HIGH-CURRENT, HIGH-FREQUENCY CAPACITORS

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The NASA Lewis high-current, high-frequency capacitor development program was conducted under a contract with Maxwell Laboratories, Inc., San Diego, California. The program was started to develop power components for space power systems. One of the components lacking was a high-power, high-frequency capacitor. Some of the technology developed in this program may be directly usable in an all-electric airplane.

The materials used in the capacitor included the following: the film is polypropylene, the impregnant is monoisopropyl biphenyl, the conductive epoxy is Emerson and Cuming Stycast 2850 KT, the foil is aluminum, the case is stainless steel (304), and the electrode is a modified copper-ceramic.

POLYPROPYLENE FILM

The physical makeup of the various polymer films is vital to the performance of the films as a capacitor dielectric, and particularly so when the longevity of the capacitor in service is so important.

Therefore the contractor was requested to analyze six films. The results are listed in table I. The film that rated the highest was polypropylene, which is the one Lewis chose. The scoring was arbitrary, but everything was scored equally. For the parameters of interest - frequency, voltage, and dielectric breakdown - it is evident that polypropylene film exhibits significant superiority for the application:

(1) Polypropylene films have lower density than the other films being considered, thus resulting in reduced capacitor weight and higher power density.

(2) Polypropylene films wet better than the other films and absorb oil to a greater degree, thus reducing the chance of damage from partial discharges during operation.

(3) Polypropylene polymer has greater crystallinity and is inherently more stable during service than the other films.

(4) Polypropylene's unique combination of temperature coefficient of dielectric constant and dissipation factor result in natural self-stabilization at a temperature just above that of the plate.

(5) The film quality of polypropylene has been raised to a very high order by the film manufacturers because of the competitive situation in the industry and because the capacitor industry is so important to the electric power industry. None of the other films tested had the uniform quality and low level of contamination of polypropylene.

(6) The superior dissipation factor of polypropylene film permits significantly greater power transfer without thermal runaway. This factor alone is so dominant in the selection process as to relegate all other films to lower status.

IMPREGNANT

The impregnant monoisopropyl biphenyl (MIPB) has extreme resistance to gamma radiation, low dielectric loss, and high corona resistance. It was absorbed well by the polypropylene (which was one of the tests that all of the films were subjected to), and it has good wetting characteristics. A good point was that the source of MIPB is in this country whereas some of the other impregnants are only available from foreign sources.

CAPACITIVE ELEMENTS

The design of the capacitor is shown in figure 1. There are two layers of polypropylene film between a split roll of aluminum foil and a floating foil. In each element this puts two capacitors in series, that is, from one connected foil to the floating foil in series with the other connected foil to the floating foil. This construction technique reduces the potential across the dielectric to half what it would be in a conventional capacitor. Using this technique reduces the potential gradient across the dielectric film and thus enhances life. One basic flaw in this thin film is the pinholes. Using two sheets of dielectric protects against pinhole short circuits.

To reduce the interfoil voltage of each element to a value that would provide the highest degree of performance reliability but could still be efficiently accommodated by the thicknesses of available dielectric materials, each capacitor element - or pad - is designed with two series-capacitor sections. To decrease the voltage yet further, two elements are then connected in series, thus reducing the ac voltage to 150 V rms. At this point there should be no partial discharges at the full capacitor operating voltage of 600 V rms plus 600 V dc bias.

The formidable rms current consistent with operating at maximum applied voltage and maximum frequency is to be dealt with by paralleling two series-connected element assemblies. This divides the current and reduces the 125 A to 62.5 A/pad, which can be handled by extended foil design of the elements.

CONDUCTOR-ELEMENT ASSEMBLY

Although the type of capacitor element assembly shown in figures 2 and 3 obviously leaves something to be desired in space utilization, the inefficiency is more apparent than real and the design gains more than it loses. The element assembly must be inherently very stable mechanically and must be extremely secure to withstand the vibration and shock associated with space vehicles. This element assembly will pass a Class III vibration test and will be safe from damage due to acceleration and shock. Electrical integrity will be maintained over the service life stipulated for this component.

The assembly of four elements is secured to the capacitor base in a layer of special epoxy resin that has the dual function of transferring heat from the bottom exposed foils directly to the capacitor base and then to the lower mounting bracket. The epoxy is Emerson and Cuming Stycast 2850KT, a material of exceptional thermal conductivity, low shrinkage, high-temperature resistance, and low-temperature coefficient of expansion.

TERMINATION

A modified bushing design (fig. 4) was employed to bring a terminal (stud) of sufficient size through the bushing to handle the highest rms current.

By this means resistive losses of the terminals were reduced to less than 4 W under maximum operating conditions. A low-profile bushing configuration would be even better, but such an insulator was not available. A layer of epoxy similar to that used internally to secure the elements was poured into the reentrant cover, around the terminals, and over the seal-off plug after the capacitor was fully impregnated and seal tested. This material helps transfer heat from the bushings to the mounting bracket and from the case to the lower mounting bracket; it also provides a redundant oil seal around the bushing flanges and over the seal-off plug.

The characteristics of the capacitor Lewis has built and tested are shown in figure 5. The capacitor operates at 600 V rms while biased at +600 V dc. The size is 0.83 μF, and the frequency is 40 kHz. It tested at 40 and 10 kHz. The design loss is less than 30 W. The temperature range is -40° C to +88° C and the volt-ampere rating is 75 kVAR. The capacitor weighs 7.9 lb.

CAPACITOR CASE

Although not immediately apparent from figure 5, this capacitor is inherently very rugged, and the hermetic seal will be maintained over the operational life. The case material, 20-g 304L stainless steel, was chosen for its strength, stability, and weldability and to provide minimum eddy current losses at the maximum operating frequency. Both cover and base are of "reentrant" configuration, to assure minimum heat damage to the interior materials during the welding operation after assembly. The only welding done after assembly of the elements into the case was the weld around the periphery of the cover.

The design loss in the four elements for the 75-kVAR unit is 15 W. There will be 2 W in the foil and 4 W going from the copper bus bars up to the terminals. So the total design loss is 21 W, which is low when compared with the amount of power flowing through the capacitor, 600 V at 125 A.

CORONA TESTING

Another test that was done was to take the split foil, build a parallel pad, and perform corona testing. When the foil was dry (no impregnant), the inception voltage was 1400 V and the extinction voltage was 1250 V. With the impregnant the inception voltage went up to 3200 V and the extinction voltage to 2800 V. Maximum peak operating voltage would probably be 1200 V or less. Therefore the capitator should not fail due to corona.

It is worthwhile to explain here the concern with the values of corona inception voltage (CIV) and corona extinction voltage (CEV) on the capacitor windings (pads) to be installed in the capacitors being prepared for vacuum endurance testing. It is generally accepted that electrical failure of a capacitor operated on alternating current is preceded by increasing partial electrical discharges (corona) in the capacitive elements. The locally generated extremely high temperatures cause deterioration of the insulating materials, both solid and liquid; and the gaseous byproducts of this deterioration either remain in the area of high electrical stress or are dissolved in the impregnant. In either event the result is progressive damage to the insulation, and the partial discharges increase to an avalanche condition, resulting in electrical failure.

If the CIV value measured on a given capacitor is at least twice the normal operating voltage, it is considered safe to assume that capacitor failure, when it inevitably comes, must result from progressive electrochemical changes in the elements. Such a condition will normally occur beyond the design life of the unit.

The CEV is the voltage at which partial discharges no longer occur, after inception has been brought about. The CEV is usually determined by increasing the applied ac voltage until CIV is obtained and then lowering the applied voltage until corona is no longer detectable. The significance of CEV lies in the fact that an ac capacitor is subjected to electrical transient stresses that are beyond the normal working stresses. If these transients are severe to the point that CIV is reached, no permanent harm will result if the CEV value is above the voltage applied after the transient condition is no longer present. For this reason, it is necessary that the CEV measured on the capacitor be greater than the normal operating voltage. However, it will be obvious that some safety factor must be present to allow for changes in capacitor characteristics over the operating life.

Model windings of the capacitor to be vacuum endurance tested have been prepared and the CIV and CEV measured at 60 Hz with no impregnant and after vacuum drying and impregnation with monisopropyl biphenyl.

The capacitors were tested at the two sets of conditions shown in table II. Condition A was the full power test; however, it was performed in air rather than vacuum because of induction heating in the vacuum tank.

500-HOUR VACUUM ENDURANCE TEST

The baseplate contained 10 capacitors, 5 on each side, as shown in figure 6.

Examination of the temperature rise values of the various areas of the capacitors (fig. 7) indicated that the fuses being connected directly to the stud of a capacitor bushing distorted the temperature conditions of the capacitor. The average temperature rise of the nearby thermocouples was 19.7 deg F; the average temperature rise of areas near unfused bushings was 8.3 deg F. Later calculation of the resistance of the 50-A fuses and determination of the heat loss in the fuses explained the temperature rise of the fused bushings. Needless to say, the 300-A fuses were located away from the capacitors during the 40-kHz vacuum endurance test.

Thermocouples 5 and 10 (fig. 6) represent center-of-cover temperature values of two capacitors in completely different locations on the temperature plate. Even so, the temperature rise values are the same - a modest 16 deg F in what would normally be the highest temperature point on a capacitor. Thermocouple 6 is the only one uniquely located, and it is on the front of the temperature plate. This is fortunate, since the rise of 26 deg F would otherwise have been difficult to explain. Although T6 is located in a normally low-rise area of a capacitor, the temperature rise in this case is the greatest of all points. The reason is that T6 is located at the confluence of four heavy cables, an area of the plate where one could expect maximum temperature.

Thermocouples 4 and 16 are identical points on capacitors on opposite sides of the temperature plate and would be expected to exhibit low values of temperature rise if the epoxy temperature transfer material was properly transferring the local interior heat collected by the bottom extended foils to the

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bracket and then to the plate. There is a cable in proximity to T4, which may account for the slightly higher value than shown for T16. T16 was located on S/N 140355, near no cable, and should be expected to have the lowest temperature rise.

Figure 8 shows how the capacitors were crowded into the vacuum tank. Running this setup with 40 kHz caused ground loops in the tank. The tank heated up and two thermocouple cables completely melted. At 40 kHz and 600 V there was a lot of induction heating. Although we tried to modify the vacuum tank, finally the test had to be run in air.

The development program is completed. Capacitors have been tested under load, but we have not had the final design review. The capacitor is sturdy because it was overdesigned. It probably can be made 30 percent smaller.

TABLE I. - RESULTS OF FILM ANALYSES

1. Mylar
2. Polycarbonate
3. Kapton
4. Polypropylene
5. Polysulfone
6. Teflon

	Material 1	2	3	4	5	6
Dielectric Strength (Major) x 2	14	14	14	18	14	14
Dielectric Constant (Minor)	5	4	5	3	4	3
Dissipation Factor * (Major) x 2	4	10	6	18	12	14
Insulation Resistance (Minor)	7	9	10	9	6	9
Temp Coeff. of Diel. Constant * (Minor)	1	8	8	7	9	8
Temp Coeff. of Diss. Factor * (Major) x 2	2	16	6	20	10	18
Freq. Coeff of Diss. Factor * (Major) x 2	4	16	8	20	10	18
Chemical Stability (Major) x 2	14	14	18	12	14	16
Density * (Major) x 2	10	14	10	18	14	6
Impregnant Absorption (Major) x 2	4	6	4	14	6	2
Corona Resistance (Major) x 2	16	14	18	16	16	6
Radiation Resistance (Minor)	7	7	8	6	5	8
Thin Film Availability (Major) x 2	18	14	8	14	10	14
Specific Heat (Minor)	5	4	5	7	4	3
Cost * (Minor)	6	5	1	8	5	3
Total	117	155	129	190	139	142

* Parameters marked with asterisk are negative coefficients; ie. a high numerical value yields a low rating.

TABLE II. - TEST CONDITIONS

	Condition A	Condition B
Number of test samples	10	10
Temperature (±5° C), °C	25	25
Barometric pressure, torr	Air	10^{-3}
Applied voltage (±2 percent), V rms	600	600
Wave shape	Sine wave	Sine wave
Frequency (±1 kHz), kHz	40	10
dc bias (±2 percent), V dc	600	0
rms current (sample, ±5 percent), A	125	30

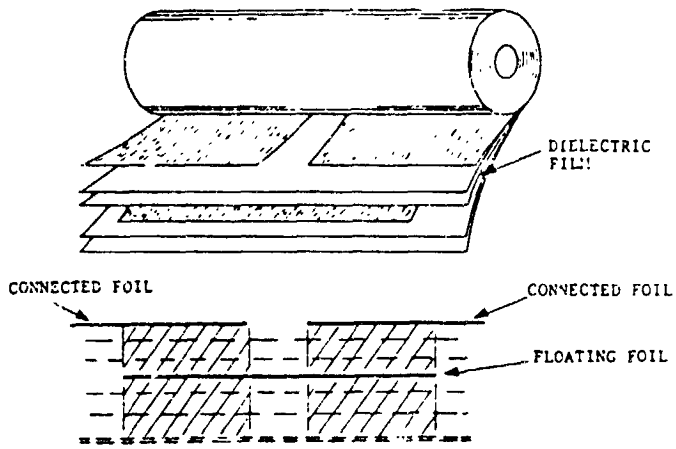

Figure 1. - Details of capacitor element.

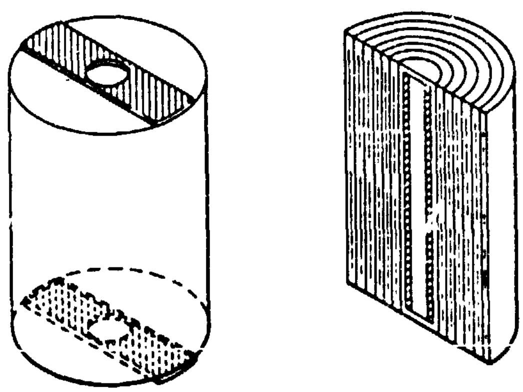

Figure 2. - Capacitor element.

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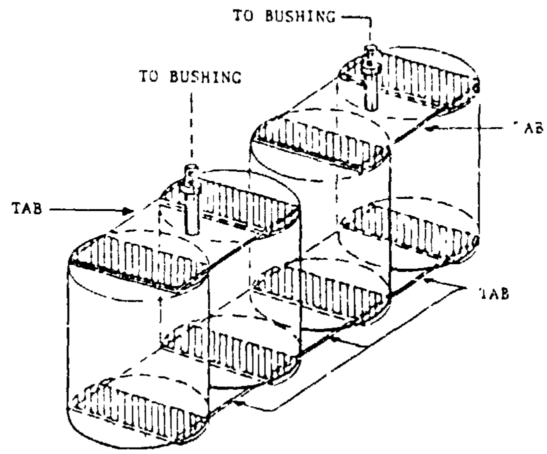

- INITIAL SOLDER SWAGING TO EXTENDED FOILS ACCOMPLISHED WITH J22 SOLDER
- TINNED COPPER TABS SOFT SOLDERED TO SWAGED PATTERN WITH 60/40 T-L SOLDER

Figure 3. - Capacitor element assembly.

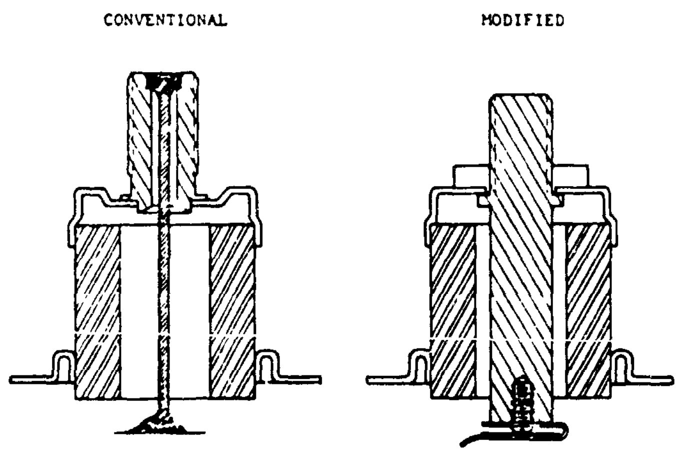

Figure 4. - Electrodes and insulator assemblies.

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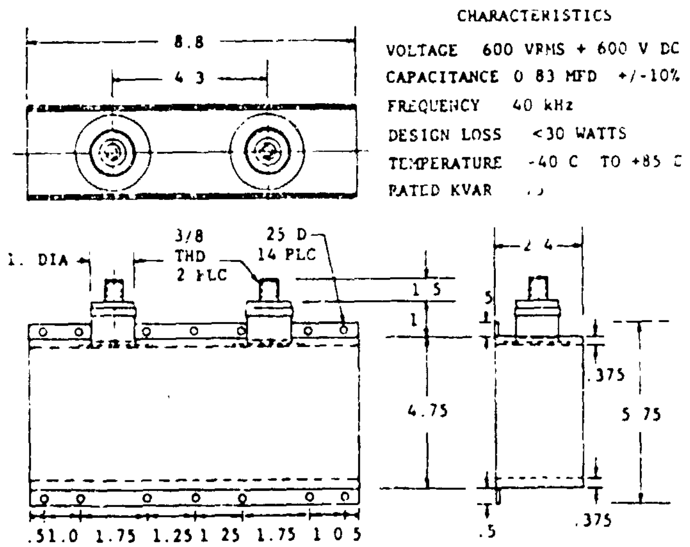

Figure 5. - Characteristics of 400-Hz capacitor.

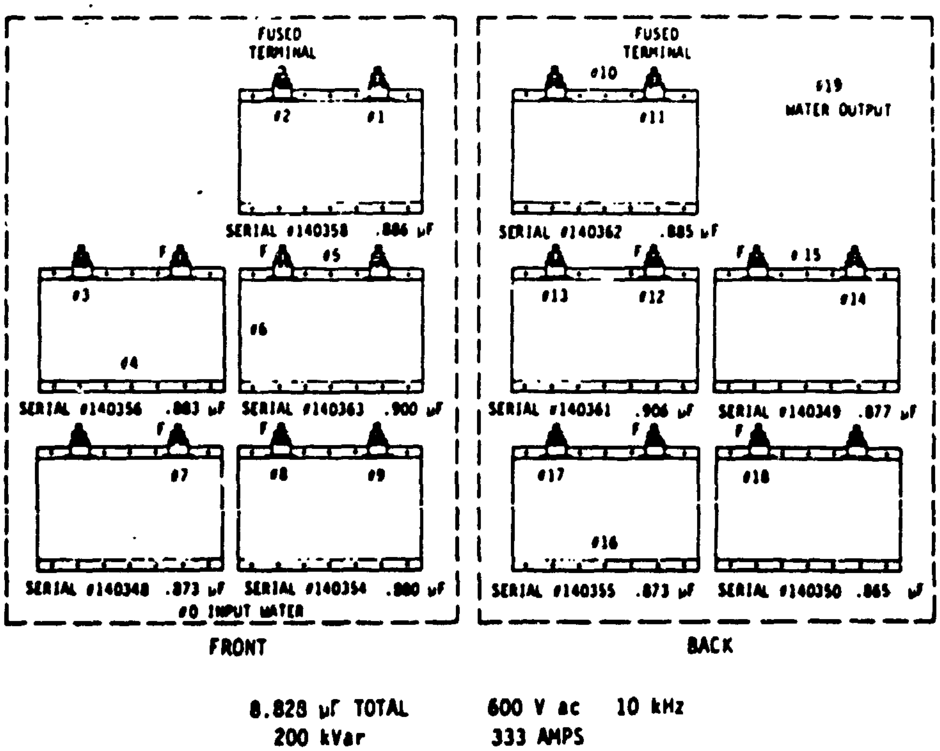

Figure 6. - Thermocouple locations for 500-hr vacuum endurance test.

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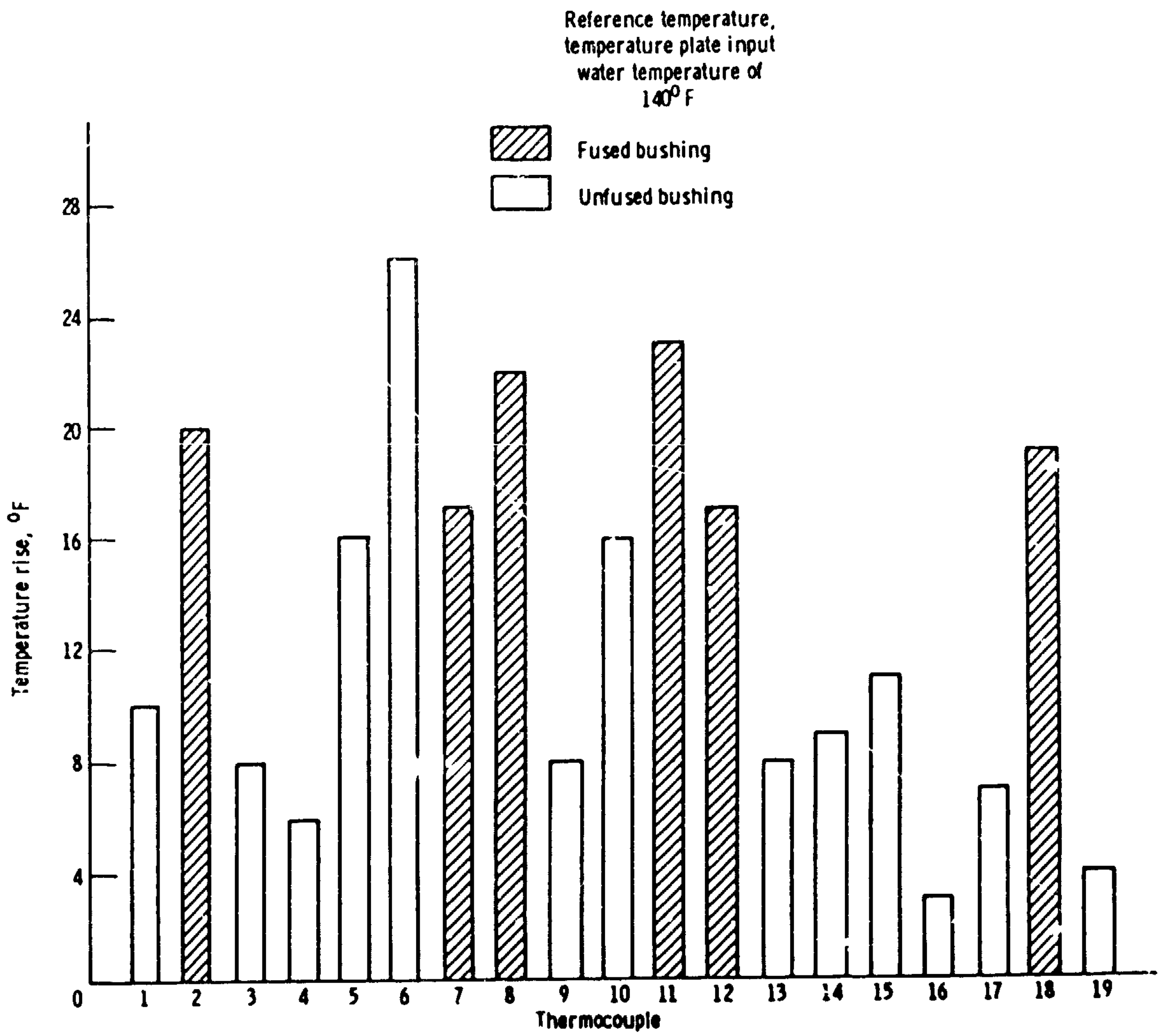

Figure 7. - Vacuum endurance test temperature rise after 503 hrs at 10 kHz.

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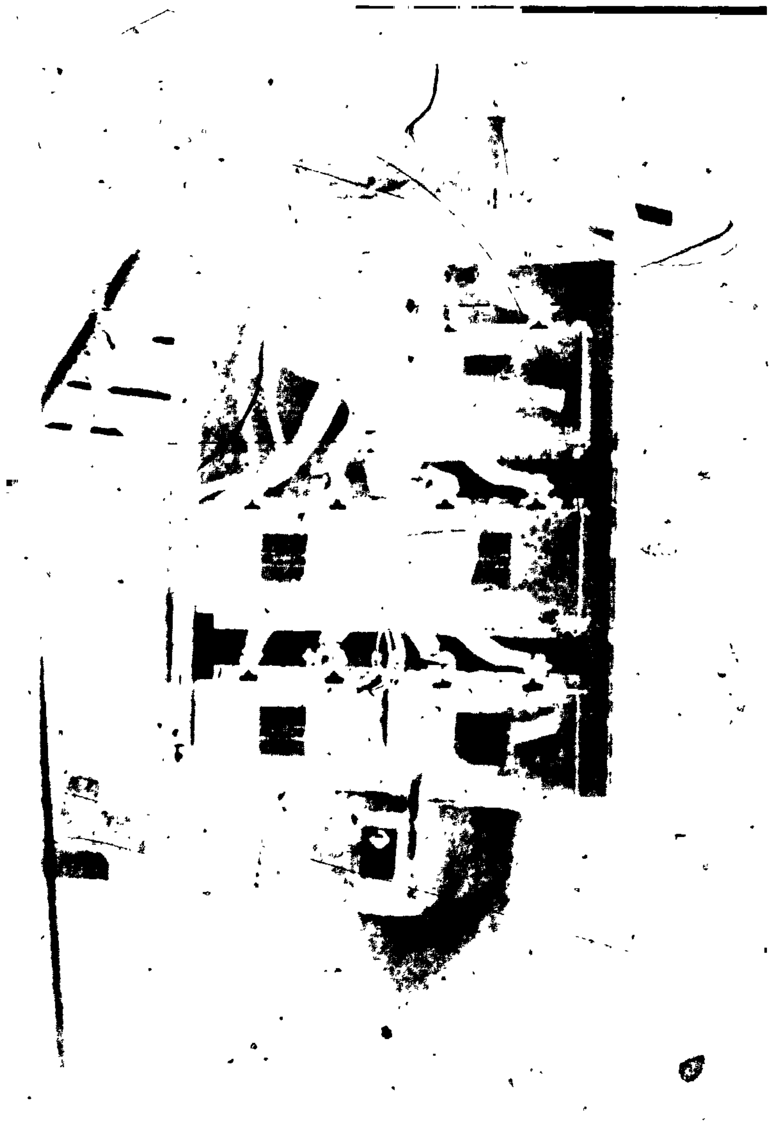

Figure 8. - Capacitor locations for 500-hr vacuum endurance test.