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Improvement Program
for
Polycarbonate Capacitors
by

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TRW Capacitors



prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

Capacitors employing polycarbonate film as dielectric have characteristics such as stability, low dissipation factor, and a potential temperature capability of 125°C which make them desirable for use in aerospace ac power applications. Since little data was available for 400 Hz ac applications, an earlier contract (NAS3-11834) was issued to TRW Capacitors to conduct a failure-forcing 5000 hour, 400 Hz life test on polycarbonate capacitors of several designs, determine causes of failure, and recommend design improvements.

The goals of the program of this contract (NAS3-15688) were to verify the adequacy of the design improvements recommended under NAS3-11834, and provide additional life-test data. The approach used to satisfy this objective was experimental. Polycarbonate capacitor samples in two voltage ratings and both metallized and film-foil construction were designed, using the recommendations of NAS3-11834, to aerospace requirements and built. They were subjected to 400 hertz, sine-wave life tests at conditions selected to stress them at, below, and above design point conditions. Approximately 334 polycarbonate capacitors were tested at constant ac voltage and temperature conditions for 5000 hours.

Since the important result of the polycarbonate tests was the verification of improved capacitor designs, approximately half of the total number of capacitors were tested at design voltage and temperature. No temperature above 125°C was used for the polycarbonate capacitors because previous work had shown that 125°C is the maximum reasonable case temperature for this type of capacitor.

The improvements incorporated in the capacitors designed for this contract eliminated the major cause of failure found in the preceding work, termination failure. However, a failure cause not present in the previous test became significant in this test with capacitors built from one lot of polycarbonate film. This particular lot was a metallized type and was used in two of the eight designs. Analyses of failed samples showed that the film had an excessive solvent content. It is postulated that under the test conditions, the solvent outgassed, creating pockets of trapped gas in the capacitor winding. These gas pockets would be sites for corona which, in turn, would cause deterioration of the dielectric and failure. This solvent problem was found in 37 of the total 46 failures which occurred in this test. The other nine were random failures resulting from causes such as seal leaks, foreign particles, and possibly wrinkles.

Considering only the samples tested at rated voltage and temperature and not including the two designs built with the above described film, a total of approximately 718,000 unit hours were accumulated with 4 failures.

These results demonstrate the adequacy of the design improvements.

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.

An earlier study under Contract NAS3-11834 was conducted by TRW Capacitors for the purpose of improving the rating determination and design of wound ac polycarbonate capacitors. In that study, ac polycarbonate capacitors were designed, and built in two ratings (1.0 uF 200 Volts ac peak; and 0.25uF, 400 Volts ac peak) and two types (metallized polycarbonate film and film-with-foil) by two manufacturers. These capacitors were hermetically sealed in metallic cases. Representative samples were subjected to a 5000-hour ac life test designed to force failures in some samples as well as allow easy completion of the test by others. Analysis of life test results and failed samples led to recommendations for design improvements and improved rating determination. The results of this earlier study are reported in NASA report CR-1897 dated August 1971.

The study reported herein was performed under contract NAS3-15688 to verify the adequacy of the design improvements recommended in the earlier study and to determine preliminary failure rates. Both metallized film and film-with-foil type polycarbonate ac capacitors were designed and built by TRW Capacitors in accordance with those recommendations. The same ratings (1.0 uF 200 Volts peak and 0.25uF, 400 Volts peak) were used. All of the capacitors were metal encased and hermetically sealed. For each rating/type combination, half of those built were impregnated and liquid filled with silicone oil and the other half with polybutene. This resulted in eight different designs.

Forty-eight samples of each design (384 total) were subjected to a 5000-hour life test at various temperature and voltage conditions. Half of the total number were tested at rated conditions to determine preliminary failure rates.

The results of this program should allow the design of high reliability ac polycarbonate capacitors which make effective use of the temperature capability of the dielectric material. Design features used in the test samples should also be of benefit to ac capacitors with other dielectric films.

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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 pinhole short is sufficient to vaporize the metallized film around the pinhole 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 sinewave 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 $DF \times 100$.

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 the axial ends of windings 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

The capacitors provided for this study were all designed and built by TRW Capacitors to the specification given in Appendix A. The design and process improvements recommended as a result of the previous contract were incorporated in these capacitors. Tables I and II give their general ratings and dimensions.

TABLE I
CAPACITOR DESIGN DESCRIPTION

Design	400Hz AC Peak ^(a) Voltage Rating (Volts)	Cap. uF	±5%	Rated DC Voltage	Construction	(b) Impregnant & Liquid Fill
NASX-1P	200	1.0	±5%	400	Metallized Polycarbonate	Polybutene
NASX-1S	200	1.0	±5%	400	Metallized Polycarbonate	Silicone Oil
NASX-2P	200	1.0	±5%	300	Polycarbonate Film/Aluminum Foil	Polybutene
NASX-2S	200	1.0	±5%	300	Polycarbonate Film/Aluminum Foil	Silicone Oil
NASX-3P	400	0.25	±5%	600	Metallized Polycarbonate	Polybutene
NASX-3S	400	0.25	±5%	600	Metallized Polycarbonate	Silicone Oil
NASX-4P	400	0.25	±5%	600	Polycarbonate Film/Aluminum Foil	Polybutene
NASX-4S	400	0.25	±5%	600	Polycarbonate Film/Aluminum Foil	Silicone Oil

^(a) Zero-to-peak voltage.

^(b) Impregnant is the material used for filling all air voids in the winding itself. Liquid fill refers to the liquid which fills the space between the winding and the outer metal encasement.

TABLE II

PHYSICAL DIMENSIONS OF CAPACITORS TESTED

Design	Outside Body Dimensions		Winding Dimensions	
	Diameter	Length	Diameter	Length
NASX-1P	2.54cm (1.0 in.)	5.41cm (2.13 in.)	2.18cm (.86 in.)	4.16cm (1.64 in.)
NASX-1S	"	"	"	"
NASX-2P	2.54cm (1.0 in.)	7.00cm (2.75 in.)	2.14cm (.84 in.)	6.03cm (2.37 in.)
NASX-2S	"	"	"	"
NASX-3P	2.54cm (1.0 in.)	5.41cm (2.13 in.)	1.98cm (.78 in.)	4.16cm (1.64 in.)
NASX-3S	"	"	"	"
NASX-4P	2.54cm (1.0 in.)	5.74cm (2.26 in.)	2.22cm (.87 in.)	4.84cm (1.91 in.)
NASX-4S	"	"	"	"

All capacitors were hermetically sealed in tin-plated brass cases. Lot history and traceability records were kept through the manufacturing process. The design life goal was 50,000 hours at rated peak 400Hz voltage at 125°C with 95% survival. Capacitor grade polycarbonate film in both metallized and plain film was used. Since polybutene and silicone oil were tested in the first study but not on identical designs, these 2 impregnants were evaluated within this study by their use in identical designs.

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 a certain dielectric thickness and one sheet of another thickness dielectric or 2 sheets of dielectric of a specific 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 NASX-1P utilized 1 sheet of .0061 mm (.00024") thick and 1 sheet of .0102 mm (.00040") thick aluminum metallized polycarbonate as dielectric having a width of 3.81 cm (1 1/2 inches). A total of 2 sheets of .0061 mm and 2 sheets of .0102 mm metallized polycarbonate were used in the winding. The winding was wound on a hollow ceramic core of 96% alumina selected for good heat conductivity but good electrical insulation resistance. The core did not have holes at right angles to the core axis like the cores used in the first study. Two or three turns of plain dielectric padding were used around the core before starting the winding materials and then padding was inserted again about 1 turn prior to finish of the winding before the materials were cut to protect from possible shorting across the cut edge. The windings were then sealed with tape. Winding ends were sprayed with metal and the 18 gage (.102 cm diameter) tin-coated copper leads with a .953 cm (3/8 inch) diameter lead head were then soldered to the sprayed ends of the windings. The lead shank was then protected while additional metal was sprayed over the top of the lead head to improve the contact between the lead head and metallized plates. A narrow strip 1.6 mm (1/16 inch) wide was masked off across the diameter of the winding to allow good penetration of impregnant. Margins of the winding were .317 cm (1/8 inch). 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. This technique increases by a factor of 2 the effective thickness of the conducting plate as a benefit for carrying currents associated with ac operation. A patent has been issued for this design technique. This design used polybutene as an impregnant and liquid fill.

Design NASX-1S is identical to NASX-1P except that silicone oil was used as impregnant and liquid fill.

Design NASX-2P consisted of 1 layer of plain polycarbonate 5.72 cm (2 1/4") wide of .0061 mm (.00024") thickness and 1 of .0102 mm (.00040") thickness along with aluminum foil which was .0063 mm (.00025") thick. A total of 2 polycarbonate sheets each .0061 mm thick, 2 sheets of polycarbonate each .0102 mm thick, and 2 aluminum foils each .0063 mm thick made up the winding. The winding was wound on a core as described for design NASX-1P. Padding of plain dielectric film was placed around the core and at the finish of the winding. The terminations consisted of 18 gage (.102 cm) tin coated copper leads with a .953 cm (3/8") diameter lead head soldered to a screen-type metal contact washer which was soldered to the extended foil edges. Several openings through the screen washer were kept free of solder to permit penetration of impregnant into the winding. Margins were .317 cm (1/8") and the impregnant and liquid fill material was polybutene.

Design NASX-2S is identical to NASX-2P except that silicone oil was used as impregnant and liquid fill.

Design NASX-3P was built utilizing 2 layers of .0127 mm (.00050") thick metallized polycarbonate as dielectric or a total of 4 sheets of this dielectric within the winding. The back-to-back assembly technique as described for design NASX-1P was utilized. The dielectric width was 3.81 cm (1 1/2 inch). The winding material was wound on a hollow ceramic core of 96% alumina. Margins were .317 cm (1/8 inch) and polybutene was used as the impregnant and liquid fill. The same leads and attachment procedure as described for design NASX-1P were used.

Design NASX-3S is identical to design NASX-3P except that silicone oil was used as impregnant and liquid fill.

Design NASX-4P utilized 3 sheets of plain polycarbonate film as dielectric with each sheet having a thickness of .0102 mm (.00040") and a width of 4.44 cm (1 3/4 inch). Aluminum foil .0063 mm (.00025 inch) thick was used as the plate material. A total of 6 sheets of polycarbonate film and 2 aluminum foil plates made up the winding. The winding was wound on a hollow ceramic core as described for the other designs. Margins were .317 cm (1/8") and termination technique was the same as for design NASX-2P. Polybutene was used as impregnant and liquid fill.

Design NASX-4S is identical to design NASX-4P except that silicone oil was used as impregnant and liquid fill.

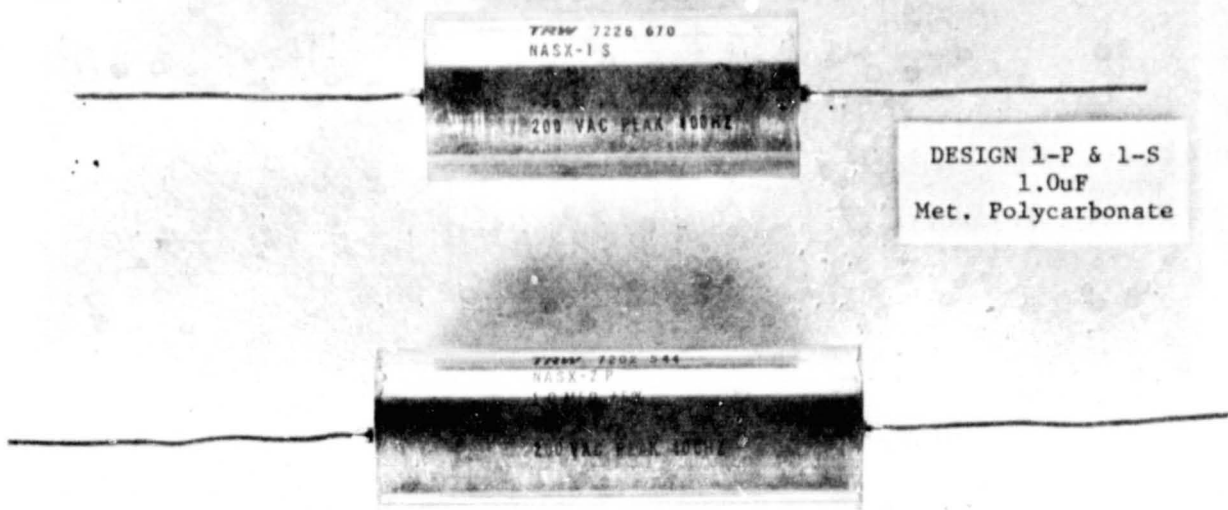
Mylar washers and endcaps were used to insulate the winding ends of all designs from the metal encasement and several turns of plain polycarbonate sheet were used to insulate the cylindrical surface of the winding from the metal encasement.

Improvements incorporated into these test capacitors as a result of recommendations from the previous contract study included the following:

- (a) The terminations were changed on the metallized capacitors with double scooping replacing the screen washer.
- (b) The ceramic cores were redesigned, eliminating the 1/32" diameter holes. The material of the core was changed to a 96% alumina ceramic which improved thermal conductivity.
- (c) An effort was made to improve eyelet rim solder seals to the metal tube through use of bright tin plated tubes and by taking more time with the hand soldering operation. Some improvement was realized.
- (d) Wrinkles were minimized through elimination of the 1/32" diameter holes through use of padding and by using the best trained winding personnel with wrinkle removing devices on the winding machine.

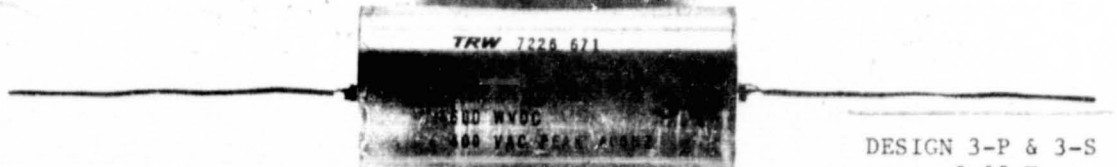
- (e) Specifications for raw material required preclearing of metallized dielectrics.
- (f) The impregnation and liquid fill process included additional time to remove air and moisture from the impregnant and longer soak time. This effort was to minimize corona.

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



DESIGN 1-P & 1-S
1.0uF
Met. Polycarbonate

DESIGN 2-P & 2-S
1.0uF
Polycarbonate Film with Foil



DESIGN 3-P & 3-S
0.25uF
Met. Polycarbonate



DESIGN 4-P & 4-S
0.25uF
Polycarbonate Film with Foil

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FIGURE 1. Representative Samples of All Test Capacitor Designs

TEST PROCEDURE

The manufactured capacitors prior to submission for final acceptance testing were subjected to a DC burn-in at 140% of rated DC voltage for 100 hours at 125°C and an AC burn-in at 400Hz sinewave using 1.25% of AC peak rated voltage at 125°C for 250 hours. This was followed by testing of electrical characteristics along with a DC dielectric strength test at 2-1/2 times rated DC voltage and an AC dielectric strength test at ambient temperature using 1-1/2 times peak AC rated voltage at 400Hz.

All samples which satisfactorily completed the above process were then subjected to a final acceptance inspection. They were examined visually for physical dimensions, marking, and workmanship. A hermetic seal test was performed to Method 112a of Mil-Std-202, Condition C, Procedure IIIa. The leak rate was not to exceed 1×10^{-8} atm cc/sec. Electrical measurements were taken of capacitance, dissipation factor, insulation resistance from terminal-to-terminal and terminal-to-case, and dielectric strength to DC and AC voltages. Corona onset voltage was checked to make sure it did not exist at AC voltage levels up to 110% of rated peak voltage.

Of each design, 48 acceptable samples were scheduled and serialized to go into the 5000-hour AC life test. An additional 7 acceptable capacitors of each design were serialized with a different type serial number and kept as replacements for the regular test capacitors. Purpose of the replacement test capacitors was to develop additional unit hours of test data for failure rate calculations. When a regular test capacitor failed, it was replaced at the subsequent 1000-hour measurement interval in which the generators were shut down.

Equipment used for acceptance testing prior to conduct of the life test is outlined below.

Capacitance (C) and Dissipation Factor (DF)	Micro Instrument Digital Readout Bridge Model 5320D, for 400Hz (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 Serial #1162-13. Includes timing devices and short indicators.

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Dielectric
Strength (AC)

Kato Engineering Co. Motor Generators, Serial numbers 64025-1 and 64025-2. The generators develop 400Hz sinewave voltages. A Fluke Voltmeter Model 931P was used to monitor voltage level.

Corona

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

Physical Dimensions Micrometer, Caliper and rule.

Upon completion of final acceptance testing, capacitors were placed into test trays in 3 different ovens for conduct of the life test. One oven (#1) operated at 110°C. Two ovens (#2 and #3) operated at 125°C. Metal body clamps riveted to metal heat sink bars held each capacitor metal case so that case temperatures of the capacitors would be maintained at the oven ambient temperature. Thermocouples were cemented to 1 capacitor in each test tray to permit continuous recording of capacitor case temperature. See Figure 2 which illustrates a typical test tray. Each oven consisted of 8 trays of 16 test positions per tray. On any particular test tray, there were 4 metallized polycarbonate film and 4 film-with-foil capacitors with polybutene impregnant, and 4 metallized film and 4 film-with-foil capacitors with silicone oil impregnant. The 16 capacitors on any particular tray were all 1.0 uF units or all 0.25 uF units. A test tray of 16 capacitors is referred to as one test group. For each capacitance value, the outline of test voltages and temperatures is given in Table III.

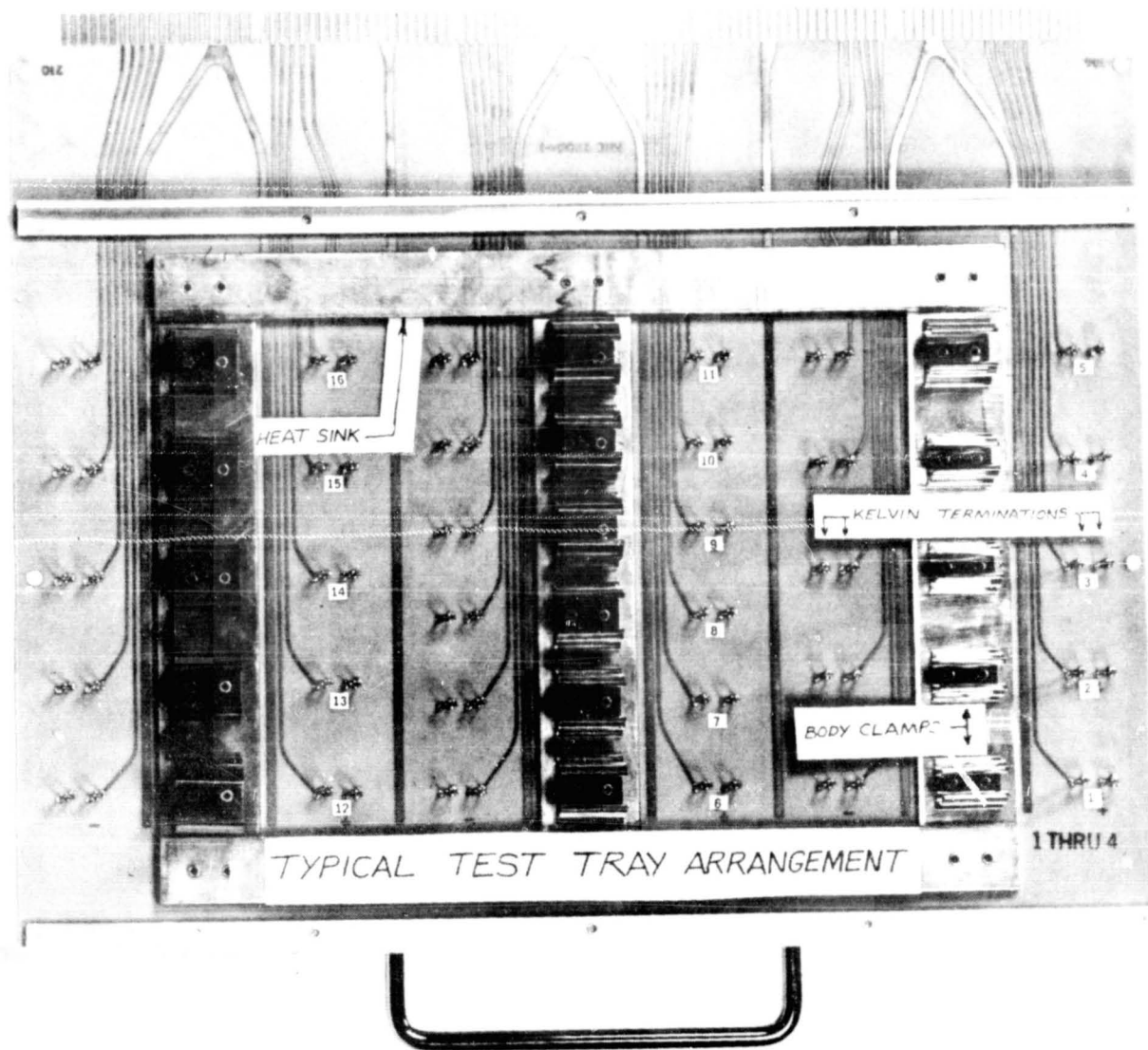


FIGURE 2. Typical Printed Circuit Type Test Tray Illustrating Heat Sinks and Body Clamps for Aid in Control of Capacitor Case Temperature

TABLE III
 OUTLINE OF TEST CONDITIONS BY TEMPERATURE
 AND VOLTAGE FOR EACH CAPACITANCE VALUE

Case Temperature	Peak Voltage 400Hz Sinewave (Percent of Rated)		
	70	100	130
110°C	One (1) Group	Two (2) Groups	One (1) Group
125°C	One (1) Group	Six (6) Groups	One (1) Group

There were a total of 12 groups tested (192 capacitors) for each nominal capacitance value. For the 1.0 uF designs, the 70%, 100%, 130% of rated voltage represents 99, 141, 184 volts rms respectively. For the 0.25 uF designs, the 70%, 100%, and 130% of rated represents 198, 283, and 368 volts rms respectively.

With both 0.25 uF and 1.0 uF capacitors tested, a total of 24 groups or 384 original test capacitors were involved. Another 56 capacitors were kept as replacement units for use when needed.

For the life test, case temperatures were maintained within $\pm 3^{\circ}\text{C}$ of specified test temperature, voltages within $\pm 2\%$ of specified levels, and total voltage harmonics did not exceed 3%. One oven (Oven #2) which was set at 125°C overheated on 2 occasions; once during initial measurement and again at the 942 hour interval. The cause was a faulty controller. The first time it overheated, the technician detected it by lowering of IR and the second time, the oven temperature control set at 135°C shut the oven down.

After the test capacitors were placed into the oven and had reached specified test temperature, initial measurements were taken of capacitance, dissipation factor, and insulation resistance, and the data recorded. The life test was then started and measurements were repeated at test temperature at 1000-hour intervals until completion of the 5000-hour test, including the 5000-hour point.

At the end of the 5000-hour test, the capacitors were returned to room ambient temperature and electrical measurements were recorded along with a repeat of the hermetic seal test and the corona test. The same instruments used for final inspection were used for measurements during and after the life test.

Failure analysis was conducted on the capacitors which shorted during the test. There were no opens. Photographs were taken of many of the failures, but not on all since the same failure mode was found in some and repeated photographs would have been redundant.

In addition to temperature recorders which monitored capacitor case temperature, voltage recorders of 8 channel, scanning, strip chart type were used to monitor voltages to all test groups. Current recorders of the continuous strip-chart type were used to monitor current to each test group and to indicate when a short or open occurred.

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 ignited for visual indication when a capacitor shorted and the fuse opened.

A portable power plant was provided and arranged so that if there had been a commercial power failure, a transfer switch would have automatically provided power from the portable power plant to the ovens to keep the temperature at the proper level. The power plant would also have provided power to the chart drives of the voltage, current and temperature recorders.

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 numbers 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, 3.75 KVA, Model 3EX9W.
Motor Generators	Kato Engineering, 6.25 KVA, Model 5EX9W.

RESULTS AND DISCUSSION

Initial Measurements

Initial room temperature electrical measurements for the eight designs tested are tabulated in Table IV. The average of all samples for each design is used. The average of capacitance, % DF, and terminal-to-terminal insulation resistance were comparable between similar designs such as 1P and 1S or 3P and 3S.

Capacitance was well within the $\pm 5\%$ tolerance specified, dissipation factor was well below the 0.30% maximum specified for metallized polycarbonate designs and well below the 0.25% maximum specified for polycarbonate film-aluminum foil designs. It was noticed that the dissipation factor for designs 3P and 3S were slightly higher than for all other designs, though well within tolerance. The terminal-to-terminal insulation resistance was well above the 150K megohms specified for film/foil or the 200K megohms specified for the metallized polycarbonate. There was considerable difference between the terminal-to-case insulation resistance of those designs liquid filled with silicone oil and those liquid filled with polybutene with the IR of the silicone oil filled parts being the lower.

Since the physical construction was the same for similar designs such as 1P and 1S, this reflects a comparatively lower insulation resistance of the silicone oil that was used, though the requirement that terminal-to-case IR be greater or equal to terminal-to-terminal IR was easily met. This followed the same pattern established for this particular measurement on the first study under contract NAS3-11834.

The corona test at 110% of peak rated voltage resulted in no detection of corona at that level on any of the capacitors submitted. The hermetic seal test with the requirement of no leaks greater than 1×10^{-8} atm cc/sec. resulted in a few capacitors of each design being rejected from their respective lot. All capacitors accepted for the life test met the requirement.

TABLE IV

INITIAL ROOM TEMPERATURE ELECTRICAL PARAMETER COMPARISONS

DESIGNS	AVERAGE %DF (a)	AVERAGE IR T-T (b) (Megohms)	AVERAGE IR T-C (c) (Megohms)	AVERAGE CAPACITANCE uF
1.0uF, Metallized Polycarbonate with Polybutene	.09	370K	62,527K	1.008
1.0uF, Metallized Polycarbonate with Silicone Oil	.10	343K	3,276K	1.003
1.0uF, Polycarbonate Film - Aluminum Foil - Polybutene	.07	433K	60,873K	1.002
1.0uF, Polycarbonate Film - Aluminum Foil - Silicone Oil	.08	271K	1,955K	1.004
0.25uF, Metallized Polycarbonate with Polybutene	.13	1279K	128,127K	.255
0.25uF, Metallized Polycarbonate with Silicone Oil	.15	1137K	3,101K	.254
0.25uF, Polycarbonate Film - Aluminum Foil - Polybutene	.08	1351K	77,345K	.257
0.25uF, Polycarbonate Film - Aluminum Foil - Silicone Oil	.08	769K	1,082K	.254

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

Temperature and Voltage Effects

The effect of temperature and voltage on performance of the capacitors is summarized in Tables V, VI, and VII. It should be kept in mind that twice as many original test parts were tested at 125°C as at 110°C. Some replacements were put into test.

The 125°C temperature exerted a small additional influence on catastrophic failures when comparing results to the performance at 110°C. A particular failure mode was evident in both designs 3P and 3S in which the lower temperature did not help too much on design 3P but did help some on design 3S.

When reviewing the effect of voltage on capacitor performance, there was only 1 failure on 1 design (design 3S) at 70% of rated voltage. On comparison of 100% versus 130% of rated voltage and keeping in mind that six times more capacitors were tested at 100% rated than 130% of rated voltage, the percent failure increases generally as expected as voltage goes up. This is particularly noticeable for designs 3P and 3S at 125°C and for good reason when the failure mechanism of those designs is understood as described later in this section.

TABLE V
 OUTLINE BY DESIGN
 OF
 QUANTITY TESTED & QUANTITY FAILED *

	TEMPERATURE							
	110 ° C				125 ° C			
	Original Test Parts		Replacement Test Parts		Original Test Parts		Replacement Test Parts	
	Quantity Tested	Quantity Failed	Quantity Tested	Quantity Failed	Quantity Tested	Quantity Failed	Quantity Tested	Quantity Failed
DESIGN 1P 1.0uF								
Met. Polycarbonate - Polybutene								
70% Rated Voltage (99 VRMS)	4	0	--	--	4	0	--	--
100% Rated Voltage (141 VRMS)	8	0	--	--	24	0	--	--
130% Rated Voltage (184 VRMS)	4	0	--	--	4	1	1	0
DESIGN 1S 1.0uF								
Met. Polycarbonate - Silicone Oil								
70% Rated Voltage (99 VRMS)	4	0	--	--	4	0	--	--
100% Rated Voltage (141 VRMS)	8	0	--	--	24	1	1	0
130% Rated Voltage (184 VRMS)	4	0	--	--	4	1	1	0
DESIGN 2P 1.0uF								
Polycarb. Film/Foil - Polybutene								
70% Rated Voltage (99 VRMS)	4	0	--	--	4	0	--	--
100% Rated Voltage (141 VRMS)	8	0	--	--	24	2	2	0
130% Rated Voltage (184 VRMS)	4	1	1	0	4	0	--	--
DESIGN 2S 1.0uF								
Polycarb. Film/Foil - Silicone Oil								
70% Rated Voltage (99 VRMS)	4	0	--	--	4	0	--	--
100% Rated Voltage (141 VRMS)	8	0	--	--	24	1	1	0
130% Rated Voltage (184 VRMS)	4	0	--	--	4	1	1	0
DESIGN 3P 0.25uF								
Met. Polycarbonate - Polybutene								
70% Rated Voltage (198 VRMS)	4	0	--	--	4	0	--	--
100% Rated Voltage (283 VRMS)	8	4	4	0	24	5	3	1
130% Rated Voltage (368 VRMS)	4	3	2	2	4	3	2	1
DESIGN 3S 0.25uF								
Met. Polycarbonate - Silicone Oil								
70% Rated Voltage (198 VRMS)	4	0	--	--	4	1	--	--
100% Rated Voltage (283 VRMS)	8	0	--	--	24	9	3	0
130% Rated Voltage (368 VRMS)	4	1	--	--	4	4	4	3
DESIGN 4P 0.25uF								
Polycarb. Film/Foil - Polybutene								
70% Rated Voltage (198 VRMS)	4	0	--	--	4	0	--	--
100% Rated Voltage (283 VRMS)	8	0	--	--	24	0	--	--
130% Rated Voltage (368 VRMS)	4	0	--	--	4	1	--	--
DESIGN 4S 0.25uF								
Polycarb. Film/Foil - Silicone Oil								
70% Rated Voltage (198 VRMS)	4	0	--	--	4	0	--	--
100% Rated Voltage (283 VRMS)	8	0	--	--	24	0	--	--
130% Rated Voltage (368 VRMS)	4	0	--	--	4	0	--	--

* Failures consist of catastrophic shorts during course of life test. There were no intermittents or opens.

Parameter Variations

The performance of the test capacitors as related to temperature and time is illustrated graphically in Figures 3 through 14. Each figure represents an average of the good parts of each design existing at the time intervals indicated.

The variation of capacitance with time and referred to as stability characteristics is shown in Figures 3 and 4 for 110°C and Figures 5 and 6 for 125°C.

Any one figure will specify a capacitance value and a legend provides identification of specific designs.

Plots of dissipation factor as a function of time show the effect of time on terminations, internal losses, and to some extent an effect of external lead oxidation. In cases where sometimes the DF would start increasing, it was discovered that movement of the lead up and down within the clip of the test tray would improve the lead to clip connection and the DF would return to a low value. The presentation of DF versus time for 1.0 uF and 0.25 uF at 110°C is shown respectively in Figures 7 and 8 and Figures 9 and 10 respectively for 125°C.

The terminal-to-terminal insulation resistance as a function of time for those tested at 110°C and 125°C is illustrated in Figures 11 through 14. Each graph is for one capacitance value but includes a curve for each design of that cap value. Insulation resistance is a quality measure of the dielectric and is affected by anything internally or externally which would increase leakage current between terminals of the capacitor.

Performance at 110°C

The stability of the 1.0 uF capacitors remained within an average of $\pm 0.25\%$ for the duration of the 5000-hour test with the polybutene impregnated parts in both metallized and film-foil designs completing the test within an average of 0.1% of the initial capacitance measurement. See Figure 3. The greatest excursion of capacitance change went from -0.40% to $+0.50\%$. The stability of the 0.25 uF ranged between $+0.24\%$ and -0.5% for the duration of the test. See Figure 4. The greatest excursion of capacitance change considering individual capacitors of the four 0.25 uF designs went from -0.80% to $+0.40\%$. Due to the larger quantity of failures in the 0.25 uF metallized designs, a clearing action is believed responsible for the slightly greater negative shift.

The dissipation factor averages at 110°C are illustrated in Figures 7 and 8 for the 1.0 uF and 0.25 uF capacitors respectively. The dissipation factor for the 1.0 uF ranged from a low of 0.03% to a high of 0.14% and for the 0.25 uF ranged from a low of .02% to a high of 0.37% on one capacitor. The original requirement that DF remain below 0.3%

for metallized polycarbonate (designs 1P, 1S, 3P, and 3S) and below 0.25% for the polycarbonate film with aluminum foil (designs 2P, 2S, 4P, and 4S) was easily accomplished except for the one metallized capacitor.

It can be noted on Figures 7 and 8 that the DF of the film-with-foil parts is lower than that of the metallized film, which is to be expected. The terminations remained excellent throughout the test as was evident on capacitors which were dismantled for other failure causes. A slight increase in DF of design 3P noted in Figure 8 could be attributed to a small increase in internal loss due to the outgassing and corona which was determined from analysis work. The improvement in termination technique as recommended in the previous study has been realized.

The terminal-to-terminal insulation resistance average values at 110°C are illustrated in Figures 11 and 12. It can be noted that for the 1.0 uF designs in Figure 11, the IR remained very consistent or increased slightly for the 1S and 2S designs which use silicone oil. For designs 1P and 2P, IR decreased some. The greatest individual capacitor excursion of IR for the 1.0 uF ranged from 0.4 megohms to 105 K megohms. The range of IR for individual 0.25 uF capacitors went from 6.5 megohms to a maximum of 430 K megohms. The variations of IR related to silicone oil versus polybutene were noted also in the 0.25 uF designs but to a greater degree. This is partly born out by the greater number of failures at 110°C in design 3P compared to 3S in which other failure mechanisms were at work. It indicates that silicone oil may be less affected by sustained heat for long hours and that polybutene may be deteriorating some.

Performance at 125°C

The stability of capacitors tested at 125°C is illustrated as averages in Figures 5 and 6 for the 1.0 uF and 0.25 uF designs respectively. The capacitance change remained within $\pm 0.25\%$ throughout the 5000-hour test for the 1.0 uF designs and ranged from +.25% to -.45% for the 0.25 uF designs. The greatest excursion of capacitance change on any individual capacitors of the 1.0 uF designs ranged from -.40% to +.49%. The outer limits of capacitance change of any of the individual 0.25 uF capacitors ranged from -.79% to +.40%. As an example, the 1 capacitor which shifted -.79% changed from .255 uF to .253 uF. The capacitor designs that did not remain within $\pm 0.25\%$ were the 0.25 uF metallized capacitors which experienced a number of failures. The failure mechanism caused some clearing which could have reduced the capacitance slightly.

The dissipation factors of capacitors tested at 125°C are presented graphically in Figures 9 and 10. The dissipation factor average remained at 0.1% or below, except for design 3S which peaked at .24% at 3000-hours and at .23% at 5000-hours. The average DF remained below the .3% initial requirement for the metallized designs and the .25% specified for the film-with-foil designs. There were several individual components on both the design 3P and 3S which went over the initial .3% DF requirement as the test progressed and this is indicative of increased internal dielectric losses due to the secondary effect of the failure mechanism prevalent in these 2 designs. The individual DF ranged from .01% to .51% for the 1.0 uF designs and from .01% to .95% for the 0.25 uF designs.

The average terminal-to-terminal insulation resistance is shown as a function of time at 125°C in Figures 13 and 14 for the 1.0 uF and 0.25 uF respectively. For the 1.0 uF design, the pattern was the same as at 110°C in which the silicone impregnated parts remained more constant. Total excursion of individual capacitor IR measurements for the 1.0 uF designs ranged from 53 megohms to 39 K megohms and for the 0.25 uF capacitors from 41 megohms to 135 K megohms. In the case of the 0.25 uF designs, there was a drop in IR in the film-foil designs 4P and 4S but only 1 failure occurred in one of these designs so the graphs illustrate by averages the trend of what happened. Because of the failures which occurred on designs 3P and 3S, the shape of the curve based on averages is affected by the ones that failed, however there was a trend for some of those parts remaining to increase in IR with time.

Summary of Failures

A summary of catastrophic failures is given below first at 110°C and then at 125°C. All failures were shorts.

Eleven (11) failures at 110°C consisted of the following:

One (1) capacitor, design 2P, failed after 875 operating hours at 184 volts rms. A wrinkle in the area of the failure plus an incomplete eyelet solder seal with some evidence of less than the normal amount of impregnant contributed to failure.

Nine (9) capacitors, design 3P, including 7 original test parts plus 2 replacement test parts failed with the cause of failure attributed to outgassing of solvents and subsequent corona due to ionization of the gaseous molecules.

One (1) capacitor, design 3S, shorted with failure attributed to the same problem described for design 3P above.

Thirty-five (35) failures at 125°C consisted of the following:

One (1) capacitor, design 1P, failed due to transients.

Two (2) capacitors, design 1S, failed because of seal leakage, loss of liquid fill and impregnant and drying out of winding.

Two (2) capacitors, design 2P, failed, both attributed to wrinkles with the possibility of weakened dielectric and excess oven heat (to 134°C) a contributing factor.

Two (2) capacitors, design 2S, with limited evidence as to what caused the failure except for a particle photographed in the material (several found within that winding) of one capacitor and the other failure attributed to weak dielectric and the short time at 134°C oven heat.

Ten (10) capacitors, design 3P, including 8 original test parts and 2 replacement test parts which failed due to solvent outgassing followed by initiation of corona or ionization of the gaseous molecules. This included 1 infantile failure which failed after 126 hours but with the same failure mechanism detected.

Seventeen (17) failures occurred in design 3S, consisting of 1 infantile failure after 8 hours in test thought due to weak material, and 16 failures due to the solvent outgassing and subsequent corona. Two of those 16 were infantile failures and 3 of those failures were replacement parts. It is possible that the outgassing noticed in 16 of the parts may have been present in the one part which failed in 8 hours since the part had actually seen 350 hours (DC and AC) of burn-in at 125°C prior to the life test. It could have sufficiently weakened the dielectric though it was not noticed during analysis of the part.

One (1) capacitor, design 4P, failed after operating 4221 hours at 368 volts rms. There was very little evidence of why the capacitor failed except a slight wrinkle was noticed near the dielectric puncture.

It should be reemphasized here that though the 0.25 uF designs in metallized polycarbonate displayed a new type failure mode which was not existent in the first contract, that all of the other six designs were tested in quantities at least twice as great at 125°C as in the first contract study and yet there was a maximum of 2 failures in any of the other 6 designs with 2 designs having only 1 failure each and 1 design with 0 failures. Outside of the 0.25 uF metallized polycarbonate performance caused by a problem in the raw material, the performance of these designs was greatly improved over that of the designs used in the previous program as a result of the recommendations incorporated.

Failure Analysis

Representative failure analyses are included in Appendix B of this report. Some photographs are included to aid in discussion of the failure causes.

Definitions

- a. Infantile - Failure which occurred in less than 1 week of operation (168 hours or less).
- b. Long Term - Failures which occurred after operating more than 1 week. (More than 168 hours).

There were 4 failures which could be regarded as infantile failures and the remaining 42 catastrophic failures could be regarded as long term, based on the above definition. The total number of catastrophic failures included 39 of original test parts plus 7 replacement test parts. Figure 15 and 16 illustrate cumulative failures vs time based on the original 32 test parts of each design for the 1.0 uF and 0.25 uF parts at 125°C respectively.

Cause of Failure

a. Material Defect

This was the most prevalent problem in the current study. It accounted for 36 failures out of a total of 46 catastrophic failures which occurred during the course of the 5000-hour life test. It also was noted only on the 0.25 uF metallized polycarbonate design in both the silicone oil and polybutene impregnated parts. A frustrating part of this was the fact that this design was patterned after the 0.25 uF metallized polycarbonate capacitor in the first contract study which experienced no failures at all.

The material used in the design was 4 layers of .0127 mm (.00050") thick metallized polycarbonate. The defect in the material was determined to be too much solvent in the film such that when the parts were exposed to test temperatures, the solvent outgassed. The production of gaseous molecules within the winding then set up conditions necessary in the presence of test voltage for ionization of the gaseous molecules to take place and the consequences of corona caused eventual failure of the capacitor. Samples of the dielectric were sent to outside sources for comment on the failure mechanism. One outside source suggested it was corona alone and suggested that we build some capacitors of the 0.25 uF metallized design and do not impregnate or enclose them so that we could see that corona would destroy them in rapid order. We built capacitors using raw material from the old contract plus other capacitors from the surplus material on hand for the current contract. They were wound, schooped, and terminated and were then subjected to 1000 hours at 368 volts rms at 400Hz and 125°C. Not a single failure occurred. Some of the parts were torn down and there was no evidence of any spots, holes, or corona. If outgassing had occurred, the gaseous molecules would have escaped since the windings were not encased. Therefore, ionization did not occur. On the regular NASA test parts, designs 3P and 3S, the gaseous molecules produced had no place to go since the windings were sealed and therefore ionization (corona) was initiated and led to capacitor failure.

Photographs are provided in Figures 17, 18, 19, and 20 to illustrate the condition found in the dielectric when the parts were analyzed. These photographs relate to Failure Analyses #8, #10, #14, and #16 which are in Appendix B.

b. Particle

There was one failure - design 2S - in which there was scant evidence of why the capacitor failed but 2 or 3 particles similar to that photographed and shown in Figure 21 were found in the winding. See

Failure Analysis #31 in Appendix B. The particle could have been in the material when purchased or could have been trapped in the winding during manufacture. The latter seems unlikely since all parts were built in a clean room with operators wearing white non-linting type gloves.

c. Weakened Dielectric and Oven Overheat

There were 2 failures - one at 8 hours on design 3S and one at 1005 hours on design 2S in which no definite reason for failure could be determined other than a weakened area in the dielectric coupled with the oven temperature raising to 134°C for a short period of time could have been responsible. Figure 22 is of the design 3S which failed in 8 hours (an infantile failure) and Figure 23 is of design 2S. The detailed analyses are Failure Analysis #1 and #13 provided in the Appendix. It is highly probable that the infantile failure was due to the solvent outgassing mentioned previously since it had been subjected to 350 hours of burn-in at 125°C.

Manufacturing Defect

- a. Wrinkle - There were almost no wrinkles in the windings dismantled and a vast improvement in this area was noted. However, there were 4 capacitors which failed in which slight wrinkles were found and may have combined with a leaky eyelet seal or the 134°C temperature in oven 2 for an affect on capacitor performance. Though no severe wrinkles were found, a photograph is provided in Figure 24. The Failure Analysis #17 which corresponds is included in the Appendix.
- b. Insufficient solder bond - eyelet rim to tube. This failure mechanism was found in the previous study. Improvements were realized on this study but the problem was not completely eliminated. A photograph as shown in Figure 25 illustrates insufficient solder run-down along the circumference of the eyelet rim. Generally, the solder adhered very well to the brightly tin plated tubes. Part of the problem is human error since they were hand soldered and the capacitor was turned too fast for the amount of solder applied, resulting in insufficient solder run-down. The other problem is that any difficulty with insufficient bond of eyelet rim to tube almost always occurs on the second eyelet to be soldered. The impregnant and liquid fill present gets hot, attempts to push its way out, and may interfere with proper solder run-down. For details, see Failure Analysis #35 in the Appendix.

Transient

One capacitor, design 1P failed when using a special fused probe to check an adjacent failed part. The failure occurred at exactly that time and since no other failure cause could be determined, the surge effect into the adjacent shorted capacitor is believed responsible. No photographs were taken but details are covered in Failure Analysis #32 which is included in the Appendix.

FAILURE RATE OBSERVATIONS AND PREDICTIONS

Failure rates observed during the 5000-hour test as well as those at 60% upper confidence level and 90% upper confidence level as determined using the chi-squared tables are shown in Table VIII. The failure rates are shown by design and then also considering all the groups together which were tested at 100% of nominal rated AC voltage and rated 125°C temperature. Failure rates at 70% and 130% of rated AC voltage at both 110°C and 125°C temperatures were not included because of the small quantities tested at those conditions.

Considering only those samples tested at design rated conditions, and eliminating those which used the film with excessive solvent content (designs 3P and 3S) there were 4 failures in approximately 718,000 unit hours. This results in an overall calculated failure rate of 1.11%/1000 hours at 90% upper confidence limit.

It is interesting to note that in cases such as for design 1P in which there were no observed failures, that the calculated failure rate at 90% upper confidence level is 1.92% per thousand hours. This is because of the limited number of component test hours. To achieve very low failure rates at high confidence levels requires millions of unit hours with a low number of failures.

TABLE VIII

Failure Rates
at
100% Nominal AC Rated Voltage and 125°C Rated Temperature

Design	Qty Tested Including Replacements)	Qty Failed	Unit Hours	Observed Failure Rate %/1000 hrs.	Calculated Failure Rate 60% UCL %/1000 hrs.	Calculated Failure Rate 90% UCL %/1000 hrs.
1P	24	0	120,000	0	.76	1.92
1S	25	1	119,300	.84	1.70	3.26
2P	26	2	118,250	1.69	2.62	4.48
2S	25	1	120,000	.83	1.68	3.24
3P	27	6	111,700	5.37 *	6.59	9.45
3S	27	9	102,000	8.82 *	10.3	13.9
4P	24	0	120,000	0	.76	1.92
4S	24	0	120,000	0	.76	1.92
<hr/>						
Total Reliability as Group	202	19	931,250	2.04	2.23	2.78
<hr/>						
Reliability of 6 Groups (Eliminating problem designs 3P & 3S) **	148	4	717,550	.56	.73	1.11
<hr/>						

* The Failure rate of these 2 designs was influenced almost entirely by the problem with the raw material. In the previous contract study, the design did not exhibit the problem and completed the 5000 hour test with 0 failures.

**If the problem in the raw material can be controlled by the manufacturer, the failure rate as shown at the bottom of the table above is a logical expectation since it was calculated using all designs except 3P and 3S.

IMPROVEMENTS REALIZED ON DESIGNS

Terminations were a problem on the 1.0 uF metallized designs of the previous contract study. There was not a single failure in the life test of this contract attributable to this cause. Terminations were excellent every time components were dismantled for failure analysis. Any increase in DF shown on the data sheets could be from oxidation of leads causing contact resistance to go up between lead and test tray clip or else could have been due to change of the internal quality of the dielectric on designs 3P and 3S due to the problem detected with those designs.

Wrinkles in the winding material were a problem mentioned in the first study. Excellent improvement was accomplished to result in a very minimum amount of wrinkles found. The general construction and appearance of the windings were excellent. There were 4 capacitors in this study that failed in which small wrinkles were present in the area of failure. These wrinkles were not severe.

Drilled holes in the ceramic core at right angles to the core axis in the first study created stress points in the material. These holes were eliminated and a core material was selected which had an improved thermal conductivity by a factor of 4 or 5 times. This problem was thus eliminated.

The windings of the metallized polycarbonate designs were well padded at the start and finish of the winding to prevent clearing at those locations across the edges of the cut dielectric. There had been an occasional problem in the first contract in which workmanship error resulted in neglect to pad the winding as specified. There were no failures due to this problem in this study.

Material defects were discussed in the first contract study. This included pin holes, weak dielectric, and could have included contamination of the raw material as received. There was very little evidence of pin holes in the capacitors tested under contract NAS3-15688. There were 2 or 3 failures without too much evidence as to why they failed in which the analysis mentioned possibility of weakened dielectric and 1 failure in which the only thing found was a small particle in the material some distance from the failure location in which it was thought that a particle could have contributed to failure. The main material defect found in the current study was a new failure mode involving the effect of the solvents in the raw material itself. This failure mode was only evident in the 0.25 uF samples. The design of these 0.25 uF samples was essentially identical to that used in the preceding study. The only difference was a slight increase in *dielectric* width from 3.175 cm (1-1/4 inch) to 3.81 cm (1-1/2 inch). This new cause of failure is discussed in more detail in the section on causes of failure.

Corona was mentioned as a failure cause in the first contract study. Great care and revised process techniques were used when building the capacitors for this study to eliminate air from the impregnant and liquid fill during those manufacturing processes. The result was that there was no corona evident on any of the test capacitors initially during the lot acceptance test. Based on these results, the process revisions and effort to eliminate air from the impregnant and liquid fill to reduce the chances of corona were successful.

RECOMMENDATIONS CONCERNING DESIGN & USAGE

Physical Dimension & Electrical Design Considerations

It is recommended that the tubes for each specific design be shortened by .317 cm (.125 inch). The diameter of the tubes for practical purposes should remain at 2.54 cm (1 inch) since this size is standard to industry and the next smallest standard diameter of 1.90cm (.750 inch) is too small. No changes in the design of the windings are recommended provided that the manufacturer can control the amount of solvent in the raw material to a very low level (.3% or less by weight is suggested). It has been learned that the thicker the film, the greater the chance of a higher level of solvent within the film. If the level of solvent suggested is difficult to control, some consideration could be given to the use of multiple layers of the thinner gage film for higher voltage designs. Other considerations could be the use of series wound type capacitors in which several sections make up the total capacitance desired. The advantage is that the voltage per section is reduced and consequently the possibility of ionization of solvent which may be outgassing from the film. A disadvantage of the series wound type capacitor is that physical size increases compared to standard design. From studies performed with corona detection equipment, corona does not seem to become a possibility until a level of 200 volts rms is reached. A two section series wound capacitor could thus handle a 375 volt rms design with little worry from corona, even if outgassing of solvent might occur.

As voltage levels go up, the possibility of outgassing and corona can become a concern as well as dielectric strength of the film. A stress limit of 11800 volts/mm (300 volts/mil) is recommended. The stress levels on the designs used herein at the 3 test voltages are as follows:

Designs 1P, 1S, 2P and 2S

at 99 volts rms	stress 6070 volts/mm (155 volts/mil)
141 volts rms	stress 8650 volts/mm (220 volts/mil)
184 volts rms	stress 11290 volts/mm (288 volts/mil)

Designs 3P and 3S

at 198 volts rms	stress 7790 volts/mm (198 volts/mil)
283 volts rms	stress 11140 volts/mm (283 volts/mil)
368 volts rms	stress 14490 volts/mm (368 volts/mil)

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Designs 4P and 4S

at 198 volts rms	stress 6470 volts/mm (165 volts/mil)
283 volts rms	stress 9250 volts/mm (235 volts/mil)
368 volts rms	stress 12030 volts/mm (306 volts/mil)

Manufacturing Improvement Considerations

There were 2 items mentioned which were related to manufacturing - wrinkles and insufficient solder bond of eyelet rim to tube. A great improvement was realized in minimizing wrinkles after the first contract study and the wrinkles mentioned in the analysis of 4 parts were slight and the degree of contribution to the failures is questionable. The wrinkles can be minimized through use of rollers adjacent to the winding mandrel while the windings are wound and the skill of the operator has some effect. Completely automatic winding is used to eliminate human error but is not always practical, depending on how the winding is put together. In the case of these designs, automatic winders could not be used because of special features of the winding.

The eyelet rim to tube solder joints were greatly improved but there were some capacitors in which failure was thought induced through leaky seals and loss of fluids. The solder seals were done by trained personnel using a hand soldering technique. If the tube is rotated too fast while applying solder, insufficient run down can occur. This situation could be improved further by mechanizing the soldering operation and through use of X-rays as an inspection procedure.

Impregnant Choice

It can be noted in Table IV that the terminal-to-case IR of those capacitors utilizing polybutene was much greater than for the capacitors using silicone oil. This gives an indication that the initial insulating qualities of polybutene may be much higher. On the other hand, a review of Figures 13 and 14 indicates better IR terminal-to-terminal as the life test progresses with silicone oil than with polybutene. This indicates that sustained high temperatures have less affect on silicone oil than on polybutene. If an application requires high temperature operation for long periods of time and terminal-to-terminal IR is a critical parameter, silicone oil would be the better choice. As far as total failures at 125°C, there were 21 failures using silicone oil and 14 using polybutene. The 2 impregnant liquids have their strong points and the selection is left to the manufacturer.

CONCLUSION

The purpose of this contract study involving construction and AC life testing of polycarbonate capacitors was to employ recommendations for polycarbonate capacitor improvements emanating from a previous contract study, to determine whether significant improvements were realized based on performance during the life test, and to analyze results, determine failure rates, and discuss factors pertinent to safe operation of polycarbonate capacitors.

Excellent results were achieved by incorporating recommended improvements outlined in the previous contract study. This included termination improvements, minimizing of wrinkles, improved manufacturing processes to remove air voids and construction error, improved cores for windings, and improved eyelet soldering. There were still a few failures attributed to eyelet seals leaking during the course of the life test and some slight wrinkles were noticed near failure areas.

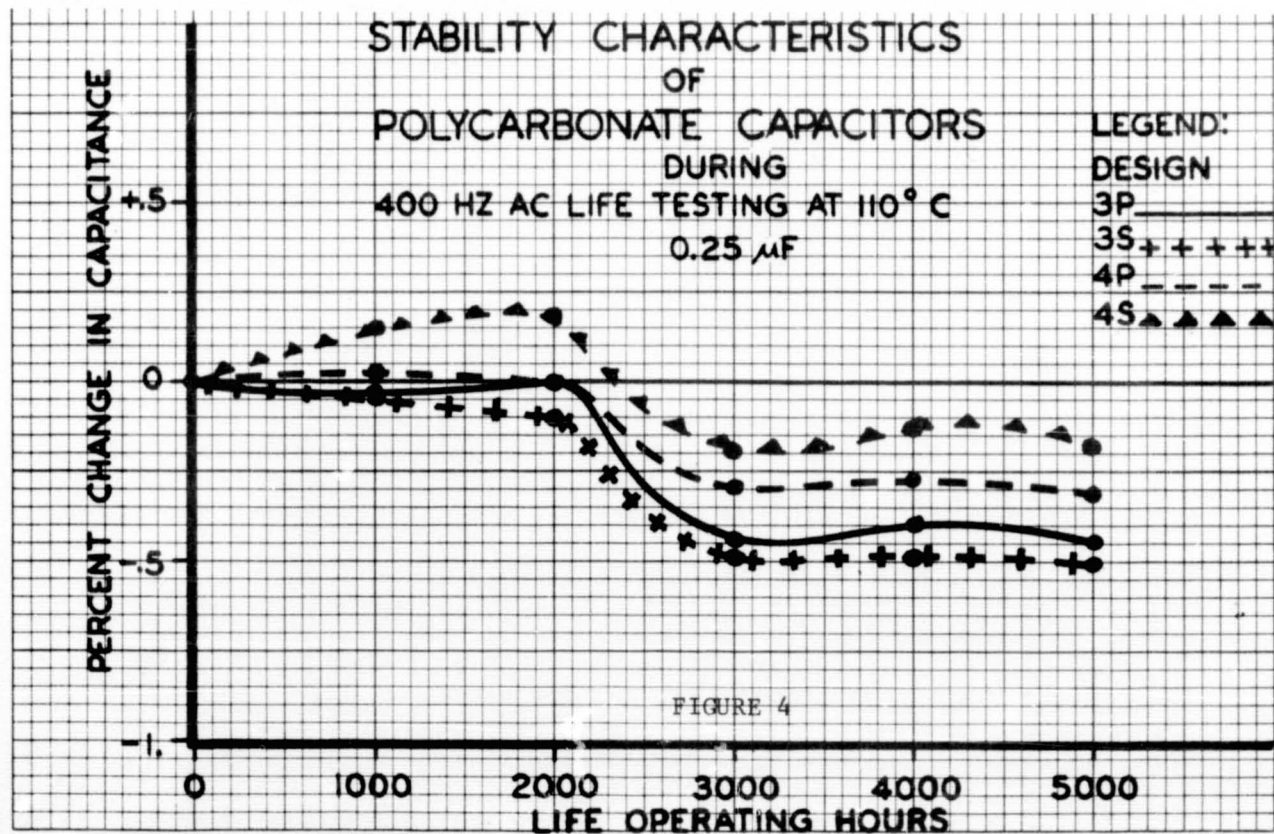
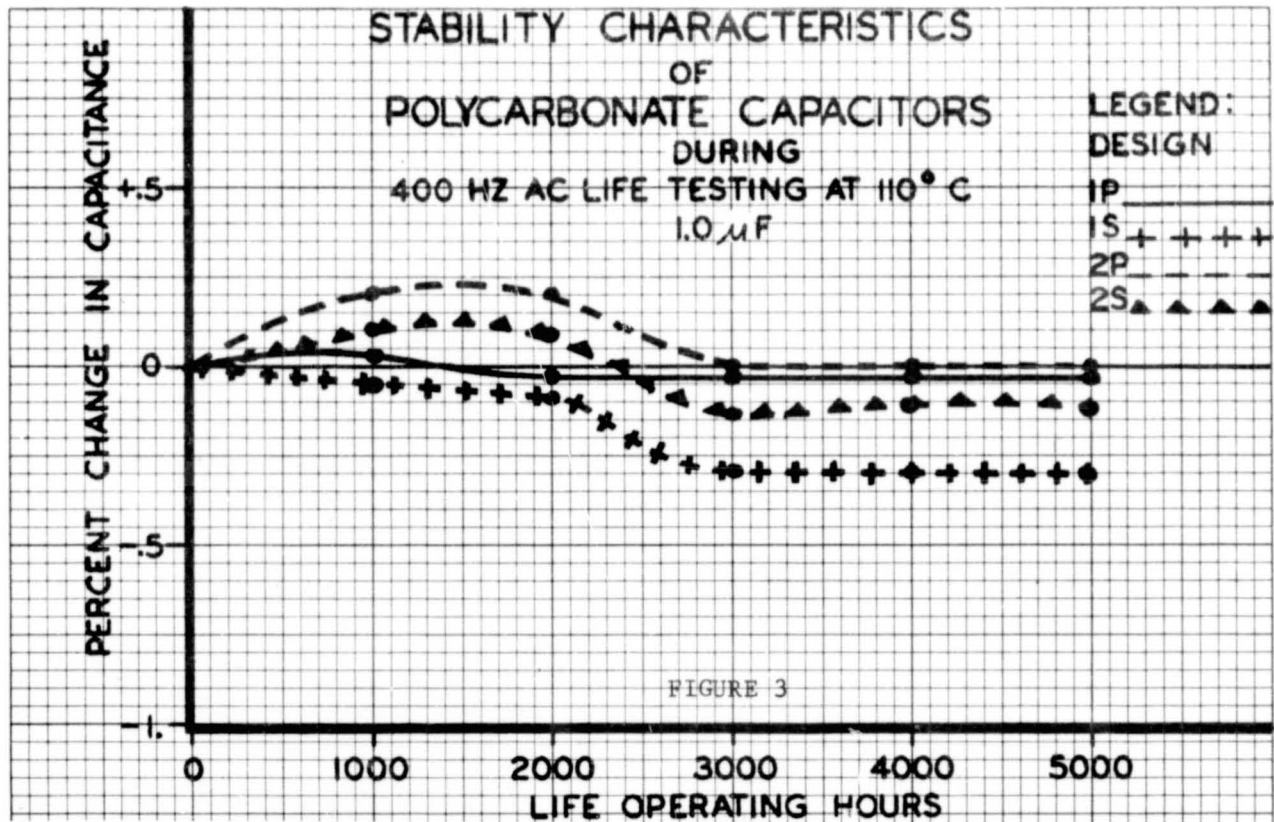
Five (5) out of eight (8) designs operated at 110°C with no failures at all. Two designs had 1 failure each at 110°C and one design had 9 failures.

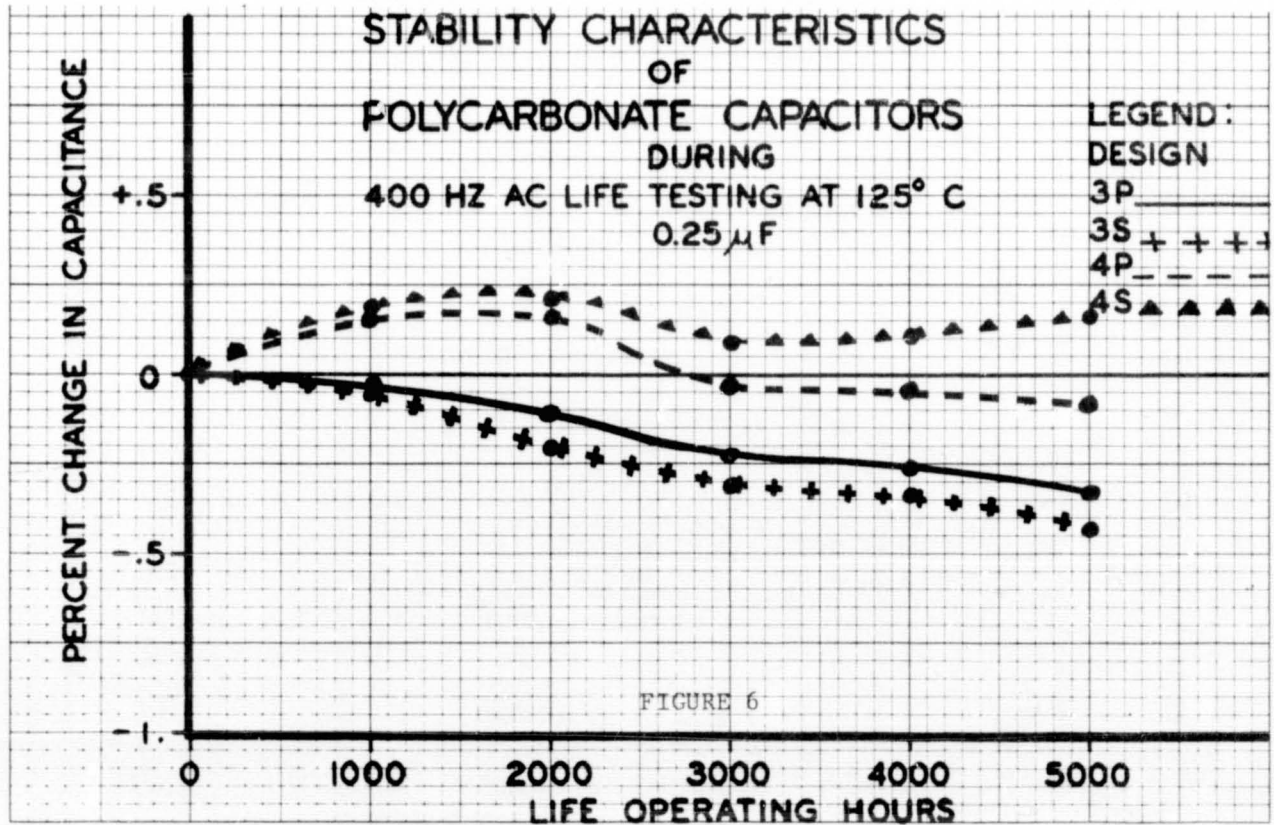
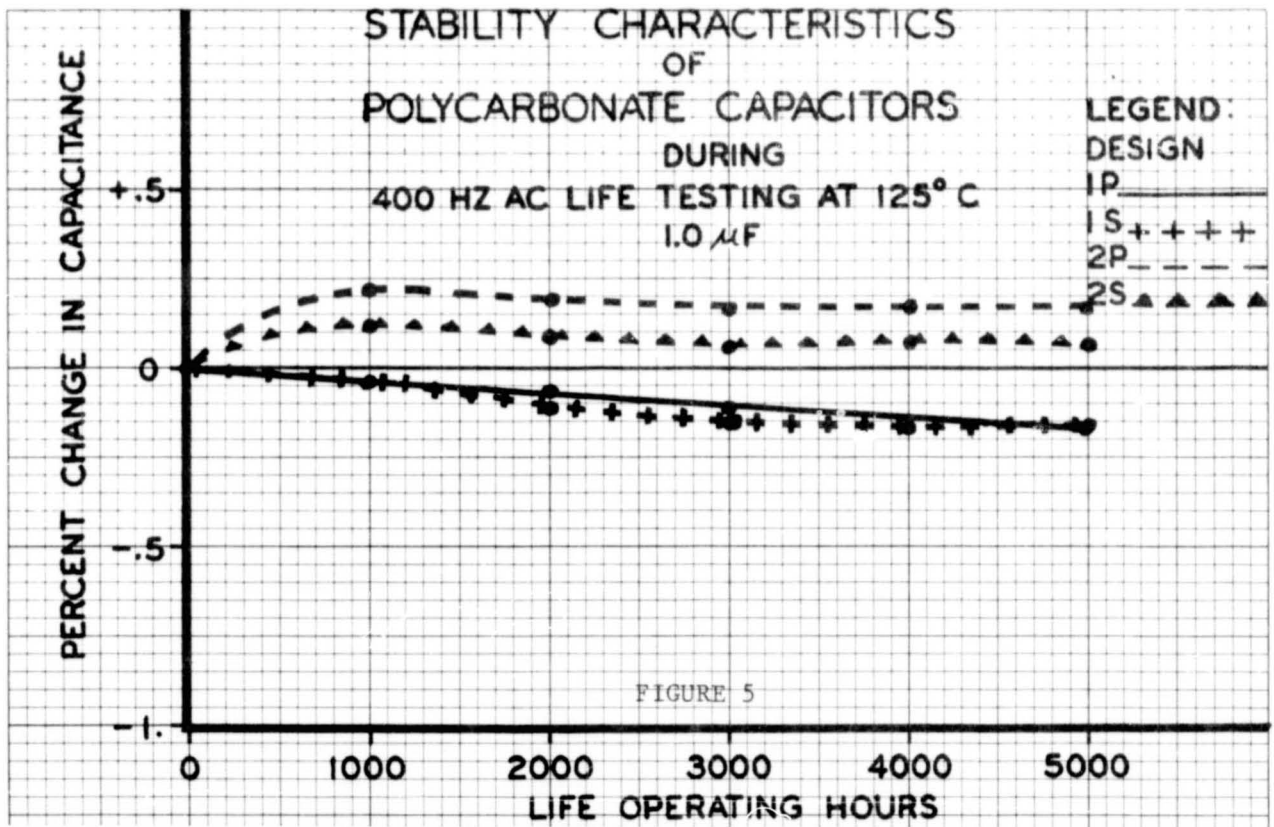
One design had no failures at 125°C, two designs had one (1) failure each, three designs had two (2) failures each, and two designs exhibiting the raw material problem had ten (10) and seventeen (17) failures respectively.

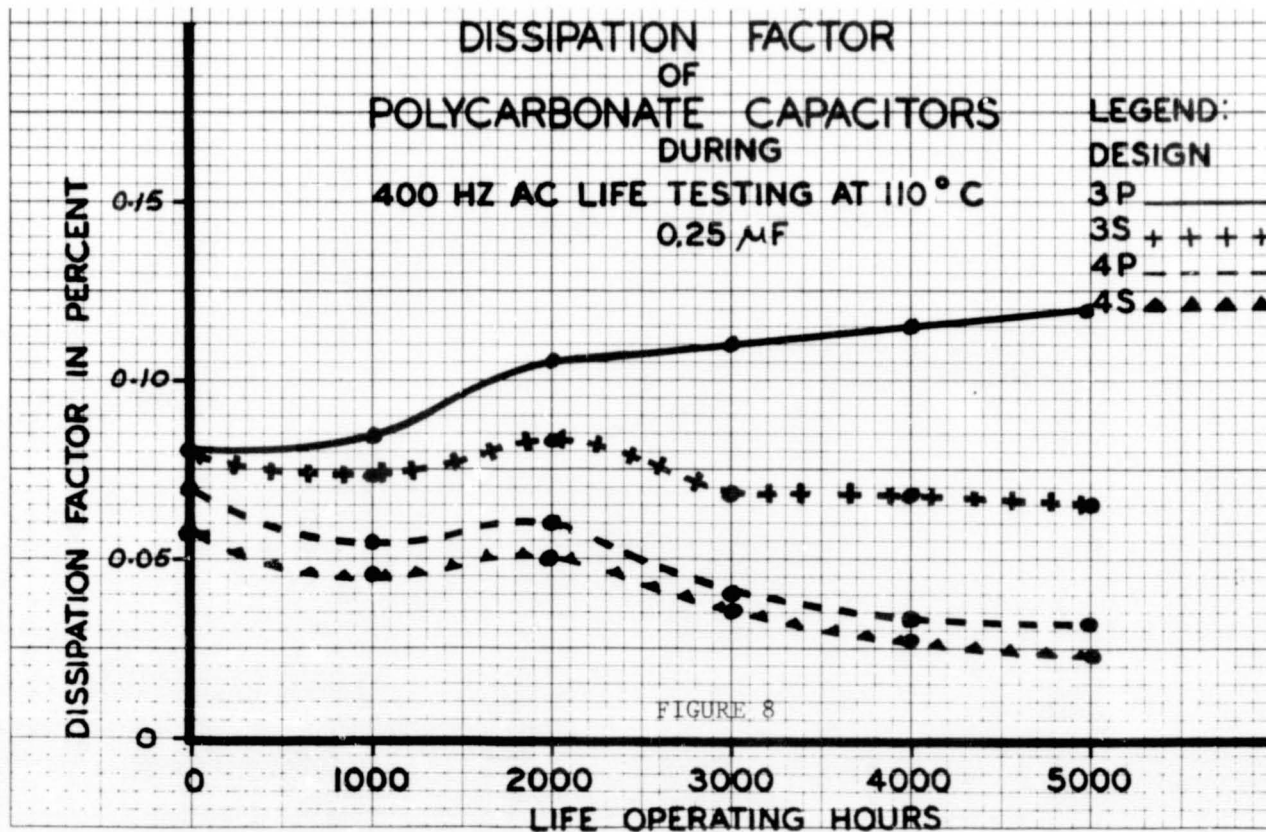
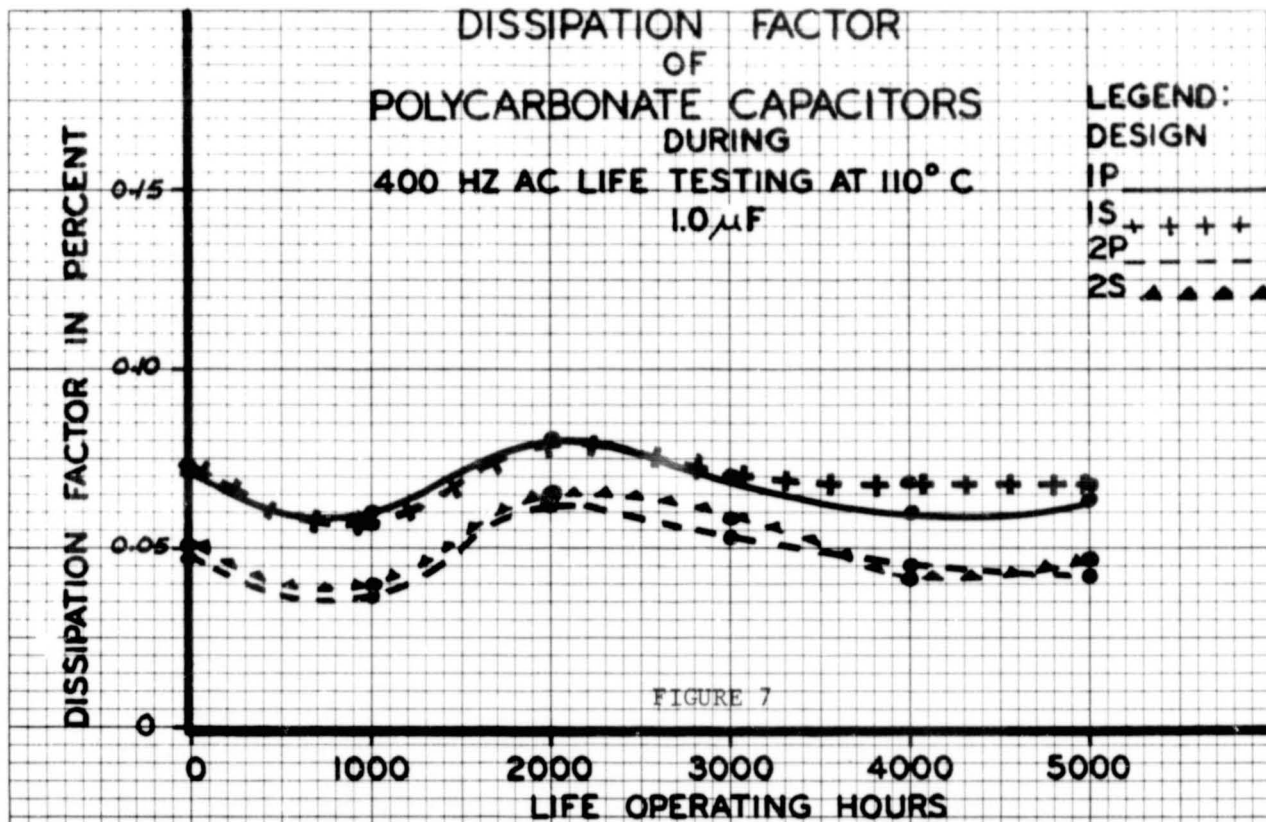
Of the total 46 catastrophic failures (namely shorts), 37 failures occurred in 2 designs due to a failure mode involving raw material. This involves outgassing of solvents which become trapped within the winding and lead to ionization of the gaseous molecules (corona) and eventual failure. The amount of solvent has a tendency to be greater as the film thickness increases. This failure cause was not evident in the preceding contract program.

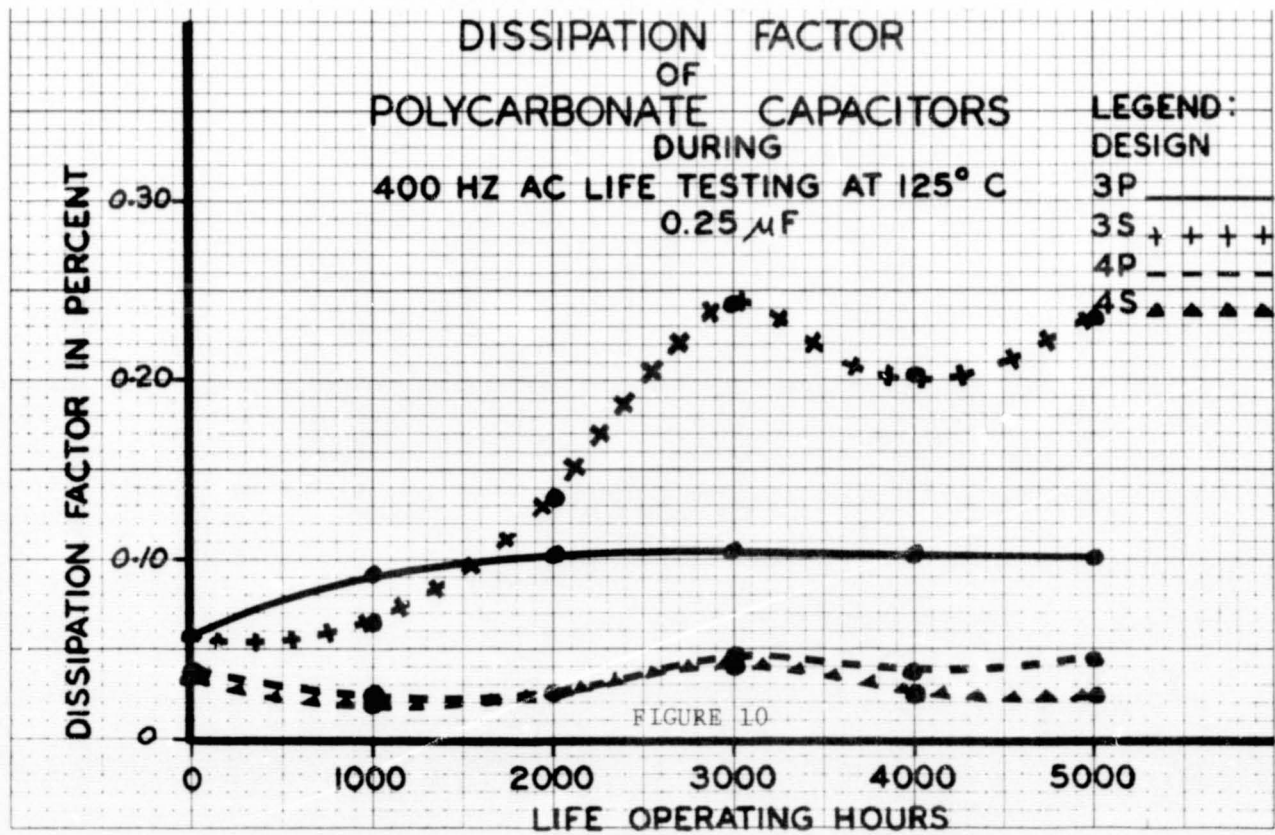
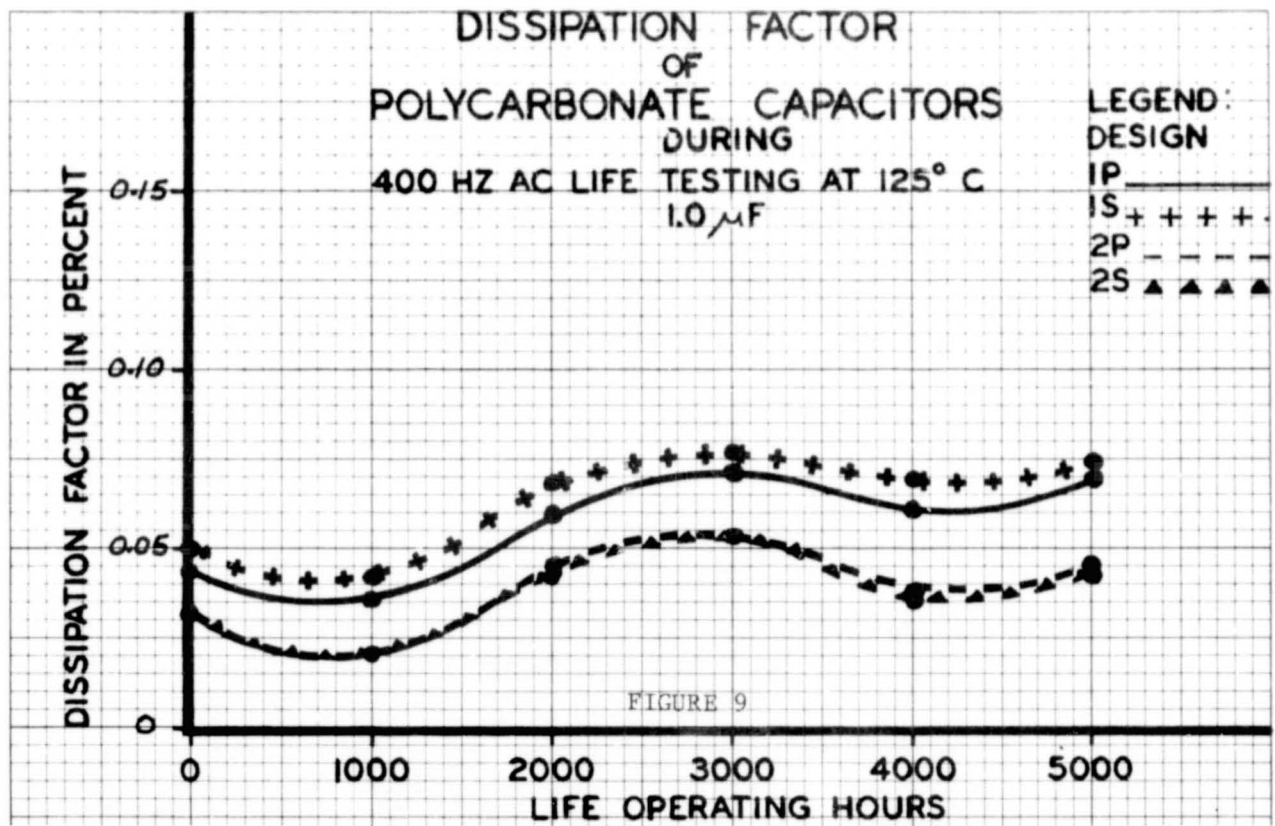
In the first contract study, there were 128 capacitors tested at 125°C with 33 catastrophic failures. In this contract study, there were 256 capacitors tested at 125°C and 35 catastrophic failures with 27 of those failures attributed to the new failure mode. The improved performance as a result of recommendations incorporated is very evident on six (6) of the eight (8) designs and would have been outstanding if it were not for the new failure mode causing problems in the one design which performed with no failures in the first contract study.

The results of this program indicate that polycarbonate ac capacitors can be expected to tolerate operation at 125°C in aerospace applications. Derating to lower temperature operation such as 110°C will improve reliability. The problem with excessive solvent content in the raw material demonstrates that the capacitor, as simple as it appears, is a complex device. All parts and assembly phases must be well controlled to assure high reliability.









INSULATION RESISTANCE CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400 HZ LIFE TESTING AT 110° C
1.0 μ F

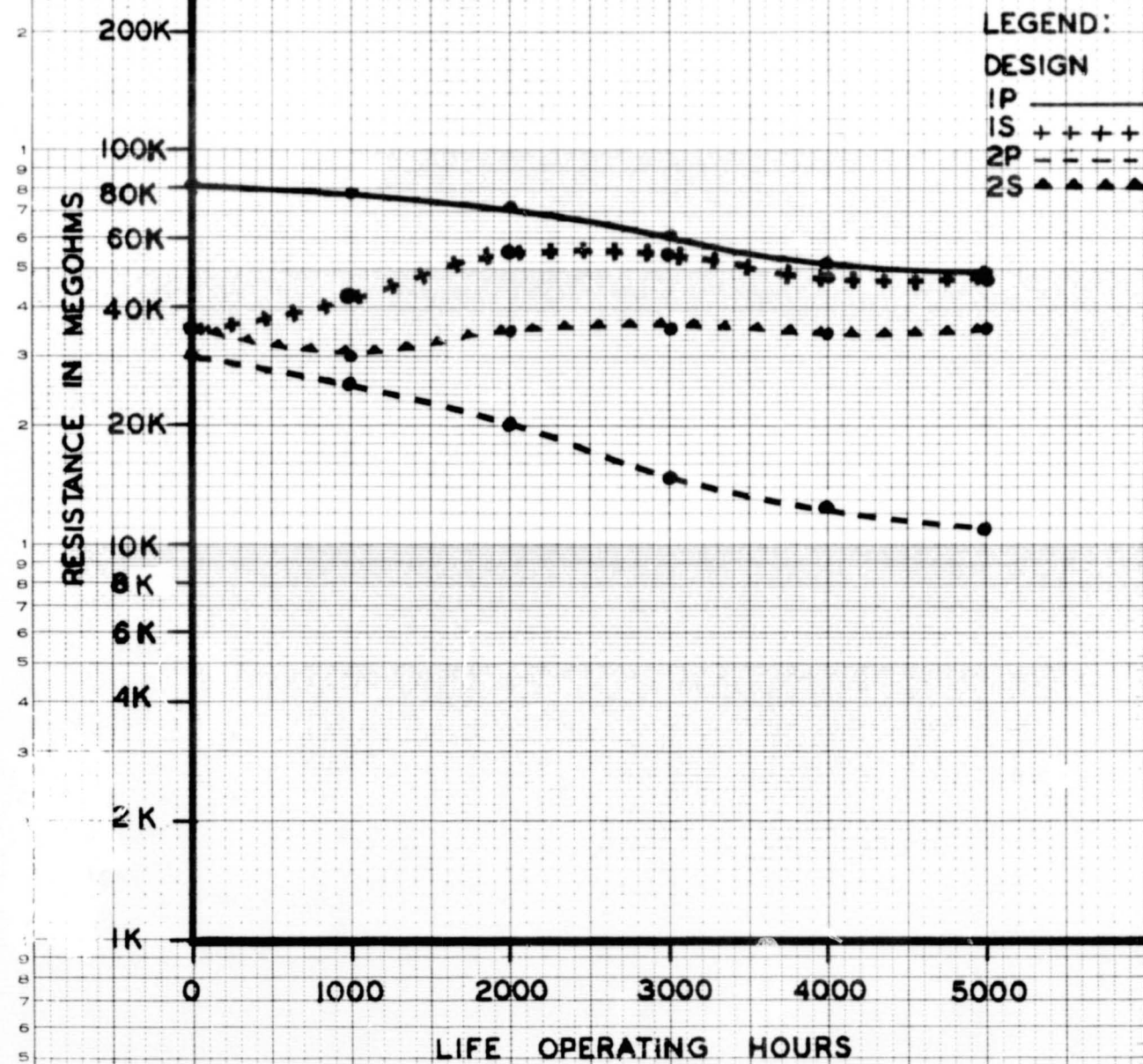


FIGURE 11

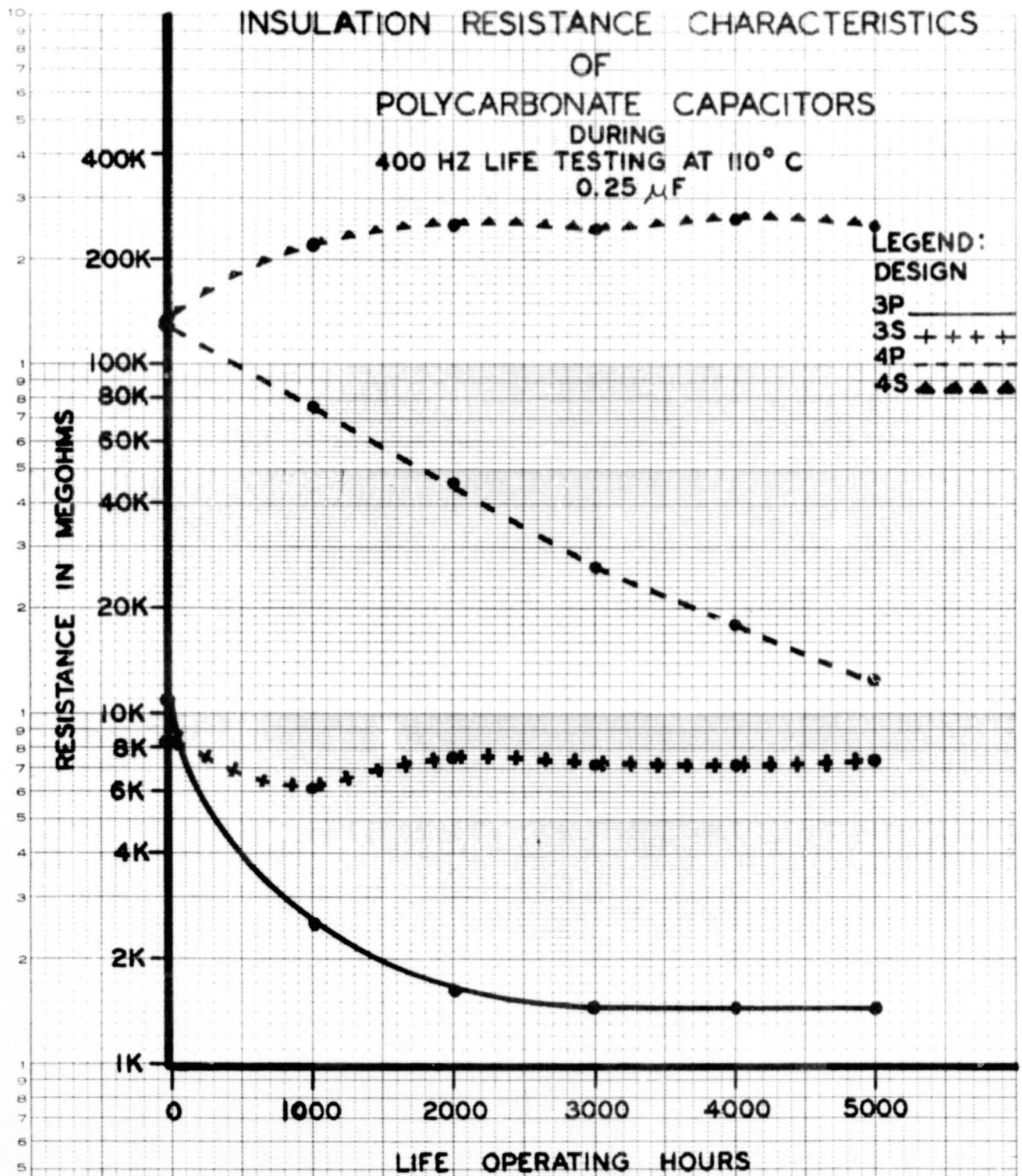


FIGURE 12

INSULATION RESISTANCE CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400 HZ AC LIFE TESTING AT 125° C
1.0 μ F

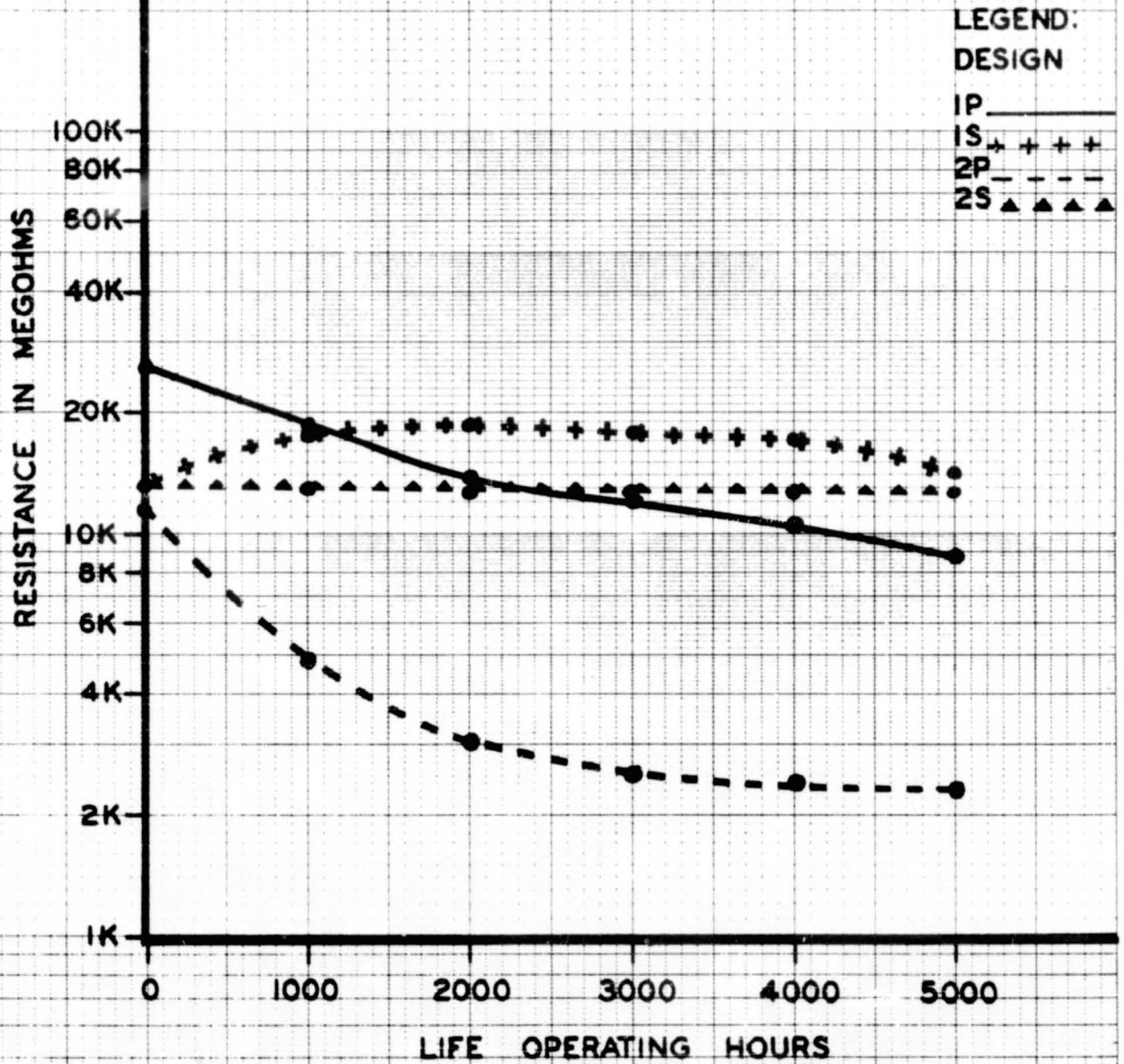


FIGURE 13

INSULATION RESISTANCE CHARACTERISTICS
OF
POLYCARBONATE CAPACITORS
DURING
400 HZ AC LIFE TESTING AT 125° C
0.25 μ F

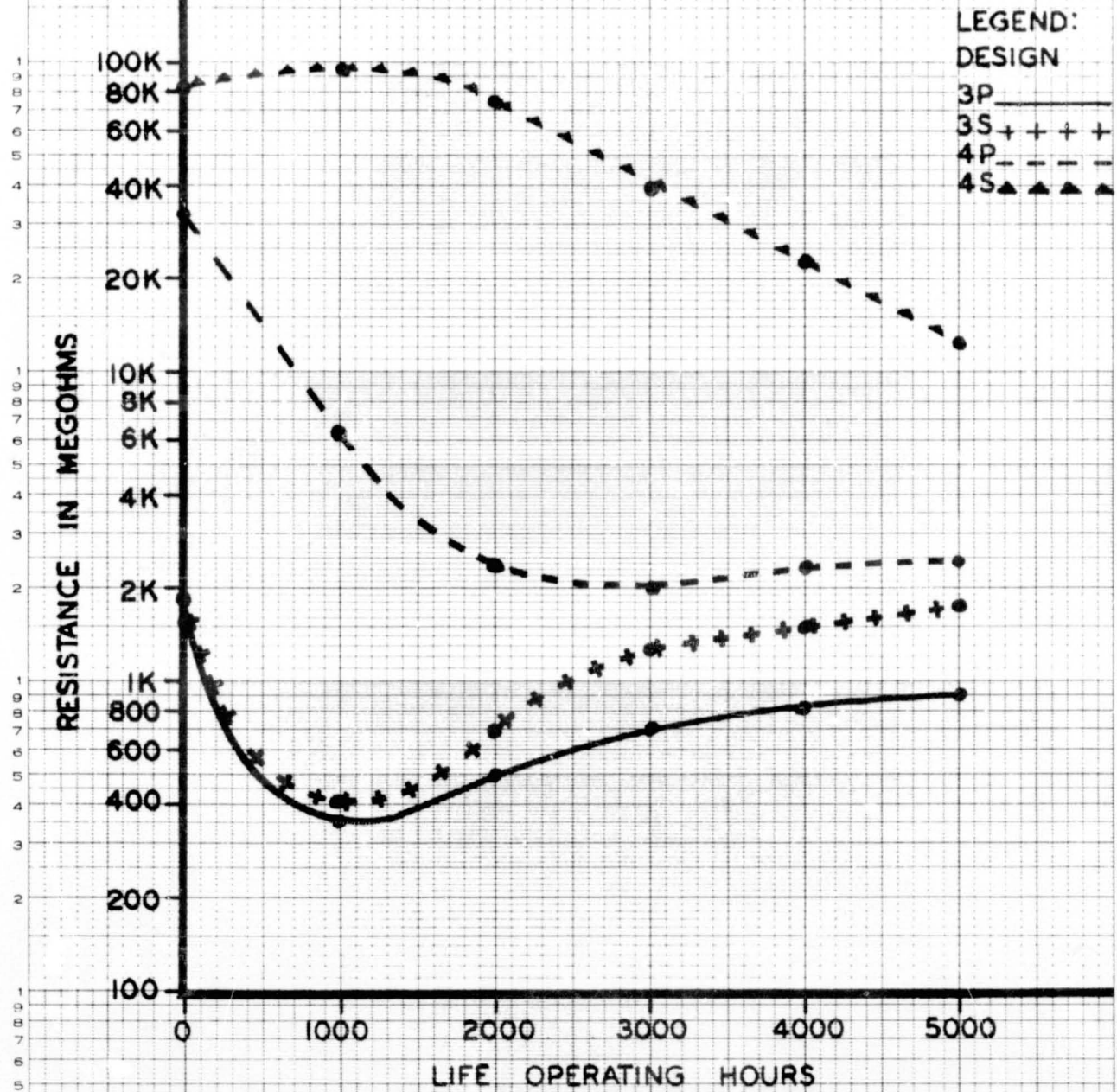


FIGURE 14

CUMULATIVE FAILURES* vs. TIME
FOR
POLYCARBONATE CAPACITORS
DURING
400 HZ AC LIFE TESTING AT 125°C
1.0 μF

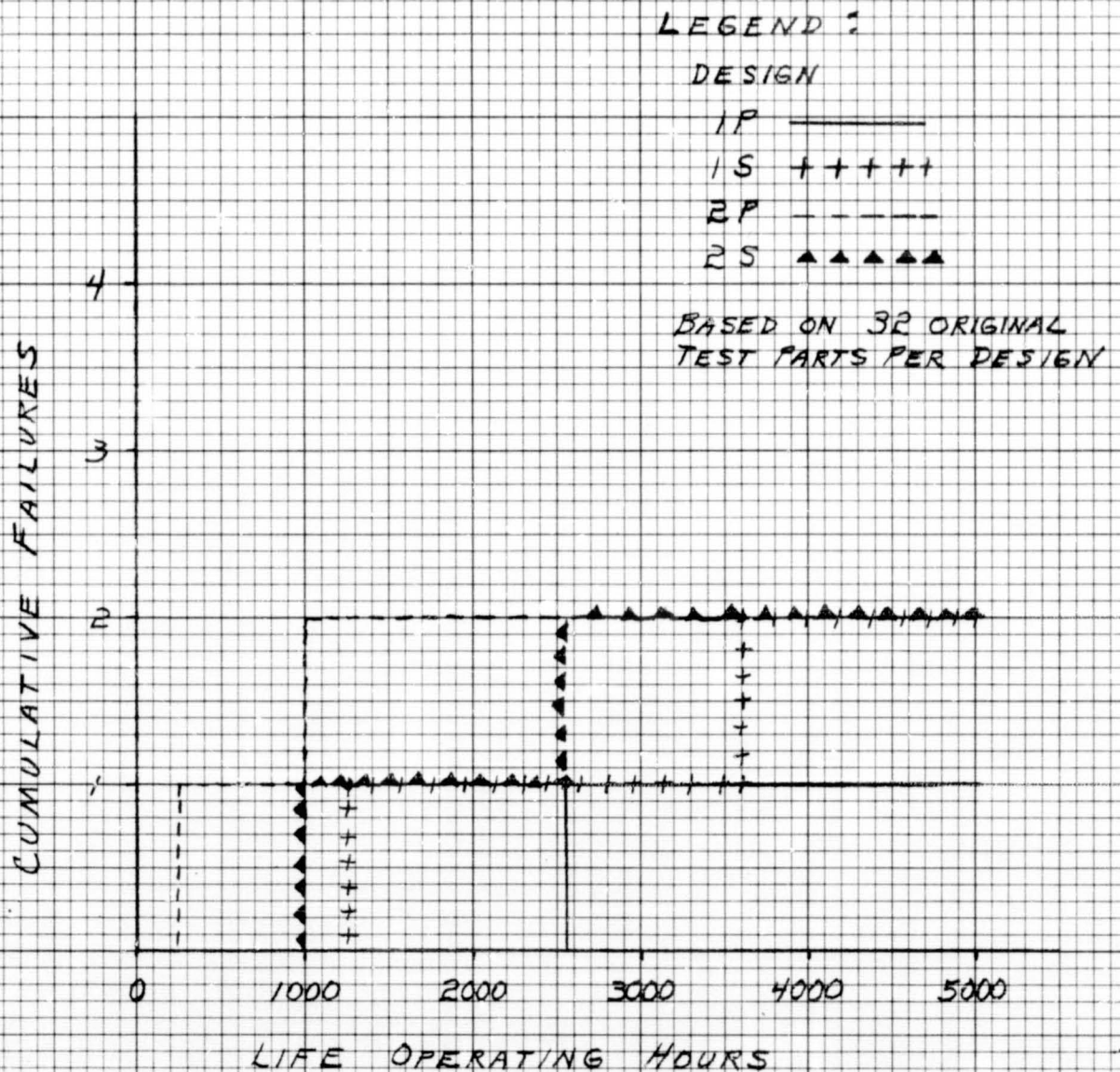


FIGURE 15

* FAILURES ARE CATASTROPHIC SHORTS. NO OPENS OCCURRED

CUMULATIVE FAILURES* vs. TIME FOR POLYCARBONATE CAPACITORS DURING 400 HZ AC LIFE TESTING AT 125°C 0.25 MF

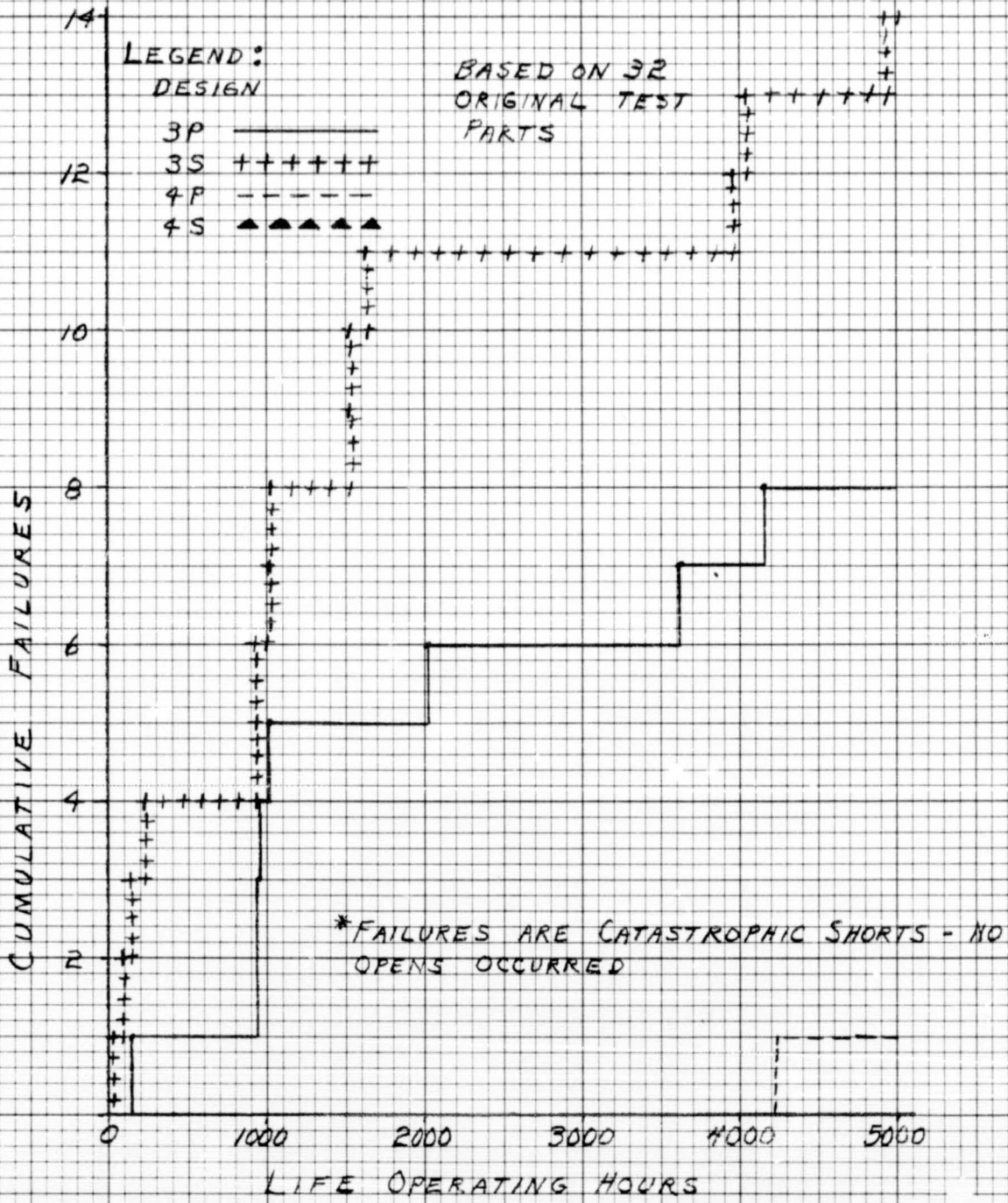
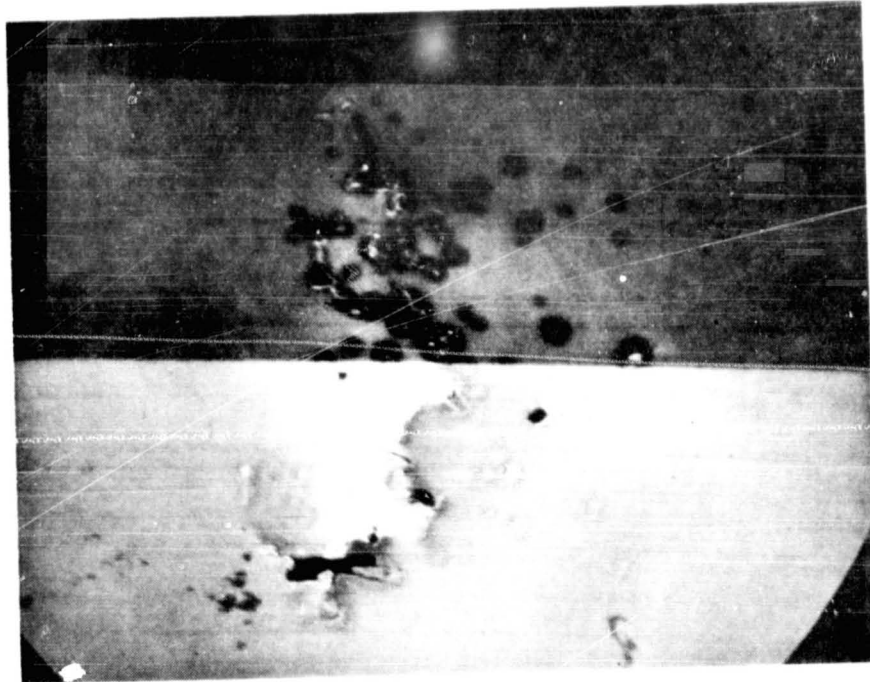
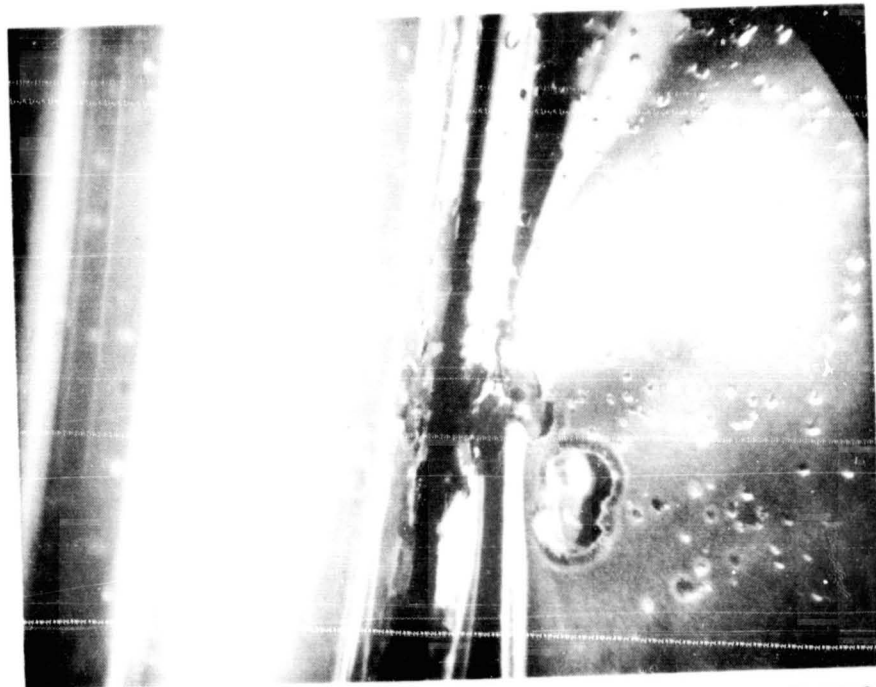


FIGURE 16



Ser. No. 27EXP04

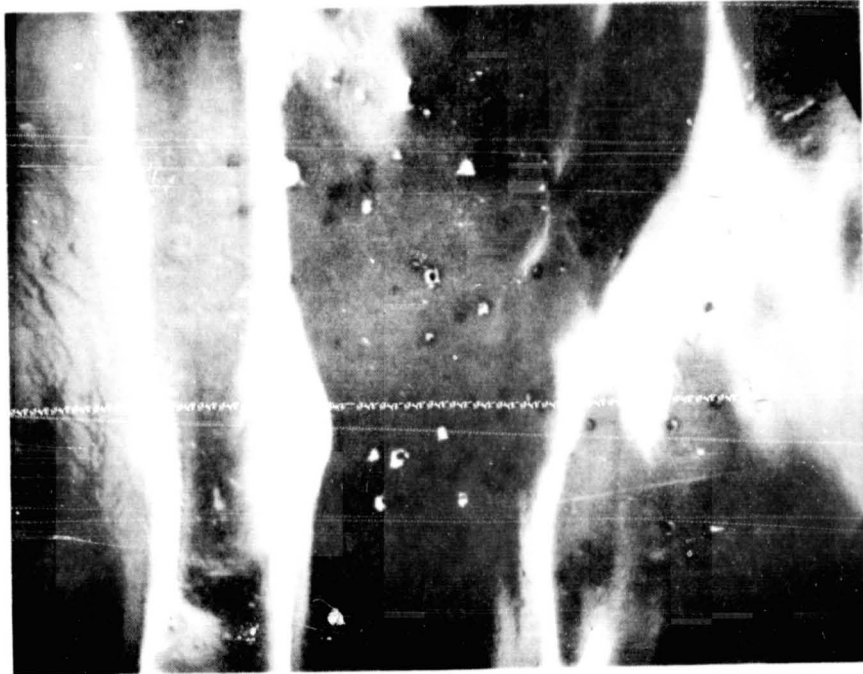
Figure 17. Dielectric failure as a result of solvent outgassing and subsequent corona from ionization of gaseous molecules produced. Design 3P. Magnification 21X. Refer to Failure Analysis #8.



Ser. No. 26FXP03

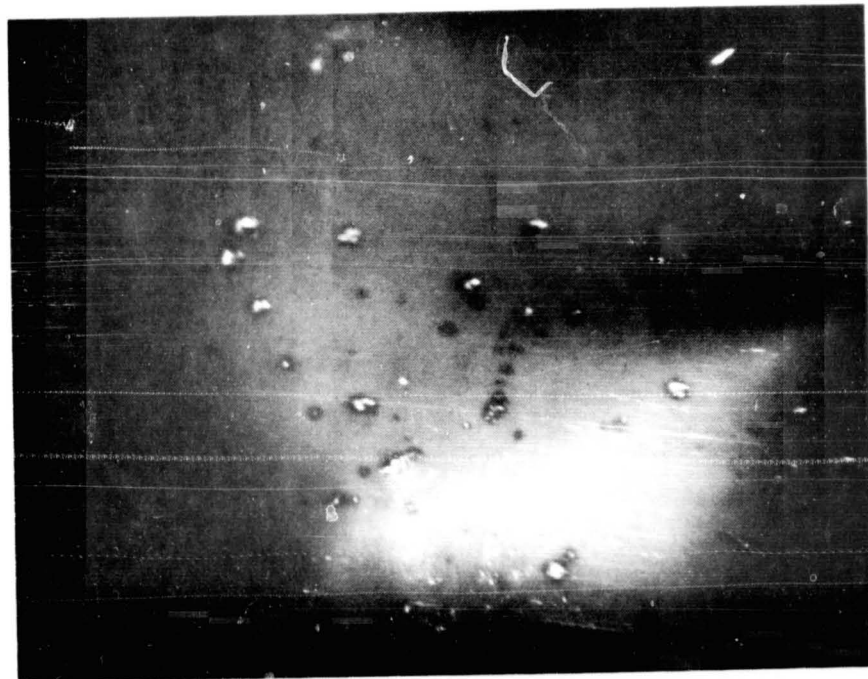
Figure 18. Another example of outgassing and subsequent effects on design 3P. Magnification 7½X. Refer to Failure Analysis #10.

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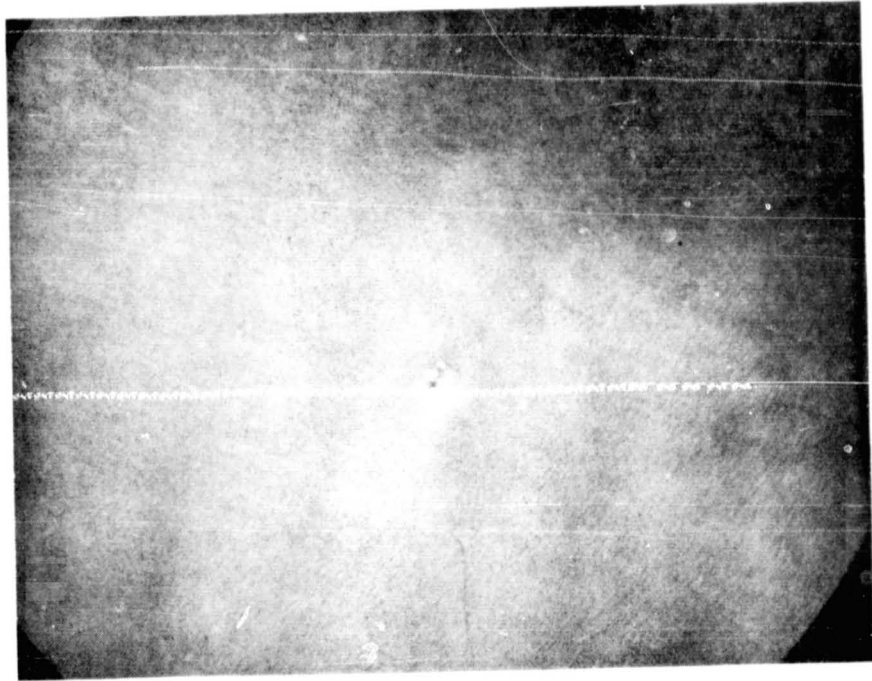
Ser. No. 26FXP01

Figure 19. Dielectric failure as a result of solvent outgassing and subsequent corona from ionization of gaseous molecules produced. Design 3P. Magnification is 13X. Refer to Failure Analysis #14.



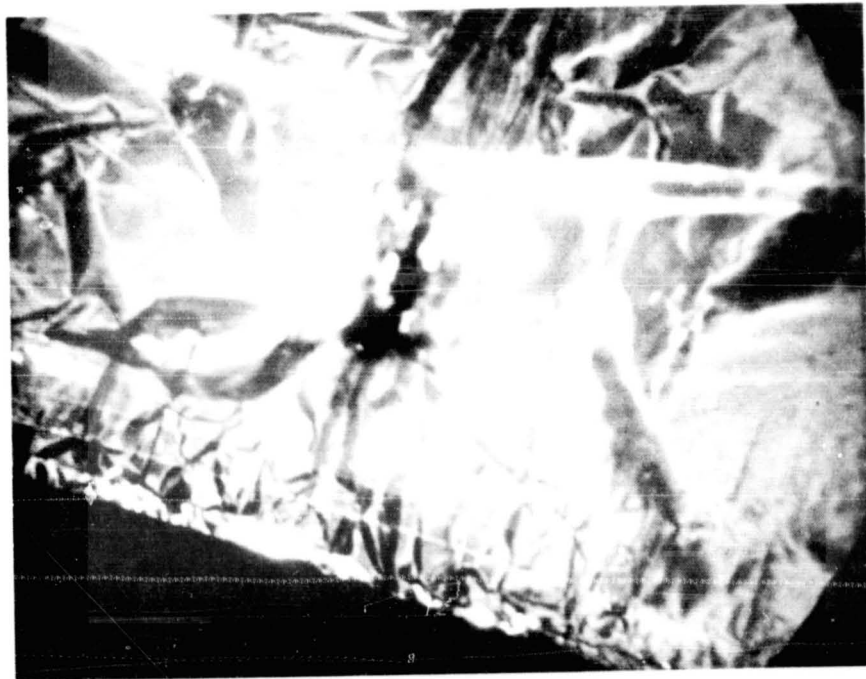
Ser. No. 27EXS07

Figure 20. Failure for same reason as on Figure 19 above but for a design 3S. Magnification 9X. Refer to Failure Analysis #16.



Ser. No. 22CFS14

Magnification 22X

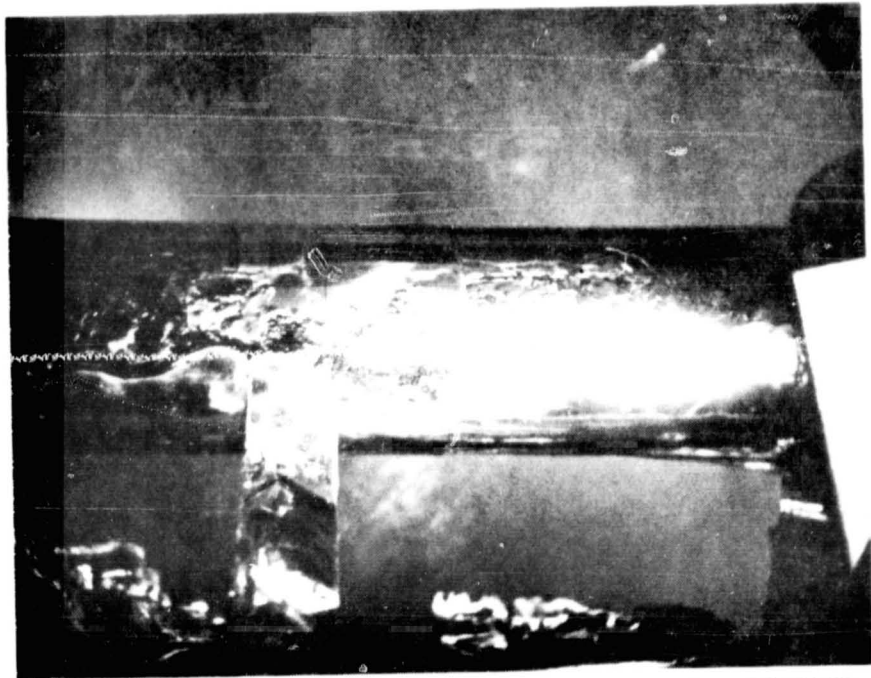


Ser. No. 22CFS14

Magnification 5½X

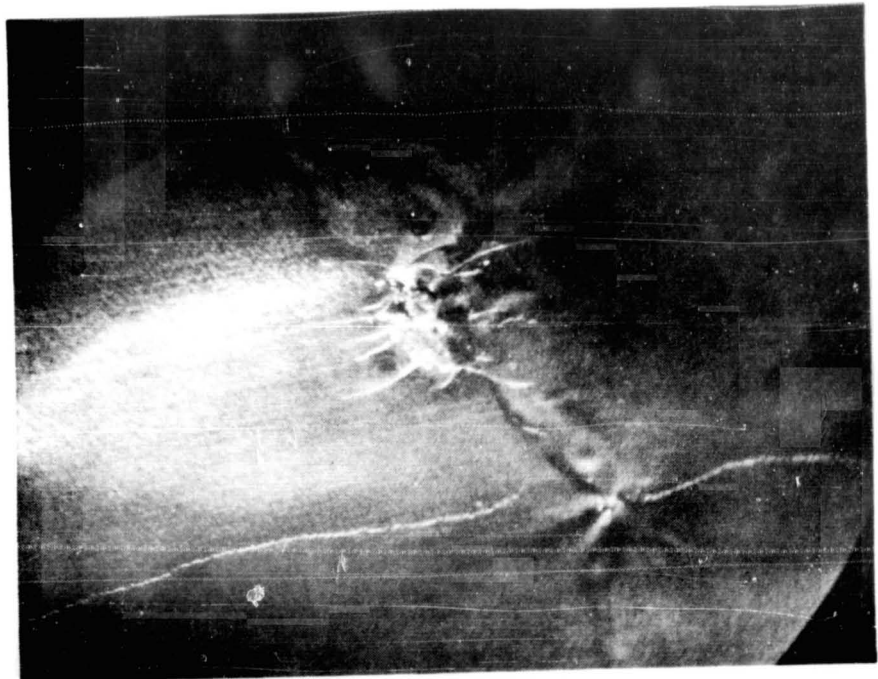
Figure 21. Two or three small particles were found in a design 2S as in the top photograph and the main failure area is shown in the bottom photograph. Refer to Failure Analysis #31.

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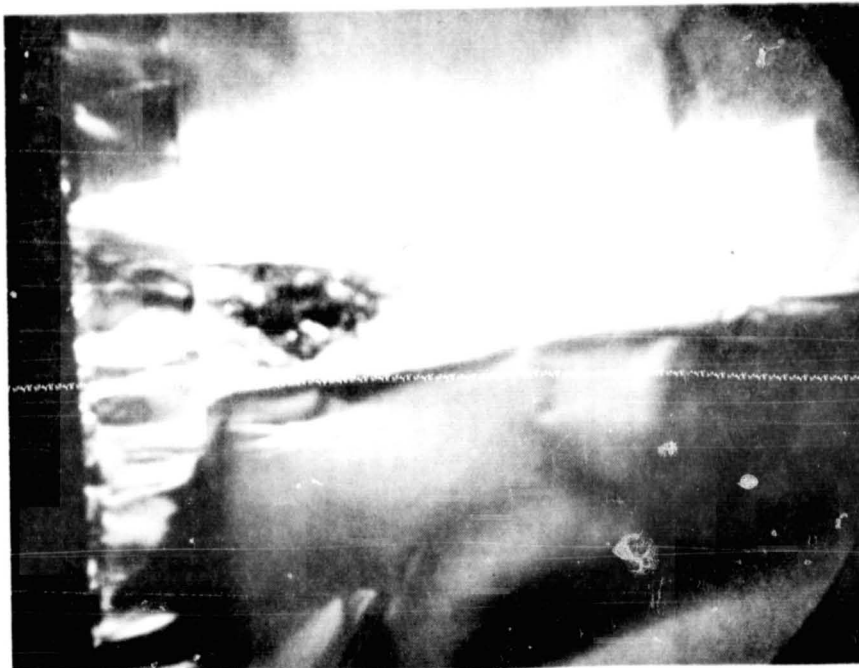
Ser. No. 26FXS05

Figure 22. An infantile failure which occurred within 8 hours. The winding is badly charred. Magnification $5\frac{1}{2}X$. Design is 3P. Refer to Failure Analysis #1.



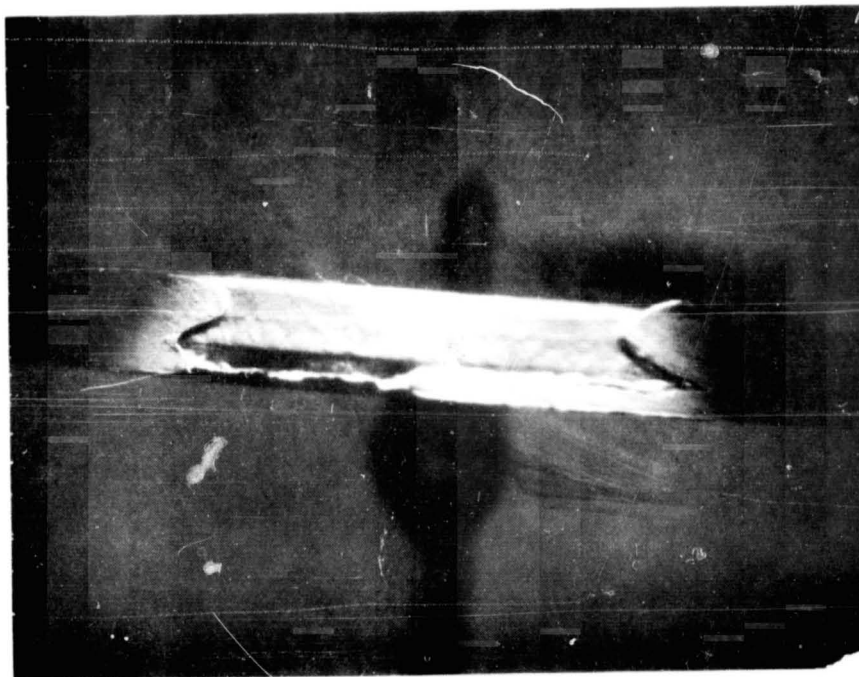
Ser. No. 24BFS14

Figure 23. Failure attributed to weak dielectric and possibility of oven overheating contributing to a hot spot near the core. Magnification 22X. Design 2S. Refer to Failure Analysis #13.



Ser. No. 32BFP09

Figure 24. A slight wrinkle was noticed at location of failure. Magnification $5\frac{1}{2}X$. Design 2P. Refer to Failure Analysis #17.



Ser. No. 17EXP03

Figure 25. This photograph shows incomplete solder run down along eyelet rim resulting in a leaky seal such as described in Failure Analysis #35 as a cause of failure. Note - The photograph is of a design 3P which failed because of outgassing but the photograph served to illustrate the poor seal defined as the problem in Failure Analysis #35 on a design 1S.

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APPENDIX A

Capacitor Specification

A. Design Requirements

All capacitors to be used in this program shall be designed in accordance with the recommendations for improved capacitor design which resulted from the program conducted under Contract NAS3-11834 and to the following requirements.

- 1) Design life - The design life for the capacitors shall be 50,000 hours at rated conditons with a 95 percent survival.
- 2) Material - The capacitors shall be constructed of the highest quality materials obtainable, consistent with present state-of-the-art. The dielectric shall be polycarbonate film. When a definite material is not specified, a material shall be used which will meet the performance requirements of this specification.
- 3) Case temperature - The rated operating case temperature of all capacitors designed for this program shall be 125°C.
- 4) Capacitance - The capacitance shall be within $\pm 5\%$ of that specified when measured in accordance with Method 305 of MIL-STD-202C except that the frequency of the test voltage shall be 400 Hz $\pm 5\%$.
- 5) Insulation Resistance (IR) - All capacitors must meet the requirements outlined in Table I 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 $\pm 5^\circ\text{C}$.

Points of measurement shall be terminal-to-terminal and between terminals and case.

Table I - Initial Insulation Resistance Requirements

Capacitor Type	IR at 25°C	
	(MΩ X uf)	Need Not Exceed (MΩ)
Film-Foil	75K	150K
Metallized	100K	200K

Note: Terminal-to-case IR values shall be equal to or greater than the terminal-to-terminal IR values.

- 6) Dissipation factor (DF) - The dissipation factor of each capacitor shall not exceed 0.3 percent for metallized-film types and 0.25 percent for film-and-foil types when measured with an ac voltage not greater than 20 percent of the capacitor's rated dc voltage at a frequency of 400Hz ± 5 percent and a capacitor temperature of 25°C ± 5 °C.
- 7) AC voltage rating - The capacitors shall be designed for operation with the specified ac voltage at 400 Hz at the rated case temperature.
- 8) Dielectric strength - Capacitors shall be capable of withstanding without damage or deterioration, twice rated dc voltage between terminals and between terminals and case for one minute. Capacitors shall also be capable of withstanding, without damage or deterioration, 150 percent rated ac voltage between terminals and between terminals and case for one minute.
- 9) DC voltage rating - The contractor shall assign a dc voltage rating to all capacitors. This rating shall be consistent with the contractor's normal rating practice.
- 10) Impregnation - Where impregnation of the capacitors is required, the design shall allow the use of either silicone oil or polybutene as the impregnant.
- 11) Capacitor element - The capacitor element must consist of conducting layers separated by layers of dielectric film. Extended-foil type construction shall be used in the film-foil types. Insulating, impregnating and filling compounds shall be suitable for the ac application. Compounds used shall not cause any adverse effect on the performance of the capacitor during operation or storage under any expected combination of environmental conditions.
- 12) Circuit design - The capacitor shall be of a simple, two-terminal design with both terminals insulated from the case.
- 13) Leads - Copper or copper-clad steel wire leads shall be used, having a tin-lead coating with a tin content of 40 to 70 percent. Leads shall be axial. Lead gauge shall be #18 AWG (.102 cm).
- 14) Case - The capacitors shall be hermetically sealed in metallic cases. The case shall not be a terminal of the capacitor. There shall be no insulating sleeve around the outside of the case.
- 15) Size - The physical size of the capacitors shall be the minimum consistent with the performance requirements.

- 16) 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 and Procedure IIIa.
- 17) Potential space environment - The capacitors shall be designed to operate continuously under the following conditions or any practical combination thereof, without degradation of electric characteristics.
- a) Gravity - both sea level and zero gravity
 - b) 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
 - c) Acceleration - 6 g's for 5 minutes along any of the three mutually perpendicular axes
 - d) Shock - 20 g half sinewave for 11 millisecond duration along each of three mutually perpendicular axes.
 - e) Vibration - as given in Table II applied along each of three mutually perpendicular axes

Table II - Vibration Levels

Sinusoidal Sweep Frequency Schedule

<u>Freq. Range</u>	<u>Acceler. Level</u>
5-19 Hz	0.05 inch D.A.*
19-2000 Hz	9.0 g's

Sweep Rate: 2.0 octaves per minute
 Sweep Time: For 5-2000 Hz, approximately 4.3 min.

Random Noise Vibration Schedule

<u>Freq. Range</u>	<u>Acceler. Level</u>	<u>Spec. Density</u>
20-400 Hz	6.5 g's rms	0.11 g^2/Hz
400-2000 Hz	18.9 g's rms	0.22 g^2/Hz

Overall Level: 20.0 g's rms

Duration: 4.5 minutes per axis

*D.A. - Double amplitude (maximum total excursion)

- 18) 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.
- 19) Traceability - The contractor must maintain traceability records back to raw material lots employed for capacitors supplied for this program.
- 20) 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

B. Construction Process

The process used to construct capacitor samples for this program shall include the following:

- 1) All raw material used in producing a capacitor of one design (film-and-foil or metallized-film) shall be drawn from single raw material lots. 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. A dielectric lot shall be defined as that material coming from one mill roll of material from one film manufacturer.
- 2) The capacitor construction process shall include a 250-hour, ac burn-in of completed samples at 125°C and 125 percent rated ac voltage.
- 3) After burn-in each and every surviving capacitor shall be subjected to final inspection and testing to assure conformance with the design specifications. As a minimum, the following inspections and tests shall be made:
 - a) Capacitors shall be visually examined to verify that materials, design, construction, physical dimensions, marking and workmanship are in accordance with specification requirements.
 - b) Hermetic seal - The integrity of the hermetic seal shall be tested in accordance with Method 112a of MIL-STD-202C. The following details apply: test condition C and Procedure IIIa. Maximum acceptable

leakage rate shall be 1×10^{-9} atm cc/sec.

Tests for hermetic seal integrity shall be performed prior to electrical characteristic tests during any series of inspection tests of which they are a part.

- c) Capacitance - The capacitance of all capacitors shall be measured in accordance with method 305 of MIL-STD-202C.

The following details shall apply:

The test frequency shall be 400 Hz ± 5 percent.
The accuracy of measurement shall be ± 0.5 percent.

- d) Dissipation factor - The dissipation factor of each capacitor shall be measured at an ac voltage not greater than 20 percent of the rated dc voltage, at $25^{\circ}\text{C} \pm 5^{\circ}\text{C}$, and at a frequency of 400 Hz ± 5 percent. The accuracy of the dissipation factor measurement shall be ± 2 percent of the reading.

- e) Insulation resistance - All capacitors shall be tested in accordance with method 302 of MIL-STD-202C. The following details shall apply:

Test potential - A potential equal to the dc voltage rating of the capacitor being tested or 500 volts dc, whichever is smaller, shall be used.

Points of measurement -

- (1) Terminal-to-terminal
- (2) Between each terminal and the case

The time constant of the measurement circuit shall not exceed one (1) minute.

The capacitors shall be stabilized at an ambient temperature of $25^{\circ}\text{C} \pm 5^{\circ}\text{C}$ before measurement of insulation resistance.

- f) Corona - Using a suitable corona test set, such as HiPotronics Model CDO-3-68, the capacitors shall be tested for existence of corona at voltages up to 110 percent of rated peak voltage. If corona is evident, record onset and offset voltages. All capacitors exhibiting a corona offset voltage less than, or equal to, the capacitors AC rated voltage shall be rejected.

Records of all inspection test results shall be made and kept as part of the data accumulated in this program.

- 4) On completion of final inspection and testing, all capacitors shall be given an individual, serialized number. These numbers shall remain attached to the capacitors throughout all further handling and testing.
- 5) All capacitors which pass final inspection shall be placed in protective storage until needed for the life-test program. Rejected capacitors shall be disposed of by the contractor in accordance with the directions of the NASA contracting officer.
- 6) A record of the yield--i.e., number of capacitors completing receiving inspection divided by the number starting in the construction process--for each type and rating shall be kept as part of the data accumulated in this program.

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. 8
Serial No. 27EXPO4 Design 3-P

Type of Failure: Short
Date Failure Occurred: 7-4-72 Date Removed: 7-21-72
Capacitance: 0.25uF Life Operating Hours: 933
Test Temperature: 125°C AC Voltage: 283 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance	
			Terminal-to-Terminal	Terminal-to-Case
@ 25°C	0.253uF	0.14	1800K megohms	82,000K megohms
@ 125°C	0.252uF	0.06	1.3K megohms	300K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External appearance was good. Eyelet rim to tube seal was good. Terminations were excellent. The amount of liquid fill was less than normally found.

Results of Analysis: Failure occurred through the dielectric. Groups of holes and spots such as shown on photograph #8A were found.

Conclusion: It is concluded that the failure was caused by evolution of solvents from the basic dielectric film. When the solvent outgasses, ionization of the gas occurs (corona) which degrades the film with time and leads to eventual failure.

Photographs:	Date Analysis Performed:	Analysis Performed By:
8A	10-15-72	Kay D. Waterman
		Reviewed By:
		Richard R. Bailey

Refer to Figure No. 17 in report.

FAILURE ANALYSIS NO. 10
Serial No. 26FXP03 Design 3-P

Type of Failure:	Short	Date Removed:	7-21-72
Date Failure Occurred:	7-4-72	Life Operating Hours:	942
Capacitance:	0.25uF	AC Voltage:	368 rms
Test Temperature:	125°C		

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance	
			Terminal-to-Terminal	Terminal-to-Case
@ 25°C	.257uF	.13	1300K megohms	120,000K megohms
@ 125°C	.258uF	.07	1.2K megohms	110K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External condition good. While dismantling, it was observed that both eyelet rim seals were well soldered, terminations were very good, and there was an abundance of liquid fill surrounding the winding.

Results of Analysis: External appearance of the winding was good. As the winding was unwound, occasionally there would be groups of tiny holes found through the dielectric. As soon as the holes penetrated through both layers, failure occurred. There was also evidence of areas where portions of the metallizing from one plate was absent or had transferred to adjacent layers. This capacitor was in oven #2 which did go to 134°C during initial measurements and to 132°C at time of failure due to a problem with the oven control.

Conclusion: Even though the oven temperature went to 134°C and to 132°C on 2 different occasions, the photographs are illustrative of the main reason for failure. The main reason for failure is concluded to be from solvents outgassing or evolving from the basic dielectric film. The gaseous molecules while yet within the winding become ionized and the secondary affect of corona degrades the film to the point of catastrophic failure.

Photographs:	Date Analysis Performed:	Analysis Performed By:
10A & 10B	12-5-72	Richard R. Bailey

Refer to Figure No. 18 in report.

FAILURE ANALYSIS NO. 13
 Serial No. 24BFS14 Design 2-S

Type of Failure:	Short		
Date Failure Occurred:	7-13-72	Date Removed:	7-21-72
Capacitance:	1.0uF	Life Operating Hours:	1005
Test Temperature:	125 ^o C	AC Voltage:	141 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance	
			Terminal-to-Terminal	Terminal-to-Case
@ 25 ^o C	1.030uF	0.10	400K megohms	700K megohms
@ 125 ^o C	1.021uF	0.05	9K megohms	120K megohms

Electrical
Measurements

@ 1000 hours	1.023uF	0.03	Shorted	---
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Failure Indicating Mechanism: Megohmmeter During 1000 Hour Electrical Measurement Interval

Physical Condition: External condition appeared good. Internal eyelet seals were excellent and plenty of silicone oil was present surrounding the winding. Termination was good. The dielectrics measured above nominal thickness.

Results of Analysis: Two small dielectric punctures were found within 8" of the ceramic core after unwinding all of the winding. There was no evidence of wrinkles and construction appeared to be very good. Photograph 13A was taken of 1 of the puncture areas. The small white streaks noticed in the photograph were hairline cracks in the material near the puncture.

Conclusion: Failure was caused by weakened dielectric, which could have been partly affected by the faulty control allowing temperature to reach up to 134^oC and partly due to an internal hot spot which is most likely to occur centrally across the width of the dielectric and near the core.

Photographs:	Date Analysis Performed:	Analysis Performed By:
13A & 13B	12-28-72	Richard R. Bailey

Refer to Figure No. 23 in report.

FAILURE ANALYSIS NO. 14
Serial No. 26FXP01 Design 3-P

Type of Failure: Short
Date Failure Occurred: 7-22-72 Date Removed: 9-6-72
Capacitance: 0.25uF Life Operating Hours: 1005
Test Temperature: 125°C AC Voltage: 368 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance	
			Terminal-to-Terminal	Terminal-to-Case
@ 25°C	0.255uF	0.12	1300K megohms	100,000K megohms
@ 125°C	0.256uF	0.06	1.7K megohms	90K megohms

Electrical
Measurements

@ 1000 hours	0.255uF	0.07	330- megohms	100K megohms
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Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: The external case was discolored and gave the appearance as shown in photograph 14A that the eyelet seal may have broken loose. In dismantling the case, the eyelet seal was found to be intact and the area surrounding the winding was well filled with polybutene. Terminations were good and strong.

Results of Analysis: Patches or groups of holes were found in the winding, giving evidence of some chemical activity which may have been accelerated by temperature and presence of voltage. This part was sent to a raw material supplier for comment.

Conclusion: It is concluded that the failure was caused by evolution of solvents from the basic dielectric film. When the solvent outgasses, ionization of the gas occurs (corona) which degrades the film with time and leads to eventual failure.

Photographs:	Date Analysis Performed:	Analysis Performed By:
14A & 14B	1-2-73	Richard R. Bailey

Refer to Figure No. 19 in report.

FAILURE ANALYSIS NO. 16
Serial No. 27EXS07 Design 3-S

Type of Failure:	Short	Date Removed:	9-6-72
Date Failure Occurred:	7-22-72	Life Operating Hours:	1005
Capacitance:	0.25uF	AC Voltage:	283 rms
Test Temperature:	125°C		

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance	
			Terminal-to-Terminal	Terminal-to-Case
@ 25°C	0.253uF	0.15	1200K megohms	500K megohms
@ 125°C	0.253uF	0.06	500- megohms	100K megohms

Electrical Measurements

@ 1000 hours	0.253uF	0.08	260- megohms	120K megohms
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Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: Externally, appearance is good. Eyelet seals were good and an abundance of silicone oil was found surrounding the winding.

Results of Analysis: Groups of holes were found, similar to that found in other parts dismantled. Failure occurred through the dielectric. A portion of the winding was sent out to a consultant for comment on the material and the reaction which is taking place.

Conclusion: It is concluded that the failure was caused by evolution of solvents from the basic dielectric film. When the solvent outgasses, ionization of the gas occurs (corona) which degrades the film with time and leads to eventual failure.

Photographs:	Date Analysis Performed:	Analysis Performed By:
16A & 16B	1-4-73	Richard R. Bailey

Refer to Figure No. 20 in report.

FAILURE ANALYSIS NO. 17
 Serial No. 32BFP09 Design 2-P

Type of Failure:	Short		
Date Failure Occurred:	7-22-72	Date Removed:	9-6-72
Capacitance:	1.0uF	Life Operating Hours:	1006
Test Temperature:	125 ^o C	AC Voltage:	141 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance	
			Terminal-to-Terminal	Terminal-to-Case
@ 25 ^o C	0.998uF	0.07	450K megohms	40,000K megohms
@ 125 ^o C	0.991uF	0.02	13K megohms	190K megohms

Electrical Measurements

@ 1000 hours	0.992uF	0.02	4.5K megohms	220K megohms
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Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External was good. While dismantling, it was noted that eyelet rim to can seal was excellent. Terminations were good as evidenced by the .02% DF at the 1000 hour reading and just prior to test resumption and failure of this part. Adequate polybutene was present.

Results of Analysis: The failure occurred within about 6 feet of the beginning of the winding. Though the winding was found to be nearly free of any wrinkles, the failure did occur through the dielectric near a wrinkle. It is probable that the failure occurred solely due to gradual weakening of the dielectric at the wrinkle.

Conclusion: Failure occurred due to extra stresses present at a wrinkle and as a result of weakened dielectric strength at the wrinkle.

Photographs:	Date Analysis Performed:	Analysis Performed By:
17A	1-5-73	Richard R. Bailey

Refer to Figure No. 24 in report.

FAILURE ANALYSIS NO. 31
Serial No. 22CFS14 Design 2-S

Type of Failure: Short
Date Failure Occurred: 10-7-72 Date Removed: 11-3-72
Capacitance: 1.0uF Life Operating Hours: 2559
Test Temperature: 125^oC AC Voltage: 184 rms

Initial Electrical Measurement	Capacitance	% DF	Insulation Resistance	
			Terminal-to-Terminal	Terminal-to-Case
@ 25 ^o C	1.011uF	0.09	280K megohms	3000K megohms
@ 125 ^o C	1.007uF	0.04	11K megohms	100K megohms

Electrical Measurements

@ 1000 hours	1.009uF	0.03	10K megohms	150K megohms
@ 2000 hours	1.008uF	0.07	10K megohms	160K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External appearance was good. Seals were good. An abundance of silicone oil was present. Terminations were good.

Results of Analysis: Failure occurred thru the dielectric after unwinding about 3/4 of the winding. In the area where failure occurred, there was no evidence of construction deficiency or wrinkles which might have contributed to failure. The dielectric thickness was measured and found to meet or exceed the nominal thickness specified. Operational charts were reviewed and equipment was operating satisfactorily at time of failure. Prior to reaching the area of failure one or two very minute specks or particles were noted in between layers of film and foil.

Conclusion: It is concluded that though no evidence of foreign particles were found in the area of failure but that a speck or particle was noticed prior to reaching the area of failure, that failure was caused by a foreign particle. No other reason for failure could be determined. A photograph #31A illustrates the puncture thru the film and foil and photograph 31B illustrates a small particle noticed in a portion of the winding.

Photographs:	Date Analysis Performed:	Analysis Performed By:
31A & 31B	1-24-73	Richard R. Bailey

Refer to Figure No. 21 in report.

FAILURE ANALYSIS NO. 32
 Serial No. 22CXP01 Design 1-P

Type of Failure: Short
 Date Failure Occurred: 10-8-72 Date Removed: 11-3-72
 Capacitance: 1.0uF Life Operating Hours: 2569
 Test Temperature: 125°C AC Voltage: 184 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance	
			Terminal-to-Terminal	Terminal-to-Case
@ 25°C	0.989uF	0.10	380K megohms	48,000K megohms
@ 125°C	0.988uF	0.05	20K megohms	210K megohms

Electrical
Measurements

@ 1000 hours	0.988uF	0.04	8.4K megohms	240K megohms
@ 2000 hours	0.987uF	0.09	53- megohms	270K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: External appearance was good. An abundance of polybutene surrounded the winding. Terminations were good.

Results of Analysis: Failure occurred through the winding dielectric at about 7 inches from the core and very near the margin. Margins were as specified. A review of the current recorder chart, the daily log, and discussion with the technician revealed that the capacitor failed while the technician was using a fused probe to verify whether or not another capacitor had failed or its fuse had failed due to fatigue. When the other shorted capacitor was temporarily refused with a fused probe, a surge of current could have affected other parts in the same test rack. This is what is suspected for causing a perhaps weakened part #22CXP01 to fail.

Conclusion: Failure occurred due to transient conditions when a fused probe was being used to double check another failed part in the same test rack. The dielectric is thought to be a bit hotter near the winding core and this may have been a contributing factor to failure near the core. No other reasons were found for failure.

Photographs:	Date Analysis Performed:	Analysis Performed By:
none	1-25-73	Richard R. Bailey

FAILURE ANALYSIS NO. 35
Serial No. 22CXS08 Design 1-S

Type of Failure:	Short		
Date Failure Occurred:	11-28-72	Date Removed:	12-22-72
Capacitance:	1.0uF	Life Operating Hours:	3602
Test Temperature:	125 ^o C	AC Voltage:	184 rms

Initial Electrical Measurements	Capacitance	% DF	Insulation Resistance	
			Terminal-to-Terminal	Terminal-to-Case
@ 25 ^o C	0.999uF	0.09	370K megohms	1000K megohms
@ 125 ^o C	0.995uF	0.06	11K megohms	150K megohms

Electrical Measurements

@ 1000 hours	0.995uF	0.04	15K megohms	210K megohms
@ 2000 hours	0.993uF	0.10	7.5K megohms	230K megohms
@ 3000 hours	0.994uF	0.31	9.5K megohms	220K megohms

Failure Indicating Mechanism: Neon Light on Fuse Board

Physical Condition: A thermocouple had been cemented to this particular capacitor to monitor case temperature of parts in the test tray. One eyelet rim to tube solder seal was not as good as it should have been. Terminations were good. There was not the abundance of silicone oil surrounding the winding as normally present.

Results of Analysis: Failure occurred through the dielectric within about 2 feet of the winding core. Construction of the winding was good with proper material and margins. Photographs 35A and 35B illustrate areas found near the point of failure. Photograph 35B in particular illustrates a degree of brittleness in the material.

Conclusion: It is concluded that failure was an indirect result of an incomplete solder seal between eyelet rim and tube in that the silicone oil surrounding the winding leaked out, causing a drying out of the winding and some embrittlement of the winding material. This in turn coupled with the greater heat present near the core has been determined as the cause of failure.

Photographs:	Date Analysis Performed:	Analysis Performed By:
35A & 35B	1-29-73	Richard R. Bailey

Refer to Figure No. 25 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).
2. Gosda, Elles, & Bailey: Design and Application of Polycarbonate Capacitors in Aerospace AC Power Systems. NASA Contractor Report No. NASA CR-1897 (August, 1971).

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