metallized Polycarbonate	400	1 1/8"	2"
27A0087-4	0.25	±5	Polycarbonate Film-Foil	400	1 1/8"	2 1/4"

NOTE: 1. The Rated Case Temperature at Rated 400 Hz AC Voltage shall be 125°C.
2. A DC rating for the capacitors shall be assigned by the manufacturer.

* Zero-to-peak voltage.

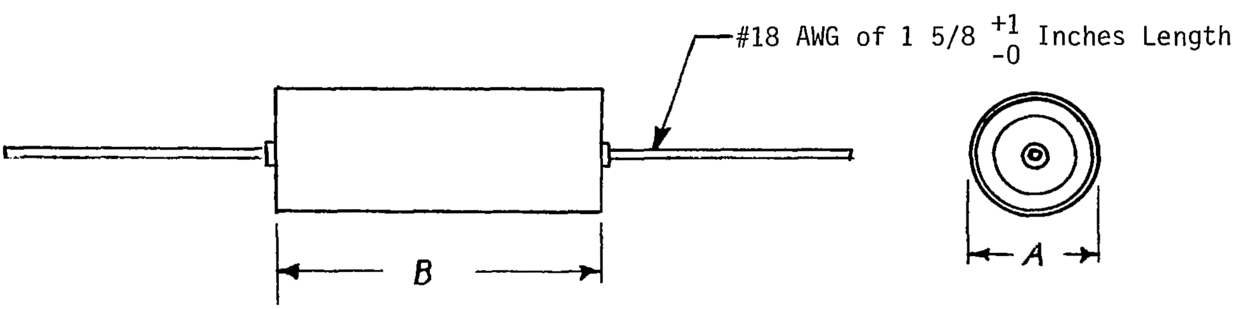


FIGURE 1

3.1.3 Leads: Copper or copper-clad steel wire leads shall be used, having a tin lead coating with a tin content of 40 to 70%. Leads shall be axial. Lead gauge shall be #18 AWG.

3.1.4 Case: The capacitors shall be hermetically sealed in metallic cases. The case shall not be a terminal. Maximum case dimensions shall be as shown in Table I.

3.1.5 Workmanship: The capacitors shall be processed in such a manner as to be uniform in quality and shall be free from pits, cracks, rough edges, and other defects that could affect life, serviceability, or appearance.

3.1.6 Design Life: The design life for the capacitors shall be 50,000 hours at rated conditions with a 95% survival. See Table I and associated applicable notes for rated voltage and temperatures. The design must be such as to minimize the possibility of corona at the AC test conditions described in Para. 4.4.

3.2 Capacitor Identification: Each capacitor shall be marked with smear resistant ink that will withstand the environmental conditions specified. Character dimensions shall be at the discretion of the supplier. The following information shall be marked on the body of the capacitor:

a) Manufacturer's identification, name or symbol
b) Manufacturer's part number
c) Capacitance
d) Capacitance Tolerance
e) DC Working Voltage
f) AC Peak Rated Voltage @ 400 Hz
g) Date Code

3.3 Traceability

3.3.1 The manufacturer must maintain traceability records back to raw material lots employed for capacitors supplied to this specification.

3.3.2 The supplier must provide the following information on the design of the capacitors submitted:

a) Source of dielectric
b) Dielectric lot number
c) Dielectric thickness
d) Margin
e) Type of impregnant
f) Type of foil
g) Any special screening tests performed

3.4 Explanation of Lot Descriptions: All raw materials used in producing a capacitor type shall be drawn from single raw material lots.

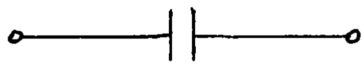
3.4.1 Capacitor Lot: A capacitor lot is defined as a group of capacitors of a single capacitance and voltage rating produced under conditions as constant as possible.

3.4.2 Raw Material Lot: A raw material lot for any single type of material, except dielectric, shall be defined as that material received at one time, in the same shipment, and purchased against a single purchase order number.

3.4.3 Dielectric Lot: A dielectric lot shall be defined as that material coming from one mill roll of material from one film manufacturer.

3.5 Electrical

3.5.1 Circuit Design



BOTH LEADS INSULATED
NO INSULATING SLEEVE

3.5.2 Dissipation Factor (DF)

Metallized Polycarbonate	$\leq$.30%
Foil and Polycarbonate Film	$\leq$.25%

The dissipation factor of each capacitor must be equal to or less than the above limits when measured at an AC voltage not greater than 20% of the rated DC voltage, at 25°C ± 5°C, and at a frequency of 400 Hz ± 5%. Accuracy of the dissipation factor measurements shall be ±2 percent of the reading.

3.5.3 Capacitance

Capacitance of four (4) items shall be as outlined in Table I. The capacitance shall be measured in accordance with Method 305 of MIL-STD-202C except that test frequency shall be 400 Hz ± 5% and accuracy of measurement shall be ±0.5%.

3.5.4 Insulation Resistance (IR)

3.5.4.1 All capacitors must meet the requirements outlined in Table II when tested in accordance with Method 302 of MIL-STD-202C. A potential equal to the DC voltage rating of the capacitor being tested or 500 VDC whichever is less, shall be used. Capacitors must be stabilized at 25°C ± 5°C.

3.5.4.2 Points of Measurement: Terminal to terminal and between terminals and case.

3.5.4.3 The time constant of the measurement circuit shall not exceed 30 seconds.

3.5.4.4 Maximum electrification for terminal to terminal measurements shall not exceed 2 minutes. Maximum electrification time for terminal to case measurements shall not exceed 1 minute.

TABLE II
INITIAL INSULATION RESISTANCE REQUIREMENTS

CONSTRUCTION TYPE	TEMPERATURE 25°C
Polycarbonate Film-Foil Terminal to Terminal	
(a) Megohms x mfds	75K
(b) Need not exceed (megohms)	150K
Metallized Polycarbonate Terminal to Terminal	
(a) Megohms x mfds	100K
(b) Need not exceed (megohms)	200K
NOTE: Terminal to case IR measurements shall be equal to or greater than terminal to terminal IR measurements.	

3.5.5 Dielectric Strength Test

3.5.5.1 Dielectric Strength: Capacitors shall be capable of withstanding twice the DC rated voltage for one minute through a limited resistance of 100 ohms per volt. The DC dielectric strength test shall consist of a terminal to terminal and a terminal to case check.

3.5.5.2 AC Dielectric Strength: Capacitors shall be capable of withstanding 130% of rated AC voltage when subjected to 60 Hz for a ten minute duration. The AC dielectric strength test shall consist of a terminal to terminal check.

3.6 Environmental

3.6.1 Hermetic Seal: The hermetic seals of the capacitors shall have a leakage rate less than 1×10^{-8} atm cc/sec when tested in accordance with Method 112a of MIL-STD-202C. The following details are applicable:

Test Condition C
Procedure IIIa

3.6.2 Potential Space Environment: The capacitors shall be designed to operate under the following conditions, or any practical combination thereof, without degradation of electrical characteristics.

3.6.2.1 Shock: 20 g half sinewave for 11 millisecond duration.

3.6.2.2 Vibration: Sinusoidal input to case along each of three mutually perpendicular axes.

5-33 cps at 0.14 inch D.A. displacement
33-140 cps at 8.0 g's peak
140-240 cps at 0.008 inch D.A. displacement
240-2000 cps at 15 g's peak

3.6.2.3 Acceleration: 6 g's for 5 minutes along any of the three mutually perpendicular axes.

3.6.2.4 Gravity: Both sea level and zero gravity.

3.6.2.5 Radiation:
Fast Neutrons - 1×10^{11} nvt, integrated dose for 10^4 hours.
Gamma - 1×10^6 rads (c), integrated dose for 10^4 hours.

4. Quality Assurance Provisions

4.1 Responsibility of Manufacturer

The manufacturer shall produce parts that will meet requirements outlined in Paragraph 3.

4.2 Receiving Inspection

TRWC shall perform tests to assure compliance with requirements of Paragraphs 3.5.1 through 3.6.1 inclusive upon receipt of part. Acceptance of parts will be based upon test results and various other examinations required to verify conformance with requirements of this specification.

4.3 Life Testing

TRWC will subject capacitors to 400 Hz sinewave voltages for a duration of 5000 hours. Test conditions are as follows:

Test Voltages: 70%, 90%, 110%, and 130% of peak rating.
Case Temperatures: 65°C, 85°C, 105°C, and 125°C.

5. Preparation for Delivery

5.1 Packaging: Parts shall be packaged for delivery so that they will meet requirements of this specification after handling and shipping. Parts shall not be bulk-packed.

5.2 Transportation: Include on all commercial bills of lading the following:

"Transportation hereunder is for the Government and the actual, total transportation charges paid to the carrier (s) are to be reimbursed by the Government."

ADDENDUM TO TRW PROCUREMENT SPEC. 27A0087

1. The capacitor supplier must supply information on source of dielectric and lot number in confidence to NASA but not to TRWC.

2. The type of impregnant can be described in general without detailing the exact chemical formula or catalog item of the impregnant supplier. An example might be "silicone oil" without referencing additional details.

3. Special screening tests can be described as "Burn-In" if this is used without details as to temperature, duration, and voltage.

4. The understanding of Page 6, para. 4.2 of TRWC spec. 27A0087 is that only defective items must be replaced, not the entire shipment. The case in which complete replacement of an item would be required would be failure of a majority of that item to pass some parameter or requirement of the spec. 27A0087.

5. Physical dimension deviations requested by one manufacturer are acceptable.

This addendum is an addition to Spec. 27A0087 and must be included with the Purchase Order to capacitor manufacturers selected.

APPENDIX B

FAILURE ANALYSES

OF

SAMPLES REPRESENTATIVE

OF

FAILURE CAUSES

Description of Appendix B Content - During the course of the test program, a failure analysis was performed on each capacitor which failed. Failure analysis numbers were assigned numerically in sequence as they were done. Photographs taken at the time an individual analysis was made were assigned a numerical number corresponding to the failure analysis number with alphabetical suffixes to distinguish between several photographs that might have been taken of the capacitor being analyzed. Representative failure analyses and some photographs were selected for use in the Final Report to help in the illustration and discussion of failure causes. For this reason, the Failure Analysis numbers found in Appendix B are not in consecutive numerical sequence. Though the failure analysis sheets in Appendix B may reference 2 or more photographs, there are situations where only 1 photograph was useful in the text of the report. Figure numbers are assigned to the photographs used in the text of the report for discussion purposes.

FAILURE ANALYSIS NO. 1
Serial No. 42FB16 Design B-2

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	7/14/69	Date Removed:	9/17/69
Elapsed Time Reading:	0 Hours	Life Operating Hours:	0 Hours
Capacitance:	1.0 mfd.	AC Voltage:	127V rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	0.991	0.08	150K megohms	14,000K megohms
@ Test Temperature	0.986	0.06	2.5K megohms	75K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External was good.

Results of Analysis: Construction was good. Reason for short was a puncture directly through the dielectric at about 3 inches distance from the start of the second foil at the start of the winding. The puncture was 5/8" in from the edge of the dielectric. No contamination was evident. Photograph #1A at 9 power magnification shows the puncture with the foil folded back so that the pinhole burnt through the foil and dielectric both can be seen. A photograph 1B at 22 power magnification shows an enlarged view of the dielectric puncture.

Conclusion: The failure was of an infantile nature and occurred as a result of the initial 400 Hz voltage application.

Photographs:	Date Analysis Performed:	Analysis Performed By:
1A & 1B	12/29/69	Richard R. Bailey

See Figure #42 in report.

FAILURE ANALYSIS NO. 3
Serial No. 43FB13 Design B-2

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	7/14/69	Date Removed:	9/17/69
Elapsed Time Reading:	1.5 Hours	Life Operating Hours:	1.5 Hours
Capacitance:	1.0 mfd.	Ac Voltage:	156 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	1.015 mfd.	0.09	140K megohms	20,000K megohms
@ Test Temperature	1.011 mfd.	0.06	6K megohms	56K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: Outside good

Results of Analysis: The failure occurred through the dielectric at a point approximately 7 feet from the beginning of the winding. The puncture occurred where a wrinkle running the length of the material intersected a wrinkle running crosswise the material. Wherever wrinkles occur, additional stresses occur on the dielectric which may lead to failure. It is believed that the plates, if given a chance, may move slightly under stresses of the varying electrostatic field associated with AC applications. The presence of wrinkles can create the voids necessary for slight movement. Mechanical stresses exerted on the dielectric where wrinkles occur contribute toward eventual failure. It is possible that the failure was due to dielectric weakness at that point but very likely that the wrinkle was the cause or contributed to the failure. Applicable voltage and current recorder charts were inspected and nothing unusual in equipment or test conditions was noted. The current to the test rack dropped off abruptly the correct amount when the capacitor failed.

Conclusion: Failure occurred through the dielectric with a wrinkle believed a contributing factor to the failure.

Photograph:	Date Analysis Performed:	Analysis Performed By:
3A	1/2/70	Richard R. Bailey

Refer to Figure 37 in report.

FAILURE ANALYSIS NO. 6

Serial No. 43FA11 Design A-2

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	7/16/69	Date Removed:	9/17/69
Elapsed Time Reading:	52.0 Hours	Life Operating Hours:	52.0
Capacitance:	1.0 mfd	AC Voltage:	156 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	1.014	0.15	130K megohms	9,000K megohms
@ Test Temperature	1.006	0.24	6.5K megohms	120K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External good.

Results of Analysis: Failure occurred from dielectric puncture located about ½ inch in from edge of dielectric and at about 3 feet from finish of winding. Nothing in the dielectric or construction was found that could contribute to the failure. The applicable voltage and current recorder charts were examined at time of failure. Voltage was correct at 155 volts rms and current dropped the appropriate amount abruptly when capacitor 43FA11 was shorted.

Conclusion: Failure occurred at a weak point in the dielectric and due to occurrence after only 52 hours of operation, is considered an infantile failure.

Photographs:	Date Analysis Performed:	Analysis Performed By:
6A	1/14/70	Richard R. Bailey

See Figure 43 in report.

FAILURE ANALYSIS NO. 7

Serial No. 47XA02 Design A-3

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	7/23/69	Date Removed:	9/17/69
Elapsed Time Reading:	56.5 Hours	Life Operating Hours:	56.5 Hours
Capacitance:	0.25 mfd.	AC Voltage:	311 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	0.244	0.15	500K megohms	2,600K megohms
@ Test Temperature	0.245	0.06	75 megohms	79K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External good. Internal - noticed that solder seal between eyelet rim and tube on one edge was poor.

Results of Analysis: The dielectric failed in at least 2 major areas with other smaller points found also. In both major breakdown areas, the material was blackened and fused together, making separation difficult. There was evidence along margin edges and other areas of carbon deposits even though many of these areas were nowhere near the point of failure. Photograph 7B shows a strip of metallizing fused to the layer of plain dielectric. This was found when separating material layers. The unusual track and transfer of metallizing could have been caused by heating along a corona track. Previous testing for corona on 10 samples indicates also that the test voltage involved with this part is considerably above the corona level.

Conclusion: Failure was due to weakening of the dielectric by action of corona.

Photographs:	Date Analysis Performed:	Analysis Performed by
7A & 7B	1/14/70	Richard R. Bailey

Refer to Figure #47 in report.

FAILURE ANALYSIS NO. 14
Serial No. 43FB16 Design B-2

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	8/19/69	Date Removed:	9/17/69
Elapsed Time Reading:	705.0 Hours	Life Operating Hours:	705 Hours
Capacitance:	1.0 mfd.	AC Voltage:	156 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	0.981	0.10	220K megohms	12,000K megohms
@ Test Temperature	0.981	0.06	7.5Kmegohms	65K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External good.

Results of Analysis: Failure occurred at a distance of about 6 feet from the start of the winding or at about 1/4 of the total winding insert length. The puncture occurred about 3/4" in from the edge of the dielectric. No contamination or evidence of corona could be found. General construction was good. Voltage and current charts show test conditions well within specifications.

Conclusion: Failure occurred due to dielectric breakdown with nothing in evidence that would have contributed to dielectric failure.

Photographs:	Date Analysis Performed:	Analysis Performed By:
14A & 14B	4/1/70	Richard R. Bailey

See Figure #46 in report.

FAILURE ANALYSIS NO. 16

Serial 45XA01 Design A-3

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	8/21/69	Date Removed:	9/17/69
Elapsed Time Reading:	760 Hours	Life Operating Hours:	760 Hours
Capacitance:	0.25	AC Voltage:	198 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	0.244	0.16	510K megohms	2,600K megohms
@ Test Temperature	0.246	0.07	100- " "	100K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External, good. Internal, solder did not run down between eyelet rim and can on one end.

Results of Analysis: Failure occurred with 8" of the start of the winding. The winding had collapsed into the mandrel hole, creating a sharp crease in the dielectric for the full width of the dielectric. Photograph #16A shows the blackened area of failure and also the crease. Magnification is at 10 power. Recorders demonstrated normal equipment operation at time of failure.

Conclusion: The mechanical stresses due to the wrinkle contributed to weakening of the dielectric and eventual failure.

Photograph:	Date Analysis Performed:	Analysis Performed By:
16A	4/13/70	Richard R. Bailey

Refer to Figure No. 38 in Report.

FAILURE ANALYSIS NO. 22
Serial No. 42FA10 Design A-2

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	10/22/69	Date Removed:	10/29/69
Elapsed Time Reading:	1,950 Hours	Life Operating Hours:	1,950 Hours
Capacitance:	1.0 mfd.	Ac Voltage:	127 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	1.012 mfd.	0.15	125K megohms	10,000K megohms
@ Test Temperature	1.011 mfd.	0.23	7K megohms	105K megohms
1,000 hour reading	1.006 mfd.	0.27	11.5K megohms*	170K megohms*

* IR read at 1/2 rated VDC

Failure Indicating Mechanism: Current drop shown on recorder.

Physical Condition: External - good. Internal - Winding was well surrounded by black silicone compound.

Results of Analysis: Construction appeared to be very good. Failure occurred on the outer turn of the material at completion of the winding. The polycarbonate had become very flaky and had decomposed. After the outer turn had been removed, condition of the polycarbonate throughout the remainder of the winding was excellent. The current recorder indicates an abrupt failure. Photographs 22A and 22B show the flaky polycarbonate.

Conclusion: Failure was caused by contamination on the outer surface which resulted in chemical attack and decomposition of the outer layer of polycarbonate under conditions of time (1,950 hours) and temperature (125°C).

Photographs:	Date Analysis Performed:	Analysis Performed By:
22A & 22B	4/15/70	Richard R. Bailey

Refer to Figure #49 in report.

FAILURE ANALYSIS NO. 23

Serial No. 44XB08 Design B-1

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	10/23/69	Date Removed:	10/29/69
Elapsed Time Reading:	1,987.5 Hours	Life Operating Hours:	1,987.5 Hours
Capacitance:	1.0 mfd.	AC Voltage:	184 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ [illegible] C	0.994	0.12	200K megohms	110,000K megohms
@ Test Temperature	0.990	0.07	650- " "	60K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External, good. Internal, the white mylar adhesive tape used to insulate winding from metal tube had discolored to a blackish green. The mylar insulating end caps and the yellow sealing tape had also turned a blackish green.

Results of Analysis: Failure occurred near start of the winding and was due to dielectric puncture and fusion of layers together. The failure may have been caused by a small circular depression in the polycarbonate as a result of passing over a 1/32" drilled hole in the winding core. The core appeared smooth except that sometimes what starts out as a small indentation is amplified by the time several rotations of the mandrel and layers of material have been added.

Conclusion: Failure occurred due to stress caused by the small 1/32" hole drilled in the winding core. Future recommendations may be to eliminate the small 1/32" diameter holes from the core.

Photograph:	Date Analysis Performed:	Analysis Performed By:
23A	4/15/70	Richard R. Bailey

Refer to Figure #39 in Report.

FAILURE ANALYSIS NO. 25

Serial No. 45XA03 Design A-3

Type of Failure:	IR Short	Test Temperature:	125°C
Date Failure Occurred:	9/8/69	Date Removed:	9/10/69
Elapsed Time Reading:	998.9 Hours	Life Operating Hours:	998.9 Hours
Capacitance:	0.25 mfd.	AC Voltage:	198 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Terminal-to-Case
@ 25°C	0.246	0.14	700K megohms	4,800K megohms
@ Test Temperature	0.247	0.07	3.6K megohms	110K megohms

Failure Indicating Mechanism: IR Reading on Megohmmeter

Physical Condition: External good.

Results of Analysis: Small pinhole punctures were found with spots surrounding them indicating clearing had occurred. The clearing may have occurred during the ac test or previously during the manufacturing stage. One such pinhole is shown in photograph 25B. The pinhole which resulted in a short is shown in photograph 25A. Both photographs were at 22X magnification. The puncture shown in photo 25A illustrates inability of the part to clear itself due to insufficient energy of the insulation resistance measuring instrument. A voltage of 500VDC was applied between terminals. Due to several parts failing, the applied voltage for IR measurement was reduced by 50% on other capacitors. Pinholes may have existed in the raw material to begin with. The clearing process usually results in lowering of the insulation resistance.

Conclusion: Failure resulted at a weak point in the dielectric and energy of IR instrument was not sufficient to clear the fault.

Photographs:	Date Analysis Performed:	Analysis Performed By:
25A & 25B	1/14/70	Richard R. Bailey

See Figures #44 and #45 in report.

FAILURE ANALYSIS NO. 27
Serial No. 35XA01 Design A-3

Type of Failure:	IR Short	Test Temperature:	105°C
Date Failure Occurred:	9/7/69	Date Removed:	9/10/69
Elapsed Time Reading:	998.9 Hours	Life Operating Hours:	998.9 Hours
Capacitance:	0.25 mfd.	AC Voltage:	198 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	0.249 mfd.	0.15	475K megohms	3,600K megohms
@ Test Temperature	0.251 mfd.	0.08	1.2K megohms	1,000K megohms

Failure Indicating Mechanism: IR reading on megohmmeter

Physical Condition: External - Good. Internal - Solder joint between eyelet rim and tube was poor on one end. Lead termination to the end of the winding was good on each end. Outward appearance of the winding was good.

Results of Analysis: Several areas of puncture gave evidence of pinholes and associated clearing. One area had clusters of pinholes and clearing spots within a 3/4" diameter. Failure occurred while measuring IR during shutdown at the 1,000 hour interval. Measuring voltage was 500WVDC. Some contamination was found but not in the area of failure. Photograph 27A indicates contamination found. Photograph 27B indicates point of failure. Several other areas were very black but had successfully cleared. These were not photographed. Magnification of photographs 27A and 27B was 22½X.

Conclusions: Failure occurred when a pinpoint puncture occurred during IR measurement at 500 volts DC and sufficient energy was not available to clear the fault.

Photographs:	Date Analysis Performed:	Analysis Performed By:
27A & 27B	4/22/70	Richard R. Bailey

See Figure #48 in report.

FAILURE ANALYSIS NO. 35

Serial No. 47XA04 Design A-3

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	8/31/69	Date Removed:	9/17/69
Elapsed Time Reading:	992.9 Hours	Life Operating Hours:	992.9 Hours
Capacitance:	0.25 mfd.	AC Voltage:	311 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	0.249	0.15	525K megohms	3,400K megohms
@ Test Temperature	0.251	0.07	1.6K megohms	90K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External good. Internal: Solder seal between eyelet rim and tube did not flow well.

Results of Analysis: Failure occurred through the dielectric at about 2 feet from the beginning of the winding. Two layers of winding material (1 layer of metallized polycarbonate and 1 layer of plain polycarbonate) had been scratched or gouged at time of winding. A straight line mark existed on both layers for a distance of about 18 inches. The two layers were then separated and the scratch or gouge existed on both layers and the scratch lines were congruent. For this reason, it is certain that the damage to the dielectric was done by something on the winding machine. Photograph 35A was done at 45 power magnification and Photograph 35B was performed at 5-1/4 power magnification. Voltage and current recorder checks verified test conditions were correct.

Conclusion: Failure occurred from weakened dielectric due to the scratched and gouged surface on 2 layers of material.

Photographs:	Date Analysis Performed:	Analysis Performed By:
35A & 35B	1/13/70	Richard R. Bailey

Refer to Figure No. 41 in Report.

FAILURE ANALYSIS NO. 36

Serial No. 43XB06 Design B-1

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	11/19/69	Date Removed:	12/16/69
Elapsed Time Reading:	2,503.5 Hours	Life Operating Hours:	2,503.5 Hours
Capacitance:	1.0 mfd.	AC Voltage:	156 rms

Initial Electrical Measurement	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	1.000	0.13	190K megohms	140,000K megohms
@ Test Temperature	1.000	0.08	590- " "	80K megohms
Electrical Measurements				
@ 1,000 Hours	0.993	0.04	280- " "	47K megohms
@ 2,000 Hours	0.989	0.08	550- " "	30K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External: Metal near glass on eyelet was discolored, possibly due to impregnant. Tube outer surface was sticky. Internal: Seal between eyelet rim and tube was good on both ends. If there was a leak, it may have been due to metal bead on eyelet itself. There seemed to be quite a bit of liquid fill yet around surface of winding. The clear mylar end cap and white mylar insulating tape had turned black.

Results of Analysis: After removing the black (originally white) mylar insulating tape, a wine colored substance was found on surface of winding. This has been noticed previously and is being analyzed by TRWC Chemistry Lab. The lead termination was good on one end of the winding and poor on the other end. Evidence of the failure was found at about 8 feet from start of winding. Material was badly burnt and layers were fused together as shown in photograph #36A. It is believed that a stress on the material as it was rolled tight over a 1/32" oil circulating hole drilled in the winding core may have contributed to failure. Photograph #36B illustrates the winding core with some fused winding material down in oil circulating hole. Voltage and current recorder charts verified that generator and current were normal at time of failure. The specification for winding the capacitor, Spec. No. 20A06176 specified in Para. 9.2 that a padding should be used at start of winding between first two sheets and last two sheets. No evidence of this padding could be found.

Conclusion: Failure occurred as a result of dielectric breakdown might have been avoided if padding had been used according to the manufacturing specification.

Photographs:	Date Analysis Performed:	Analysis Performed By:
36A & 36B	4/27/70	Richard R. Bailey

Refer to Figure #40 in Report.

FAILURE ANALYSIS NO. 41

Serial No. 42XB06 Design B-1

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	1/25/70	Date Removed:	2/6/70
Elapsed Time Reading:	3,954 Hours	Life Operating Hours:	3,954 Hours
Capacitance:	1.0 mfd.	AC Voltage:	127 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	1.008	0.12	180K megohms	100,000K megohms
@ Test Temperature	1.005	0.08	530- " "	90K megohms
Electrical Measurements				
@ 1,000 Hours	0.998	0.03	210- " "	105K megohms
@ 2,000 Hours	0.994	0.13	440- " "	59K megohms
@ 3,000 Hours	0.985	2.38	450- " "	62K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External - Good. Internal - The white mylar insulating tape had turned a blackish green as well as the clear mylar insulating end caps.

Results of Analysis: It was noticed that dissipation factor was recorded at 2.38% at the 3,000 hour interval and only 0.13% at the 2,000 hour level. When the capacitor was dismantled, some evidence of arcing was visible under the lead-head to winding termination. This is shown in photograph #41A at 6X magnification. In unwinding the capacitor, a dielectric puncture was found within about 1/4" from the poorly terminated end of the winding. Material layers were fused together from the beginning at the winding core for about 9 feet of insert length. Recorders verify proper equipment operation at time of failure.

Conclusions: Increased heating due to higher dissipation factor caused by the problem on one end at termination apparently affected strength of dielectric and consequently resulted in dielectric failure.

Photographs:	Date Analysis Performed:	Analysis Performed By:
41A & 41B	5/6/70	Richard R. Bailey

Refer to Figure #24 in Report.

FAILURE ANALYSIS NO. 42

Serial No. 43XA02 Design A-1

Type of Failure:	Short	Test Temperature:	125°C
Date Failure Occurred:	2/21/70	Date Removed:	4/20/70
Elapsed Time Reading:	4,355 Hours	Life Operating Hours:	4,355 Hours
Capacitance:	1.0 mfd.	AC Voltage:	156 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	1.043	0.09	180K megohms	4,000K megohms
@ Test Temperature	1.047	0.10	170- " "	530- " "
Electrical Measurements				
@ 1,000 Hours	1.041	0.31	85- " "	72K megohms
@ 2,000 Hours	1.033	0.52	160- " "	210K megohms
@ 3,000 Hours	1.001	0.75	37- " "	160K megohms
@ 4,000 Hours	0.967	1.20	5.7- " "	160K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External - A brown compound was found on each end, believed to be baked-on impregnant. Internal - The black silicone rubber-like compound had apparently been burnt since flakes of a grayish brown (originally black) compound existed.

Results of Analysis: The outer layer of dielectric material fell off the winding. A puncture centered between ends of the winding was noticed. Photograph #42A shows one eyelet which had been lifted from end of can before starting failure analysis. There was no evidence of any impregnant left inside the tube or winding and evidence on both external ends of the tube that impregnant had been forced out. As the winding was being unwound, a brown residue was noticed spotted throughout the winding and was determined as residue from the baked out impregnant. Some of these spots on damaged winding are visible in photograph #42B. Review of the test data revealed a continual lowering of the capacitance with time, an increase in DF to 1.20% at the 4,000 hour interval, and a decrease with time of terminal-to-terminal IR.

Conclusion: Loss of impregnant and ever increasing DF contributed to eventual dielectric failure.

Photographs:	Date Analysis Performed:	Analysis Performed By:
42A & 42B	5/7/70	Richard R. Bailey

Refer to Figure #36 in Report.

FAILURE ANALYSIS NO. 46
Serial No. 41FA12 Design A-2

Type of Failure:	DF	Test Temperature:	125°C
Date Failure Occurred:	1/29/70	Date Removed:	4/20/70
Elapsed Time Reading:	5,000 Hours	Life Operating Hours:	5,000 Hours
Capacitance:	1.0 mfd.	AC Voltage:	99 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	1.012	0.14	130K megohms	9,200K megohms
@ Test Temperature	1.003	0.20	6.5K megohms	82K megohms
Electrical Measurements				
@ 1,000 Hours	1.003	0.25	10K megohms	47K megohms
@ 2,000 Hours	1.001	0.30	5.6K megohms	38K megohms
@ 3,000 Hours	1.002	0.29	4.7K megohms	45K megohms
@ 4,000 Hours	1.003	0.50	4K megohms	43K megohms
@ 5,000 Hours		> 10.0	4.5K megohms	58K megohms
Final at 25°C		> 10.0	130K " "	2,900K megohms

Failure Indicating Mechanism: Capacitance Bridge

Physical Condition: External, good except for solder joints around the leads.

Results of Analysis: Seal test shows very little if any leakage. X-rays reveal one bad termination. When tube was removed from eyelet, the termination fell off. The lead head was completely oxidized and looked somewhat charred resulting from a poor solder joint between the lead head and the swedging. Lead head was burned into the swedging as shown in photograph 46A. The opposite lead head came loose easily. It was oxidized and charred but some small bright spots on the swedging where the head was soldered indicated it was making contact. A special jig was used to measure capacitance and dissipation factor of the winding without the leads attached. The capacitance measured 1.001 uf and the DF .12%.

Conclusion: Bad termination resulting from cold solder joints caused oxidation and burning of the lead head which eventually led to DF failure. Photograph 46A shows the oxidation and charring on the swedging.

Photograph:	Date Analysis Performed:	Analysis Performed By:
46A	6/4/70	Kay Waterman

Refer to Figure No. 32 in Report.

FAILURE ANALYSIS NO. 48

Serial No. 42XA03 Design A-1

Type of Failure:	DF	Test Temperature:	125°C
Date Failure Occurred:	1/29/70	Date Removed:	4/20/70
Elapsed Time Reading:	5,000 Hours	Life Operating Hours:	5,000 Hours
Capacitance:	1.0 mfd.	AC Voltage:	127 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance Terminal-to-Terminal	Insulation Resistance Terminal-to-Case
@ 25°C	1.009	0.09	300K megohms	40,000K megohms
@ Test Temperature	1.023	0.07	3.2K megohms	320K megohms
Electrical Measurements				
@ 1,000 Hours	1.023	0.03	49K megohms	370K megohms
@ 2,000 Hours	1.020	0.11	6.2K megohms	310K megohms
@ 3,000 Hours	1.021	0.36	26K megohms	300K megohms
@ 4,000 Hours	1.023	3.01	48K megohms	400K megohms
@ 5,000 Hours		$>$10.0	1K megohms	380K megohms
Final @ 25°C	Open	Open	380K megohms	90,000K megohms

Failure Indicating Mechanism: Capacitance Bridge

Physical Condition: External - Leads are corroded. Some solder buildup on one eyelet seal. Internal - Solder joint between eyelet rim on one end and case was poor in that solder built up externally on eyelet but did not run into joint. The insulating cap between end of winding and eyelet at end of can was brittle on both ends. Termination on one end pulled off easily, taking the schooping along with it. The schooping (metal end spray) and end of winding appeared to be charred and oxidized.

Results of Analysis: Though bond between lead head to schooping (metal end spray) was good, the adhesion between schooping (metal end spray) and the metallized plates of the winding was poor resulting in a heating effect which in time destroyed the contact area completely. Evidence of the ever increasing DF with time is found in reviewing electrical measurements at the 1,000 hour intervals.

Conclusion: Insufficient contact area between the schooping and winding caused this DF failure. Contributing to the failure was oxidation due to the presence of air because of the seal leakage.

Photograph:	Date Analysis Performed:	Analysis Performed By:
48A	6/4/70	Kay Waterman

Refer To Figure # 28 In Report.

REFERENCE

1. Dysart, W. C.: The Determination of Voltage and Temperature Values for Polycarbonate AC Life Tests. NASA Contractor Report No. NASA CR-72297 (July 26, 1967).

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