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FINAL TECHNICAL REPORT

TECHNOLOGICAL DEVELOPMENT OF CYLINDRICAL
AND FLAT SHAPED HIGH ENERGY DENSITY
CAPACITORS

December 1977

NASA LEWIS RESEARCH CENTER CONTRACT NAS 3-20090

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FOREWORD

This report documents the technical work performed by the Hughes Aircraft Company during the period 22 April 1976 to 15 September 1977 for NASA Lewis Research Center under Contract NAS 3-20090. The NASA Project Managers at Lewis Research Center were Norman T. Grier and Thomas J. Riley. The Program Managers at Hughes Aircraft Company were Dr. Robert D. Parker and Dr. Joseph A. Zelik. All work was performed at Hughes' Culver City facility.

SUMMARY

The objectives of this program were to develop cylindrical wound metallized film capacitors rated $2\mu\text{F}$ 500 VDC that had an energy density greater than 0.3 J/g , and flat flexible metallized film capacitors rated at $2\mu\text{F}$ 500 VDC that had an energy density greater than 0.1 J/g . Polysulfone, polycarbonate, and polyvinylidene fluoride (PVF2) were investigated as dielectrics for the cylindrical units. PVF2 in $6.0\text{ }\mu\text{m}$ thickness was employed in the final components of both types. Capacitance and dissipation factor measurements were made over the range 25°C to 100°C , and 10 Hz to 10 kHz. No pre-life-test burnin was performed, and six of ten cylindrical units survived a 2500 hour AC plus DC life test. Three of the four failures were infant mortality. All but two of the flat components survived 400 hours. Finished energy densities were 0.104 J/g at 500 V and 0.200 J/g at 700 V, the energy density being limited by the availability of thin PVF2 films.

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I. INTRODUCTION

The program reported herein was a follow-on to a previous NASA contract completed in 1975 by Hughes Aircraft. In that original program, basic material and design studies were made, and a small number of capacitors were built and tested. The present program was intended to further develop fabrication procedures for both cylindrical and flat high energy density capacitors. Repeated reference will be made throughout this report to the results of the first study, contained in NASA CR 124926, dated February 1976.

The program was divided into a series of 8 tasks:

- I. Development of Cylindrical Capacitors
- II. Cylindrical Samples Fabrication
- III. Development of Flat Flexible Capacitors
- IV. Flat Capacitor Samples
- V. Life Testing
- VI. Failure Analysis
- VII. Capacitor Characteristics
- VIII. Capacitor Manufacturing Report

Each of these Tasks except the sample fabrication Tasks, II and IV, is discussed in a chapter in the body of this report.

II. DEVELOPMENT OF CYLINDRICAL CAPACITORS

In Task I techniques were developed to fabricate small cylindrical capacitors using 2 μm to 25 μm (8 GA to 100 GA) metallized dielectric film. The objective of the task was to produce high energy density capacitors using polycarbonate, polysulfone or polyvinylidene fluoride capacitor film. For this task 8 GA and 14 GA polycarbonate and 24 GA polyvinylidene fluoride films were used. The basic approach taken was to improve upon the past methods for winding the components, starting with building a capacitor winder to specifically handle narrow widths of small gauge films. This program was successful in winding wrinkle free components using 14 and 24 GA film. Although films thicker than 24 GA were not used, it is expected that thicker gauge films would be very easy to wind, based on the ease of winding high quality parts with the 14 and 24 GA material. The 8 GA material was very difficult to handle and no wrinkle free parts were produced from the 8 GA film using the winding techniques that were successful with the thicker films. After several attempts at winding capacitors from 8 GA film, the development efforts with this film were stopped since it appeared that a fairly large amount of time would be required to develop winding techniques for this film.

A requirement of this contract was that the successful and unsuccessful methods for winding capacitors from the above mentioned films be documented and reported. The sequential steps taken to develop the high energy density cylindrical capacitors produced on this program are presented below. Unsuccessful and successful techniques are included. The detailed procedure for manufacturing these components is presented in Section 6 of this report.

The nominal specifications for the cylindrical capacitors to be produced using the fabrication techniques developed in Task I were:

1. Rating: 2 μ F, 500 VDC, 5 A AC, 10 kHz
2. Energy density: greater than 0.4 joule/gram uncased
greater than 0.3 joule/gram cased
3. Design life: The design life shall be at least five (5) years of continuous operation at rated conditions.
4. Case temperature: The rated operating case temperature range of all capacitors shall be -30°C to 100°C .
5. Design of capacitor packaging: The capacitor packaging shall be a simple two terminal design with both terminals insulated from the case. The packaging shall be of a type suited for use in space and aircraft environments.

The required energy density rating for these components is incompatible with the operation at 500 V of capacitors wound of these films in the thinnest gauges available. The maximum theoretical energy densities achievable are 0.178 J/gm with the 24 GA polyvinylidene fluoride film and 0.203 J/gm with the 14 GA polycarbonate film. These values are calculated for uncased capacitors that have no air gaps between layers (i. e., tightly wound), and no margins or cores. For the uncased components fabricated on this program, the maximum energy densities at 500 V were 0.104 J/gm with the 24 GA polyvinylidene fluoride film and 0.118 J/gm with the 14 GA polycarbonate film. The PVF2 components would achieve an energy density of 0.200 J/gm at 700 V and would probably operate satisfactorily there. For the 8 GA components, assuming that they can be fabricated, the electric field in the material at 500 V would be 6,250 V/mil. Although a small sample of the material might show a dielectric strength of this magnitude in an electrical breakdown test, it is very unlikely that components of this gauge material would be sufficiently free of defects in the film to achieve a part that would operate at 500 V.

The cylindrical capacitors developed on this program are of improved quality over previous parts since they showed a lower infant mortality and an increased life. The capacitors are completely wrinkle free. Those parts that were electrically failed and disassembled showed carbonized failure

zones occurring randomly within the components, not just within a few inches of the core as did the previous components.

CAPACITOR WINDER

A small capacitor winder was specifically designed and built to wind developmental capacitors from narrow widths of thin gauge capacitor films. This machine uses AC torque motor tension control to provide constant dynamically controlled low tension in the film during the winding operation. Since the films are very delicate, low tension is required to avoid film wrinkling, stretching, or rupture. The tension must also be constant for all speeds of the winding spindle to yield good quality, uniformly wound components. The low tension requirement dictates that the tensioning system presents a low frictional torque on the film bobbin shafts. DC torque motors were not used since they have an inherent frictional torque due to brush drag on their commutators which is too large for winding delicate capacitor films. Frictional brake systems for controlling film tension are also undesirable since their braking torque varies with the winding speed so that the film tension becomes speed dependent. AC torque motors do not have brushes and as a result have only a very low bearing friction. The capacitor film bobbins are mounted directly on the shafts of the torque motors. Inertia and friction of the tension sensing arms also have been minimized. The tension sensing arms are equipped with easily adjustable pneumatic dampers which prevent oscillations in the tension control system when the winding operation is started or when the winding speed is changed. The rollers on the tension sensing arms and the finger rollers which guide the films onto the mandrel are all equipped with low friction instrument bearings. The winding spindle and the idler assembly which supports the nondriven end of the winding mandrel use machine type split spring collets to facilitate experimentation with different diameters of winding mandrels. Positioning of the film bobbins with respect to an arbitrary position along the winding mandrel is easily accomplished by axial adjustment of the torque motor mounts. This machine was designed to have a short span of film

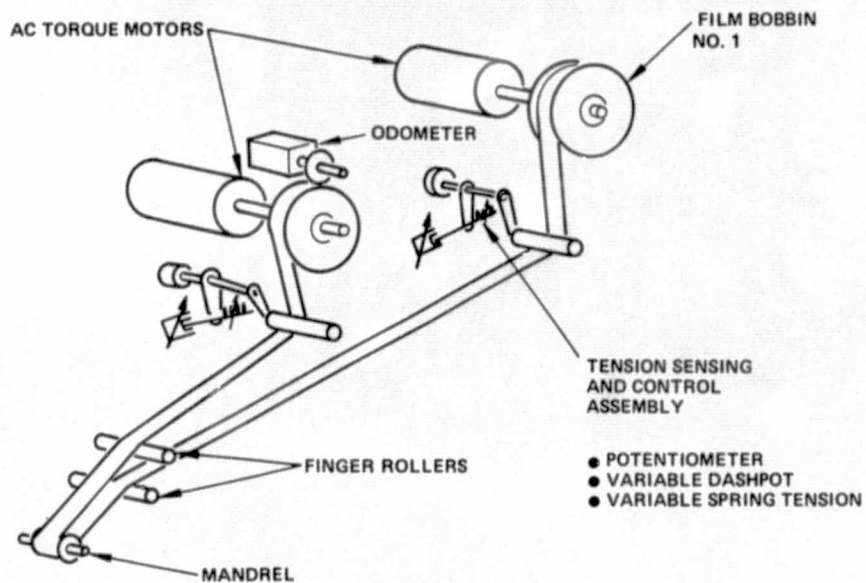
between the bobbins and the mandrel to minimize axial run out of the film while a capacitor is being wound. To further control the positioning of the films, all shafts on the machine have been carefully made parallel. Drawings of the capacitor winder are provided in Appendix A beginning on page 81, and photographs and a sketch are found in Figure 1.

OPERATION OF THE CAPACITOR WINDER

Initial Winding Development Effort:

The initial capacitor development work was done with 11/16 inch width 14 GA polycarbonate film. Metal rods of 1/8 inch and 3/8 inch diameter were used for mandrels. The film was bonded to the mandrels using ordinary rubber cement. Several trial and error steps were taken to determine the optimal adjustment of the tension controls and of the positioning of the finger rollers to obtain wrinkle free capacitors. It was found that wrinkle free windings of one layer per turn could be wound, but that once a circumferential wrinkle initiated, further wrinkling could not be avoided. By placing a finger roller near the mandrel, i. e., about 1 inch center to center, no wrinkling of a single layer winding occurred, even at maximum winding speed.

After successfully winding one layer "capacitors," development of a winding procedure for two layer capacitors was started using the same 14 GA film. A finger roller was positioned about 1 inch from the mandrel. This roller was used either to separate the two films or to superimpose the films before they reached the mandrel. Wrinkle free two layer capacitors could be produced even at maximum winding speed (440 spindle RPM), but it was not possible to maintain good registration of the two films. The two layer windings always showed unpredictable and uncorrectable axial run out of one of the films. To correct the poor film registration, the finger rollers were crowned to provide positive control of the positioning of the films. The crowned rollers were not successful in maintaining good registration of the two films during the winding operation. Rather, the crowned rollers generated a wrinkle in the films which could permanently crease the film when the film tension was high.



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Figure 1a. Capacitor winder - original configuration.

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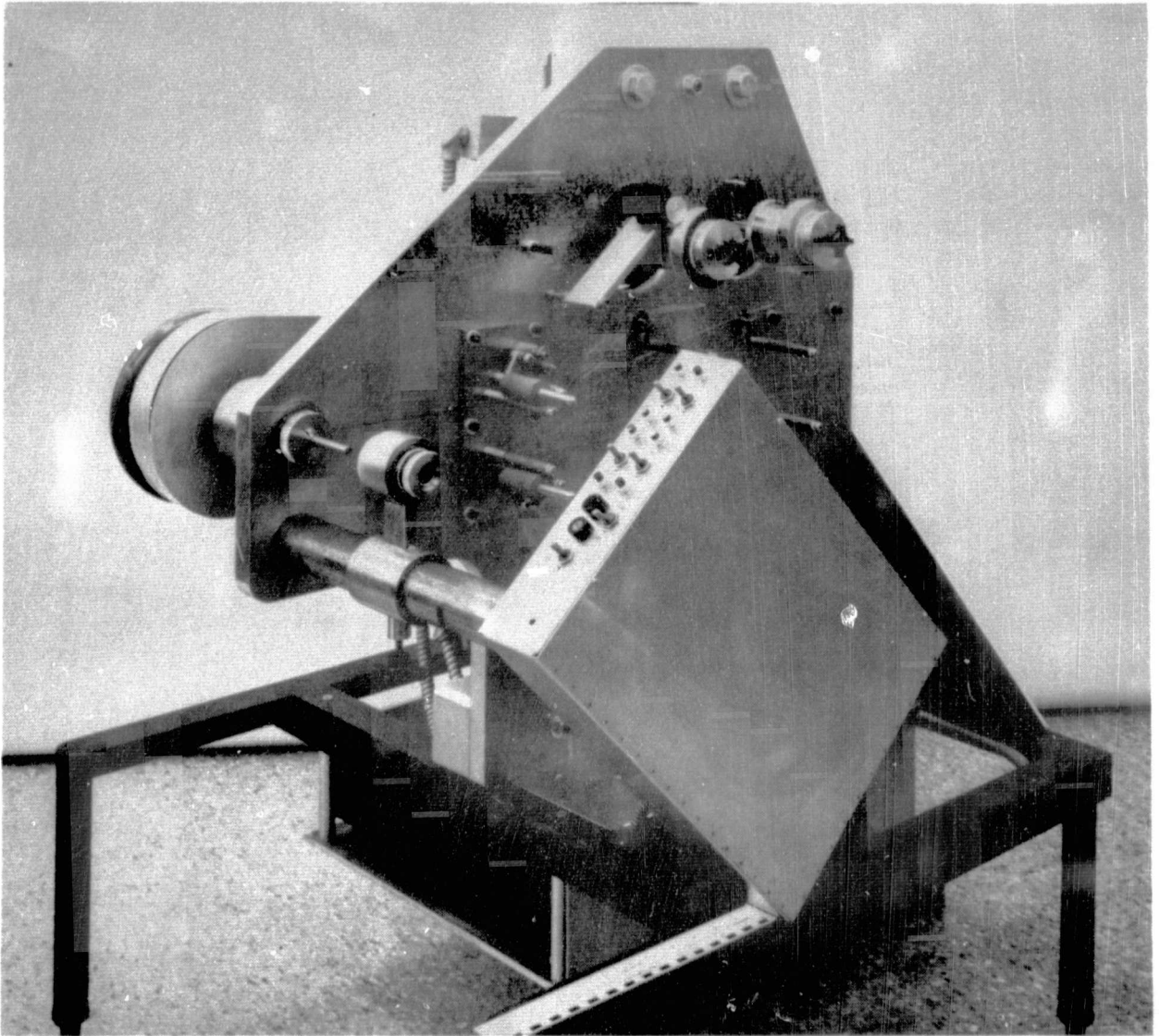


Figure 1b. Capacitor winder, operator's position.

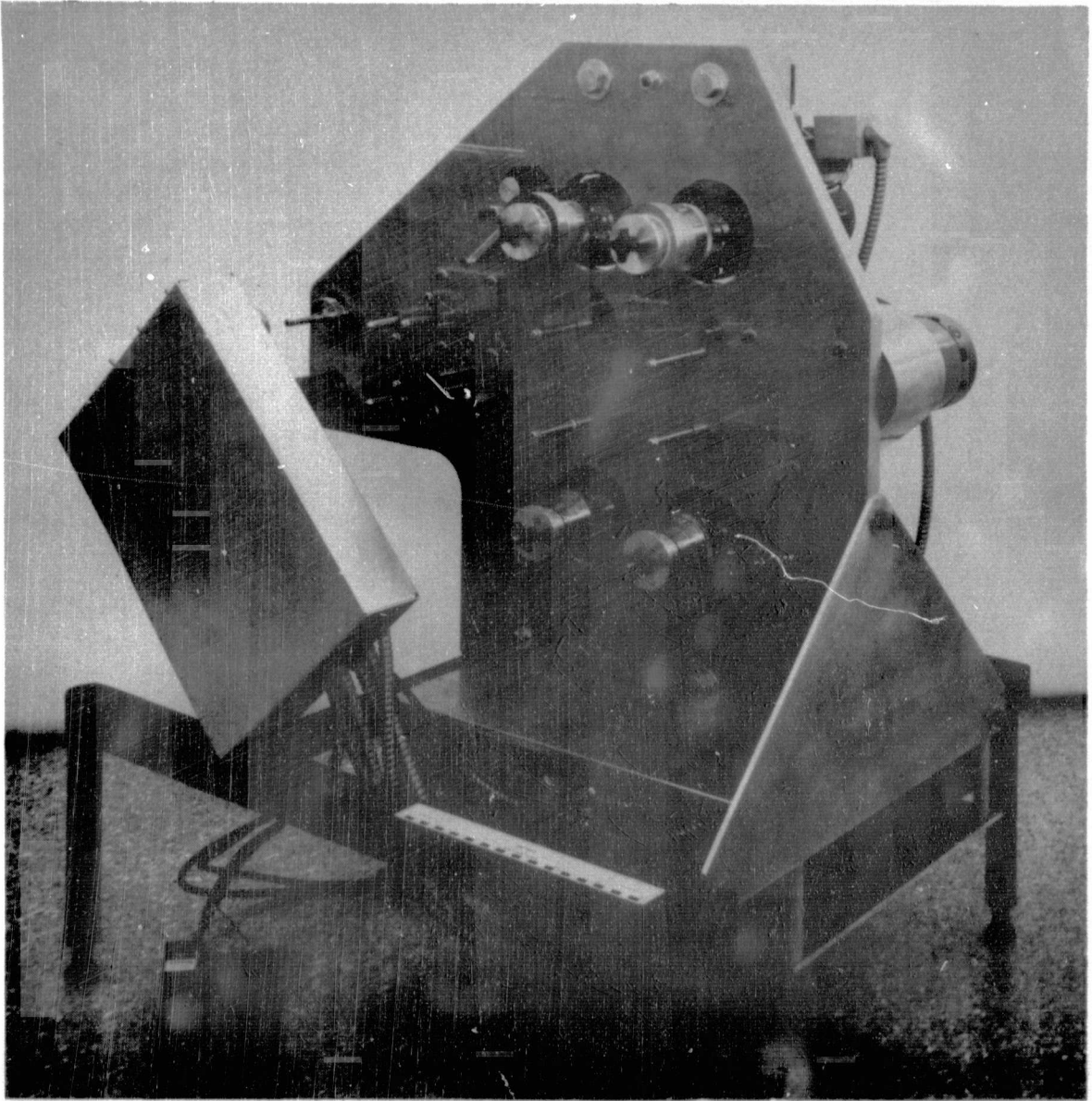


Figure 1c. Winder showing 4 spindles.

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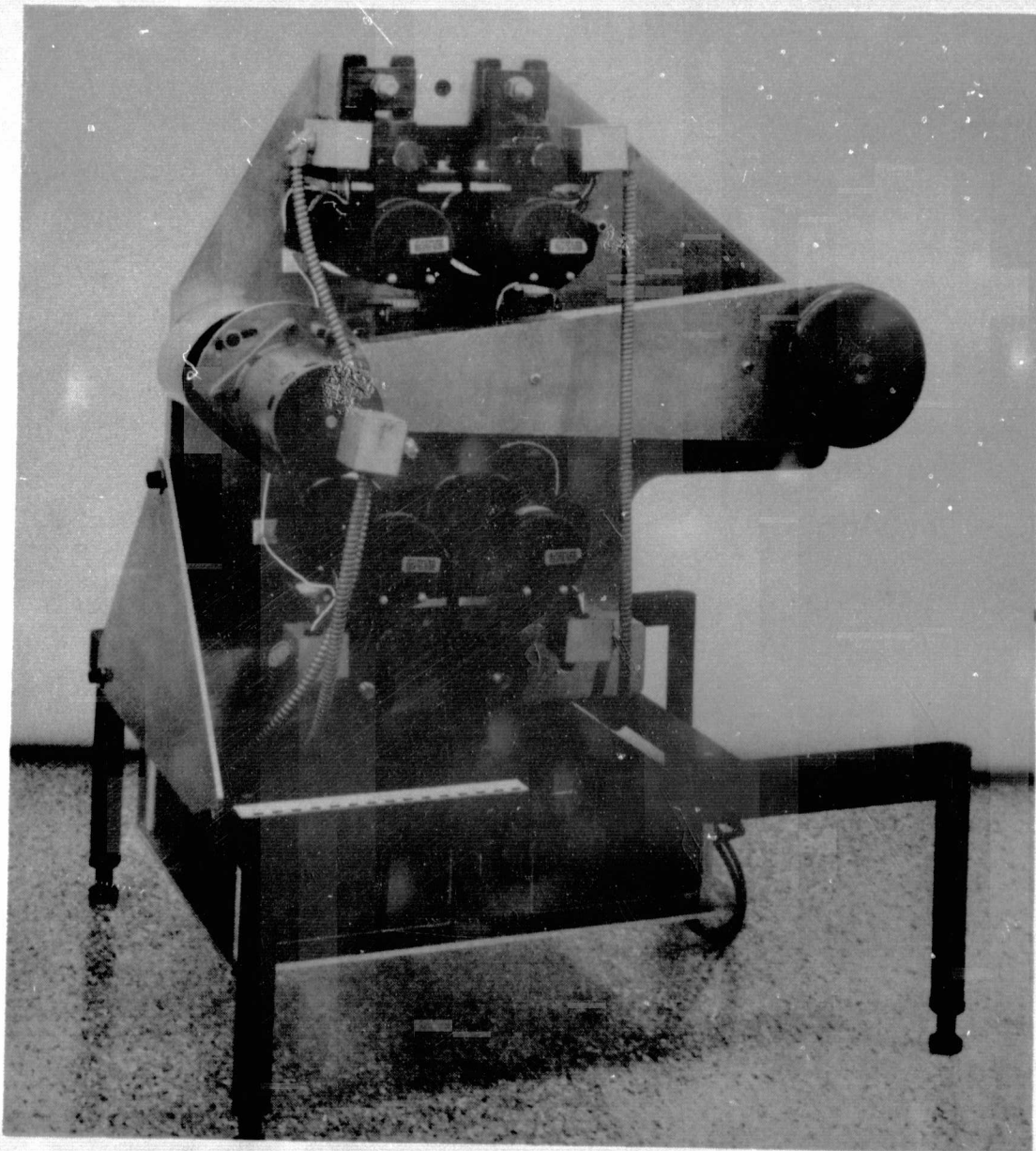
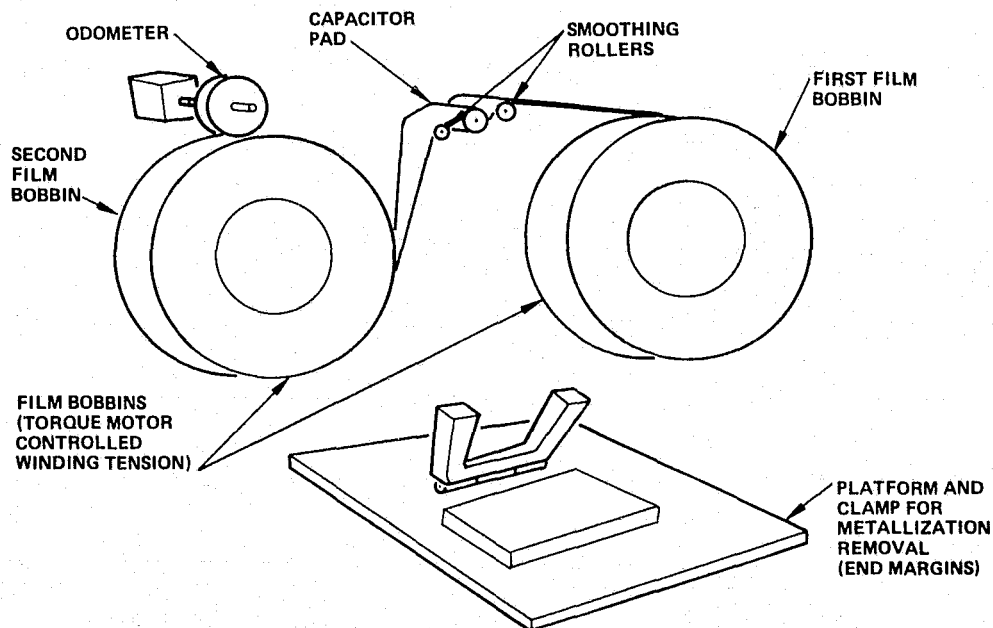


Figure 1d. Winder drive mechanism.

Reconfiguration of the Capacitor Winder

After many attempts were made to eliminate axial run out of the films in a two layer capacitor, the winder was reconfigured to minimize the distance between the film bobbins and the mandrel. The spindle was positioned between the upper film bobbins, and a fixture containing two small smoothing rollers was built and placed on the mandrel. These rollers were located on opposite sides of the mandrel $3/8$ inch from the mandrel axis. The film travelled from the bobbins over the smoothing rollers and onto the mandrel as shown in Figure 2. Tension control arms were not used, and the tension was set by adjusting the amplitude of the input voltage to the torque motors. In this configuration two layer 14 GA polycarbonate film capacitors were readily wound at any speed with good layer registration. The films were easily aligned for attachment to the core by laying the end of the first film directly over the second bobbin. The first film was then bonded to the core, and after a few turns were wound, the second film was bonded to the core over the first film. A small platform was mounted beneath the spindle where the second film could be clamped while metallization



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Figure 2. Capacitor winder - final configuration.

was removed to form margins on the film ends. The finished capacitors were removed from the smoothing roller fixture by either disassembly of the fixture or trimming the ends of the core.

DEVELOPMENT OF CYLINDRICAL CAPACITORS

After the capacitor winder was reconfigured, several wrinkle free cylindrical capacitors were fabricated using 11/16 inch wide, 1/16 inch margin, 14 gauge metallized polycarbonate film. Most of these components were wound on 1/8 inch diameter plexiglass rod cores. The films were bonded directly to the core using a rubber cement which is typically used as a paper adhesive. When the desired length of film was wound, the capacitor was completed by cutting the second film and winding over the cut end with two or three turns of the first film. The first film was then cut, and its cut end cemented to the capacitor pad. This construction is shown in Figure 3. Rubber cement was used on these capacitors due to its convenience of application.

Electrical connection was made by bonding a terminal to the ends of the capacitors with silver conductive paint with a lock nut screwed on the protruding end of the plexiglass rod to provide mechanical strength to the contact. This is shown in Figure 4.

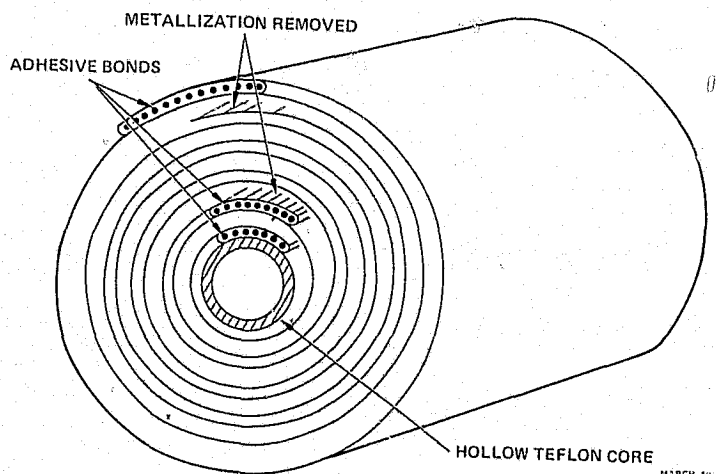


Figure 3. Construction of cylindrical capacitor.

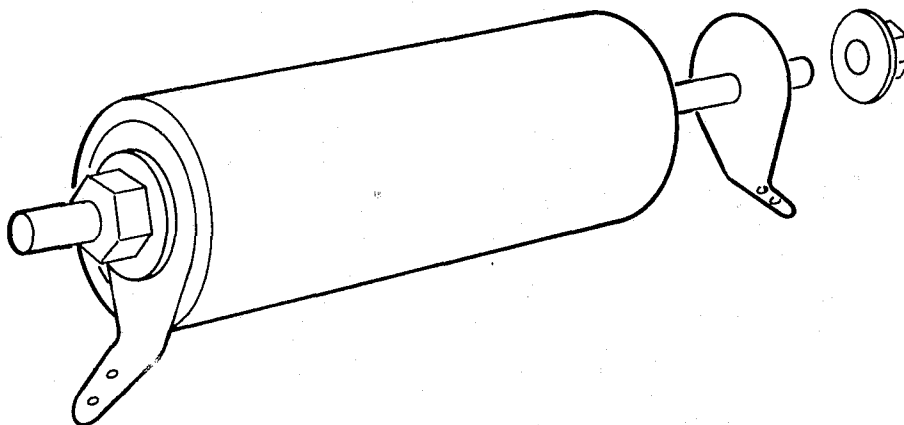


Figure 4. Electrical terminations on cylindrical capacitors.

Capacitance and breakdown voltage were measured on three of the capacitors giving the data shown in Table 1. The capacitance variation is larger than usual because tight specifications were not imposed on the winding length.

When the shorted capacitors were unwound, each showed a burned and carbonized zone extending through many layers and located at about 1/4 to 1/3 of the radial distance between the core and the circumference of the capacitor. The failure did not appear to be due to a wrinkle in the capacitor.

When fabricating capacitor A10, the metallization was chemically removed from both ends of the second film to avoid high field concentrations at the cut ends. Chemical metallization removal was accomplished using a sodium hydroxide etch solution, a dilute acetic acid neutralization solution, and a deionized water rinse. These capacitors were not fabricated in a dust free environment so that the failures could have been initiated by dust particles wound into the capacitor or a pin hole in the film.

TABLE 1. CAPACITOR DATA

Capacitor Number	A8	A9	A10
Capacitance at 1 kHz	1.454 μF	1.805 μF	1.678 μF
DC Breakdown Voltage*	(no test)	480 V	540 V
*The breakdown voltage is the voltage where the component short circuited.			

The PVF2 capacitor film was received in-house after the capacitor winder was reconfigured and operated successfully with 14 GA film. Several developmental capacitors were wound on polystyrene cores using 11/16 inch wide, 1/16 inch margin 24 GA PVF2 film. These components were tested for their capacitance and breakdown voltage, and then disassembled to observe the mode of electrical failure. All components were wrinkle free and showed carbonized areas at random positions in the capacitors.

A dust free laminar flow enclosure was designed and built to house the capacitor winder. An antistatic nylon curtain formed one wall of the enclosure and allowed easy access to the enclosure. Subsequent capacitors fabricated on this program were wound in this enclosure.

Two additional cores were selected for the capacitor development work. Both were teflon tubing of 0.12 inch and 0.10 inch outside diameters and with weights per inch of 0.203 gm and 0.104 gm respectively. The method of assembly of the capacitors remained the same as for previous components. The teflon tubing was sodium etched to prepare its surface for bonding. The first film was bonded to the core using Loctite adhesive, which is compatible with mineral oil. After winding three or four turns of the first sheet, the second sheet was bonded to the core. About 1/2 inch of metallization was removed from the beginning of the second sheet. By using a very small amount of adhesive, bonding was accomplished without causing an appreciable imprint of the adhesive layer in the initial turns of the capacitor. When the desired length of the second film was wound, the metallization was removed from the end of the second sheet, and the end was wrapped into the capacitor. The end of the first sheet was secured with a piece of kapton tape. In all but the first capacitor wound with the PVF2 film, the second sheet was axially offset from the first sheet by about 1/32 inch to allow good electrical connection to the two sheets with a metal filled electrically conducting adhesive. On two of the capacitors, conducting epoxy (Emerson and Cuming conducting epoxy No. 56-C) was used, but this made disassembly of the capacitor after the breakdown voltage test very difficult. On the remaining components, conducting silver paint (Pelco colloidal silver, #1603-1) was used.

Terminal lugs were added to the capacitor pad to provide leads for the tests. Figure 5 shows the details of the electrical connections. Before any electrical tests were conducted, the capacitors were subjected to five 100 V pulses of each polarity to establish a good electrical contact between the conducting adhesive and the aluminization on the film. This voltage pulsing procedure has been found to establish good electrical contact between conducting adhesive and aluminum.

Eight additional PVF2 capacitors were wound, all using the 0.12 inch diameter cores. Four of the capacitors were tested dry, and the remaining four were tested after being impregnated with freon. The impregnation process consisted in first drying the capacitors at 185°F for 12 hours, and then vacuum impregnating them with distilled freon. Table II gives the capacitance of these components along with data on their weight and the length of film in the second sheets. The results of the breakdown voltage tests are presented in Table III.

Capacitor B1 showed a low capacitance and a high dissipation factor because of poor electrical contacts to the capacitor film. The two films were wound exactly on top of each other so that little metallization was available at the ends of the capacitor for contact with the conducting adhesive. Capacitor B4 was not tested for high voltage breakdown because it was apparently shorted while the initial 100 V impulses were applied to it.

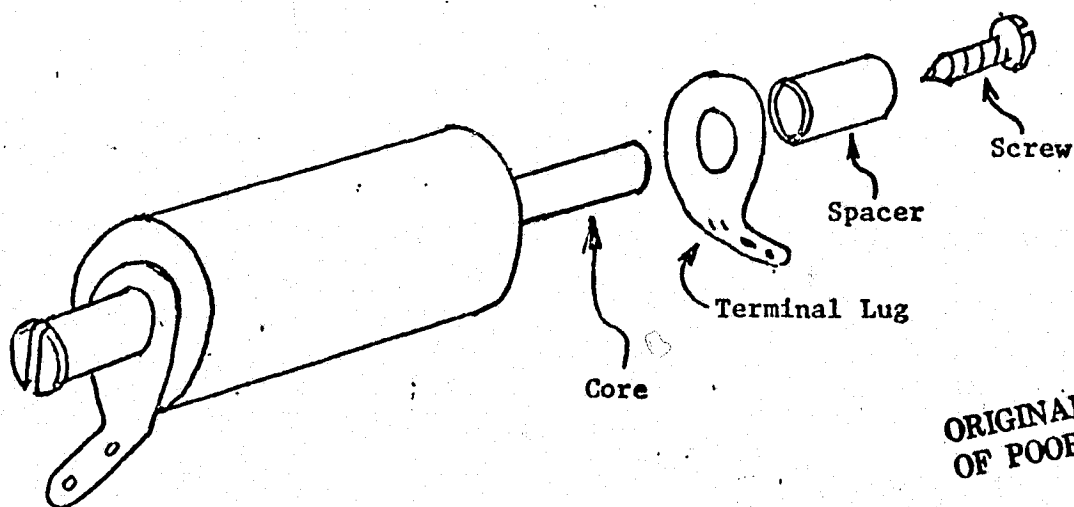


Figure 5. Electrical connections to cylindrical capacitors

TABLE II. CAPACITOR DATA

Capacitor No.	Capacitance (at 1.0 kHz) (μ F)	Dissipation Factor at 1.0 kHz (%)	Length of Second Sheet (cm)	Al Removed From Ends of Second Sheet	Calculated Weight of Capacitor Pad (gm)
B1	0.671	126	591	Yes	2.75
B2	1.921	1.67	603	No	2.68
B3	2.375	1.38	690	Yes	3.21
B4	0	--	670	Yes	3.25
B5	2.228	1.44	652	Yes	2.86
B6	2.270	1.38	652	Yes	2.88
B7	2.274	1.40	664	Yes	2.87
B8	2.316	1.44	666	Yes	2.89

TABLE III. BREAKDOWN VOLTAGE LEVEL

Capacitor No.	Breakdown Voltage	Test Condition
B1	0	Dry
B2	540	Dry
B3	600	Dry
B4	0	Dry
B5	675	Freon
B6	350	Freon
B7	400	Freon
B8	1050	Freon

The failure analysis of Capacitor B2, which did not have the metallization removed from the ends of the second sheet, indicated that there was some arcing at the ends which removed the aluminization, but this did not cause the electrical failure of the component. Several of the components tested at high voltage shorted at the margin. The disassembly of the components indicated that the capacitors were wrinkle free, and that the imprint of the initial bonding zones did not lead to failure of the components.

The breakdown voltage performance of the freon impregnated components was generally disappointing. Prior to impregnation, the components were labeled with Liquid Paper type correction fluid which is not soluble in freon. After the impregnation process, however, small particles of this "paint" were in the freon bath. Some of these small particles could have been introduced into the capacitor during impregnation causing breakdown at a fairly low voltage. On subsequent capacitors this method of labeling was not used.

These capacitors achieved an average energy density at 500 V of 0.104 J/g. This number is based on the actual capacitance and weight of the component without termination, and is about 40% less than the theoretical maximum energy density of 0.178 J/g. Higher maximum energy densities could be achieved if thinner gauge PVF2 film were available. The above components could achieve an energy density of 0.20 J/g at 700 V.

Only one of these PVF2 film capacitors operated at or above 700 V (B8 at 1050 V). The manufacturer quotes a breakdown voltage for 24 GA PVF2 of 2.5 kV dc, so that the present failures occurred well below the capability of the material. The most probable causes of the low breakdown voltage were particulate contamination of the film or pin holes in the capacitor film.

In the course of winding the PVF2 capacitors, metal flakes were observed to be loosely adhering to the metallized surface of the PVF2 film. Investigation of two of these particles using the scanning electron microscope and Energy Dispersive X-ray Analysis showed that they were pieces of vapor deposited aluminum of about 1-1/2 mil thickness. These particles probably came from the vapor deposition apparatus used to metallize the roll of PVF2 film before it was slit and wound on bobbins. These particles were relatively large and were readily observable by the operator since they were adhering to the surface of the film facing the operator. Any particles adhering to the underside (non-metallized side in this instance) would not be detectable to the operator and would most likely be wound into the capacitor. These particles may have caused the low breakdown voltages of some of the PVF2 film components.

The final development in the process for fabricating the capacitors that were life tested was a method for electrically etching away metallization to form the end margins on the second sheet of the capacitors. This was accomplished by grounding the film with a large area electrode (about $1/2$ inch²) and then sweeping a needle electrode held at 70 VDC over the film where the metallization was to be removed. The axis of the needle was held at a small acute angle with respect to the surface of the film, and the needle was moved in a circular sweeping motion such that the needle contacted the metallization when the needle was moving towards the grounding electrode. For each sweep of the needle electrode, the needle was advanced approximately $1/16$ inch onto the remaining metallization. A potential of 70 VDC was found to adequately remove the metallization without blackening or burning the film.

DESIGN OF A LIGHT WEIGHT CAPACITOR CASE *

A light weight case was designed which is suitable for use in space and aircraft environments. The major design goals were:

- Weight of case 1.25 gm or less
- Two terminal case with both terminals insulated
- Reasonable manufacturability

This case should also be capable of meeting MIL environmental requirements. Since the capacitor may be impregnated with oil or other dielectric fluid, the case must be completely leak-free, bakeable at high temperatures, and constructed from materials which are compatible with the impregnant. Also, the construction and assembly operations should not require the invention of new technology.

Several capacitor case designs were considered. An all plastic case would be extremely light weight and low cost, and would be satisfactory for many applications. The major limitations are the high permeation of gases through plastics and the difficulty of meeting the environmental requirements. A light weight all glass case could be designed, except it would be very fragile. Other proposed designs used indium and gold diffusion seals for the end

*This work was performed on the previous contract, NAS 3-18925.

caps. Such seals would be delicate and not necessary to make a moderately light weight case.

The design which is proposed is similar to standard hermetically sealed commercial and MIL capacitors. These usually consist of a metal cylinder with glass-to-metal seal end caps soft soldered to the cylinder. The major change to achieve light weight is redesign of the end cap.

CASE DESIGN

As a basis for comparison, a cross-sectional view of a typically hermetically sealed capacitor is shown in Figure 6.

This design is used for high reliability military applications and is made by Components Research, Inc. The total weight of the case is 3 gm. The case cylinder is nickel alloy tubing. The end caps are kovar-glass. The capacitor section has extended foils which are spray metallized on each

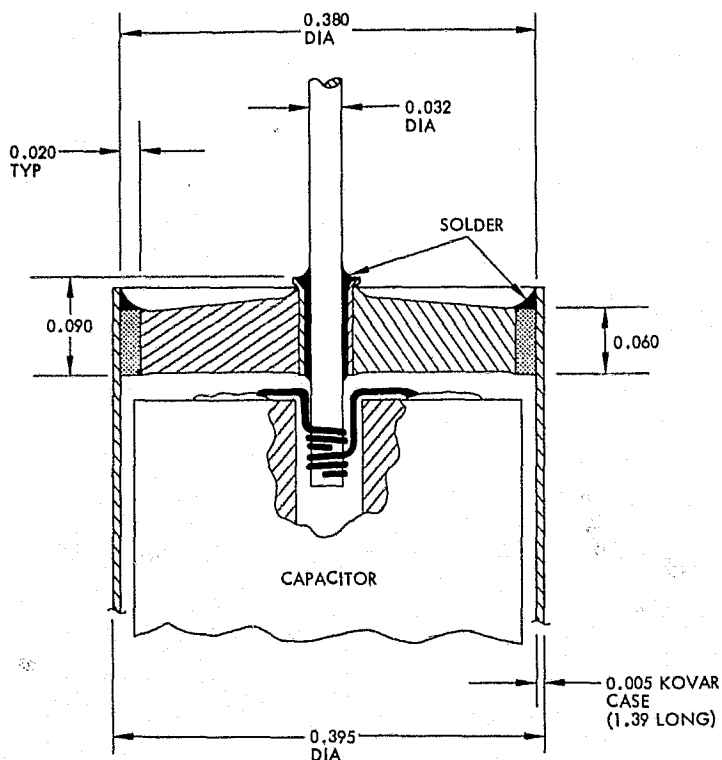


Figure 6. Standard MIL-type capacitor case — view of one end.

end. Wires are soft soldered to the metallization and the wire lead for the electrical connection. To hermetically seal the component the end caps are soft soldered to the case. After impregnation the lead opening in the end cap is sealed with soft solder.

The case for a high energy density capacitor should be substantially lighter in weight. The commercial case described above weighs 3 gm. Several approaches may be taken to achieve this. The one selected is to design a case similar to the typical case shown in Figure 6. It is apparent that the case cylinder can be made from thinner wall material. The two end caps, however, account for two-thirds of the total weight, therefore lighter end caps have to be designed.

The proposed light weight capacitor case design is shown in Figure 7. For convenience the case cylinder is Kovar with a wall thickness of $127\text{ }\mu\text{m}$ (5 mils). Kovar is used for the cylinder to permit joining the Kovar end cap and cylinder by welding. Either heliarc or resistance welding are

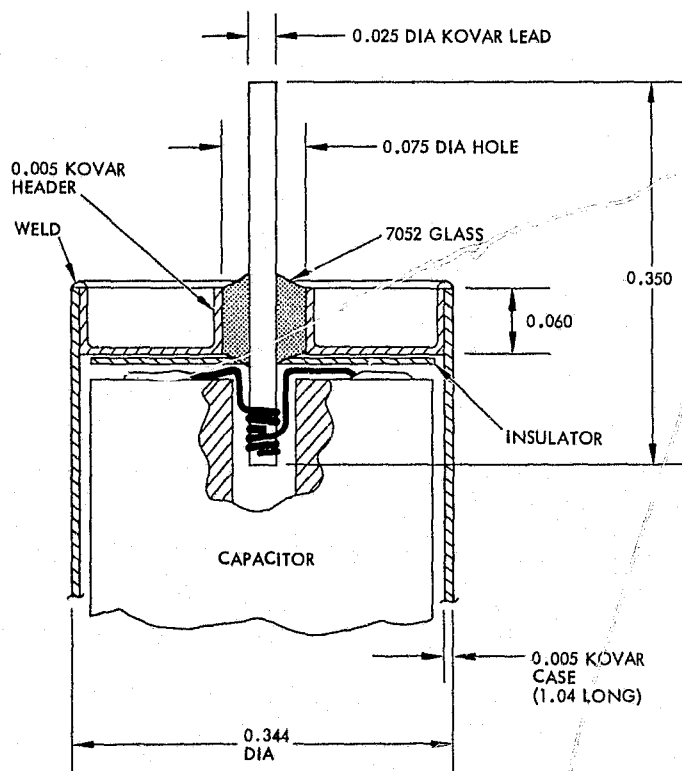


Figure 7. Improved very lightweight case.

feasible. The operation may be performed manually for small quantities and automatically for production. Alternatively, the end cap and cylinder may be soft soldered. This might be desirable for prototype and development work, but the end cap would be slightly heavier. A soft soldered case might be disassembled easily and reused. No special tools or equipment are needed. It should be pointed out that the clearance required for welding and soft soldering are different. For welding a tight or interference fit is necessary. For soft soldering a radial clearance of approximately 0.004 inch is required.

The end cap is specially designed for this application. The Kovar is designed to be made on a lathe or screw machine. With some changes it could also be stamped. Sealing of the glass to the Kovar is normally done in a high temperature furnace. It is possible to make prototypes or small quantities of end caps by hand or in a vertical glass lathe. Also, a very large variety of standard feedthroughs are commercially available. By compromising the design and somewhat increasing the weight, a standard feedthrough could be used.

The process of assembling the capacitor is an important factor in achieving high energy density and reliable performance. The design of the above case is consistent with the stringent process requirements. The construction is entirely of metal and glass. The case may be chemically cleaned and vacuum baked at elevated temperatures. Kovar and glass are compatible with normal impregnants. For convenience the leads are soft soldered but they could be welded to eliminate the lead-tin solder.

The calculated weight of the proposed light-weight capacitor case, shown in Figure 7, is summarized in the following table:

<u>Item</u>	<u>Number Required</u>	<u>Material</u>	<u>Weight (gm)</u>
Case	1	0.005 Kovar	0.749
Kovar Lead	2	0.025 Dia Kovar	0.023
Glass Bead	2	Type 7052 Glass	0.010
Kovar Cup	2	0.005 Kovar	0.079
Insulator	2	0.005 Kapton	<u>0.008</u>
		Total Weight	0.989

III. DEVELOPMENT OF FLAT FLEXIBLE CAPACITORS

On task III of this program, a high energy density flexible flat capacitor was developed using metallized 24 GA PVF2 capacitor film. This component consists of 11 layers of capacitor film bonded together, with connections via conducting adhesive electrodes. In order to develop this component several technical problems had to be solved in the areas of interfilm bonding, and electrical connection to the final component. A contractual requirement is that the successful as well as the unsuccessful methods for fabricating these components be documented and reported. The detailed fabrication method development process is presented below, giving both the successful and the unsuccessful procedures used to finally arrive at a method for producing flat capacitors. The detailed manufacturing procedure for building flat capacitors is presented in Section 6.

The nominal specification for these components requested in the contract are:

Rating: $2\mu\text{F}$, 500 V dc, 5 A ac, 10 kHz

Operating temperature: -30°C to 100°C

Energy density: greater than 0.1 J/g

For the final developed components, the energy density was greater than 0.1 J/g at 500 V on the average.

The development of the flat capacitors progressed in two phases:

1. Film bonding technique development.
2. Electrical connection development.

For clarity these phases will be discussed separately, even though problems in each phase were often identified and solved simultaneously.

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FILM BONDING TECHNIQUE DEVELOPMENT

Adhesive Coated Film Technique Development

The initial approach taken for fabricating flat capacitors was to precoat the PVF2 film with adhesive and then to bond several layers of film under pressure and at elevated temperature.

A coating machine for the application of a thin layer of adhesive to the 6 μ m PVF2 film was constructed and is shown in Figure 8. This machine, which was operated on a laminar flow bench to prevent film contamination, consists of feed and take-up reels, dip tanks, and a heated drying tower.

Two adhesive systems were evaluated to determine coating thicknesses achievable, character of dried films (i. e., wrinkled, puddled, blotchy, tacky) cure temperature, and handling ease. The two adhesive systems considered were: an epoxy-polyamide system curing at 325 $^{\circ}$ F and a solid epoxy/amine salt system curing at 200 $^{\circ}$ - 250 $^{\circ}$ F. Both these adhesives presently appear to give satisfactory coatings on the PVF2 films.

The coating machine gave a smooth, flawless, dry adhesive coating. The machine and performance characteristics are as follows:

- Adhesive type: Epoxy-polyamide dissolved in denatured ethyl alcohol; solids content: 2%
- Solution Sp. Gr.: 0.820
- Film Speed: 6 inches/minute
- Coating Thickness: 1-2 microns (2 sides)

However, on drying, the film edge which had been metallized curled badly and introduced a serious problem for the lamination process. Several layers of coated film were bonded together using a specially built vacuum/air bag press fixture. This fixture is a rectangular enclosure divided into two horizontal chambers separated by a rubber diaphragm. The laminate was placed below the diaphragm, and the entire enclosure is evacuated. After the laminate was degassed, the upper chamber was slowly pressurized. The diaphragm initially touches and compresses the center of the laminate and

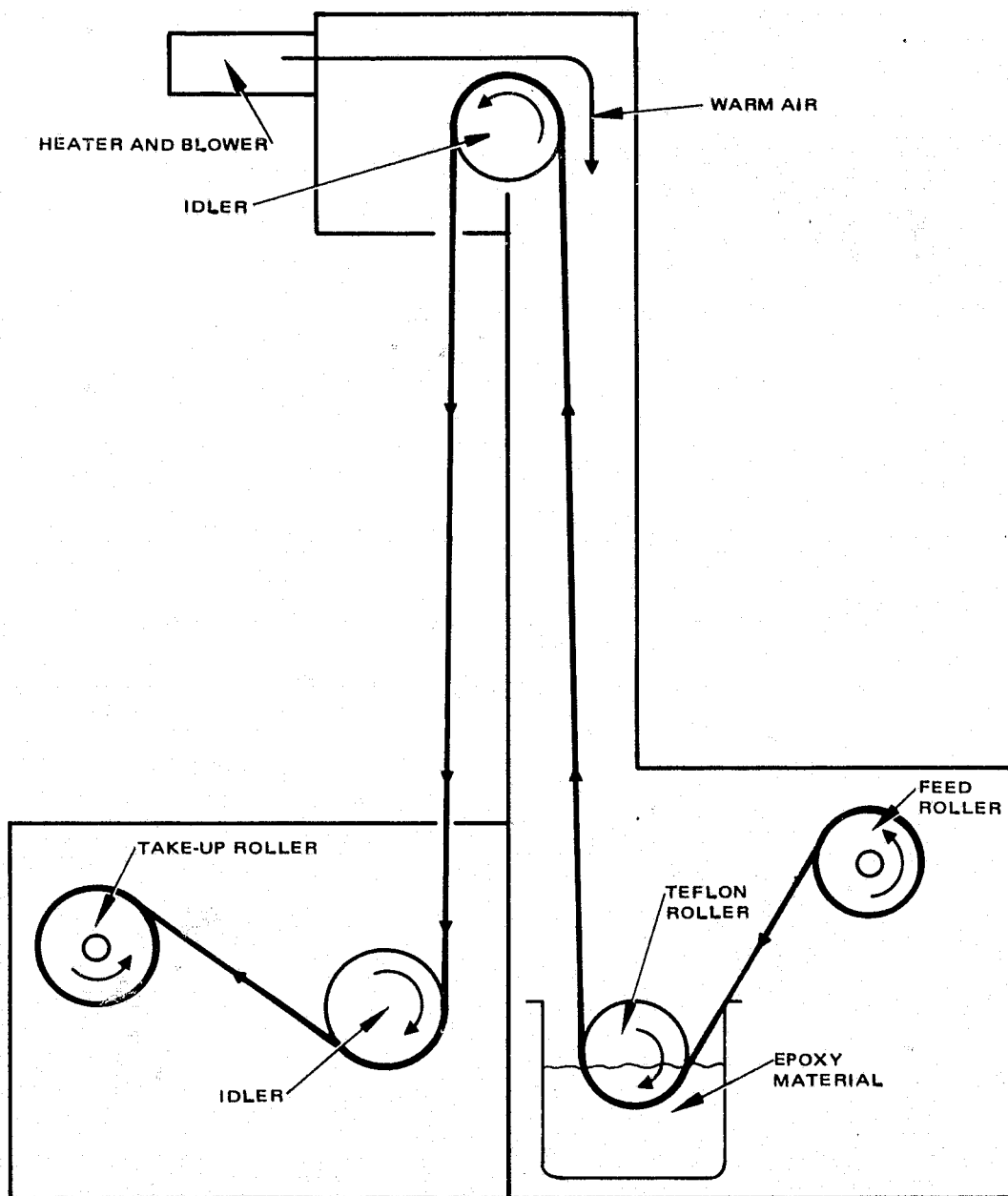


Figure 8. Schematic of drying tower.

radially smoothes any wrinkles in the films. This press was expected to give an essentially void free laminate. The first lamination test was unsuccessful because the curled PVF film, when stretched on the holding frames, would not lie sufficiently flat, and when it was pressed down by the bladder of the tool, undesirable creases in the film were formed.

Additional runs were made with the film coating machine to try to achieve uncurled coated PVF films. None of the runs was successful. It was found that the PVF film is sensitive to organic solvents, particularly the Ketone types, and will curl badly when placed in solvents used for adhesive solutions.

Next, pressure sensitive adhesives were used rather than the thermosetting types. This concept was abandoned due to film handling difficulties. The film coating machine was used to apply either a pressure sensitive silicone or a tacky epoxy adhesive. When joining the individual layers it was difficult to eliminate small air bubbles, resulting in a poor quality capacitor. Also, removing the film from the coater was very difficult. Slight contact with any object or with the film itself resulted in immediate adhesion and unacceptable wrinkling when trying to "unstick" the film.

After the poor results with the precoated films, this approach for building a flat capacitor was abandoned.

Wet Lay-Up Technique Development

After the precoated film lamination technique was abandoned a "wet lay-up" method for fabricating flat capacitors was tried.

In this method, a 10" length of PVF film is stretched on a flat plate and a small amount of liquid epoxy adhesive with long pot life is puddled across the midline of the film. Spacers are laid at each end of the film to keep a 50 mil space as the next length of film is stretched over the first. Now starting at the midline, the second film is pressed down to the first to laminate them. Working from the midline toward the ends, a complete lamination (up to the spacers) is made without trapping air. The spacers are removed and the process repeated for additional layers. When sufficient layers have been laminated, a final pressing to squeeze out excessive adhesive and a heat cure would take place.

The concept of using a "wet lay-up" technique to fabricate flat capacitors proved to be quite practical and was used successfully to produce an eight laminae capacitor, 4-1/2 inch x 5 inch in size. In the fabrication of this first capacitor, two laminae were stretched over a flat plate and were secured at the corners with pressure-sensitive tape. A low viscosity (600 cp) room curing epoxy adhesive was introduced into the center area between these laminae using a long-tipped syringe. The adhesive was spread over the entire film bond area with a standard plastic "rub-out" squeegee. After the assembly was carefully smoothed, the next lamina was laid down in the same manner. When eight laminae were assembled, the lay-up was room-cured. In the fabrication of this first capacitor, no pressure was used to squeeze out excessive adhesive, and a 2 micron bond-line thickness was achieved.

The wet lay-up technique was greatly improved by fabrication of simple tooling to hold the PVF smooth, taut, and in proper position. Dowel pins were placed on the four corners of the lamination plate, and a set of aluminum stretcher bars, 16 mils thick, were drilled to slip over the dowel pins at each end of the plate. The PVF film was then attached to the stretcher bars with double-sided pressure-sensitive adhesive film - the spacing between the bars being determined from the spacing of the dowels on the lamination plate. Fabrication of a capacitor was done in the same manner as described for the first capacitor, except the adhesive can now be puddled in the center of each lamina before the subsequent lamina is added. The lamination fixture is shown in Figure 9.

Heat and pressure were applied in a press after lamination of subsequent capacitors to reduce bond-line thickness and to speed adhesive cure. Uniform loading had a tendency to cause the laminae to slip in relation to one another. The 100°F cure temperature caused the film to wrinkle due to differential thermal expansion between the aluminum spacer bars and the PVF film.

Development work was continued on the "wet lay-up" technique to produce well registered, wrinkle free flat capacitors. The first idea investigated was compressing the wet lay-up with a pressurized bladder to squeeze out excessive adhesive and to reduce the bondline thickness. Ideally the pressurized bladder would first compress the center of the lay-up to prevent

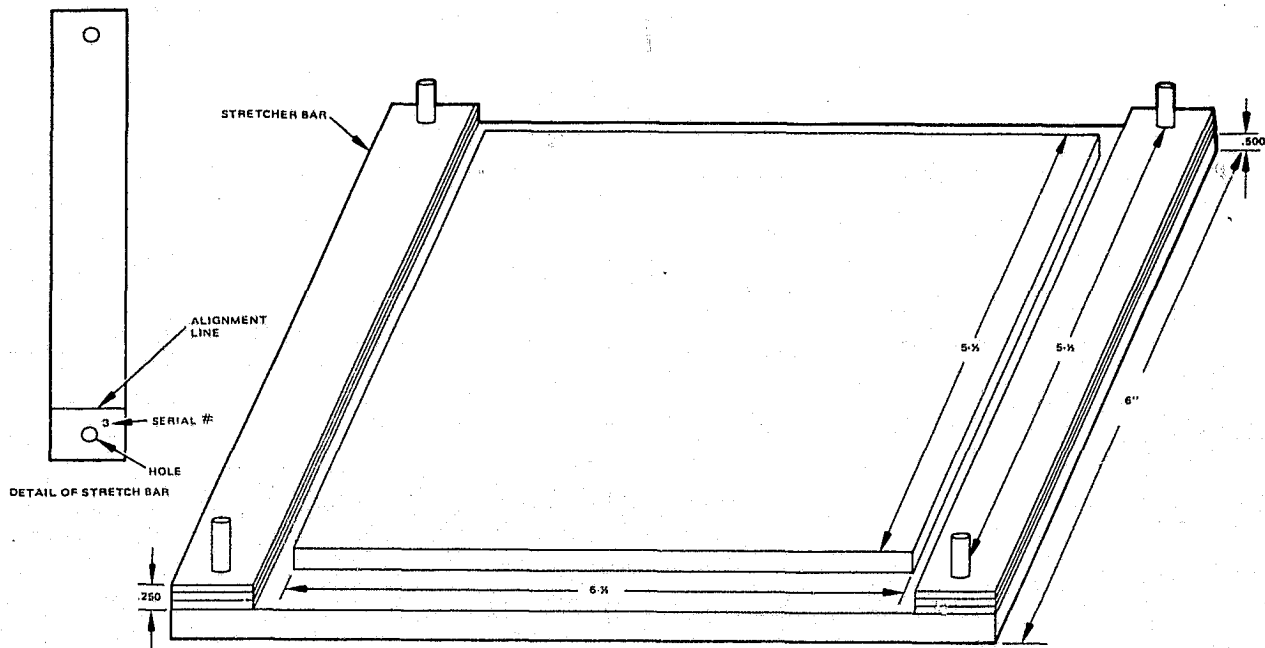


Figure 9. Wet lay-up registration fixture.

slippage of the laminae; then as the pressure was increased, it would squeeze out all excess adhesive. In practice, however, the viscosity of the adhesive was too high to be able to squeeze out the adhesive. As a result the adhesive was captured in place, and thick ridges of adhesive were left in the capacitor. Slippage of the individual laminae (loss of registration) also occurred, so development of this technique was discontinued in favor of improving the "squeegee" method for removing excess adhesive.

An important factor in the "squeegee" method is a low viscosity adhesive which can be easily swept out from between the laminae without tearing, wrinkling or otherwise damaging the metalized PVF film. Two approaches for reducing the viscosity were investigated: heating the adhesive, and adding reactive diluents to an epoxy based adhesive. Heating was quite successful, and using allylglycidyl-ether (AGE) as a diluent showed promise.

The heated adhesive approach was selected for continued development because of the relative ease of controlling the adhesive temperature and because of a potential for allergic reactions to the AGE diluent. Four four-layer capacitors (4-1/2 inch x 5 inch area) were made with each successive

assembly showing improvement over the prior one. The final capacitor was essentially wrinkle free with an average bondline thickness of 1.5 micron. Heating the adhesive presents one technical difficulty: the film stretches and causes some wrinkling at the edges.

The "wet lay-up" technique was improved by using a vacuum bag to hold the laminae in place during the final hand squeegee application to remove excess adhesive and to prevent wrinkling of the capacitor during cure (see Figure 10). Without the vacuum bag, the uncured capacitor assembly was very much subject to wrinkling during the heat cure cycle. The adhesive used was Shell Epon 815 with curing agent A, mixed 112:6.

Using the techniques thus far developed, an additional four layer capacitor and an eight layer capacitor were fabricated for preliminary electrical tests. Electrical contacts were made to the individual laminae by scarfing two corners of the capacitor border and attaching #32 AWG copper wires with conducting paint.

The results of capacitance measurements are given in Table IV.

Note that the dissipation factor of the eight layer capacitor varied, apparently due to the quality of the electrical connection to the individual aluminized layers. A poor electrical connection results in a high contact resistance and a corresponding high dissipation factor. Poor connections also are easily damaged by high current densities.

TABLE IV. CAPACITANCE OF FLAT CAPACITORS

Specimen Number	Size (cm)	Number Layers	Thickness (μm)	Weight (grams)	Capacitance (μF)	Dissipation Factor (%)	Energy Density [†] at 500 V (Joules/gram)
1	11.4 x 16.1	4	32	0.870	0.473	6.9	0.068
2a	11.4 x 16.1	8	68	1.88	1.50	10.6	0.100
2b*	11.4 x 14.2	8	68	1.67	1.35	14.5	0.101
2c*	11.4 x 13.2	8	68	1.54	1.26	6.3	0.102
*Reruns of 11.4 cm x 16.1 cm capacitor after trimming and reattachment of leads to improve the electrical connections.							
[†] Energy density includes conducting paint but does not include leadwires.							

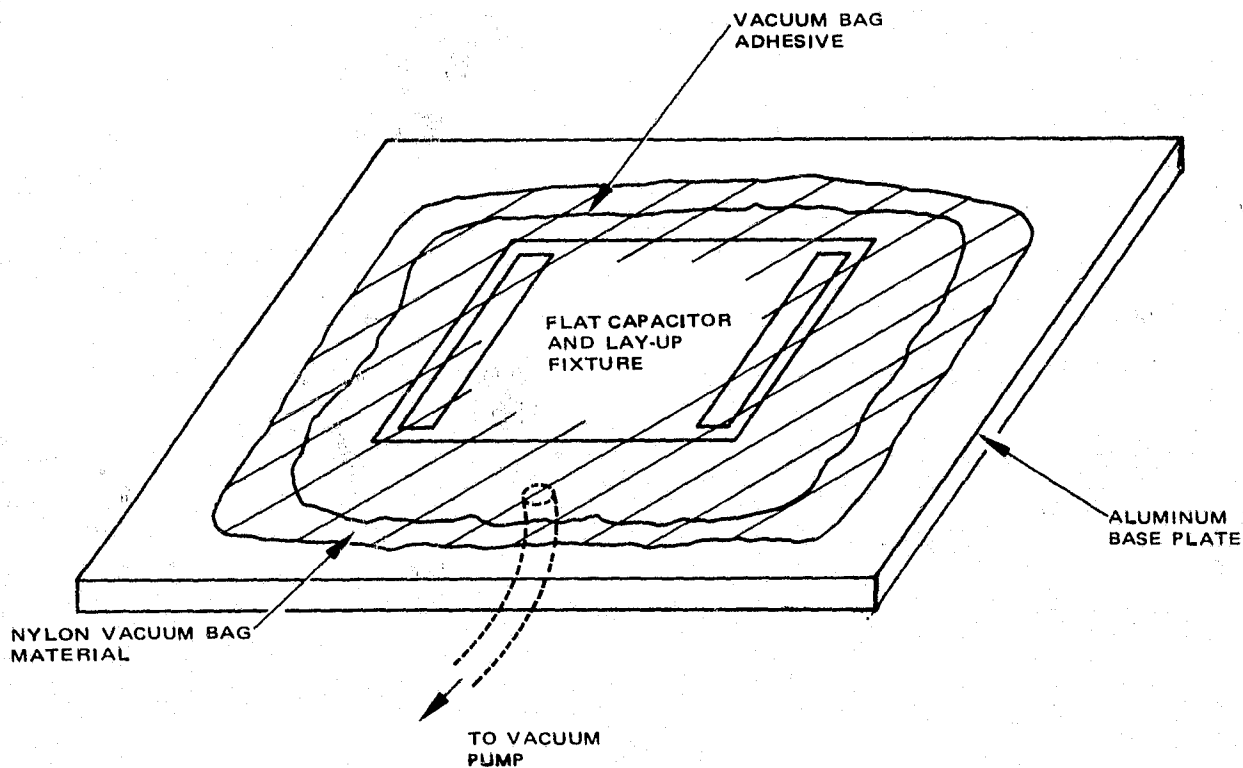


Figure 10. Final squeegee arrangement, with vacuum bag.

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The laminates were also tested to determine their corona inception voltage. Visible flashover at the knife trimmed edges of the four layer capacitor occurred at 120 V dc and at about 90 V dc on the eight layer laminate. The four layer capacitor was subjected to higher voltages in the expectation that the edge flashover would burn away interlayer conducting paths caused by the trimming operation and consequently increase the corona inception voltage. During the process of raising the applied voltage, the electrical contact areas on the four layer capacitor were damaged.

Several additional flat capacitor pads were fabricated with the objective of both increasing the breakdown voltage level of the capacitors and of improving the current-carrying capability of the electrical contact areas.

One step towards improving the breakdown level was the addition of margins on all sides of the flat capacitors. This was accomplished by etching the edges of the aluminized surface with a 10% solution of NaOH. The excess etchant was neutralized with acetic acid, and then the surface was washed with water and dried.

A new approach to the "wet lay-up" technique was tried in an effort to prevent fine wrinkles in the finished laminate which are believed to be sites for the initiation of internal discharges. Fine wrinkling was attributed to differences in the thermal expansion of the film and the adhesive during the cure cycle. The new process involves the fabrication of wrinkle-free two-layer laminates which are then stacked to form a multilayer capacitor. The increased stiffness of the double layers was expected to prevent the fine wrinkles from occurring during the final cure cycle.

The first two-layer capacitor had wrinkles of much larger radius of curvature than the typical fine wrinkles occurring in previous laminates. This laminate had a capacitance of $0.166\mu\text{F}$ and showed initial electrical breakdown at 800 V dc. Large amounts of internal discharge were first detected when 1000 V dc was applied to this capacitor. To provide a large area for electrical connection to the inner conductors, the two layers of the capacitor were offset by about $1/32$ inch. No damage to the electrical connections was observed after the high voltage breakdown test. These results were taken to indicate that high voltage capability and good quality electrical

contacts are attainable with the flat capacitors. It was not evident at this time that interlaminar arcing in multilayer capacitors causes very high surge currents in the contact areas which can severely damage the electrical contacts.

A second two-layer laminate was fabricated which was large enough to produce a six-layer capacitor. This pad was not properly confined in the adhesive curing process and contained areas with fine wrinkles. Initial electrical breakdown occurred at 350V dc. Some of the electrical failure sites occurred along scratches in the metallization generated by the squeegeeing operation. The concept of building double layer laminates for stacking to produce larger capacitors was abandoned due to additional difficulties in building a multilayer layup. The primary difficulties are the possibility of scratching the metallized surface when squeegeeing out excess adhesive and when cleaning off the laminate prior to stacking.

To minimize the problem of scratching the metallization, a new low viscosity adhesive system was formulated consisting of 100 gm Epon 815 epoxy (Shell Chemical Company) and 35 gm Jeffamine 230 curing agent (Jefferson Chemical Company). This adhesive can be used at room temperature to obtain a very thin bond line, and it also can be cured at room temperature.

A six-layer capacitor was made using this new adhesive and having margins on all edges. This capacitor showed severe electrical contact problems with early failure at the contacts when about 100V dc was applied. Further improvement of the electrical contacts was clearly needed. On the next laminates the edges were treated with an epoxy stripper which softened the edges so that individual lamina could be exposed for the application of conducting paint or adhesive. This method of exposing the contact areas frequently removed some metallization resulting in poor electrical contact performance. To guide the efforts to improve the electrical contacts, a study was done to determine the current carrying capability of the basic conducting adhesive to metallized film contact system. This study is reported below.

The final method used for fabricating high quality flat capacitors was as follows: The component was laid-up using the laminating fixture which held each layer taut and wrinkle free and in a precise position within the

lamine. Films were attached to stretcher bars, and an additional margin was produced on each layer perpendicular to the original film margin. The films were laid-up with their metallized surface towards the fixture and each layer increased the overall width of the component, thereby exposing electrical contact areas for each layer of the capacitor.

Adhesive was applied over each layer to act as a lubricant for squeegeeing the previous bondline and to provide adhesive for attaching the next layer. The finished lay-up was vacuum bagged and cured initially for 17 hours at room temperature and then 4 hours at 120°F. After the component was removed from the fixture, the adhesive was removed from the electrical contact areas. The component was terminated using conducting epoxy inlaid with copper wire. The wires were extended beyond the edge of the component to act as leads. This "pyramid" type lay-up is shown in Figure 11.

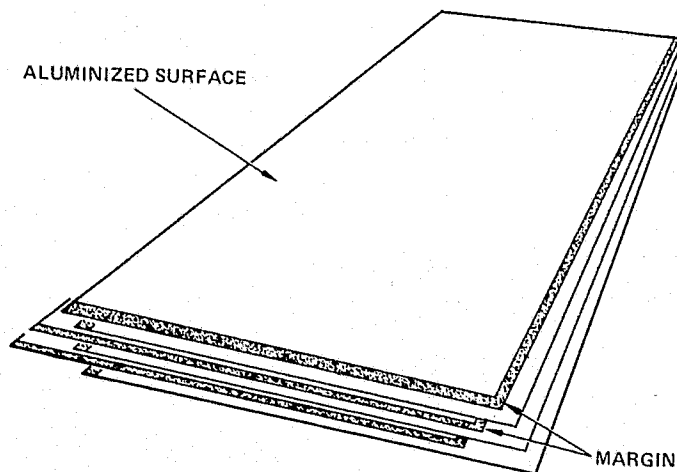


Figure 11. Pyramid construction of a flat capacitor.

Development of Electrical Contacts

For the first flat capacitors electrical contact was established with the individual laminae by slicing the edge of the capacitor at a very acute angle with a sharp blade and then applying conductive adhesive to the exposed conductive layers. This is illustrated in Figure 12. The resulting electrical contacts were very unsatisfactory since they were usually of high resistance and easily destroyed by component arcing.

Two flat capacitors were fabricated primarily to investigate the burn-out problems encountered with the metal-filled adhesive electrical connections used to interconnect the layers of the laminate. The edges of these laminates were softened with epoxy stripper to expose individual layers and consequently allow good contact with the metallization of each layer. This approach was not very successful as the stripping operation damaged the exposed metallization. Experimental evidence indicates that arcing between adjacent layers of a multilayer flat capacitor causes very high surge currents in the metal-filled adhesive contacts as the remainder of the capacitor is discharged via the arc. This current surge can apparently completely destroy the electrical contacts. The current carrying capability of these electrical contacts was investigated experimentally to determine the effects of current surges and the contact area needed to reliably handle a 5 A ac ripple current as is specified for these components.

A series of experiments were performed to observe the effects of a high surge current on the conducting adhesive contacts. Surge currents were generated by discharging a 1.8 μF capacitor through a specimen consisting of two electrodes bonded to a piece of metallized (PVF2) film with conducting

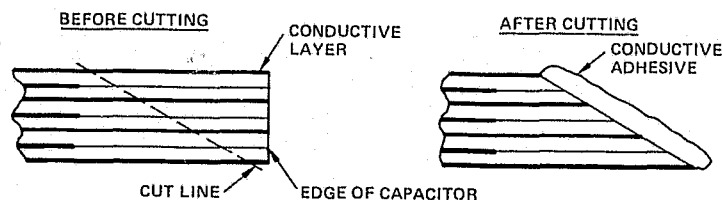


Figure 12. Initial process for making electrical contact on flat capacitor.

adhesive. The initial test specimen consisted of a piece of metallized PVF2 film with two contacts of conducting silver paint each having a circumference of about 1-1/4 inch. A resistance of about 1 ohm was measured between the two contacts. The capacitor was charged to 500 V and was discharged across the specimen so that the initial current surge was approximately 500 A. The contacts were instantly disconnected from the film, and the aluminization immediately beyond the periphery of the contacts was vaporized. By repeating the experiment at lower voltages it was found that the contacts worked satisfactorily for discharge voltages in the 200 - 250 V range. Conducting epoxy contacts were also investigated. The epoxy remained bonded to the PVF2 film, but above about 300 - 350 V, arcing and damage to the metallization on the film occurs.

The current carrying capability of the contact is related to the length of the periphery of the contact area. One test used conducting epoxy contacts with a 4 inch border. The discharge voltage limit with this specimen was 350 V. At this voltage some of the metallization between contacts was blown away in dendritic patterns and surface arcing was prevalent. Since the surge current lasts for only a few microseconds ($RC = 2 \mu\text{sec}$), the heating of the PVF2 film was small and no damage occurred.

These preliminary results illustrated the possible modes of failure of the electrical contacts when subjected to surge currents.

Two types of tests were conducted to determine the current carrying capability of conducting adhesive contacts on aluminized PVF2 film. One test investigated the continuous current capability of the contact system to determine the length of contact needed to carry a 5.0 A rms ripple current. The second test investigated surge current levels that can damage the contacts or the film. The test specimens were pieces of aluminized PVF2 film about 3 inches wide by 4-1/2 inches long with two parallel electrodes of conducting epoxy applied about 1-1/2 inches apart (see Figure 13). Two sets of specimens were fabricated. One set of 10 specimens used standard metallized PVF 2 film which has approximately 400 - 500 \AA thickness of aluminization. The second set of 8 specimens had approximately 900 \AA of additional aluminum vapor-deposited over the original metallization. The test data is given in Tables V and VI for the continuous and surge current tests respectively.

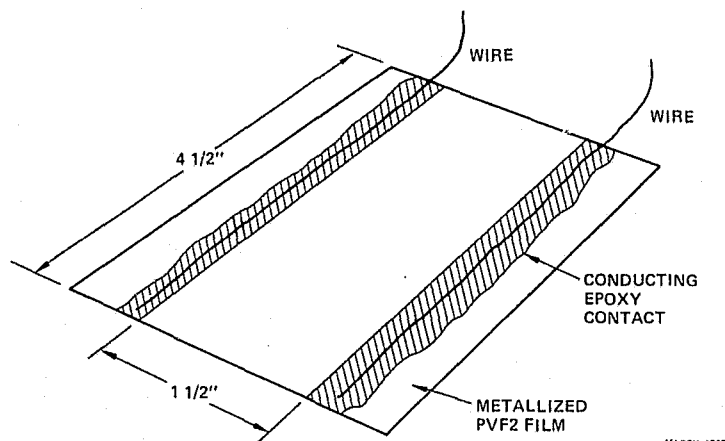


Figure 13. Electrical contact study test specimens.

TABLE V. CONSTANT CURRENT TESTS ON PVF2 FILM WITH CONDUCTING EPOXY CONTACTS

Specimen No.	Material	100 V Impulse	Current at Failure
1	Std*	No	3.00
2	Std	No	2.00
3	Std	Yes	3.00
4	Std	Yes	3.40
5	Std	Yes	4.05
11	Added Metal**	Yes	8.00
12	Added Metal	Yes	9.50
13	Added Metal	Yes	9.50
14	Added Metal	Yes	9.50
<p>*24 GA PVF2 Film metallized at P. J. Schweitzer with ~400 - 500 Å aluminization thickness.</p> <p>**Standard 24 GA PVF2 to which ~900 Å additional aluminization has been added.</p>			

TABLE VI. SURGE CURRENT TESTS ON 24 GA PVF2 FILM
WITH CONDUCTING EPOXY CONTACTS

Specimen No.	Charging Voltage of Surge Generating Capacitor	Initial Resistance of Specimen (Ohm)
6	488*	0.8
7	400	1.0
8	400	1.0
9	300	0.8
10	200	0.8
15	488	0.3
16	488	0.22
17	488	0.22
18	488	0.3
*Maximum voltage available from 500V power supply used to charge 1.8 μ F capacitor.		

For the continuous current tests, the current was increased incrementally and held at any one value for 1 to 2 minutes. The initial experiments showed wide scatter in the current level where the contacts failed and the current dropped to zero. One specimen (No. 3) showed no conduction at all. Also, after a specimen had "failed" but was retested, it was found to again show some conduction. Specimens 1 and 2 were retested after their initial failures, and the applied voltage was increased until the specimens again conducted. These specimens showed a high contact resistance, and at about 30 V across the specimens the metallization at the contact boundaries burned away. The remaining specimens were preconditioned by discharging a 1.8 μ F capacitor charged to 100 V through them. This voltage impulse procedure was repeated 5 times in both polarities for each specimen. The preconditioned specimens gave fairly consistent results in the subsequent tests, with failure of the continuous current specimens only through fusing of the film. The specimens no longer evidenced the behavior where the conductivity would disappear and then return.

It was also observed that having the lead wire imbedded in the entire length of epoxy contact minimized the occurrence of hot spots in the contacts.

When the standard metallization specimens were subjected to repeated high surge currents, failure always occurred by vaporizing sequential portions of the metallization to disconnect the electrodes. Once metallization removal was initiated, it would continue at considerably lower surge current levels. No damage was observed on the increased thickness of metallization specimens, even at the highest applied current surges.

The surge-current-induced damage on the standard metallization specimens illustrated ways in which the metallization on the film can be damaged while fabricating a flat capacitor. Two specimens showed arcing and metal removal along several parallel scratches in the metallization. Two other specimens showed arcing which initiated at a small defect in the metallization and which propagated in dendritic patterns in the central portion of the specimen, as if following a fine crack in the metallization. Actually the localized heating and thermal expansion of the polyvinylidene fluoride film by each arc caused the cracking in the metallization to propagate. These faults may not be readily visible, but they represent a high resistance to a current surge, and consequently are sites for arcing and metal loss. On two of the specimens, metal loss was primarily at the border of the electrodes.

Test results indicate that the standard metallized PVF2 material with conducting epoxy contacts should be able to carry a current of 0.5 A per inch of contact. On the typical flat capacitor with a length of 5 inches, a 5 inch contact length would be adequate to carry a continuous current of 2.5 A per sheet of the capacitor. Since a 2.0 μ F capacitor consists of 10 sheets, a 5.0 A rms ripple current would be distributed over 5 sheets, so that a current of 1.0 A per sheet would be carried by the contacts.

It appears that a flat capacitor fabricated with the standard PVF2 material with good quality contacts would be entirely adequate to handle a 5.0 A rms ripple current. The material and contacts would still have potential problems with current surges when arcing between two layers of the capacitor caused the entire capacitor to discharge through the arc zone. With very careful construction of the capacitor, and careful handling of the

film to avoid damage to the metallization, arcing between layers should be prevented at an operating voltage of 500 V dc. Also, to ensure good contacts, future capacitors will be constructed in a "pyramid" structure, where successive layers of the same polarity are displaced by a small amount (c. 1/32 inch) so that a good contact can be established with each layer. Figure 9 illustrates the pyramid construction of a flat capacitor.

A strip of PVF2 film that had added metallization was used to construct a 5 layer flat capacitor using the pyramid structure. Some curling of the edges of the film due to the vapor deposition process made alignment of the various sheets very difficult while fabricating the capacitor. Tests of this capacitor gave promising results in that the contacts remained intact even after the capacitor developed severe arcing. The final components used standard film with the pyramid layup with careful consideration to the handling of the film. In this way components useable at 500 V dc and with a 5 A rms ripple current were achieved.

IV. LIFE TESTS

The life testing prescribed in the statement of work was simple and straightforward. The requirements were:

- 20 capacitors, 10 each type
- 500 VDC plus 20 V 10 kHz AC
- 2500 hours, 25°C exposure.

This life test was identical to that employed on the previous program, so the same test fixtures were used. The components were fabricated according to the procedures contained in Part VII of this report. The cylindrical units were mounted in a single common case, to save time.

CIRCUITRY

The design of the life test circuitry requires one main inverter and five secondary inverters. In Figure 14 the main inverter and one secondary inverter are shown; the four other inverters attach to the four sets of windings on T_1 .

LIFE TEST RESULTS

No preliminary burn-in testing, as is customarily used in the passive parts industry, was performed. This testing selects and eliminates components that would fail in "infancy," on the first part of the bathtub curve.

For the wound capacitors, there was one failure during initial run-up and four failures during test. At least three of these failures would have been eliminated with the burn-in.

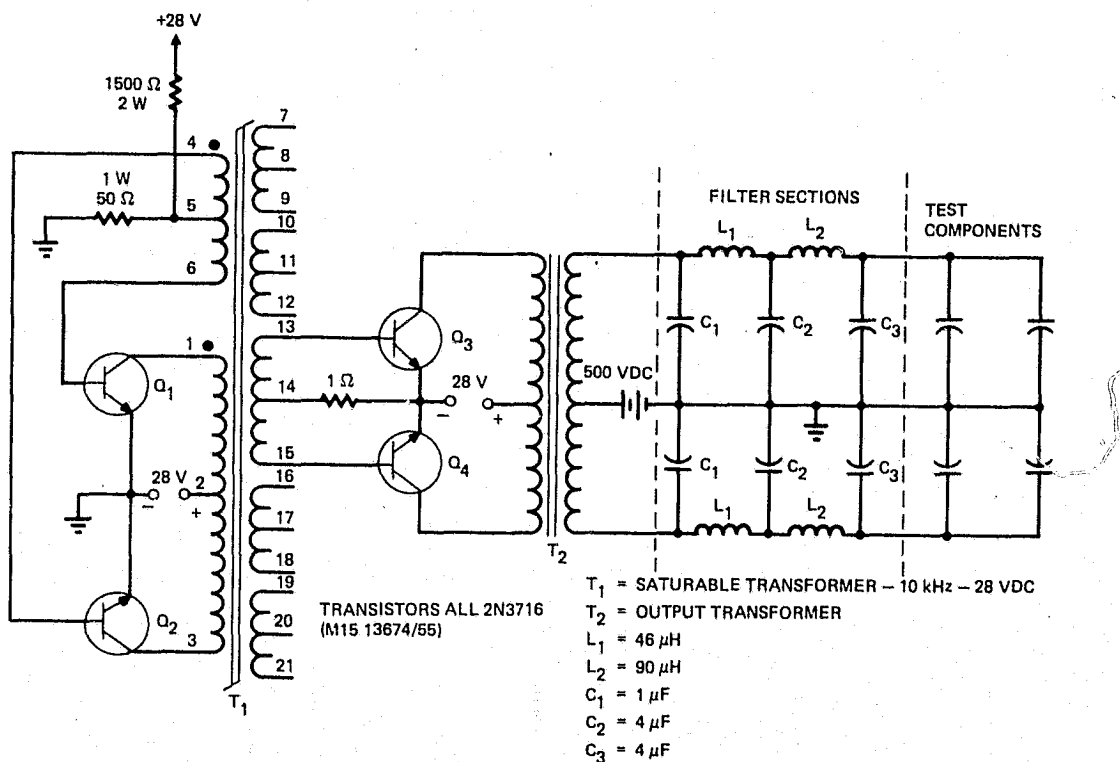


Figure 14. Life test circuit.

For the flat capacitors, all units had failed by 500 hours. Because of the behavior during voltage run-up, it was felt that these components would be entirely satisfactory below 400 V.

The test results are summarized in Table VII.

TABLE VII. LIFE TEST DATA

Serial	Type	Failure	Hours
1	Cyl	Short	0.1
2	Cyl	Short	243
3	Cyl	None	2500
5	Cyl	None	2500
6	Cyl	Short	346
7	Cyl	None	2500
9	Cyl	None	2500
10	Cyl	Short	1.3
12	Cyl	None	2500
13	Cyl	None	2500
14	Cyl	Short	1540
16	Flat	Open	400
17	Flat	Shorted	60
18	Flat	Open	400
19	Flat	Shorted	8
20	Flat	Open	435
21	Flat	Open	405
22	Flat	Open	467
23	Flat	Open	400
24	Flat	Open	405
25	Flat	Open	485

V. FAILURE ANALYSIS

Numerous failure analyses were performed on failed and non-failed capacitors throughout the program. The failed components showed failures about evenly divided between bulk and metallization edge. The majority of these failures were found about two-thirds of the way along the length of the winding toward the outside. No winding wrinkles were found. Some non-failed components were found to contain Al fragments which were traced to an improperly cleaned metallizer.

METALLIZATION PROBLEMS

During the early winding stages where PVF2 film was used, the machine operator noticed metallic flakes that occasionally appeared on the surface of the metallization. Subsequent investigation revealed that the flakes were not falling off the winding machinery, but were actually in the rolls of film as-received from the metallizer.

A scanning electron microscope overview of a typical flake is shown in Figure 15. This flake is approximately 125 mils (0.32 cm) long by 25 mils (0.06 cm) wide. Figure 16 shows an SEM view of the edge of the flake, which is 1.1 mil (28 μm) thick. Figure 17 shows detail of the surface structure at a magnification of 15 times that used in Figure 15. An X-ray dispersive analysis performed on the flake showed a composition of pure Al. Metallurgic analysis showed that the flake was probably a result of vapor deposition on a metallizing machine surface. Discussions with the metallizer confirmed this hypothesis, although the metallizer stated that this problem has never been reported before.

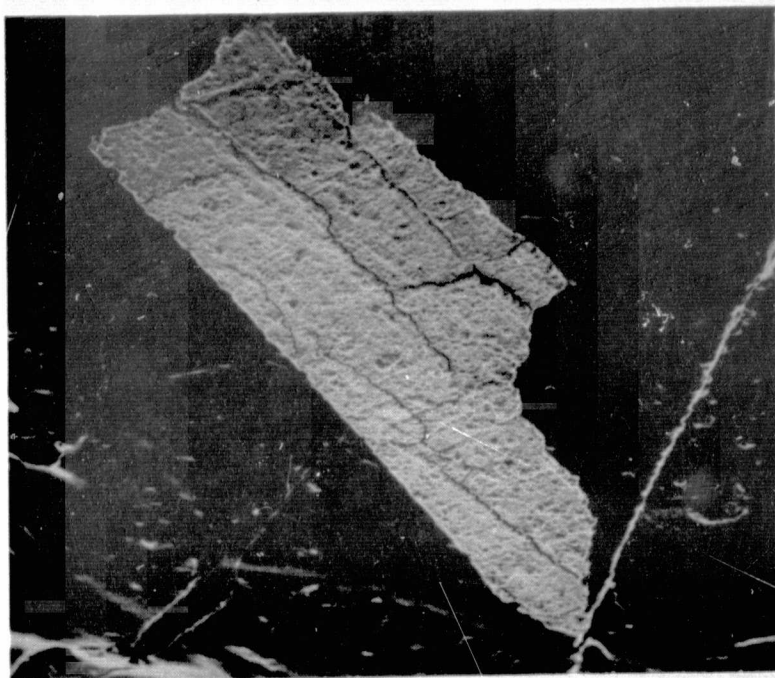


Figure 15. Metal flake.

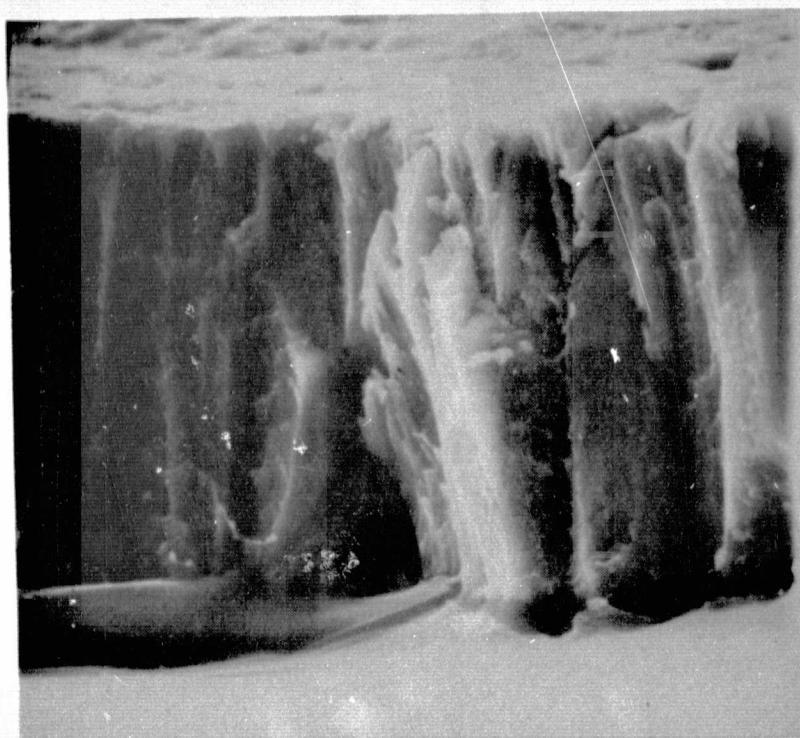


Figure 16. Edge view of metal flake.

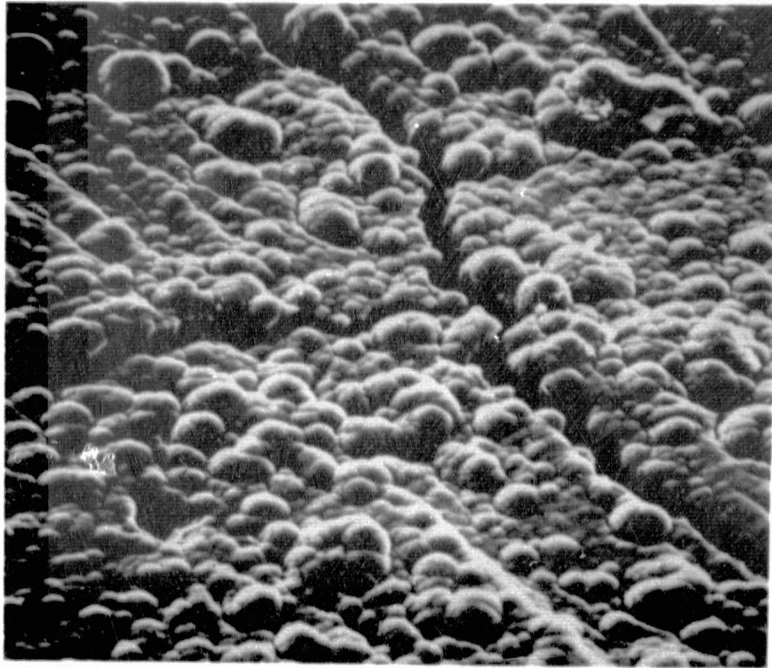


Figure 17. Surface detail.

The effect of an aluminum chip 1.1 mils thick interleaved in a capacitor winding composed of film 0.25 mil thick is not hard to imagine. The failed components did not show conclusive evidence of having failed because of the aluminum chips, but the burned failure sites were in most cases larger than the observed chip sizes. During winding of the components which were subsequently life tested, the winding machine operator was instructed to work slowly, monitor the film, and remove all chips she found. This problem was significantly worse on the PVF2 film than on the PS film.

FLAT FAILURES

The failures in the flat capacitors were sudden burns which were accompanied by sharp popping noises. Some of the burns were through several layers and resulted in layer shorting and reduction of measured capacitance. Failure normally did not occur until several burns had accumulated. There were no termination failures.

Figures 18 and 19 show the distribution of burns on the surface of capacitors 19 and 20, respectively. Figure 20 shows a close-up of one of the burns in S/N 19. Several layers of film are clearly visible through the hole. Figure 21 shows a similar close-up of a burn in S/N 20. The reason the burns were so severe is that, when a failure occurs, all the energy stored in the capacitor dissipates at the site of the fault.

CYLINDRICAL FAILURES

The cylindrical failures were uniform burns in the film that occurred part way between the middle of the winding and the finish. Compared to the failures observed on the previous program, these failures are much smaller and less severe.

Figures 22 and 23 show overall views of the failure sites in units 1 and 14, respectively. Comparing these photographs to Figure 29 in NASA CR-124926, it is clear that the new winding process and core construction have essentially eliminated wrinkles and winding non-uniformities.

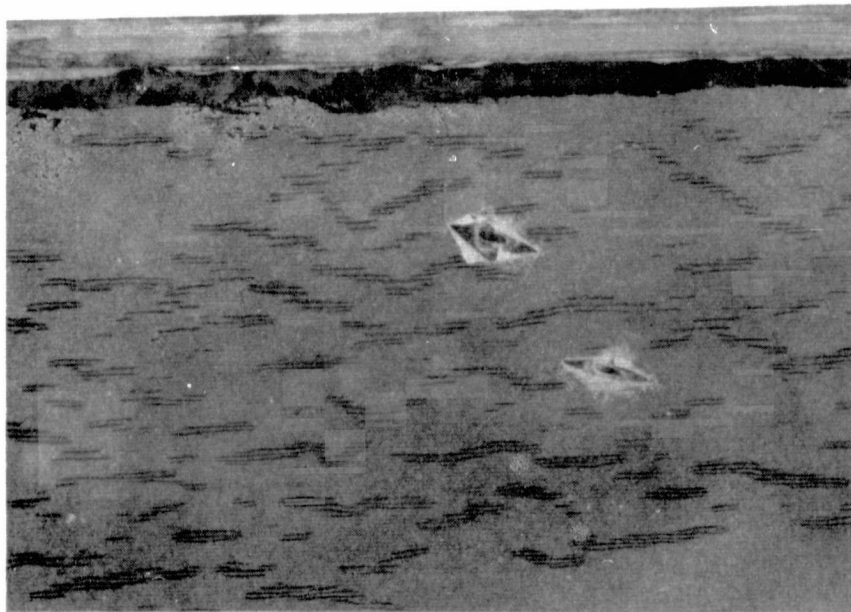


Figure 18. Flat capacitor failure, serial 19, 1.3X.

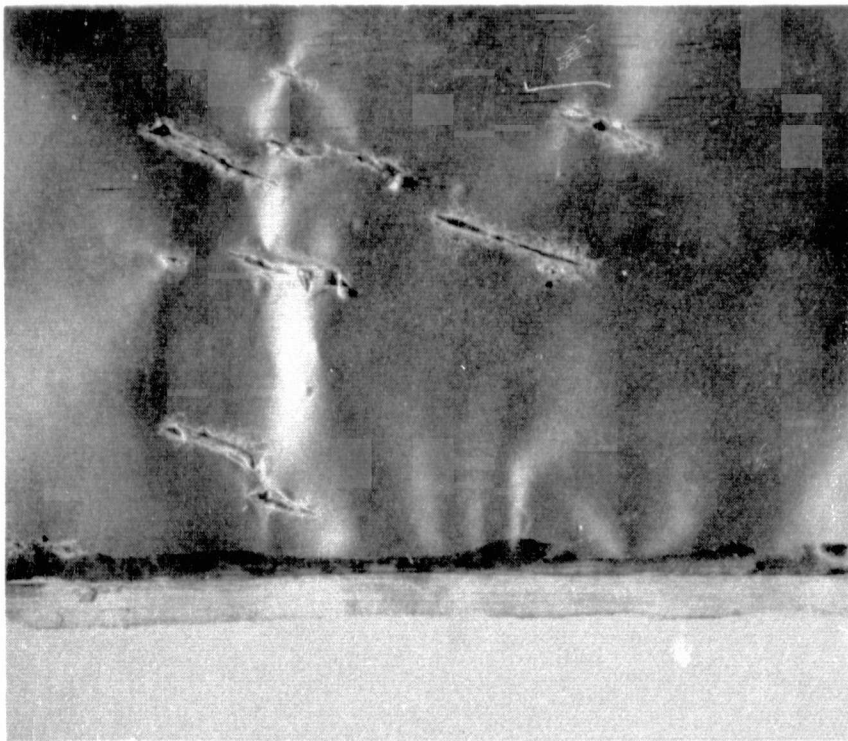


Figure 19. Flat capacitor failure, serial 20, 1.2X.

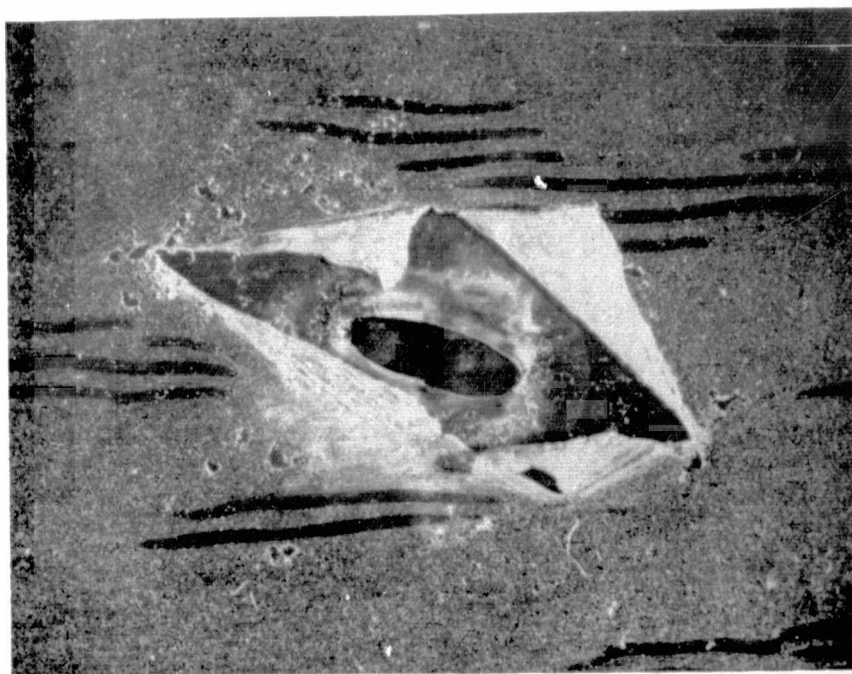


Figure 20. Burn in flat capacitor, S/N 19, 8X.

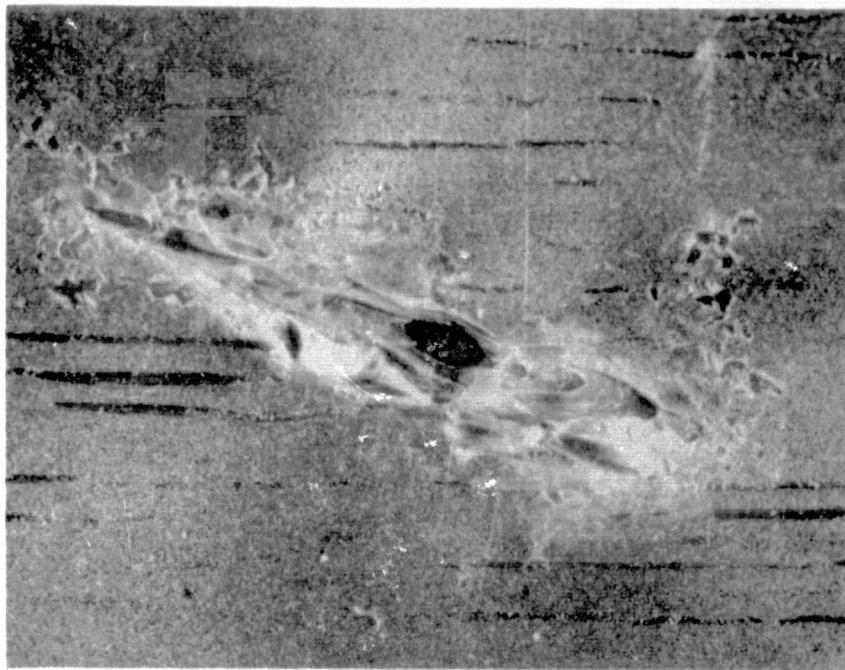


Figure 21. Burn in flat capacitor, S/N 20, 8X.

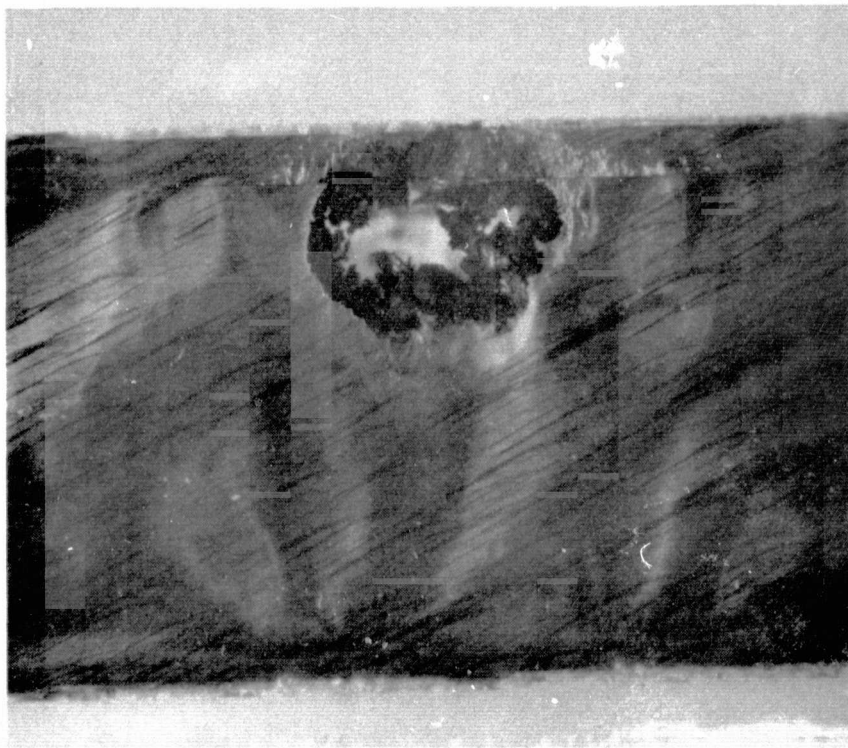


Figure 22. Failure in cylindrical unit S/N 1, 4X.

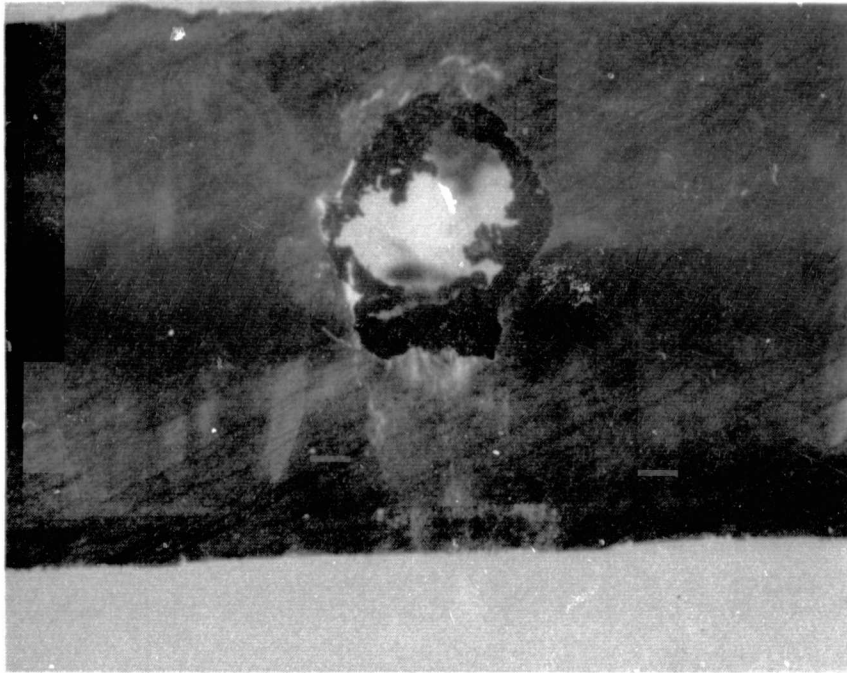


Figure 23. Failure in S/N 14, 4X.

Figures 24 and 25 show the failure location on two different turns of component S/N 1. Figures 26 and 27 show similar information for component S/N 14. Comparing these to Figure 29 of the previous report, one is struck by how small and uniform the failures are.

These failures are tentatively assigned to bulk failure in the insulation. However, there is substantial suspicion, because of the difference between these failures and those previously seen, that the Al fragments might be involved. No fragments were found at the failure sites, as explained above.

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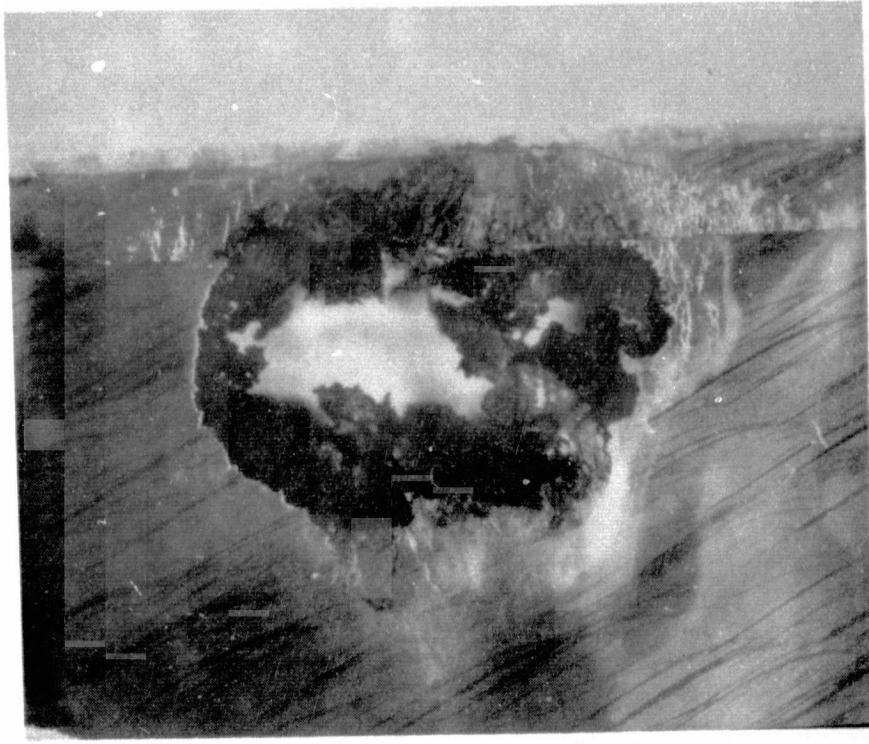


Figure 24. Primary failure in S/N 1, 8.0X.

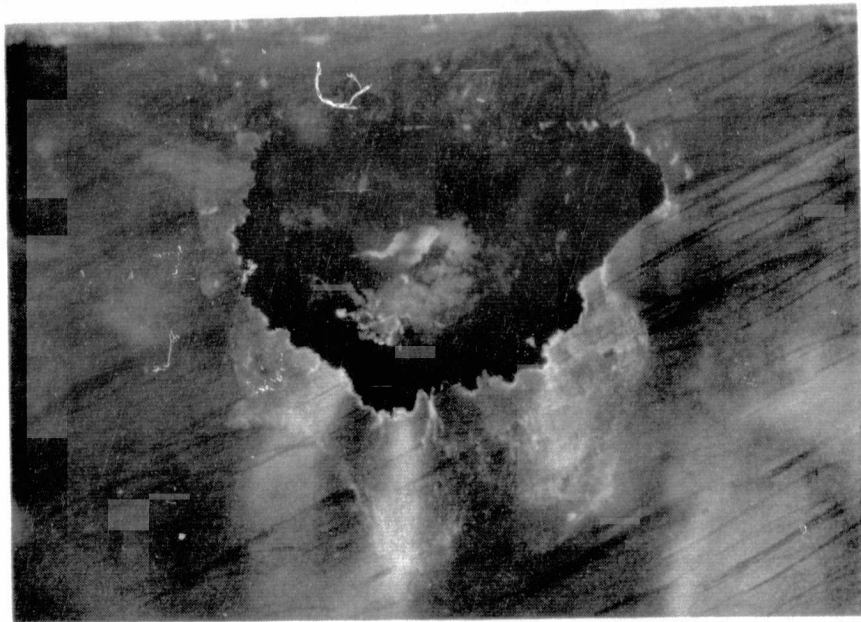


Figure 25. Failure in S/N 1, 1 turn from
Figure 22, 8.0X.

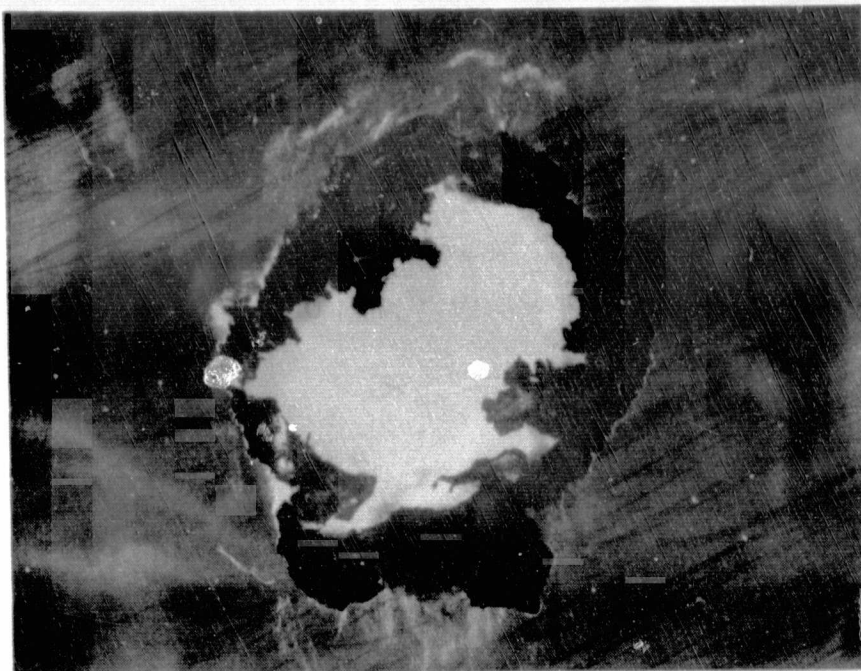


Figure 26. Primary failure, S/N 14, 8X.

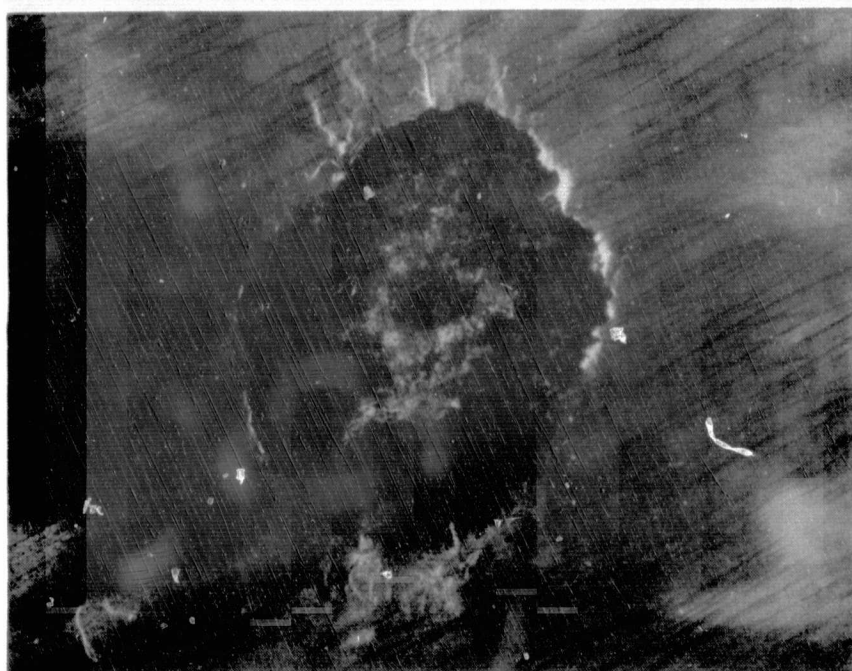


Figure 27. Failure 1 turn from Figure 24, S/N 14, 8X.

VI. CAPACITOR CHARACTERISTICS

The requirement of this set of tasks was to electrically characterize 100 capacitors fabricated for the life tests. These characterizations included capacitance, dissipation factor, leakage current, and corona spectrum for each capacitor, over a range of temperatures.

The detailed measurement requirements of Task 7 are as follows:

- Estimate of Energy Density
- Maximum Operating Voltage
- Capacitance vs Frequency to 100 kHz at 25°C, 75°C, and 125°C
- Dissipation Factor vs Frequency to 100 kHz at 25°C, 75°C and 125°C
- DC Resistance at 25°C, 75°C, and 125°C
- Corona Inception Voltage and Quantitative Pulse Count

The first two of these are derived parameters, found from the CIV. They will be treated at the end of this section. The techniques and results for the direct measurements are discussed first.

CAPACITANCE AND DISSIPATION FACTOR

At first glance, the measurement of capacitance and dissipation factor is straightforward. There is a bridge, the General Radio 1615A, that measures C and DF from 0 to 100 μ F up to 100 kHz. However, at frequencies larger than 1 kHz, the known internal bridge error is:

$$\left[\pm 3 \times 10^{-5} \% + 2(C_F) \times 10^{-3} \% \pm 3 \times 10^{-7} \text{ pF} \right] \times (f_{\text{kHz}})^2$$

This error, caused principally by residual inductance in the bridge transformer and lead wires, is quite large at 100 kHz. Figure 28 shows a frequency response curve made by the Hughes Primary Standards Laboratory, using a 2.0 μF silver mica capacitor calibrated by the National Bureau of Standards. This capacitor is very stable with frequency, and so, were the measuring apparatus accurate, the curve would be a straight line. The deviation of the curve from a straight line represents the inaccuracy. The values found are within the stated accuracy, but this was nevertheless judged unsuitable for use on this program.

An alternative method using the same bridge but with auxiliary equipment had been previously developed in consultation with General Radio. This method has an accuracy of about ± 2.5 percent and a precision better than 0.1 percent, but both the measurement and the calculations are involved. The circuitry is shown in Figure 29. A phase-locked amplifier is used to obtain the null in place of the usual detector. The calculations then are:

$$C_x = C_{EM} + C_B - \frac{C_{EM} C_B D_E^2}{C_B + C_{EM}}$$

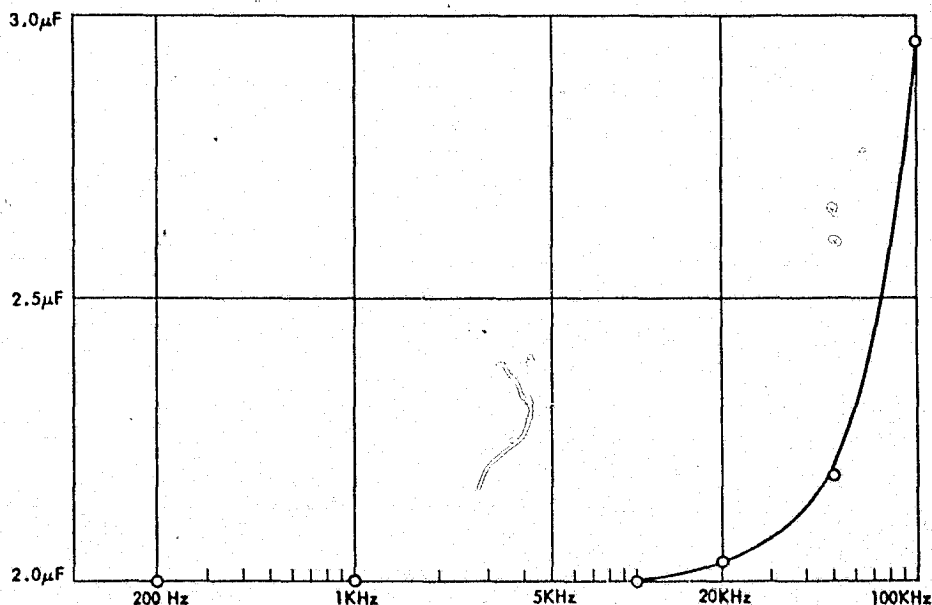


Figure 28. GR 1615A frequency response.

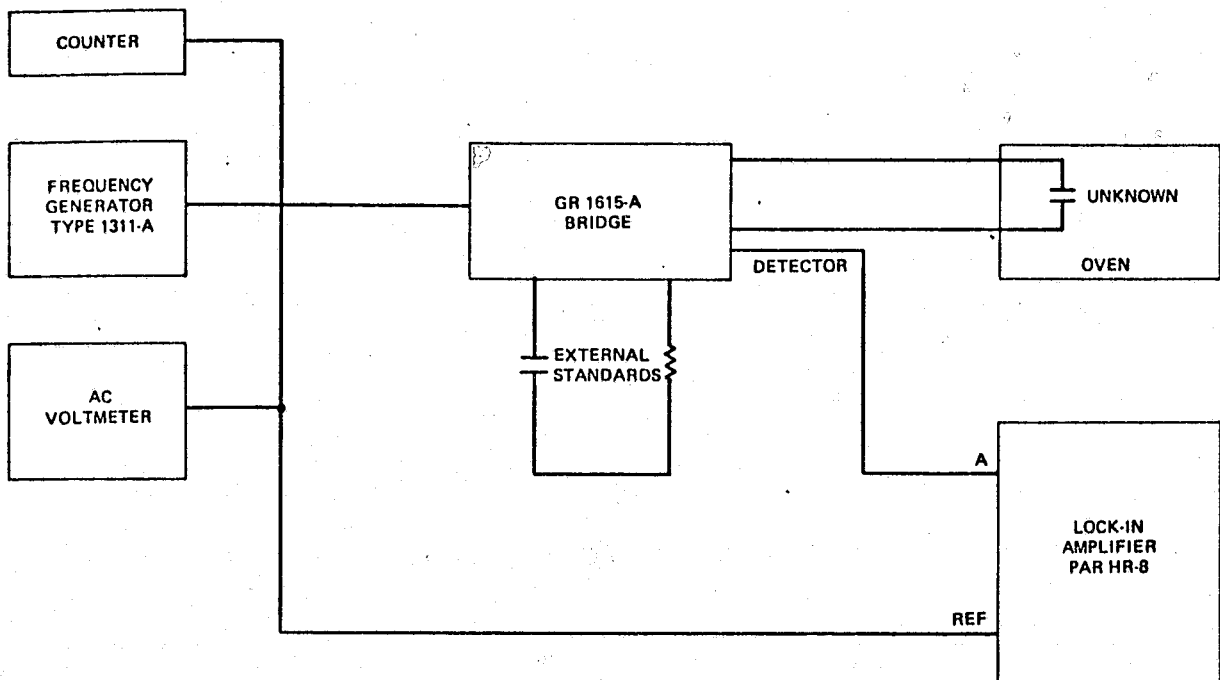


Figure 29. Precision parameter measurement circuit.

and

$$\text{DF percent} = \frac{C_{EM} D_E}{C_B + C_{EM}} \times 100 \text{ percent}$$

where

$$D_E = R_E \times 2 \pi f \times C_E$$

$$C_{EM} = C_E \times \text{multiplier (farads)}$$

$$C_E = \text{External Capacitor (farads)}$$

$$C_B = \text{Bridge Capacitance Reading (farads)}$$

$$C_X = \text{Unknown Capacitance (farads)}$$

$$R_E = \text{External Resistance Standard (ohms)}$$

$$\text{percent DF} = \text{DF of } C_x \text{ (percent)}$$

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Measurement above 10 kHz involves the use of additional substantial corrections to account for series bridge transformer inductance, transformer resistance, and cable and connector skin effect. Repeated attempts to measure values of C and DF at frequencies above 10 kHz for these 2 μ F capacitors have yielded results which are not dependable. Therefore, curves are given for frequencies to 10 kHz only.

Figure 30 shows the variation of capacitance versus frequency for the life test components, and Figure 31 shows the variation of dissipation factor. The 75°C line is above the 100°C line because of the properties of the PVF2.

DC RESISTANCE

DC resistance was measured for each component. Figure 32 shows typical curves versus temperature for each of the component types. The spread of values was 7 percent for the wound units and 19 percent for the flat units.

CORONA INFORMATION

Three different corona tests are required by the statement of work:

- Corona at peak rated AC voltage (at 60 Hz)
- AC and DC Corona Inception Voltage
- Quantitative Corona Distribution

Tests were performed on Hughes high sensitivity corona detection apparatus.

Rated AC voltage is 39.8 V rms, as determined from the specification in Task 1, paragraph A. No capacitor showed detectable corona at 40 V rms.

AC and DC corona inception tests were carried out for all units. In every case, AC CIV was above 50 V rms, which is the limit of our apparatus as presently constituted. On wound capacitors, the DC CIV was greater than 700 VDC, which was the upper limit of the test. On flat capacitors, the DC CIV was above 600 V, although occasional self-healing shorts developed.

No quantitative measurements are presented because no corona was observed.

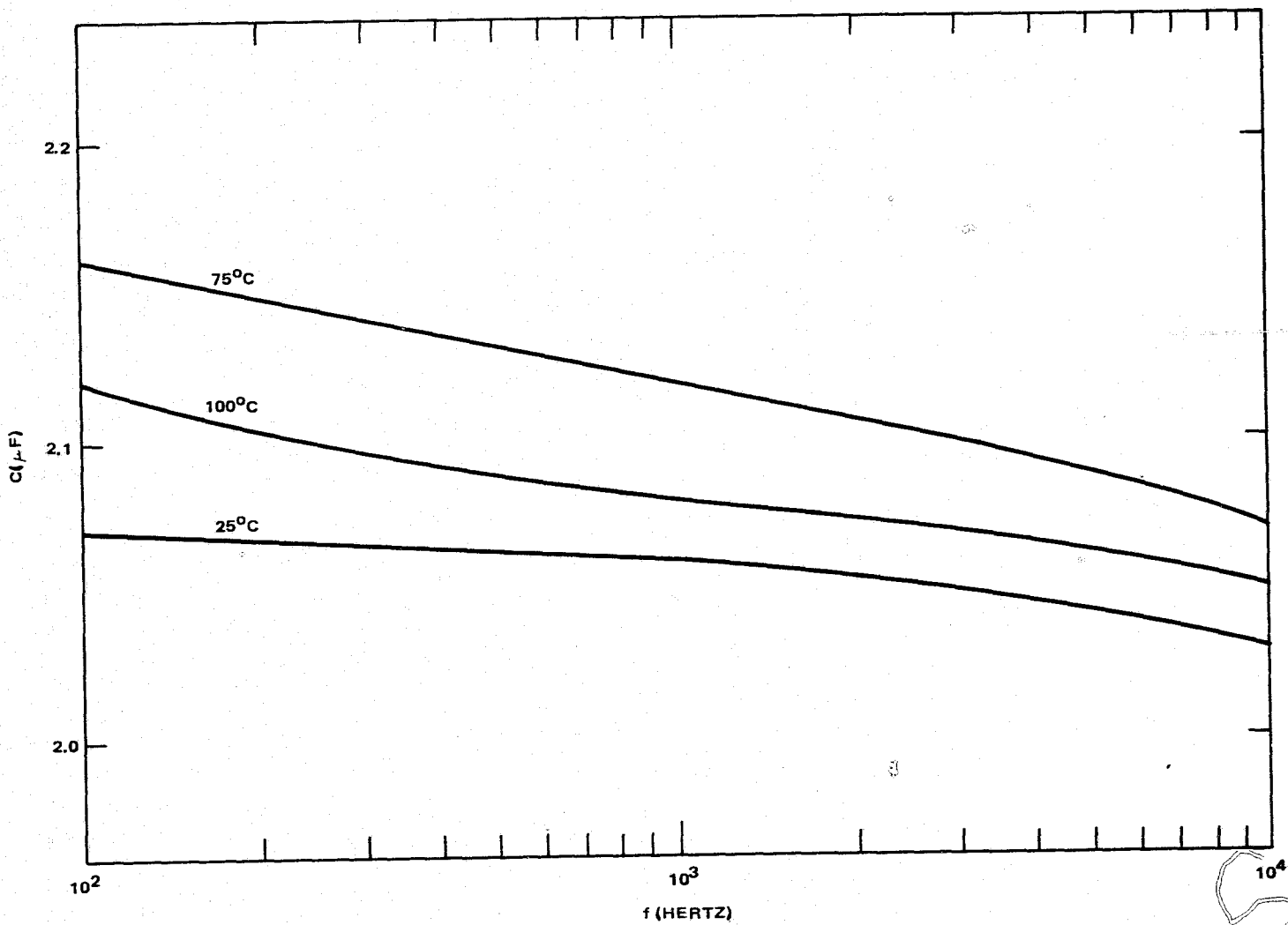


Figure 30. Capacitance vs. frequency.

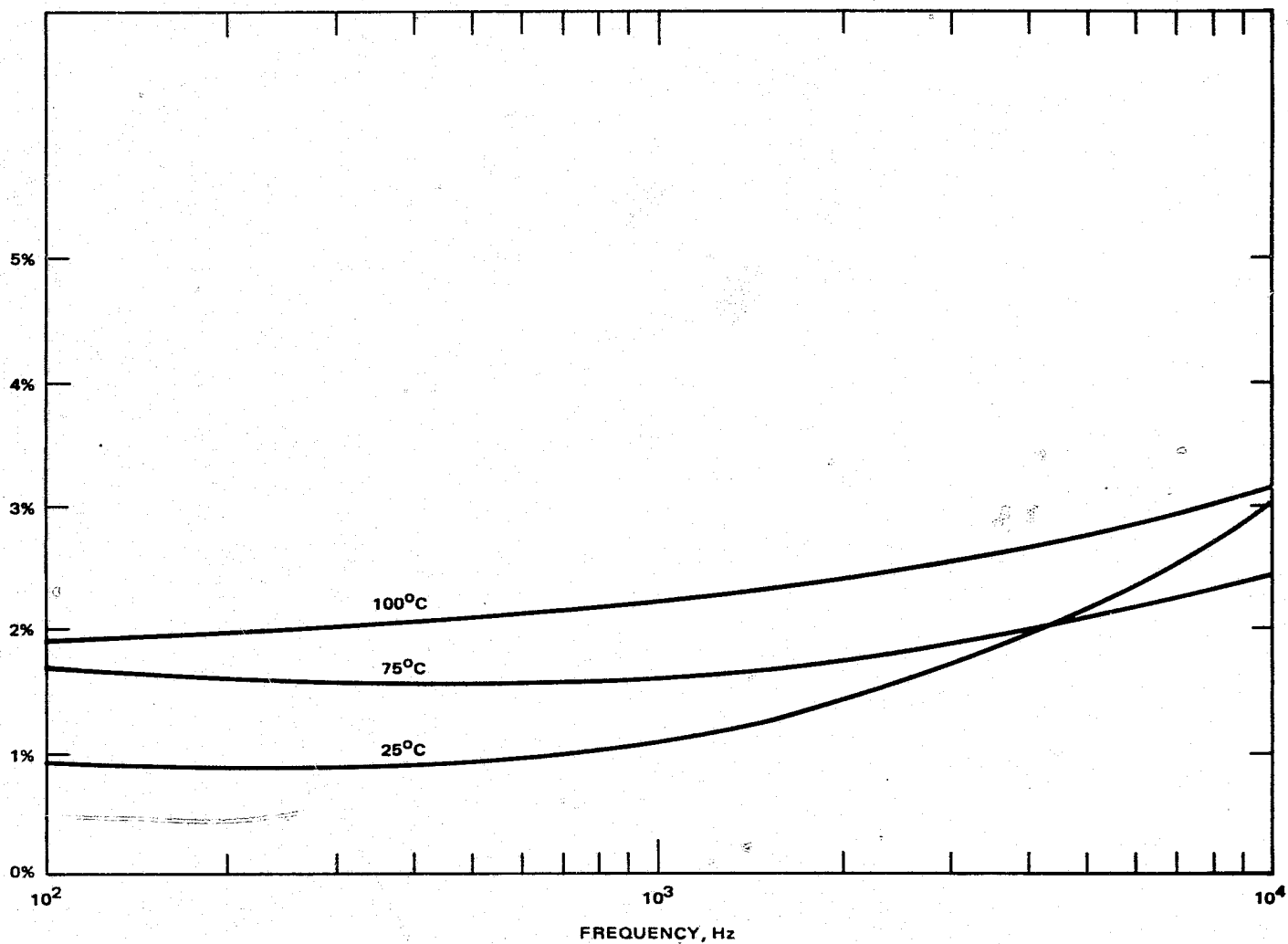


Figure 31. Dissipation factor vs. frequency.

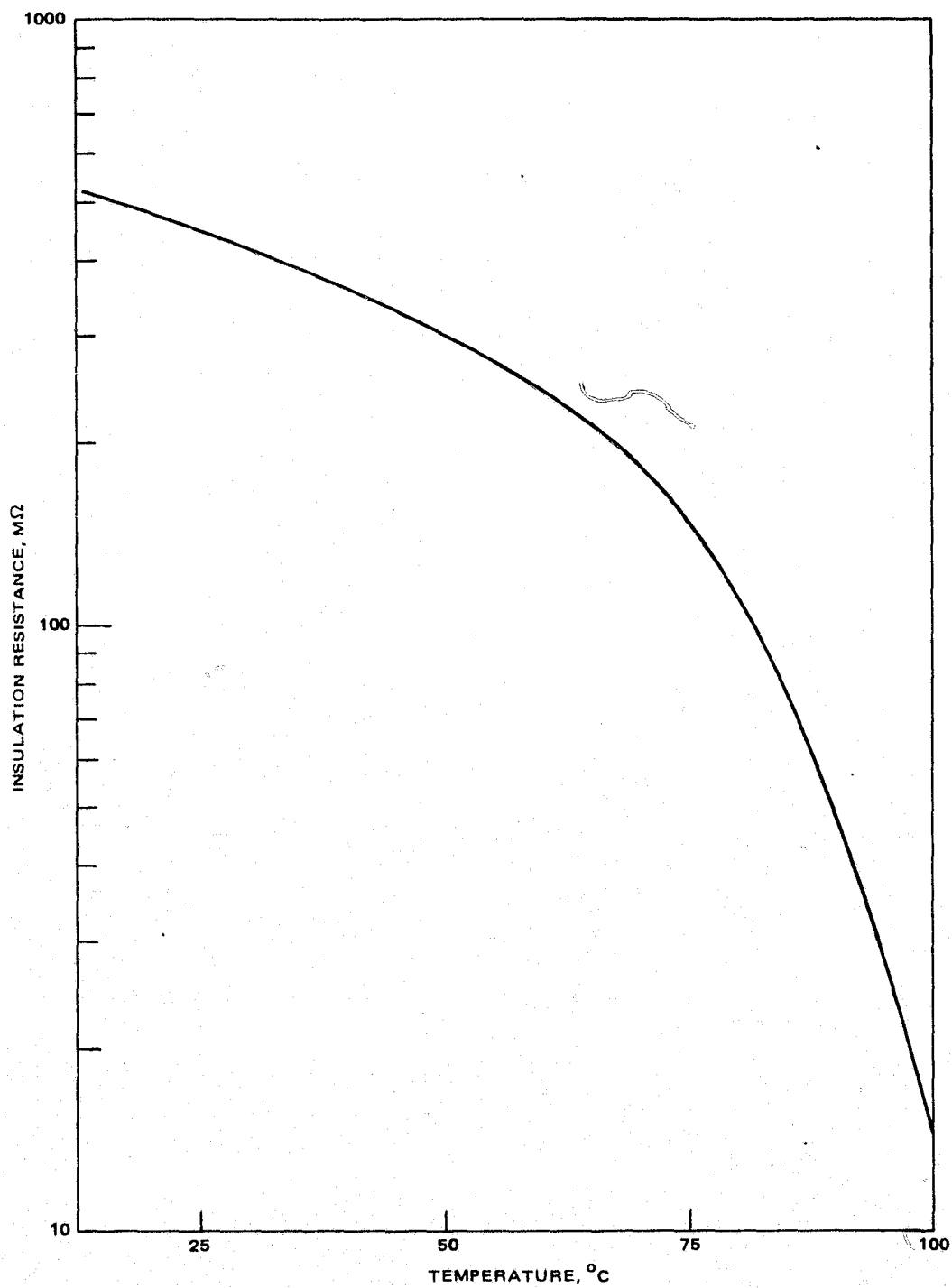


Figure 32. Insulation resistance vs. temperature.

LIFETIME AS A FUNCTION OF CORONA

Capacitors made from thin single metallized polymeric film do not in general have the same type of corona signature as is familiarly found with thicker solid insulations. This is particularly so if the capacitor is operated at a high electric stress, as is the case in this application.

In a transformer, usually one sees a moderate level of corona which grows with time and eventually leads to shorting and failure. This is usually true no matter what the temperature.

In the single film large value capacitor, much of the time the failure is a single massive failure at a thermally activated flaw, and is preceded by an entirely negligible amount of corona. This makes lifetime prediction from corona data difficult.

ENERGY DENSITY AND OPERATING VOLTAGE

The cylindrical capacitors all have energy densities of 0.104 J/g at 500 V and 0.200 J/g at 700 V. They would all operate at 500 VDC satisfactorily.

The flat capacitors all have energy densities of 0.1 J/g at 500 V. However, for long term service operation should be at 400 V. At this voltage the energy density is 0.064 J/g.

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VII. DETAILED PROCEDURE FOR CAPACITOR MANUFACTURE

MANUFACTURING OF CYLINDRICAL CAPACITORS

The following materials, equipment and procedures were used to produce high quality metallized film cylindrical capacitors of energy density greater than 0.1 J/gm uncased using either 24 GA (6 μ m) polyvinylidene fluoride (PVF2) film or 14 GA (3.5 μ m) polycarbonate (PC) film. These two film components were wound wrinkle free on hollow teflon cores using a winding machine that applied constant dynamically controlled tension to the film during the winding operation. Some metallization was removed to provide margins at both ends of the second film of the components.

* Materials List for Unterminated Capacitor Pad

Capacitor Films:	24 GA polyvinylidene fluoride film (Kureha Chemical Industry Co., Ltd., Japan) cut to 11/16 inch width and metallized with a 1/16 inch margin at the Peter J. Schweitzer Division of the Kimberly-Clark Corp. (2 to 4 ohms per square)
	14 GA polycarbonate film, 11/16 inch width with a 1/16 inch margin (Peter J. Schweitzer Division of the Kimberly-Clark Corp.)
Capacitor Core:	0.12 inch O. D. Teflon spaghetti tubing
Adhesive:	Loctite 404 Quick-Set adhesive (Loctite Corp.) or Eastman 910 adhesive (Eastman Kodak Corp.)
Tape:	Kapton Tape, 1/2 inch width (Minnesota Mining and Manufacturing Co.)

The details of the manufacturer's address, catalogue numbers and specifications for ordering these materials are given below in the Materials Procurement Section.

Additional Material Used

Teflon Etch: Sodium etch solution

Acetone

Deionized Water

Equipment Used

Capacitor Winder: Film bobbins mounted on AC torque motors to provide constant dynamically controlled film tension. DC motor spindle drive to provide variable winding speed and reversible winding direction.

DC Power Supply: 0 to 100 V capability, current limited.

Needle Electrode: Typical scribe point geometry.

Dust Free Enclosure: To house capacitor winder.

Capacitor Winder

The capacitor winder used to wind the cylindrical capacitors was an experimental machine designed to dynamically maintain constant film tension during the winding operation. For the width and gauges of the films used in fabricating these components, the tension was controlled by setting the level of the 60 Hz input to the torque motors on whose shafts the film bobbins were mounted. The level was set slightly below the level where some wrinkles could be introduced into the pads when the winder was operated at its full speed of 440 rpm. No direct measurement of the tension in the film was made. The winder was configured as indicated in Figure 33. The spindle was located midway between the film bobbins, with smoothing rollers located on either side of the spindle at $3/8$ inch from the spindle axis. A number 43 twist drill slipped through the teflon core acted as the winding mandrel. The mandrel was supported in a $1/8$ inch collet on one end and in a hole in a removable plate at the other end. The smoothing rollers were held in a fixture that slipped over the core prior to winding the capacitor. To remove the completed component, the mandrel was removed and then either the fixture was disassembled or the core ends were trimmed away.

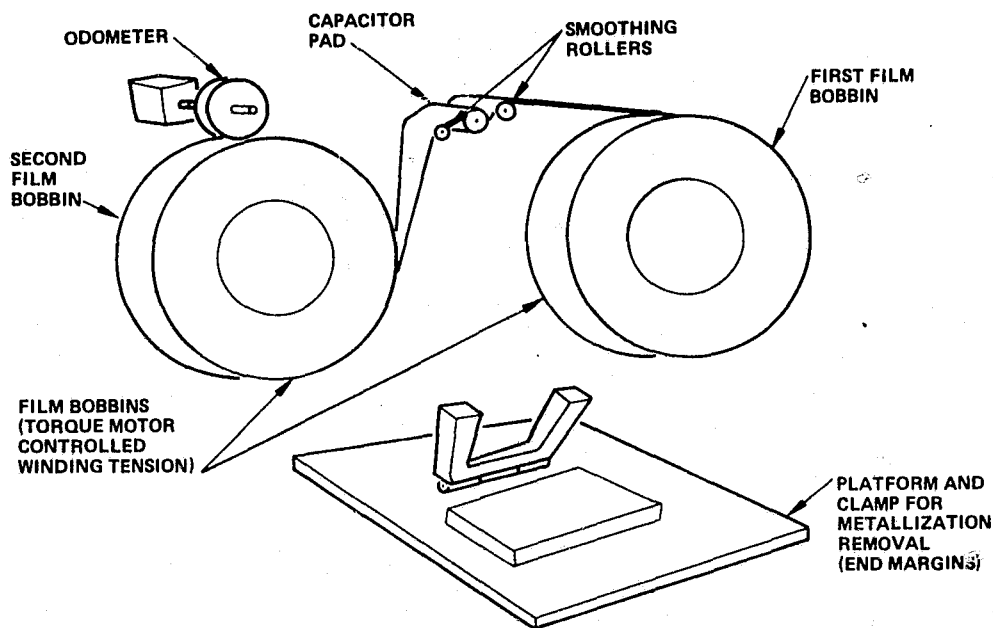


Figure 33. Capacitor winding configuration.

Core Preparation

The teflon tubing was etched to prepare its surface for bonding. A length of teflon tubing with its ends plugged was submerged in the room temperature sodium etch solution for two minutes. During this time the etch solution was constantly stirred. The tubing was rinsed with acetone, then with tap water, and finally with deionized water to remove all of the etchant and any residual contamination. Sections of tubing approximately 2 inches long were cut to form the capacitor cores.

Precis of the Winding Procedure

To wind a capacitor, the tubular teflon core is mounted on the winding mandrel with the smoothing roller fixture in place. The first film of the capacitor is aligned over the core and then bonded to the core with the Loctite adhesive. Before bonding the second film to the core, metallization is removed around the bonding area on the second film to provide a margin at the beginning of the second film. The film is aligned and bonded to the core, and the excess film is cut away. After winding the desired length of film, metallization is again removed from the end of the second film, and the second film is wound into the capacitor pad. The first film is cut and the component is tied off with a piece of Kapton tape. After removal from the

winder, the core ends are trimmed and the component is ready for electrical termination with flame sprayed tin.

Detailed Procedure for Winding a Capacitor

Before the core is placed on the winding mandrel, the hole in the mandrel supporting plate is carefully centered with the spindle axis. The core and mandrel are inserted through the support plate, through the smoothing roller fixture and into the spindle collet. The first film is aligned by passing it between the core and a smoothing roller and then laying it across the second film bobbin, and aligning it with the second film bobbin. The first film bobbin is then locked with the torque motor brake. The first film is bonded to the core using a small amount of Loctite adhesive applied with a wooden Q-tip stem. A line of adhesive approximately $3/32$ inch wide is applied to both the core and the film. After the bonding operation, the excess film is trimmed away with an exacto knife using a number 11 triangular blade. The first film bobbin torque motor control is switched to the "wind" position to apply tension to the film, and two or three turns are wound onto the core prior to bonding the second film. The bobbin for the second film was axially displaced about 0.040 with respect to the first film bobbin in the direction of the first film margin. This displacement ensures that the metallized surfaces of both films are sufficiently exposed to allow good electrical termination with either conducting adhesive or flame sprayed metal.

Before the second film is bonded to the core, the metallization is removed from a portion of the film to provide a margin of $1/4$ inch at the beginning of the second film. This is accomplished by grounding the film with a large area electrode (about $1/2$ in²) and then sweeping a needle electrode held at 70 V DC over the film where the metallization is to be removed. The axis of the needle is held at a small acute angle with respect to the surface of the film, and the needle is moved in a circular sweeping motion such that the needle contacts the metallization when the needle is moving towards the grounding electrode. For each sweep of the needle electrode, the needle is advanced approximately $1/16$ inch onto the remaining metallization. A potential of 70 V DC was found to adequately remove the metallization without blackening or burning the film. The needle electrode should

be wiped with a tissue after each metallization removal operation to remove any contamination which could increase the electrode-to-film contact resistance and cause localized burning of the film. Small increments of the metallization should be removed with each sweep to prevent removal of metallization beneath the grounding electrode. The metallization operation is performed on a platform located 5 inches below the spindle axis.

The second film is then aligned with respect to the first film on the core with a small offset of about 0.040 inch in the direction of the margin of the first film. With the bobbin torque motor brake applied, the second film is bonded to the core at the area of metallization removal using the same procedure as for bonding the first film. The second bobbin torque motor control is then switched to the "wind" position to apply tension to the second film for the winding operation. For the above-desired set-up, an operator standing at the support plate end of the mandrel will see the spindle turn in a clockwise direction, and the smoothing rollers will be positioned beneath the films. To achieve a nominal 2 μ F capacitance value, 600 cm of the PVF2 film or 1000 cm of the PC film are wound. The length of film is measured directly using an odometer which rides on the second film bobbin.

After the desired length of film is wound, metallization is again removed from the second film to provide a margin at the end of the second film. This is done by switching the second film tension control to the "free" position and repeating the metallization removal procedure. The second film is then cut in the cleared area, and the end wound into the capacitor. The capacitor is finished by winding one or two additional turns of the first film, cutting the film and tying off the pad with a piece of Kapton tape at least 1/2 inch wide and cut to the length of the capacitor. The capacitor is ready to be removed from the winder for application of electrical terminations on the ends of the capacitor pad.

Termination

The electrical connection to the metallization is accomplished by a variant of the extended-foil construction common to larger components. Flame-sprayed tin is used to connect to alternate layers, as in Figure 34.

A wire with two gold leads welded on is inserted into one end of the core, and the two gold leads are ultrasonically soldered to the tin, as in Figure 35. The larger wires protrude through the case for the final termination.

This termination is not particularly porous to capacitor impregnants, so stripes are masked off on each end, and remain unsprayed to enhance impregnation.

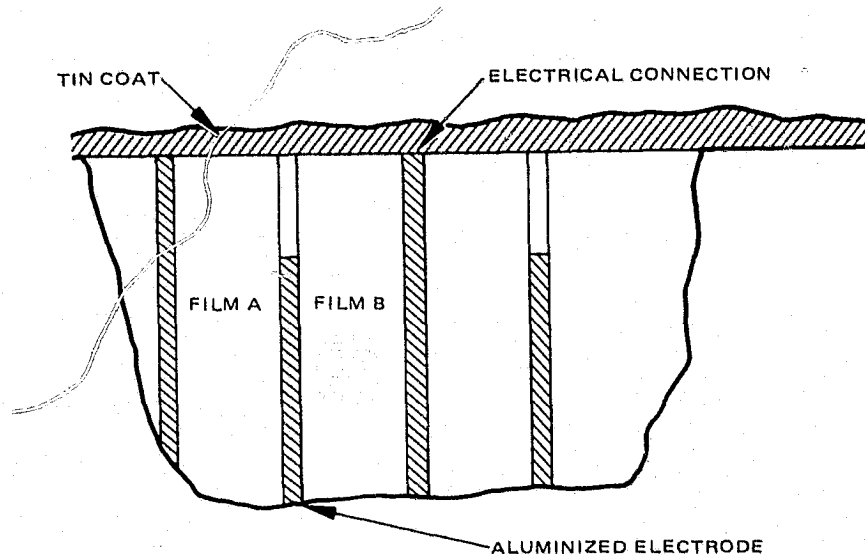


Figure 34. Detail of metallized film connections.

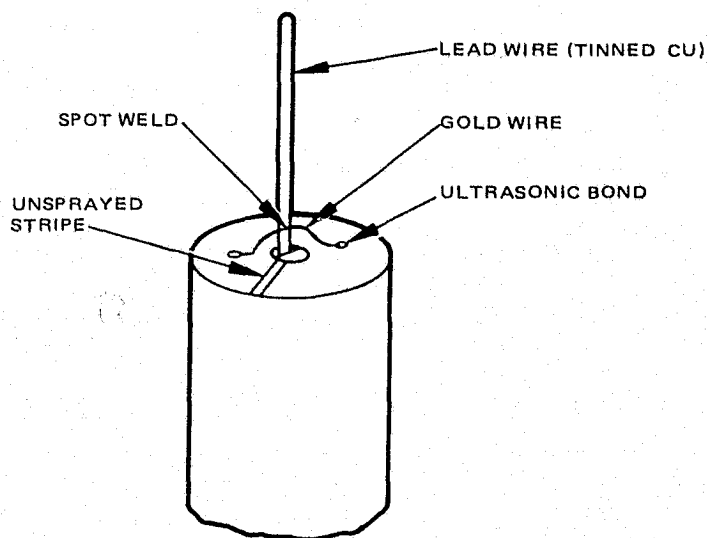


Figure 35. End connection detail.

Impregnation

Numerous fluids are used for capacitor impregnation, so that the impregnation process is necessarily tailored to the peculiarities of the particular fluid. The process described here is for mineral oil. Very slight modifications are used for silicone fluids.

The capacitor sections are placed in a vacuum oven and baked at a temperature above 100°C for at least 24 hours. The temperature depends on the material, and is about 110°C for both materials used here. The length of time for the bake is determined by monitoring the insulation resistance (IR) of the components. When the IR stops changing, the components are sufficiently dry.

While the sections are being baked, the fluid is treated to remove particles, moisture, and ionic contaminants. Particles were removed by filtering, moisture by vacuum baking, and ionic contaminants by clay filters. These treatments are necessarily severe, the end point specifications being:

particles - none larger than $0.4\ \mu\text{m}$

water - 35 ppm

resistivity - $10^{15}\ \Omega\text{-cm}$

During this process the impregnation fluid is also degassed by the vacuum-bake cycle. The cycle lasts 24 hours at 100°C and -10 microns pressure. Analyses for water and particles are made and the resistivity measured at the end of this time.

The baked components are removed from the vacuum oven and placed in an oil impregnation unit. This apparatus consists of a heated vacuum chamber, and evacuated fluid storage reservoir, connecting tubes, and miscellaneous fixtures. The apparatus in present use at Hughes is a modified Red Point ESL-2020. The components remain in the heated evacuated chamber for 3 hours, and are then filled with heated fluid from the side loader (fluid storage reservoir). Following this, the components are allowed to cool under vacuum to room temperature. Then the vacuum is broken and the component cases sealed.

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Sealing

It is most desirable to seal the containers under vacuum at the end of the impregnation cycle. Where the cases are large, this may be possible. However, if it is not, the process must be designed to minimize the amount of gas/contaminants re-introduced into the oil.

Corona Test

The finished capacitor should be corona tested at 600 V DC for three minutes. If no corona pulses larger than 1000 picocoulombs are observed, the component is considered to be of satisfactory quality.

MANUFACTURE OF FLAT FLEXIBLE CAPACITORS

The following materials, equipment and procedures were used to produce flat flexible capacitors of energy density greater than 0.1 J/gm. These components are of nominal 2 μ F capacitance and consist of 11 layers of metallized 24 GA PVF2 capacitor film. They measure 6.3 inches long, 4.8 inches wide and 0.003 inch thick. The overall width of the finished capacitor is wider than the 4.5 inch width of the film since the metallized edge of each successive layer is laid up 0.025 inch beyond the edge of the previously laid up layers. The resultant exposure of some of the metallized surface of each layer provides sufficient film surface to ensure good electrical connection to each layer of the capacitor.

Materials List for the Flat Capacitors

- | | |
|----------------------|--|
| Capacitor Film: | 24 GA polyvinylidene fluoride (Kureha Chemical Industry Co., Ltd., Japan) cut to 4.5 inch width and metallized with a 1/16 inch margin at the Peter J. Schweitzer Division of the Kimberly-Clark Corp. |
| Laminating Adhesive: | Epon 815 epoxy resin (Shell Chemical Co.), 20 parts; Jeffamine 230 curing agent (Jefferson Chemical Co.), 7 parts. |
| Conducting Adhesive: | Emerson and Cuming conducting epoxy No. 56-C. |
| Copper Wire: | No. 32 AWG bare copper wire. |

Additional Materials Required

Dilute Solution of Sodium Hydroxide

Dilute Solution of Acetic Acid

Deionized Water

Double Back Adhesive Tape: 1/2 inch wide transfer adhesive tape
(Minnesota Mining and Manufacturing Co.)

Epoxy Stripper: Electro Cold Stripper (Americal Petrochemical Corp.)

Vacuum Bagging Film: Capron 80 Nylon sheet (Allied Chemical Co.)

Vacuum Bag Sealant: Vacuum Bag Sealing Compound (Schnee and Morehead Chemicals Inc.)

Tongue Depressors

The details of the manufacturer's address, catalogue numbers and specifications for ordering these materials are given below in the Materials Procurement Section.

Equipment Used

Lay-up Fixture: This fixture is shown in Figure 36. The stretcher bars are part of the fixture, and are marked with a fiducial line for alignment of the films at the margin edges. The bars are in numbered pairs and are used in a specific sequence.

Soft Rubber Squeegee

Laminar Flow Bench or Dust Free Enclosure

Precis of the Fabrication Procedure

To produce a high quality flat capacitor, the component is laid-up using a fixture which holds each layer taut and wrinkle free and in a precise position within the laminate. Films are attached to stretcher bars, and an additional margin is produced on each layer perpendicular to the original film margin. The films are laid-up with their metallized surface towards the fixture and each layer increases the overall width of the component, thereby exposing electrical contact areas for each layer of the capacitor.

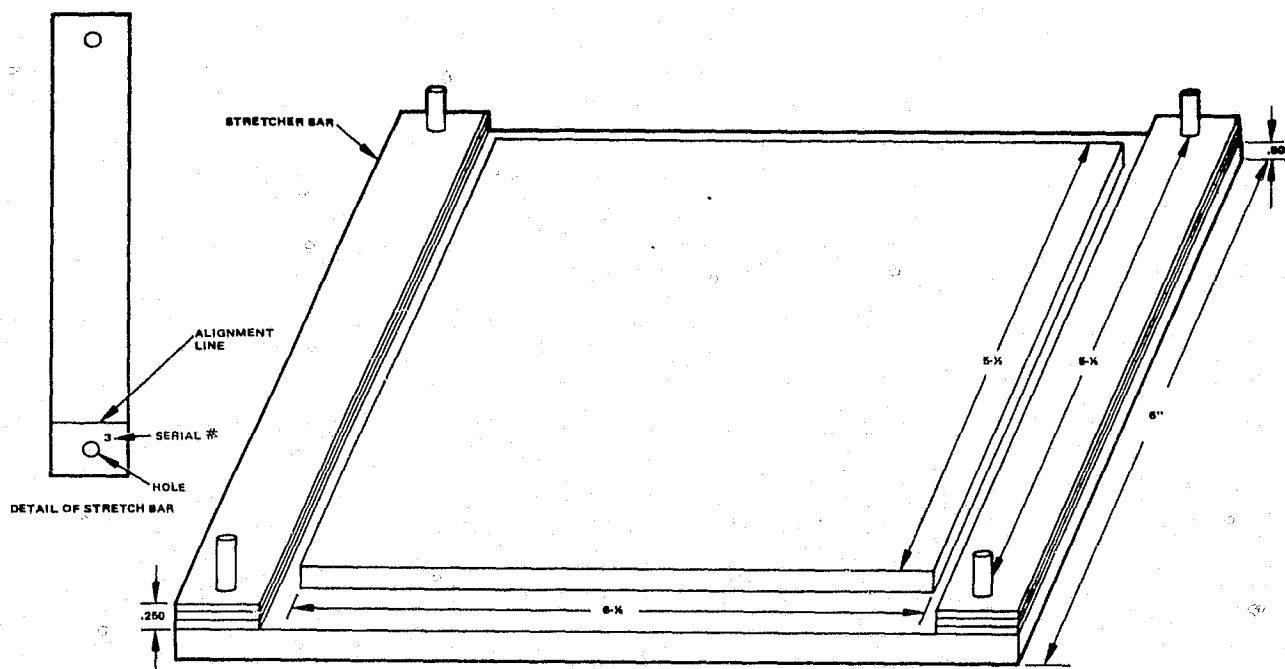


Figure 36. Layup fixture.

Adhesive is applied over each layer to act as a lubricant for squeegeeing the previous bondline and to provide adhesive for attaching the next layer. The finished lay-up is vacuum bagged and cured initially at room temperature and then at 120°F. After the component is removed from the fixture, the adhesive is removed from the electrical contact areas. The component is terminated using conducting epoxy inlaid with copper wire. The wires are extended beyond the edge of the component to act as leads.

Detailed Procedure for Fabricating a Flat Capacitor

The entire operation of assembling the flat capacitor, from unrolling the film to vacuum bagging the finished laminate, should be done in a dust free environment. The first step in the fabrication of a flat capacitor is the attachment of stretcher bars to the film. A length of film adequate for five or six capacitor layers is unrolled and held taut between two metal blocks with the metallized surface facing upward. Transfer adhesive is applied to the top surface of the stretcher bars. A pair of stretcher bars

is placed on the laminating fixture with a spacer under each bar to hold them level with the mid portion of the fixture. The fixture is placed under the film, and the film is carefully aligned with the stretcher bars. Then the film is attached to the bars by pressing on the film near the centers of the stretcher bars and then smoothing the film along the bars with a tongue depressor. The bars are carefully lifted from the fixture, the fixture is repositioned, and another pair of bars are attached. This process is repeated until all the pairs of stretcher bars are attached to the film. The film is then cut into the individual layer segments, and the segments are hung using the stretcher bars to prevent wrinkling of the film.

An additional margin is etched on each film segment perpendicular to the existing film margin. This is done by placing the segments on the fixture and etching away the metallization along a 1/4 inch wide zone centered on the line which will be the edge of the finished component. For each film segment positioned with the metallized surface facing upward and with the film margin towards the technician, a margin is etched on the right hand side of the film. The metallization is first removed with a solution of sodium hydroxide. Next the etchant is neutralized with dilute acetic acid, and any remaining residue is removed with deionized water.

When laying-up the capacitor, successive layers are rotated about an axis perpendicular to the fixture by 180° with respect to the previous layer, so that the component has margins at all edges.

The lay-up procedure begins with the covering of the fixture with a sheet of nylon. Laminating adhesive is puddled on the nylon and distributed over the sheet using a squeegee. The adhesive acts as a lubricant to prevent damage to the first layer of the component during the squeegeeing operations. When cured, the adhesive weakly adheres to the nylon sheet. The first layer of the capacitor is laid onto the fixture with the metallized surface facing the fixture and is aligned by the stretcher bars. Laminating adhesive is puddled on to the film and spread with the squeegee. Each additional layer is added and the adhesive is applied and squeegeed as for the first layer. The layers are laid-up with the metallized surface facing the fixture and in sequence such that each successive layer increases the overall width of the component by extending its metallized edge 0.025 inch beyond the edge of the

existing lay-up. The lamination process is completed by adding the nylon vacuum bag and sealing it with the vacuum bag sealant. The bag is evacuated and additional squeegeeing is done to remove all excess adhesive from the laminate. Figure 37 shows the basic lay-up scheme for the finished component.

The squeegeeing operation must be done very carefully to be sure that the adhesive is completely distributed between each layer so that no voids remain, and that the films are not damaged by wrinkling or by the metallization being scratched or cracked. By squeegeeing the film on the nonmetallized surface, the possibility of damaging the film is greatly reduced.

The laminate is cured for 17 hours at room temperature and then for 3 hours at 120°F. The component is removed from the fixture by cutting through the vacuum bag along the stretcher bars. The nylon surface layers are carefully peeled away, and the component is trimmed through the center-line of the etched margin areas with scissors.

Electrical Termination

Epoxy stripper is used to remove the laminating adhesive from the electrical contact areas of the capacitor. Conducting epoxy is applied over the contact areas, and one or more No. 32 AWG bare copper wires are embedded along the entire length of the contact area. The wire are extended one or more inches beyond the edge of the component to provide leads for

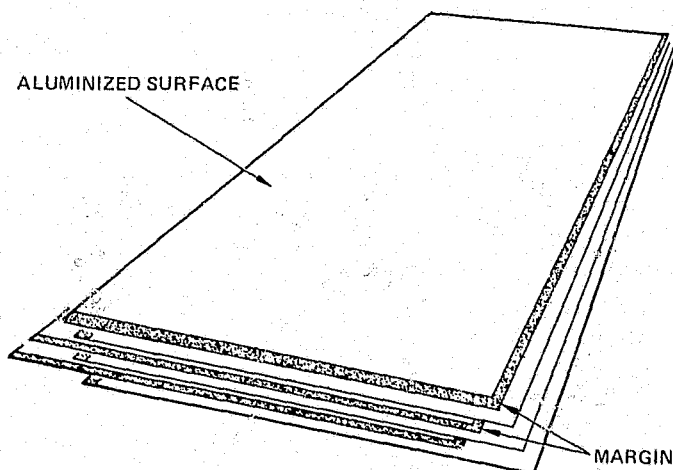


Figure 37. Pyramid construction of a flat capacitor.

the capacitor. The operation of applying the electrical contacts is facilitated by taping the capacitor to a piece of cardboard. Care must be taken not to short-circuit the component by extending any of the conducting adhesive over the margin of the top layer. The conducting epoxy is cured either at room temperature for 8 hours or at 160°F for 3 hours. Finally a 100 V impulse is applied across the component to decrease the resistance of the conducting epoxy-to-aluminum contacts. To do this a 1.8 μ F capacitor is charged to 100 V and then discharged across the flat capacitor 5 times in each polarity.

Acceptance

The components are screened by high voltage testing them to 600 V DC. Prior to the high voltage test, the capacitance and dissipation factor are measured. Some components produce audible and visible arcs as the voltage is raised to 600 V. In general the arcing clears the component of defect sites. After the component is held at 600 V for 3 minutes, the component is again checked for its capacitance and dissipation factor. If the final measurements of these parameters are in agreement with the initial measurements, the component is considered to be of acceptable quality.

MATERIALS PROCUREMENT

This section lists all the materials required for the fabrication of cylindrical and flat capacitors. For materials that are not common laboratory reagents, the manufacturer's address, catalogue number and any relevant specifications for ordering are included. The grade of the laboratory reagents and the formulation of the teflon etch are given.

Acetic Acid Solution

Dilute solution of reagent grade glacial acetic acid (approximately 10% glacial acetic acid)

Acetone

Reagent grade

Capron 80 Nylon Sheet

Capron 80 Vacuum Bag Nylon Sheet

Allied Chemical, Fibers Division
Film Department
Morristown, N.J.

Conducting Epoxy

56-C Epoxy with Catalyst No. 9

Emerson and Cuming, Inc.
604 W. 182nd Street
Gardena, CA 90247

Eastman 910 Adhesive

Eastman Kodak Co.
Rochester, New York

Order to Mil. Spec. MIL - A - 46050

Electro Cold Stripper

T416HV Brush Type

American Petrochemical Corp.
2639 W. Grand Ave.
Chicago, Illinois 60612

Epon 815 Epoxy Resin

Epon 815 Resin

Shell Chemical Company
Plastics and Resins Division
113 W. 52nd Street
New York, New York 10020

Order to Mil. Spec. MIL-R-9300

Jeffamine 230 Curing Agent

Jefferson Chemical Co.
Houston, Texas

Kapton Tape

No. 5524 Kapton Tape

Minnesota Mining and Manufacturing Co.
St. Paul, Minn.

Loctite 404 Quick-Set Adhesive

Loctite Corp.
Newington, Conn. 06111

Order to Mil. Spec. MIL-A-46050

Polycarbonate Capacitor Film

14 GA Kimfol Polycarbonate Film, 11/16 width

Peter J. Schweitzer Division
Kimberly-Clark Corp.
Lee, Mass. 01238

Polyvinylidene Fluoride Capacitor Film

24 GA Kureha KF Film

Kureha Corporation of America
420 Lexington Avenue, Suite 2144
New York, New York 10017

This film was slit and metallized with a
1/16 inch margin at the Peter J. Schweitzer
Division of Kimberly-Clark Corp. (see
Polycarbonate Capacitor Film)

Sodium Hydroxide Solution

10% solution by weight of reagent grade sodium
hydroxide.

Teflon Etch Solution

Composition:

Sodium metal chips, wire or ribbon	46 gm
Naphthalene	128 gm
Tetrahydrofuran	1.0 liter

All reagents are commercial grade

Teflon Spaghetti Tubing

0.12 inch O.D. standard teflon spaghetti tubing

Tongue Depressor

Standard 6 inch tongue depressor

Transfer Adhesive Tape

No. 467 Transfer Adhesive Tape

Minnesota Mining and Manufacturing Co.
St. Paul, Minn.

Vacuum Bag Sealant

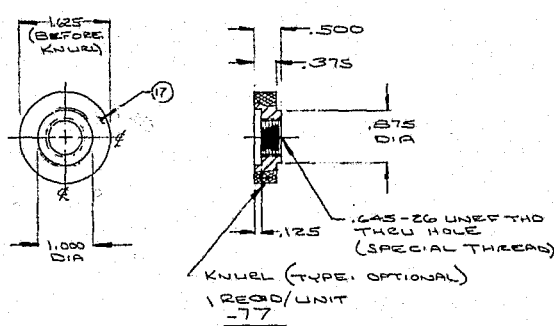
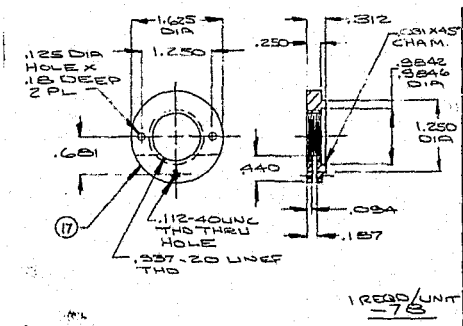
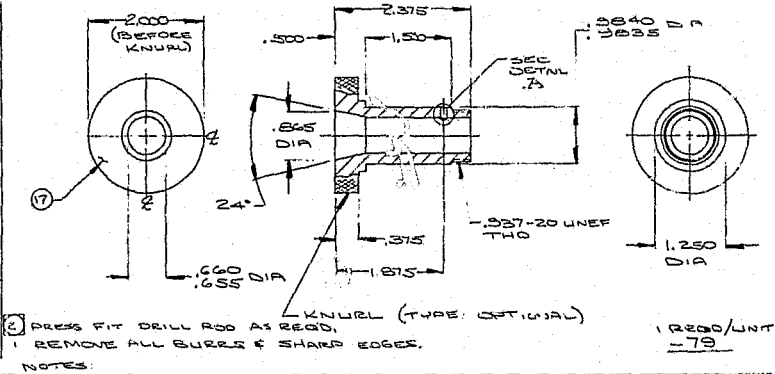
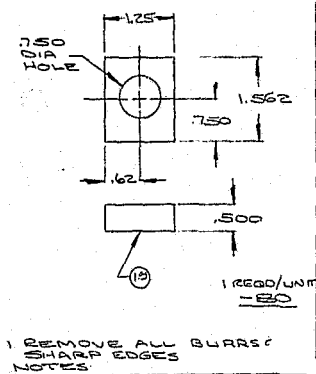
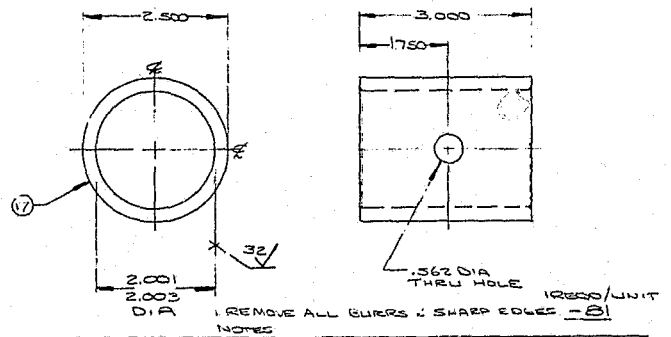
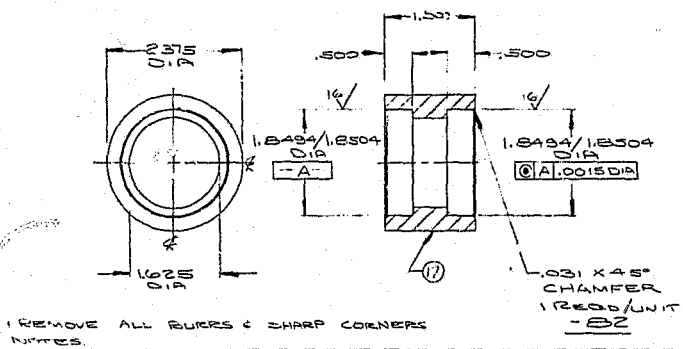
No. 9151 Vac Seal Tape (Pink) vacuum bagging
compound

Schnee-Morehead Chemicals Inc.
111 N. Nursery Road
P.O. Box 1305
Irving, Texas 75260

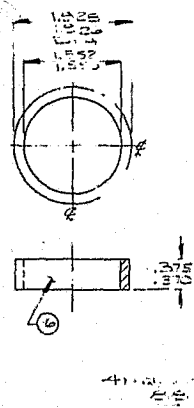
APPENDIX A

This appendix contains all the drawings for the cylindrical winder constructed for this program.

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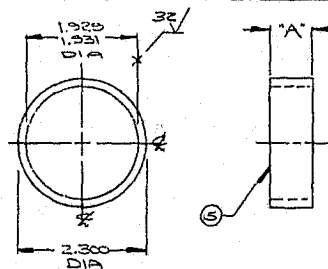


Capacitor winder 4 spool



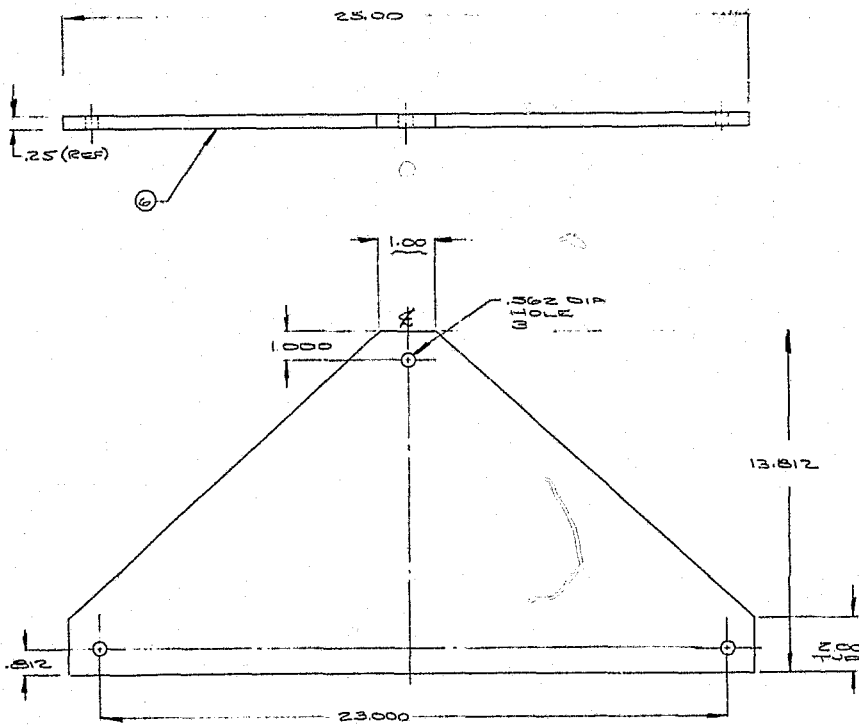
32221. INT

४१०

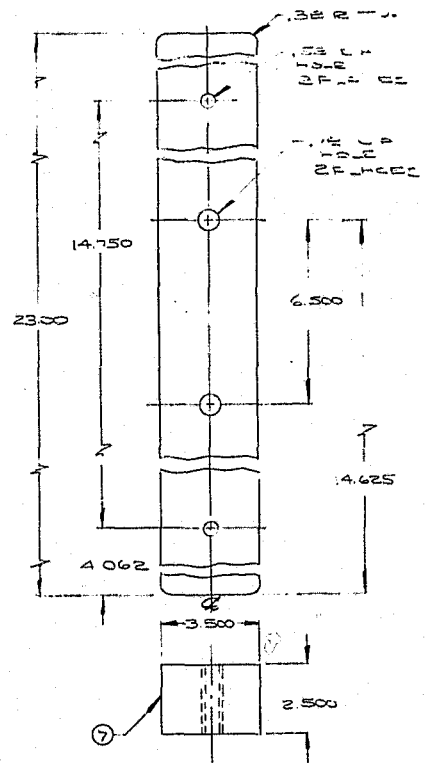


2 BEACH REEF/LINE
REINFORCE A BURST CLAMP EDGES
NOTES:

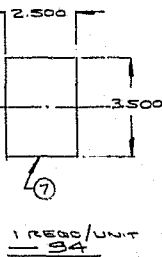
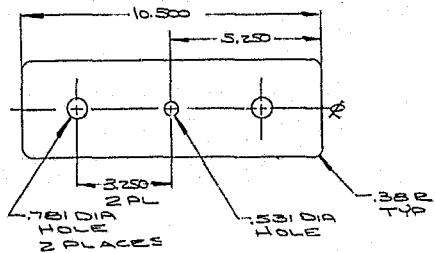
84



1 REQD/UNIT
— 36



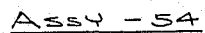
1 REQD/UNIT
— 35



1 REQD/UNIT
— 34

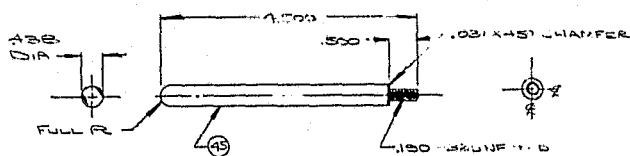
NOTES - UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & SHARP EDGES
2. CHROMATE (CONVERSION) COAT
METHOD OPTIONAL

Capacitor winder 4 spool



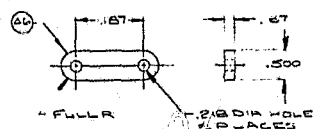
- SEASTROM MFG CO
GLENDALE, CA
TEL # 245-9121

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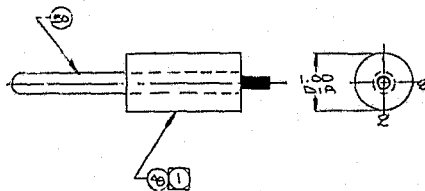
1. REMOVE ALL BURS & SHARP EDGES
NOTES

2 REQD/UNIT
-59



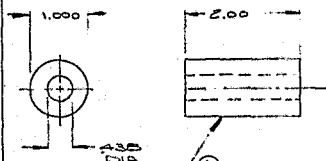
7. 4 REQD/UNIT
REMOVE ALL BURS & SHARP EDGES
NOTES

-58



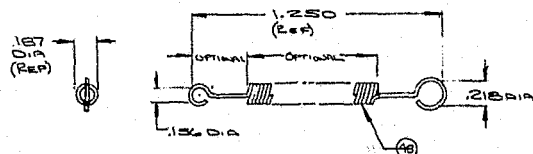
1. BEND IN PLACE (METHOD OPTIONAL)
NOTES

2 REQD/UNIT
-56



2 REQD/UNIT
-57

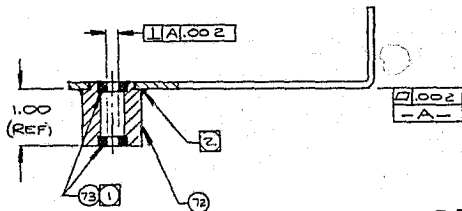
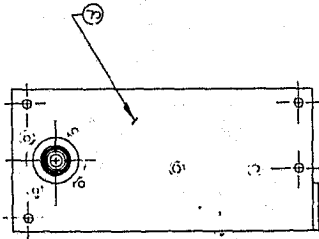
(SUPPLIES)



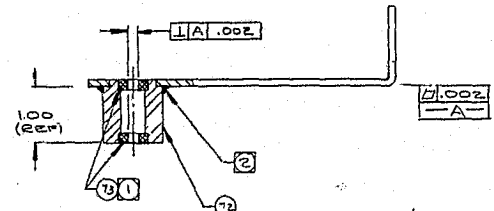
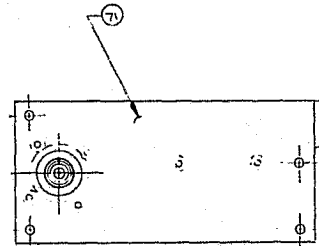
3. 2 REQD/UNIT
2. MAKE IN ACCORDANCE WITH MIL-S-6715
1. SPRING DESIGN REF MAT'L 00-3/16, WIRE DIA: .031 STAINLESS
MAX LOAD = 7.0 LBS, FREE LENGTH = 1.250 INCH PER INCH = 11.7
INITIAL TENSION = .9 (REF) LBS AT .251 DEFLECTION
INITIAL TENSION = .9 (REF) LBS AT .408 DEFLECTION
NOTES

-55

Capacitor winder 4 spool

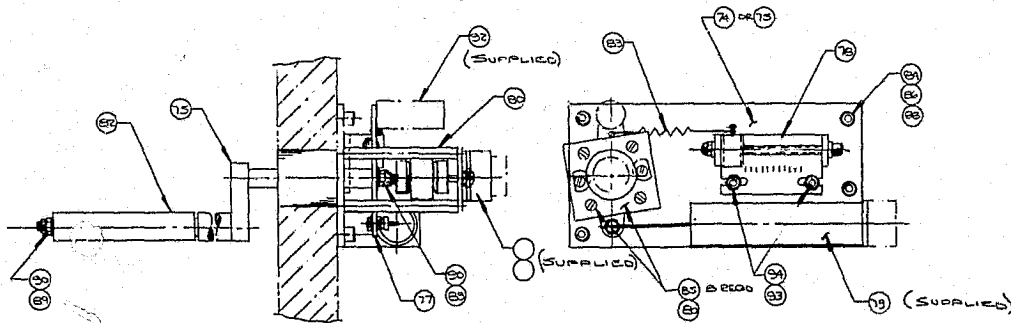


2 RECD/UNIT
- 53



2 RECD/UNIT
- 52

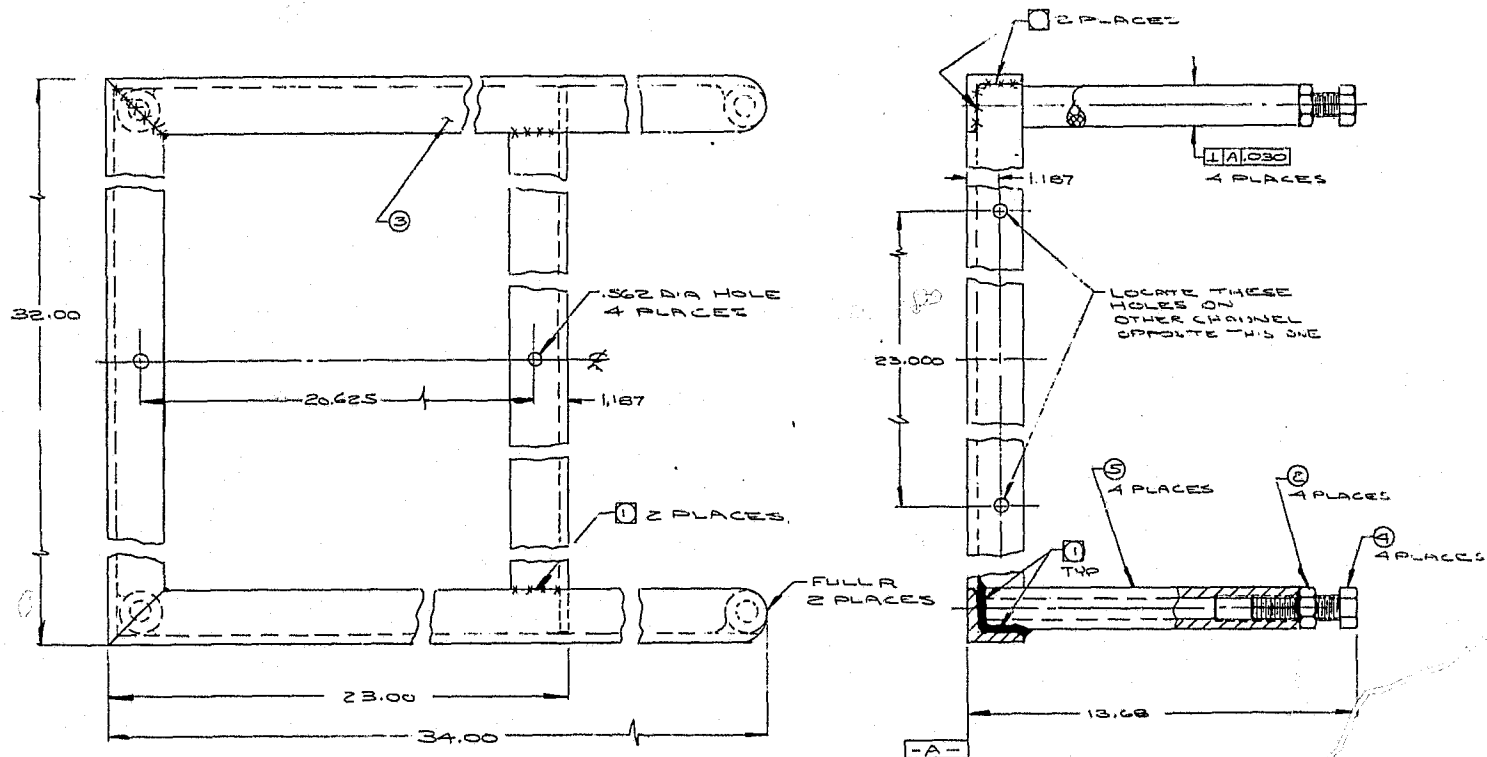
- 1 BEARING MAY BE PURCHASED FROM:
FAIRBANKS BALL BEARING CO., LA, CA AN 3-74'S
2 BRASS PER MIL-B-12883, TYPE C GRADE OPTIONAL
3 BEARINGS TO BE A LIGHT PRESS FIT INTO HOUSING (F71 OR EQUIV)
- NOTES



- 1 MAY BE PURCHASED FROM:
SEASTAR, MP6 Co.
GLENNDALE, CA 91201
- NOTES

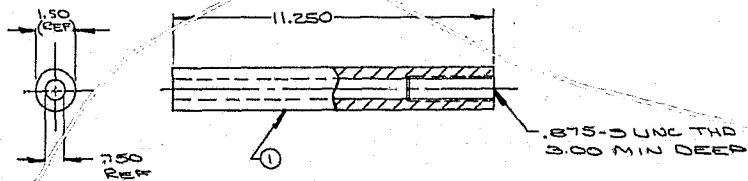
QTY	ASSEMBLY DESCRIPTION	QUANTITY REQUIRED
51	SHOWN	2
52	OPPOSITE	2

Capacitor winder 4 spool



① WELD ASSEMBLY TOGETHER AS REQD METHOD (OPTIONAL)

NOTES



1 REMOVE ALL BURRS & SHARP EDGES
NOTES

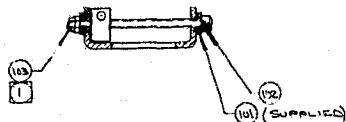
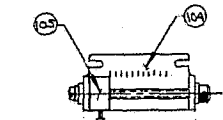
4 REQD/UNIT
— 87 —

Capacitor winder 4 spool

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3. 4 READ/UNIT
2. MAKE IN ACCORDANCE WITH MIL-S-6715
1. SPRING DESIGN REF MATL. WIRE DIA. .012 CROS REF
MAX LOAD (LBS) 1.0 RATE 1 LBS/INCH
INITIAL TENSION .10 LBS

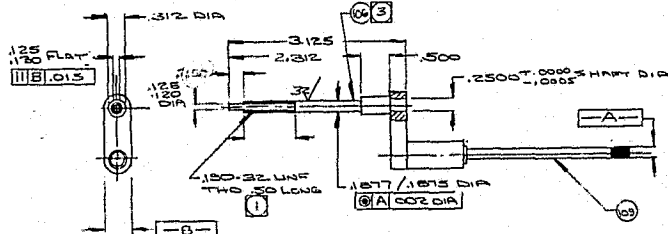
25. 2



2. 4 REQ'D/UNIT

TIGHTEN NUT UNTIL IT IS A
SNUG FIT
NOTES.

976.
NOTES.

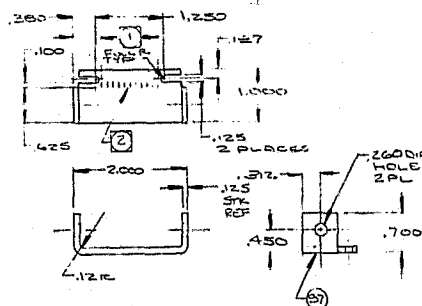


3) PART TO BE A LIGHT PRESS FIT INTO ASSY-36 AS SHOWN
REMOVER ALL BURRS & SHARP EDGES.
MODIFY OD OF THREADS TO EQUAL OD OF SHARP
NOTES:

NOTES

AREA/LINE

- 43 -



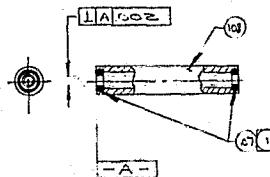
4 REQD PER UNIT

REMOVE ALL BURRS & SHARP EDGES

2 MARK UNIT 10 = MENTIONS SHOWN PER
HPO-S, TYPE II, CLASS 2

10 EQUAL SPACES AT .100 EA - 1.000

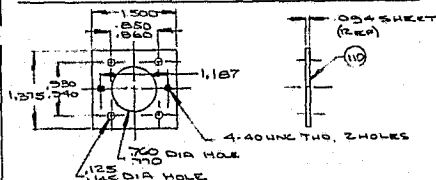
2000



2 REQD/UNIT

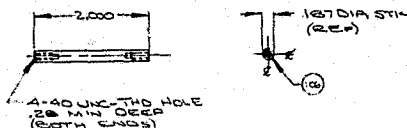
1 BEARINGS TO BE A LIGHT PRESS
FIT INTO HOUSING (FN-1 OR EQUIV)

NOTES:



2 REQD/UNIT

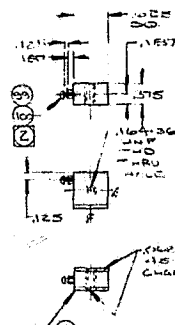
1. REMOVE ALL BURRS & SHARP EDG
NUTS



2 16 REQD/UNIT

1. REMOVE ALL BURS, SHARP EDGES

NOTES

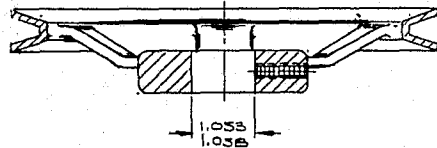
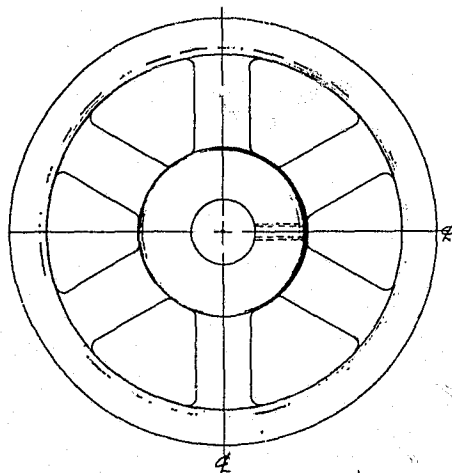
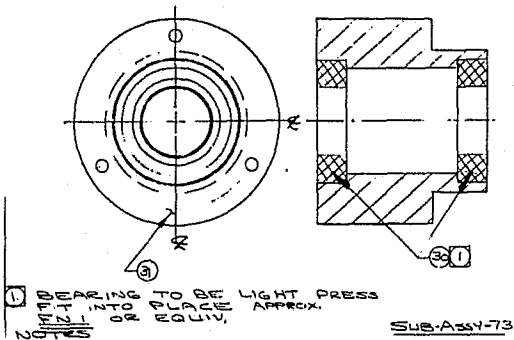


W A REGG LINT

2. PROB. 5 - 11 PLACE
(7-5-1 ONE LOW 1)

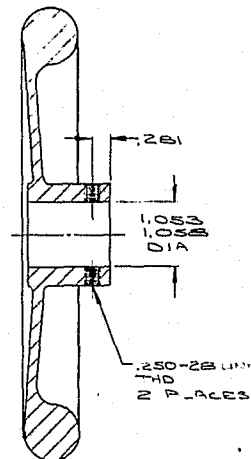
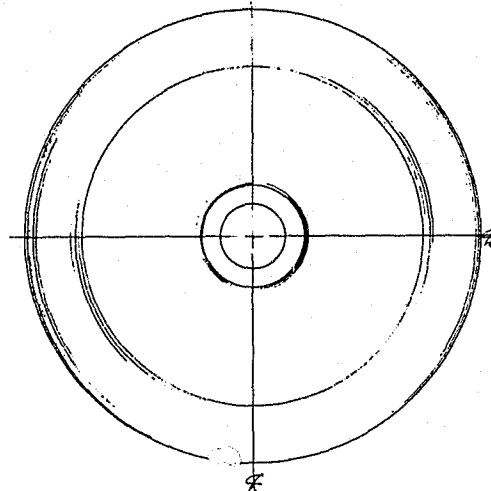
1 REMOVE ALL BJERS &

64000
NCTE



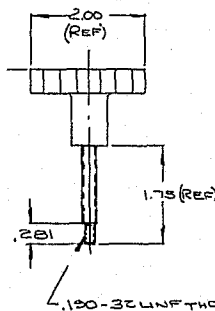
1 MAKE FROM BOSTON GEAR CATALOG #60
P/N PV3 7
NOTES

71



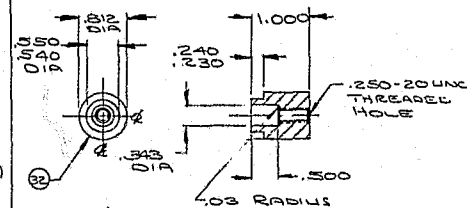
1. MAKE FROM REID TOOL COMPANY
P/N VNSB
NOTES

72



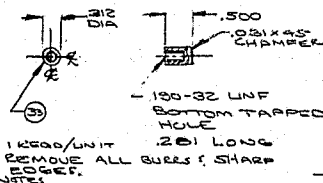
3. MAKE FROM REID TOOL
SUPPLY COMPANY
P/N: KA-1
2 1 REQD/UNIT
1 REMOVE ALL BURRS & SHARP
EDGES
NOTES

70



2. 1 REQD/UNIT
1. REMOVE ALL BURRS & SHARP
EDGES
NOTES

69

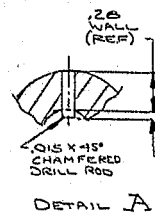
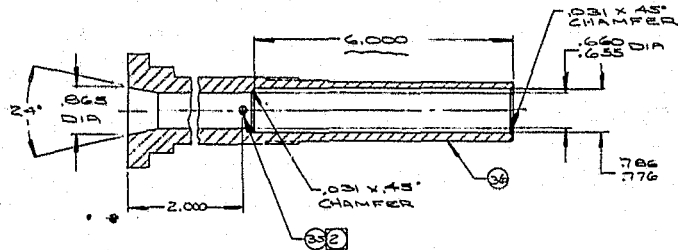
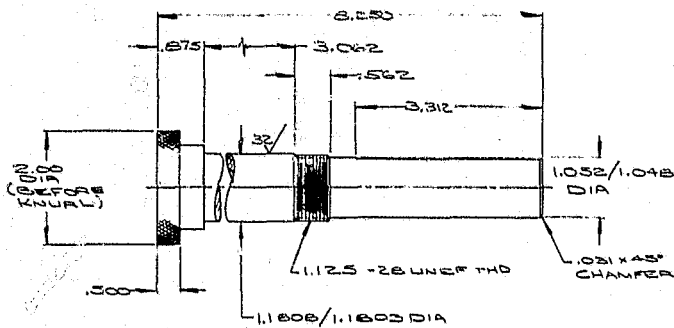


1. 1 REQD/UNIT
1. REMOVE ALL BURRS & SHARP
EDGES
NOTES

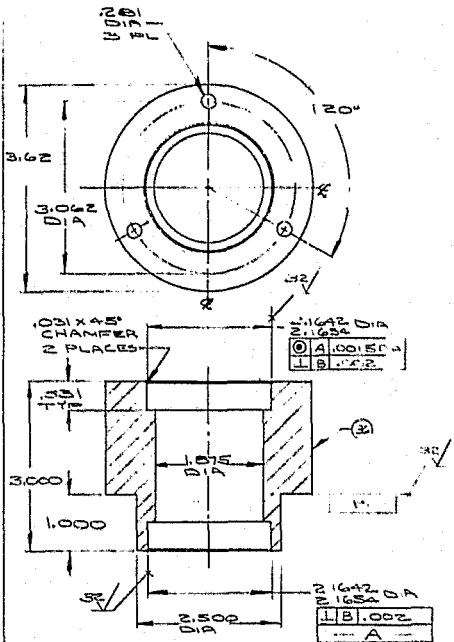
68

1 MAY BE PURCHASED FROM
FAFNIR BALL BEARING
LA, CA TEL # AN 8-7415

Capacitor winder 4 spool

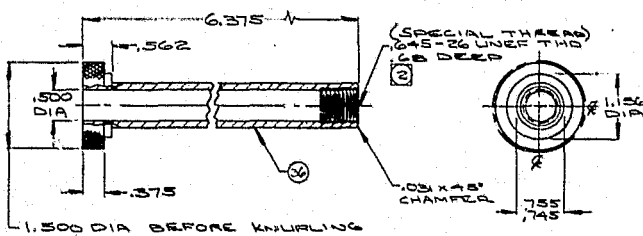


1 REQD/UNIT
-67



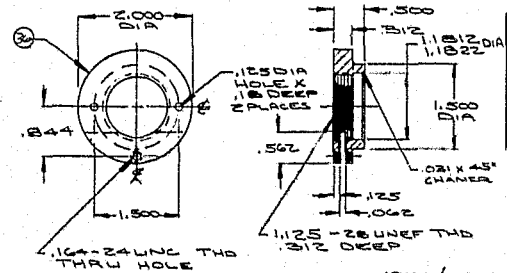
1 REMOVE ALL BURRS & SHARP EDGES. 2 REQD/UNIT
-66

2 PRESS FIT IN PLACE AS SHOWN (FN1 OR EQUIV)
1 REMOVE ALL BURRS & SHARP EDGES
NOTES:



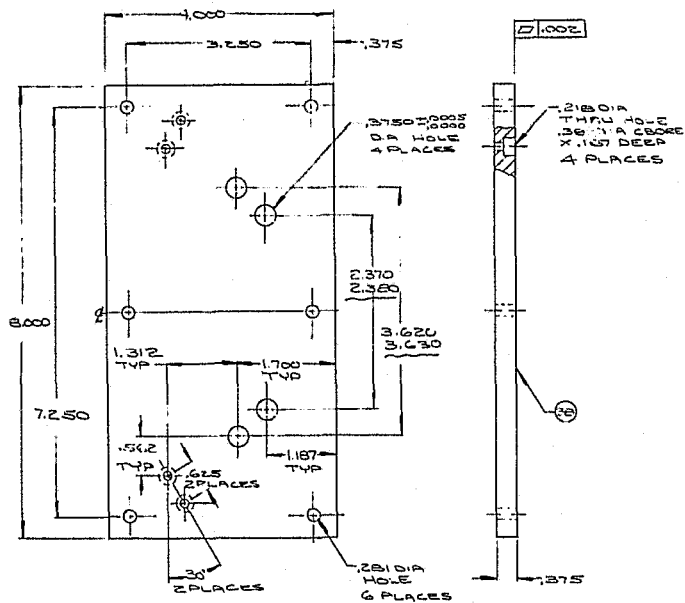
1 REQD/UNIT
-65

2 SPECIAL THREAD
1 REMOVE ALL BURRS & SHARP EDGES.
NOTES:



1 REMOVE ALL BURRS & SHARP EDGES. 2 REQD/UNIT
-64

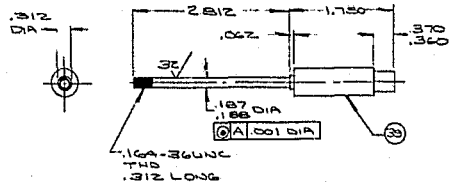
Capacitor winder 4 spool



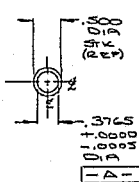
1 REMOVE ALL BURRS & SHARP EDGES.
NOTES:

1 REQD/UNIT
-63

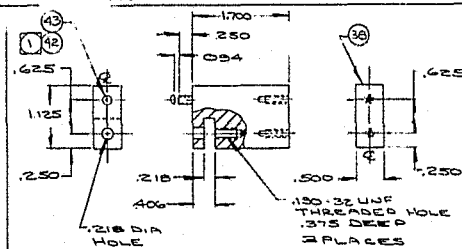
1 DETAIL TO BE A LIGHT PRESS FIT INTO PLATE (APPROX FNI OR EQUIV) 1 REQD/UNIT
NOTES: SUB. A. 1 (6)



2 A REQD/UNIT
1 REMOVE ALL BURRS & SHARP EDGES
NOTES:



-62



3 2 REQD/UNIT
2 REMOVE ALL BURRS & SHARP EDGES
1 TO BE LIGHT PRESS FIT (FNI OR EQUIV.)
NOTES:

-60

Capacitor winder 4 spool