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TANTALUM CAPACITOR BEHAVIOR UNDER FAST TRANSIENT OVERVOLTAGES

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16. Abstract

Tantalum capacitors were tested to determine failure time when subjected to short-duration, high-voltage surges caused by lightning strikes. Lightning is of concern to NASA because of possible damage to critical spacecraft circuits. The test was designed to determine the minimum time for tantalum capacitor failure and the amount of overvoltage a capacitor could survive, without permanent damage, in 100 microseconds. All capacitors tested exhibited good recovery from the transient one-shot pulses with no failure at any voltage, forward or reverse, in less than 25 microseconds.

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SUMMARY

A lightning strike is a short-duration, high-current surge. In the upper 2-percentile strike, the current rises to 200 000 amperes within 2 microseconds and falls to zero in 100 microseconds. Lightning strikes couple voltage pulses of 300 microseconds or less into nearby electrical and electronic circuits.

Little or no information is available about the behavior of a capacitor subjected to a single high-amplitude voltage pulse of less than 100-microseconds' duration. The laws of kinetics demand that movement of any mass, no matter how small, requires some time. Therefore, a capacitor rupture or punch-through failure should take some minimum time because material must be moved across the electrode gaps. This test was devised to determine if this minimum time is comparable to a lightning strike risetime. The results and conclusion of the test and their applicability to lightning-induced transients are given in this report.

INTRODUCTION

The prime concern of NASA relative to lightning is the frequency with which spacecraft have been struck on the launch pad and the resultant possible damage to critical spacecraft circuits. The spacecraft power buses that are common to most circuits link large values of magnetic flux and are of particular concern. These buses are shunted by many tantalum capacitors used as input filter capacitors in the circuits fed by the buses. These filter capacitors act as a reservoir for the excessive displacement currents in the magnetic-flux-linked loops, protecting other components in the circuits, up to the point of a voltage rupture or punch-through of the capacitors. When a lightning strike occurs, the capacitor must withstand a large voltage in a short time period; however, there is a possibility of capacitor survival, even if the pulse voltage amplitude is several times the rated voltage.

The test setup used to measure capacitor response to high-voltage fast transients is shown in figure 1. The equipment used consisted of a commercially available, highly specialized, high-voltage tester with two plug-ins; a 50-megahertz oscilloscope with a camera; thirty 18-microfarad, 50-volt dry tantalum capacitors; fifteen 6.8-microfarad, 50-volt wet tantalum capacitors; a safety shield; a 50-V dc power supply; and a 200-ohm bleed-off resistor. Test capacitor values were chosen to closely approximate average values found on the spacecraft buses.

The commercially available high-voltage tester was used with two plug-ins with the following output characteristics.

Plug-in	Maximum voltage	Maximum current	Generator impedance
Medium current	2500 volts	12.5 amperes	200 ohms
High current	40 volts	750 amperes	0.053 ohms

The primary objective of the test was to determine the absolute minimum time for a tantalum capacitor to fail. This time would be the vertical asymptote of a time-failure voltage plot. The secondary objective was to determine the amount of overvoltage a capacitor could survive, without permanent damage, in 100 microseconds, which corresponds to lightning time duration.

DISCUSSION

The purpose of this test was to characterize capacitor responses to fast transient overvoltages so that the damage, resulting from lightning-induced voltage surges, could be assessed.

Lightning risetime intervals range from 2 to 100 microseconds, and falltime from 100 to 200 microseconds. The induced electromotive force (emf) in circuits that link with the magnetic flux is proportional to the time derivative of the lightning current (fig. 2). Thus, voltage surges caused by lightning will range from 2 to 300 microseconds. Because the risetime for the current is generally less than the falltime, the induced electromotive force will be greater in absolute magnitude during the risetime.

Capacitor failure occurs when migration of some material across the gap between the electrode foils provides a conductive path for fault current. Migration of the material impelled by the electromotive force must require an indeterminate minimum time to complete the trajectory. This time is unknown, but equations of kinetics establish that it must be greater than a microsecond. This test was initiated to determine this minimum time. The ideal waveform for overstress was envisioned as a reasonably flattop voltage pulse, with a duration controllable from approximately 1 to 300 microseconds. A sudden break from the flattop during the interval would indicate the time required to fail at the constant voltage. To obtain this ideal waveform, a variable voltage source generator of near zero impedance would be required. The nature of the test and test equipment prevented an ideal flattop voltage pulse. Generator source impedance caused the leading edge of the waveform across the test capacitor to be a resistance-capacitance (RC) charge-up curve. However, useful data were obtained that may help to evaluate capacitive networks overstressed by lightning-induced voltages.

To determine failure time for a given constant voltage level using a real test voltage pulse, an analytical method was derived to extract data from the varying voltage curve. A typical voltage waveform with a varying slope is shown in figure 3. The voltage V_1 was assumed to have remained constant through the time interval t_1 to the intercept at V_2. This assumption is conservative because any instantaneous voltage on the curve is greater than V_1 in the interval t_1. Because there is no voltage breakdown for the figure 3 example, a capacitor showing this test waveform will not fail in less time than t_1 at voltage V_1. If a failure should occur (as shown in the typical curve in fig. 4), then, using this analytical method, it can be conservatively stated that the test capacitor cannot fail at a constant voltage V_1 in less time than $t_{fail} - t_1$. The accuracy of this method for determining minimum failure time is inversely proportional to the slope of the curve between the selected voltage intercepts. For an accurate value of time to fail, then, the portion of the test curve used for analysis should be as close to a zero slope as possible.

By using the analytical method just described, it was determined that, on the average, dry tantalum capacitors overstressed with forward polarity voltage fail at 190 percent of rated voltage in 100 microseconds. The 100 microseconds represents the portion of the curve nearest a zero slope on the test waveforms immediately preceding a voltage breakdown. The choice of intercept points is fairly subjective, and the results obtained depend on them; nevertheless, the approximate value is reasonably consistent.

The reverse voltage limit on dry tantalum capacitors is approximately equal to the forward rated voltage for an interval of approximately 100 microseconds. The voltage waveforms show that capacitor survival voltage progressively increases as the time is shortened. The forward voltage tolerance of the wet tantalum capacitors is 300 percent of rated voltage for approximately 140 microseconds.

Reverse voltage tolerance of wet slug capacitors is somewhat obscured by the electrochemical inertia of the sulfuric acid electrolyte. This effect delayed migration of fault material and thereby prevented a pronounced rupture or punch-through. Failure occurred, on the average, at 100 percent of forward rated voltage at approximately 250 microseconds.

When reverse testing was continued with the very-high-current generator plug-in (750 amperes available at 56 volts), the sacrificial current leakage could not delay the time to failure. Therefore, failure time is independent of small leakages. When failure occurred, the time interval was found to average approximately 30 microseconds, with a lower limit of 25 microseconds. This time interval was also noted as being the minimum time to fail in the flat portion of the forward voltage tests. The frequency of occurrence of the 25-microsecond minimum interval indicates that, almost independent of voltage, a tantalum capacitor cannot fail in less time because of the kinetics of the failure mechanism.

Oscilloscope photographs of test voltage waveforms, together with a description of the test setup for each case, are presented in the appendix. Other methods of evaluating the test results may be used to compare the criteria presented in this report.

All the capacitors that were overvoltaged with the fast transients were subsequently subjected to an instantaneous application of the 50 volts (rated voltage) in the forward direction. All returned to normal pretest leakage of 1 microampere or less, with the exception of those that were reverse voltaged. The reverse-voltaged dry capacitors leaked as much as 50 microamperes (worst case) compared to approximately 1 microampere average leakage before they were overstressed. The worst leakage on the wet capacitors for reverse voltage was 1.5 microamperes, compared to less than 0.5 microampere before the overstress. Post-test leakage values are given in the appendix.

RESULTS

For overvoltage transients of 100 microseconds' duration, voltage tolerance for a single pulse, with no permanent damage, is evaluated as follows:

Function	Percent of rated voltage	
	Dry capacitors	Wet capacitors
Forward	190	300
Reverse	100	100

All capacitors exhibited good recovery from the transient one-shot pulses. This recovery ability decreases with repeated transient pulses.

CONCLUSIONS AND RECOMMENDATIONS

No failure would be expected to occur with these tantalum capacitors, almost independent of the voltage, in less time than the 25 microseconds observed in the test. More testing should be performed using faster high-current generators of higher voltage with a greater range of capacitor type, rated capacitances, and rated voltages. Capacitor response to fast high-voltage transients should be explored thoroughly because the results are useful in designing equipment that must withstand high-voltage transient surges.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, December 16, 1974
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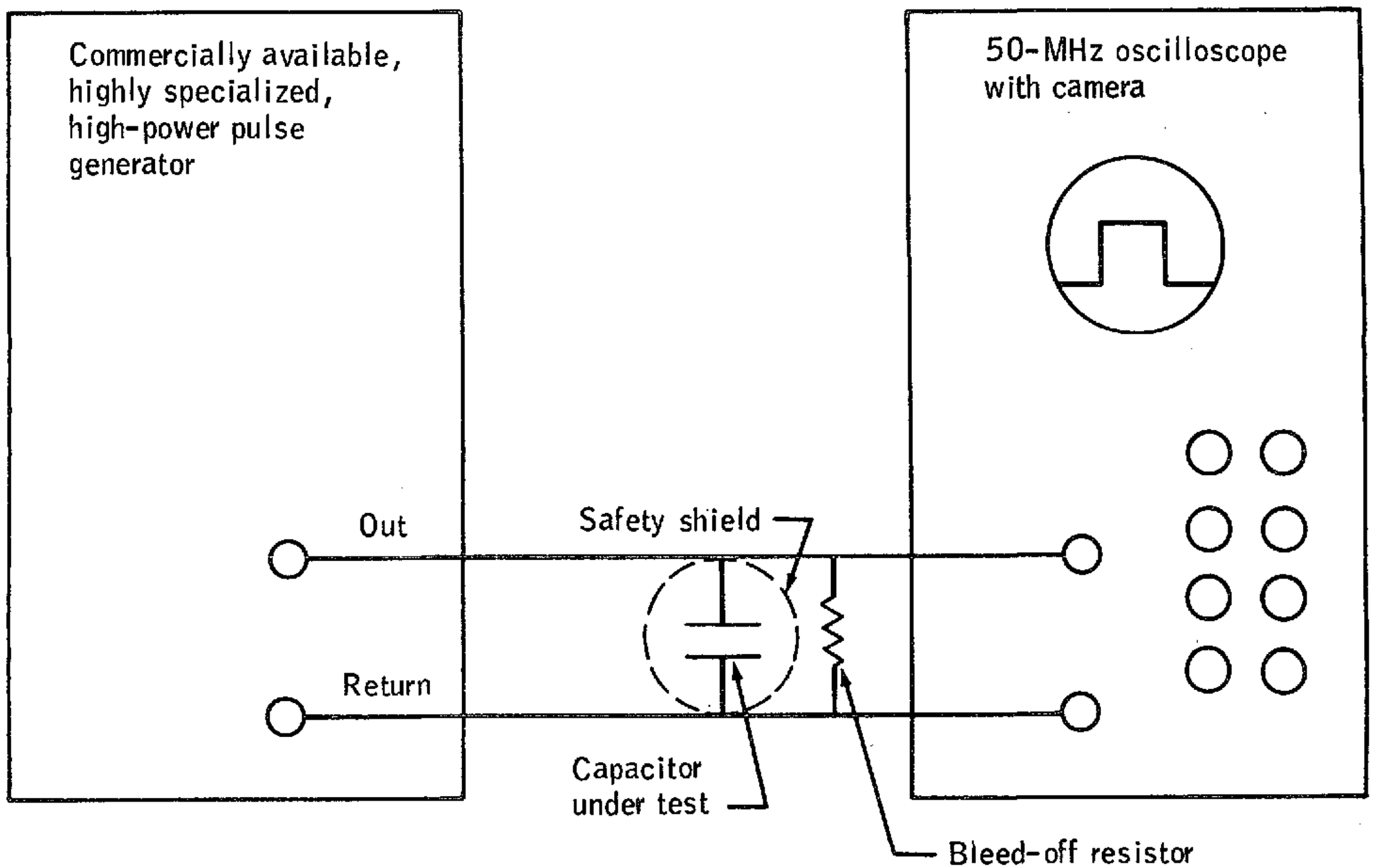


Figure 1.- Tantalum capacitor test configuration.

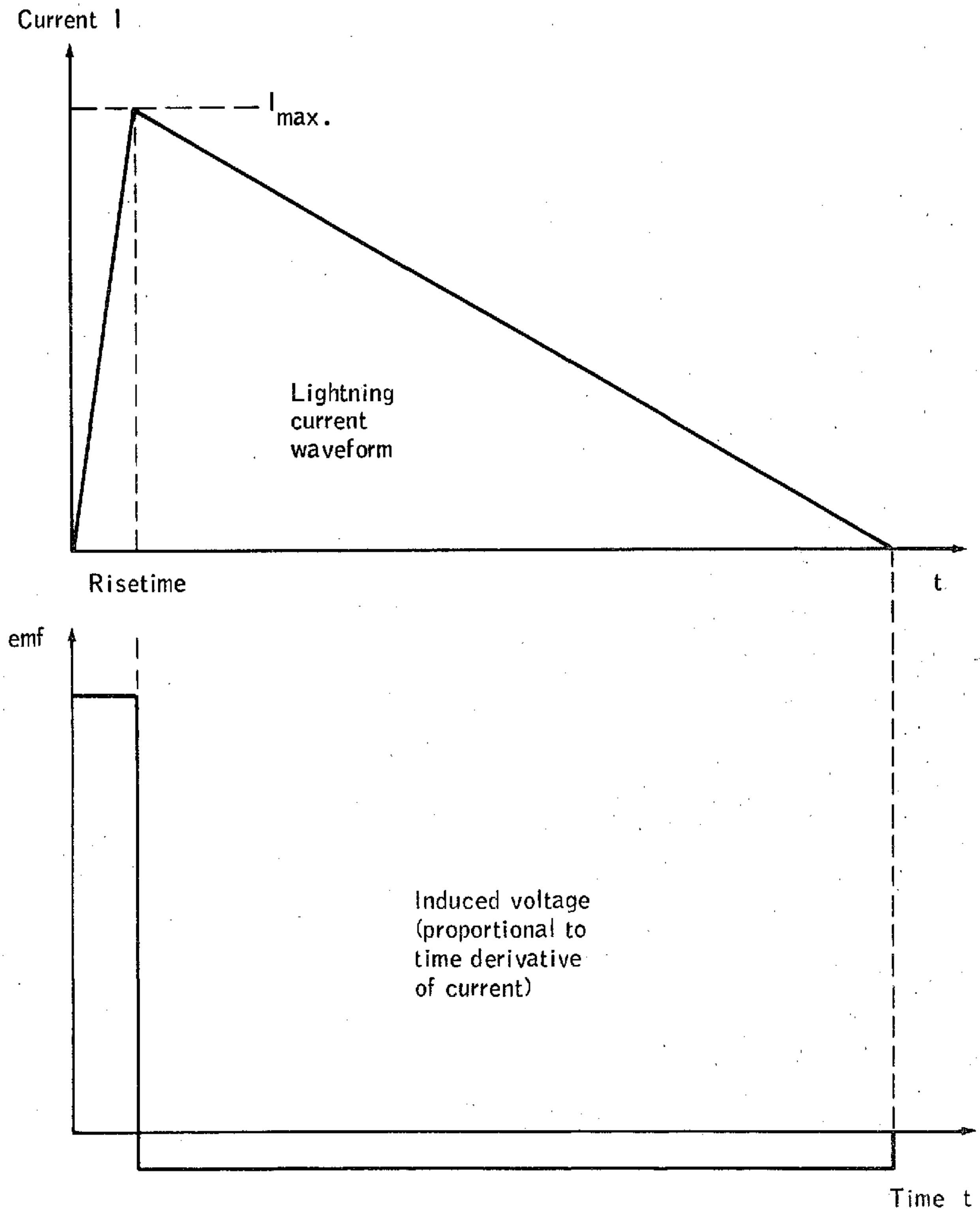


Figure 2.- Graphic solution of lightning-induced emf.

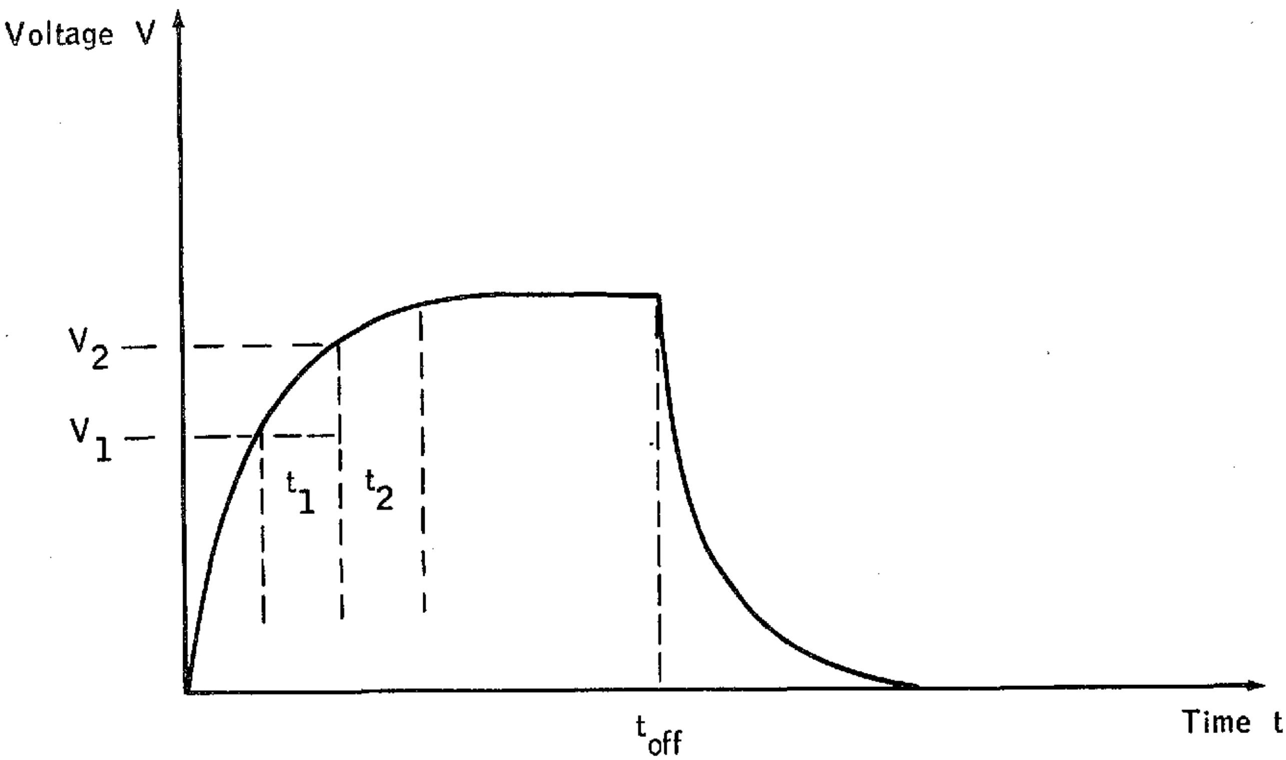


Figure 3.- Varying slope voltage waveform.

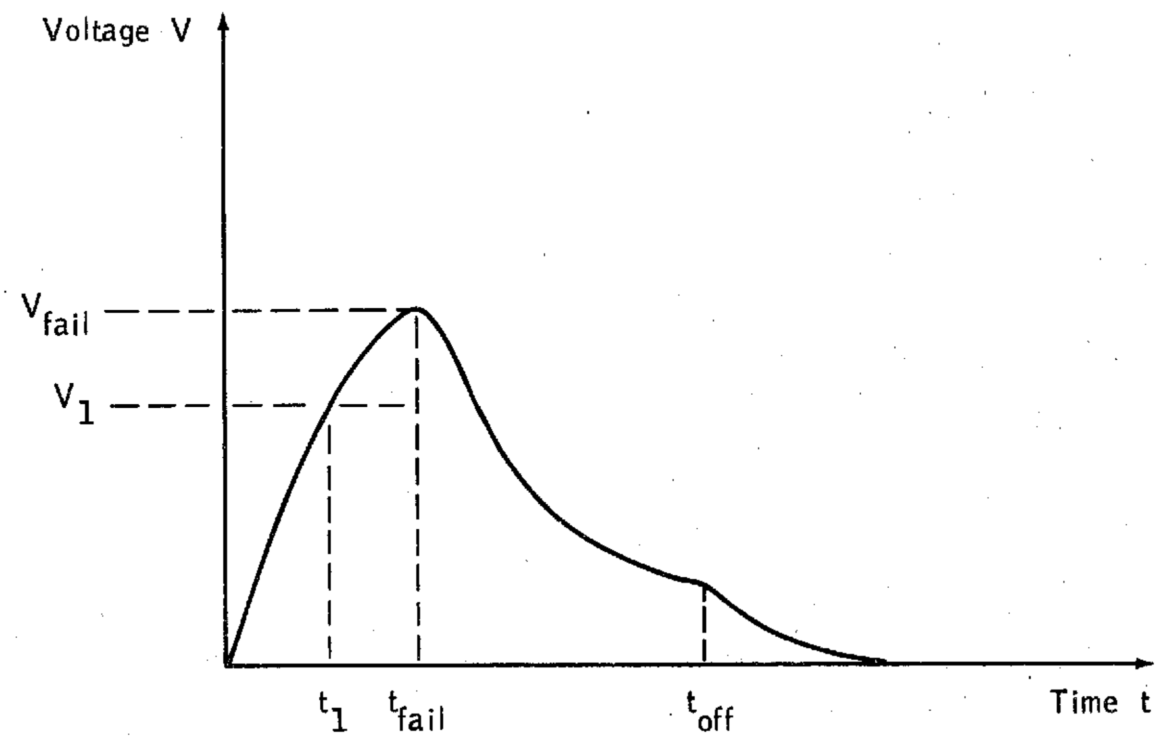


Figure 4.- Failure curve example.

APPENDIX

OSCILLOSCOPE PHOTOGRAPHS

This appendix contains the oscilloscope photographs of the test voltage waveforms. The setup for each test is described in table I. The post-test leakage values are given in table II.

TABLE I.– OSCILLOSCOPE PHOTOGRAPH INDEX

Photograph no. and type (a)	Oscilloscope scale		Pulse time, μsec	Failure at –		Comments (b)
	V/cm	μsec/cm		Voltage, V	Time, μsec	
1 (DF)	20	50	490	None	None	
2 (DF)	50	50	490	75	340	Same capacitor as no. 1
3 (DF)	50	50	495	100	350	
4 (DF)	50	50	295	110	175	
5 (DF)	100	50	300	100	115	Most pronounced failure of series
6 (DF)	100	50	300	100	145	
7 (DF)	100	50	300	90	110	Note multiple healing
8 (DF)	50	20	152	100	132	
9 (DR)	5	50	50	None	None	
10 (DR)	5	50	500	None	None	Same capacitor as no. 9
11 (DR)	10	50	500	None	None	Same capacitor as no. 9
12 (DR)	20	50	500	None	None	Same capacitor as no. 9
13 (DR)	50	50	500	95	395	Same capacitor as no. 9
14 (DR)	50	50	500	90	400	Breakpoint ill-defined
15 (DR)	50	50	500	95	215	Same capacitor as no. 14
16 (WF)	50	50	500	None	None	
17 (DR)	50	50	500	80	300	Breakpoint ill-defined; same capacitor as no. 16
18 (DR)	50	50	500	80	285	
19 (DR)	50	50	295	75	150	Same capacitor as no. 18
20 (WF)	20	50	500	None	None	
21 (WF)	50	50	500	140	310	Slight leak; same capacitor as no. 20
22 (WF)	50	50	300	150	150	Leaking but no breakdown
23 (WF)	50	50	300	130	95	Leaking
24 (WF)	50	20	98	160	72	Leaking
25 (WF)	50	50	245	None	None	
26 (WR)	10	50	490	None	None	
27 (WR)	20	50	490	None	None	Same capacitor as no. 26; intermittent leaks
28 (WR)	100	50	500	None	None	Same capacitor as no. 26
29 (DF)	20	10	67	None	None	(c) (d)
30 (DF)	20	10	67	None	None	
31 (DR)	20	10	67	52	45	
32 (WF)	20	10	67	None	None	(d)
33 (WR)	20	10	67	None	None	
34 (DR)	20	10	67	48	34	(e)
35 (DR)	20	10	67	56	56	
36 (WR)	20	10	67	None	None	
37 (WR)	20	10	67	54	25	
38 (WF)	50	50	500	None	None	

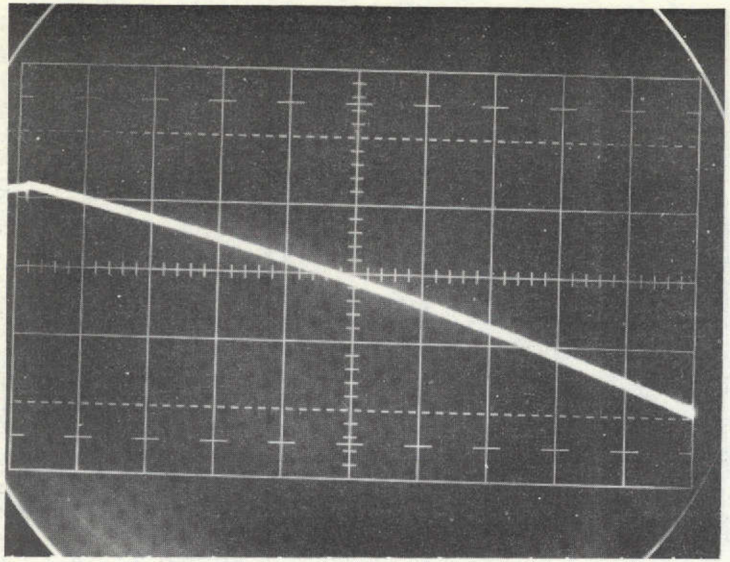
[a](DF) dry forward, (DR) dry reverse, (WF) wet forward, and (WR) wet reverse.

[b]The voltage produced by the high-energy generator is a negative-going pulse; thus, it appears in all photographs. Change of polarity on the test capacitors was controlled by turning capacitor end for end.

[c]The first hump in the waveform is due to an inductive kick from the high-current transformer plug-in beginning with test sample no. 29.

[d]The maximum output voltage of the high-current plug-in was insufficient to overstress the capacitors in the forward direction.

[e]The response pattern of this capacitor is so different from the other dry-reverse-voltaged capacitors that it is considered to be an originally defective capacitor. Post-test leakage current, however, stabilized at 5 μA with rated voltage of 50 V dc applied.



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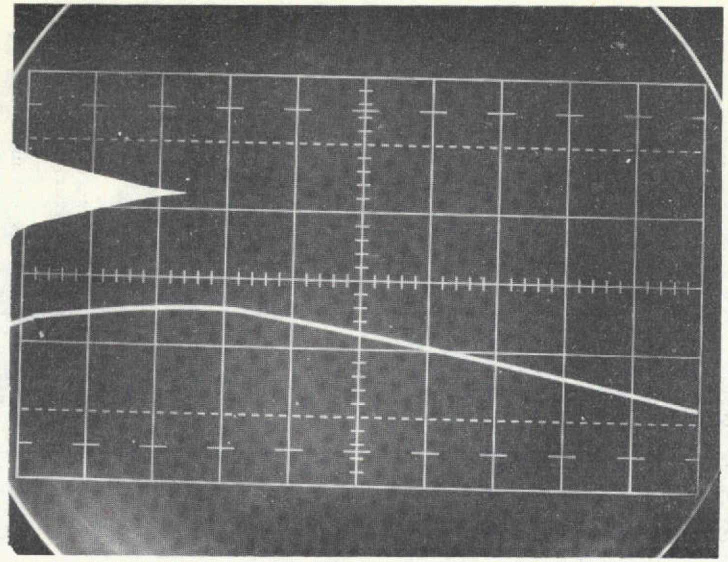

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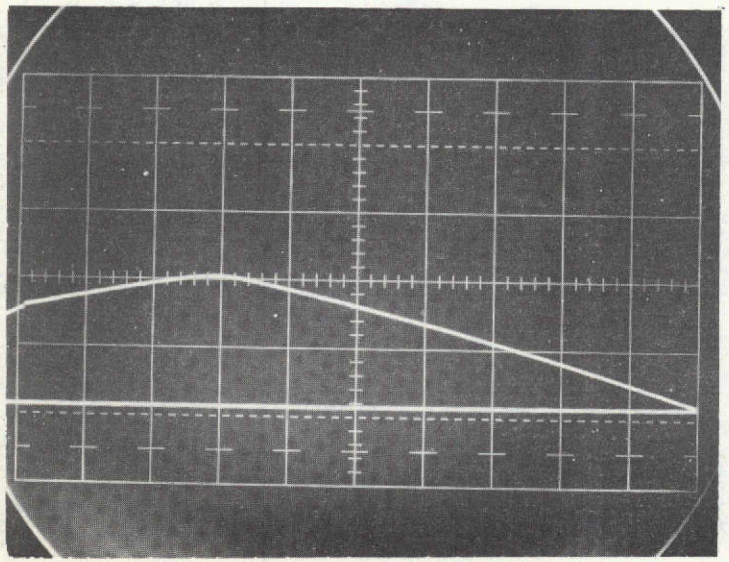

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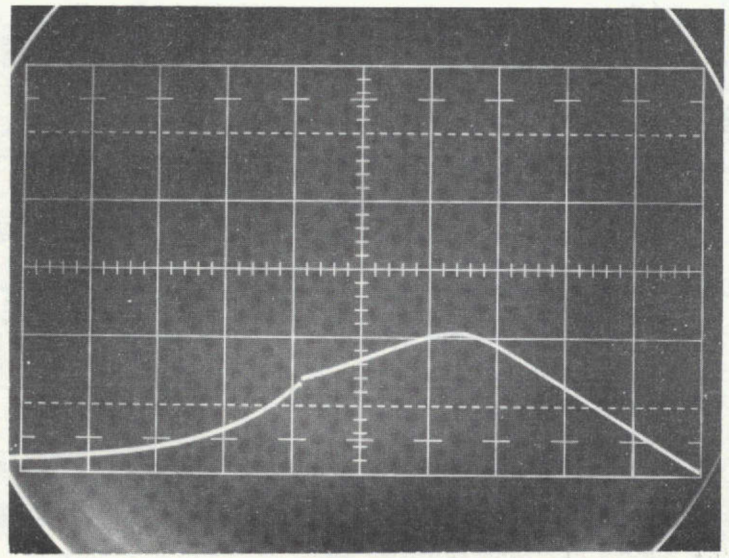

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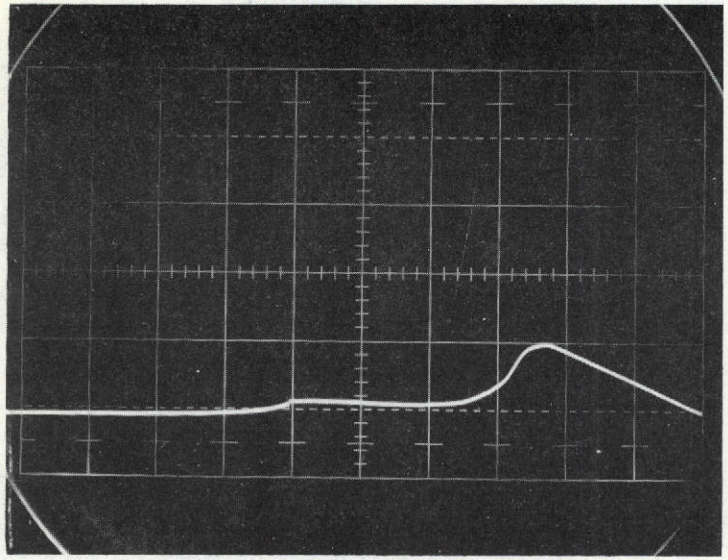
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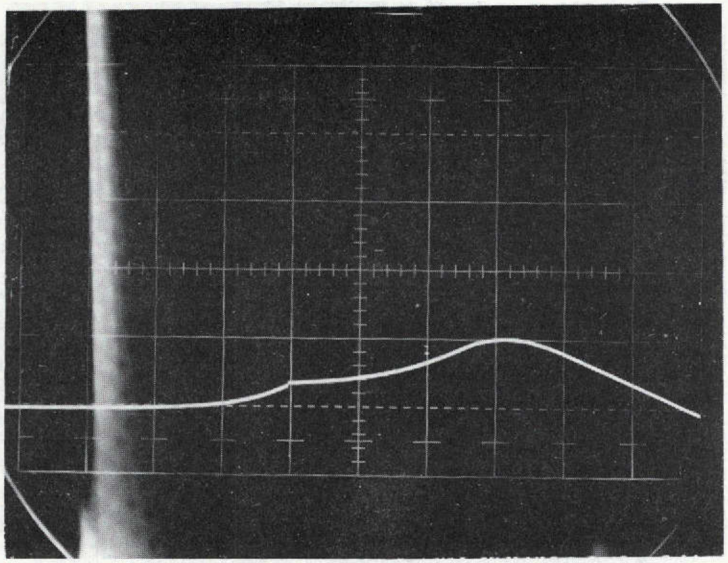
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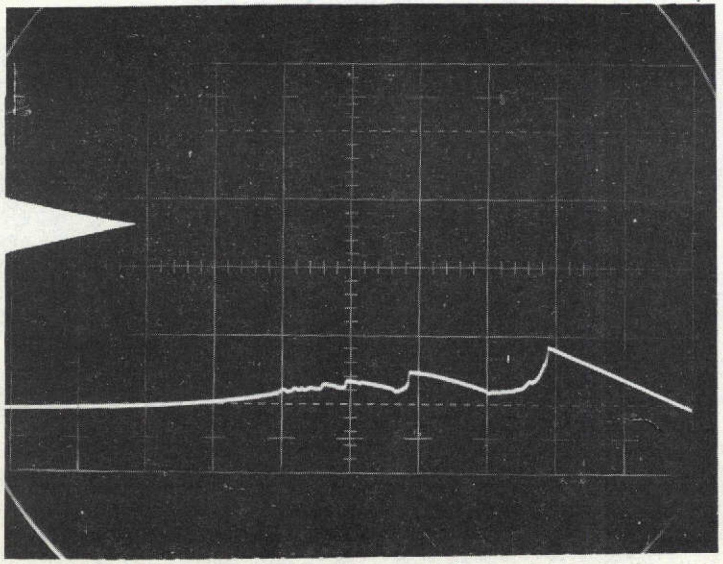
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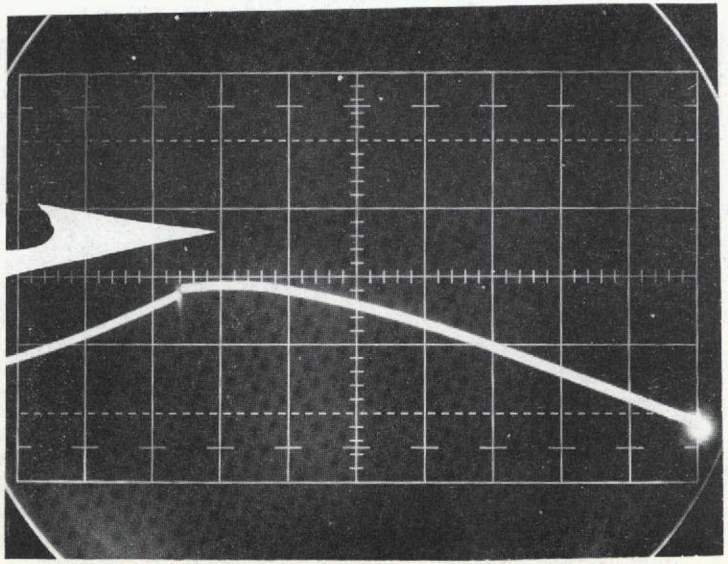
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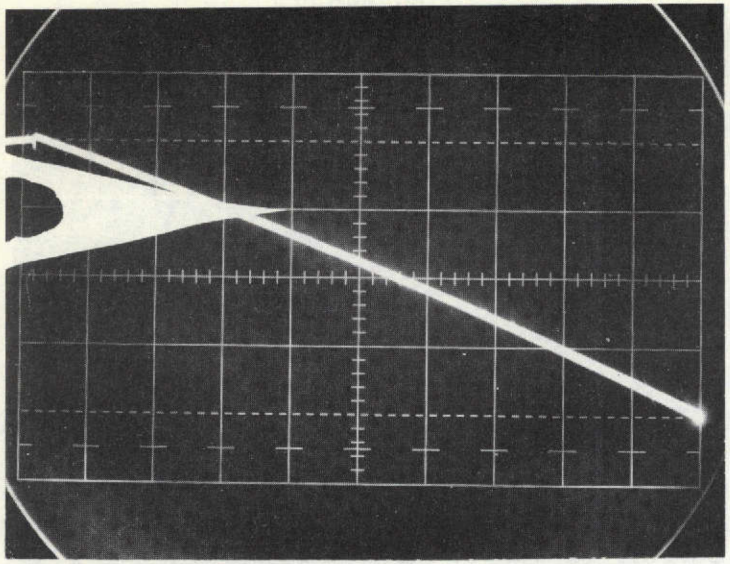

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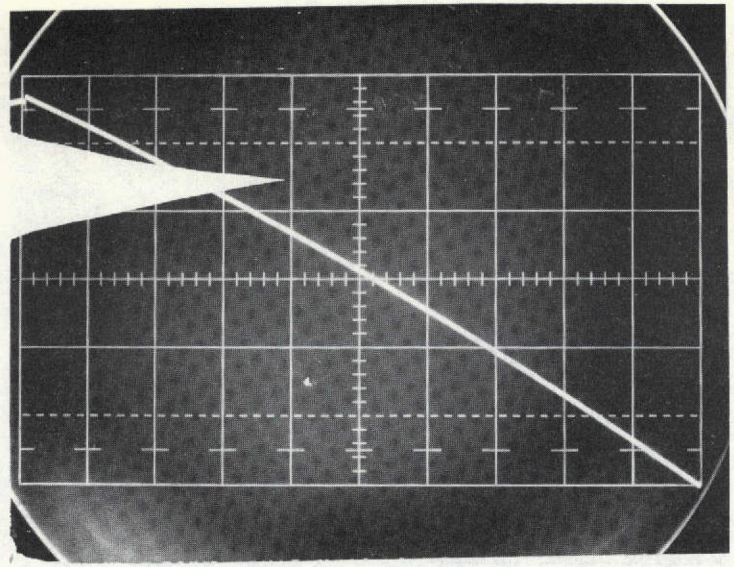

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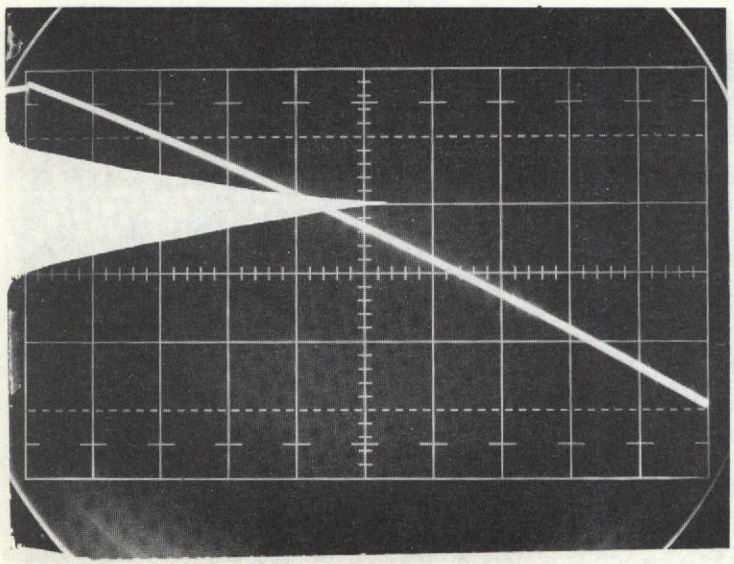

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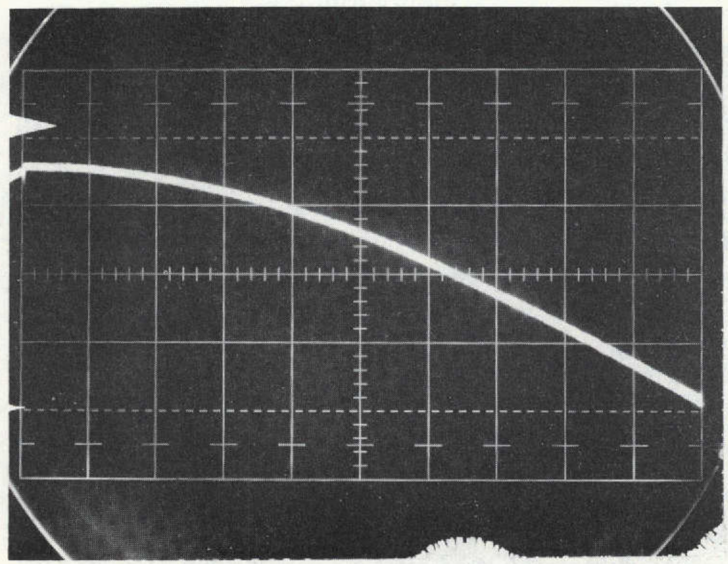

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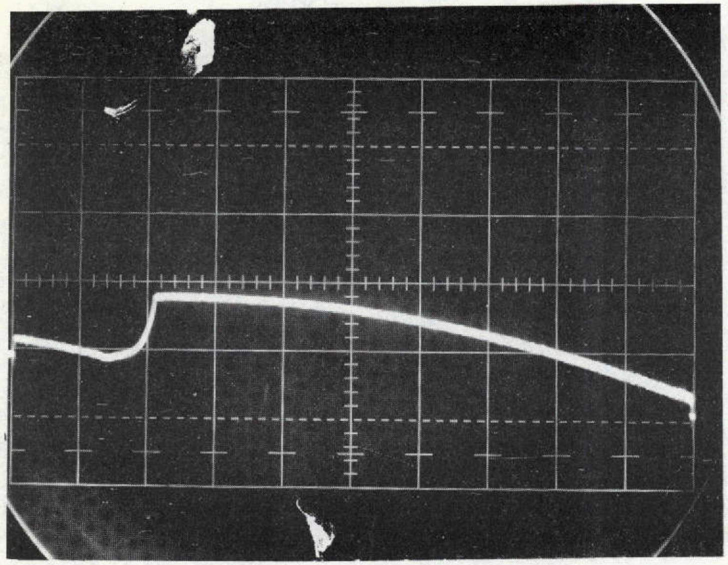

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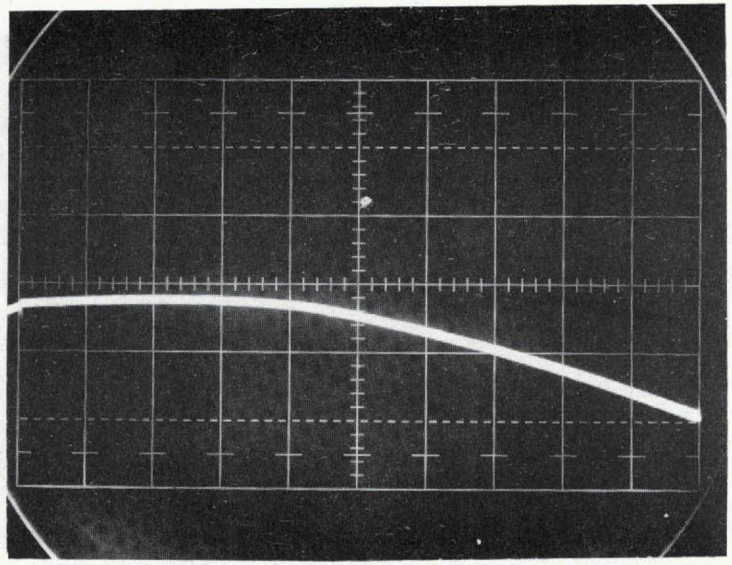

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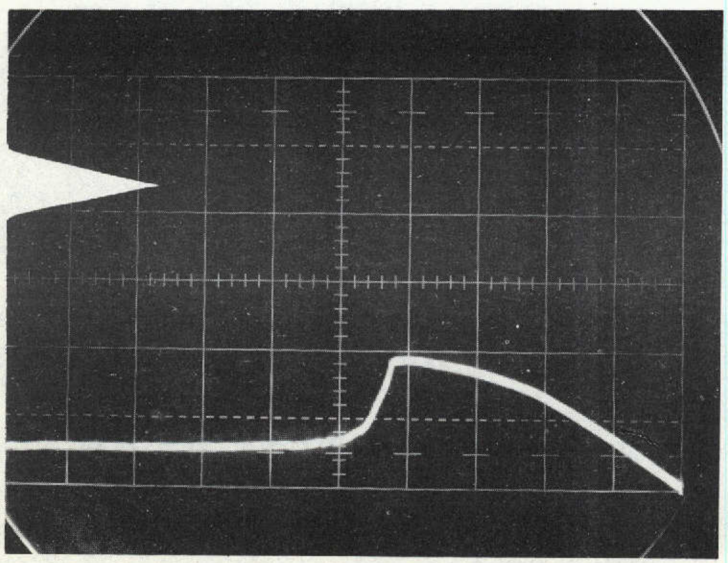

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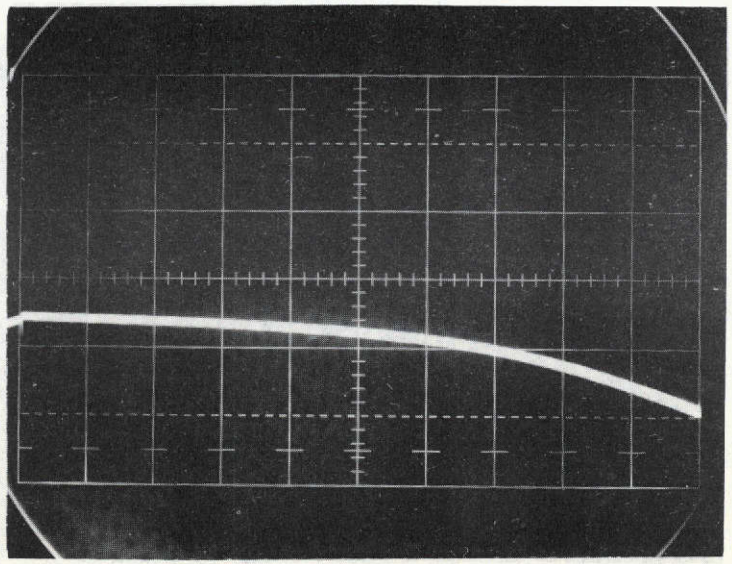

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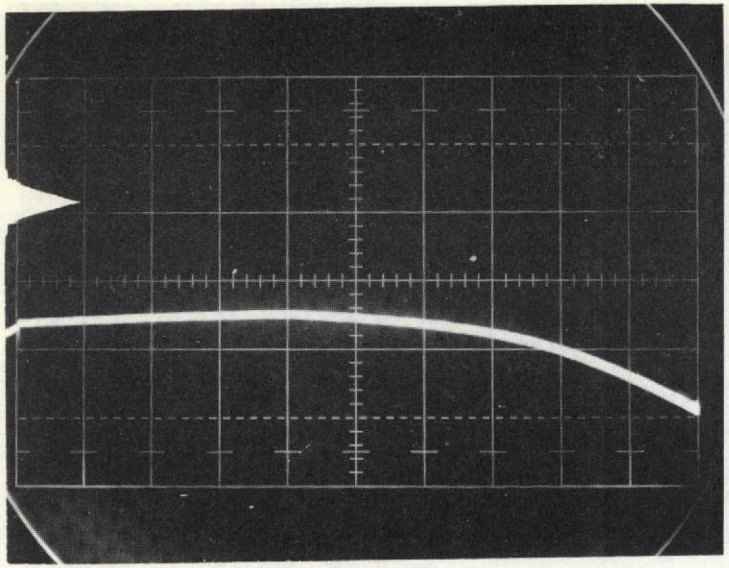

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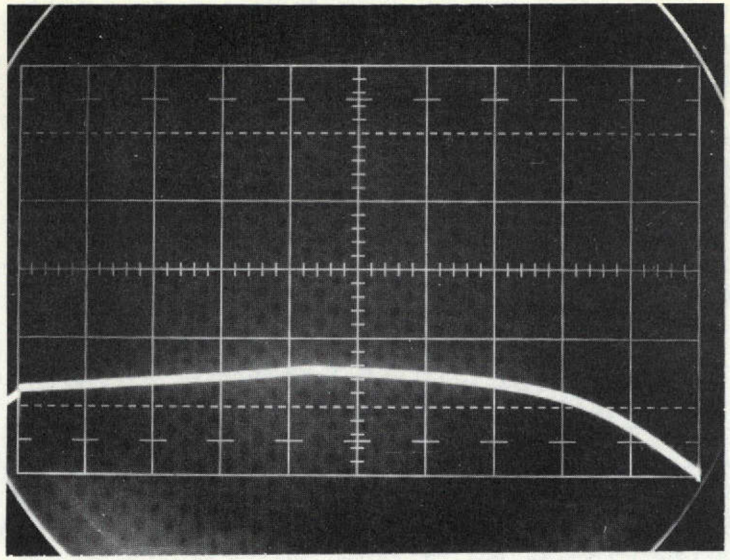

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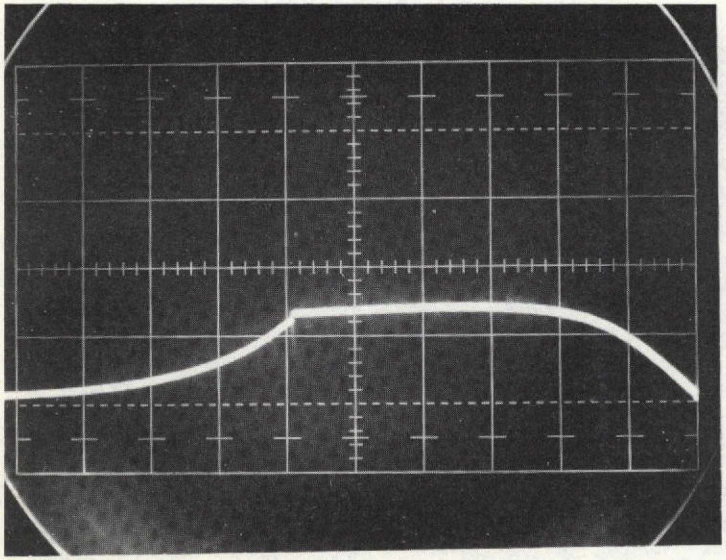

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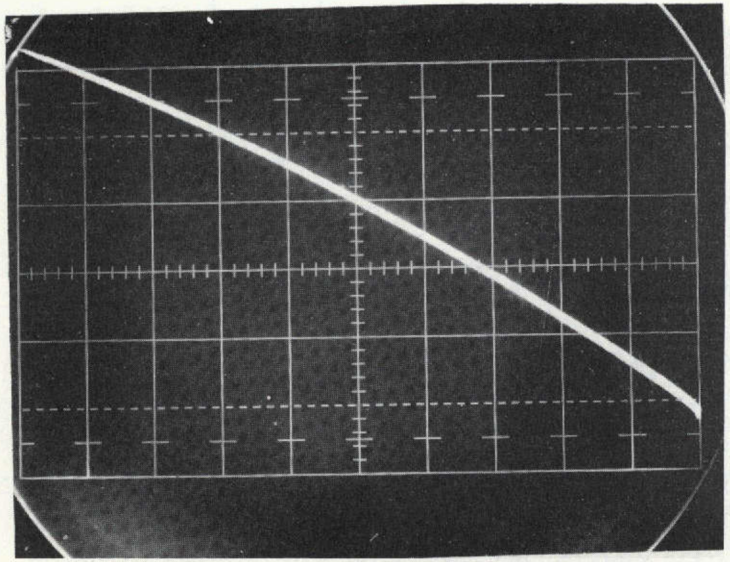

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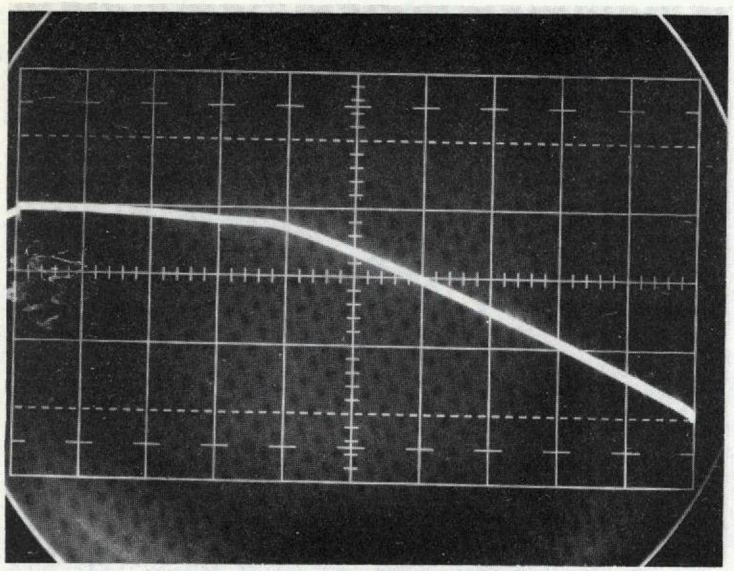

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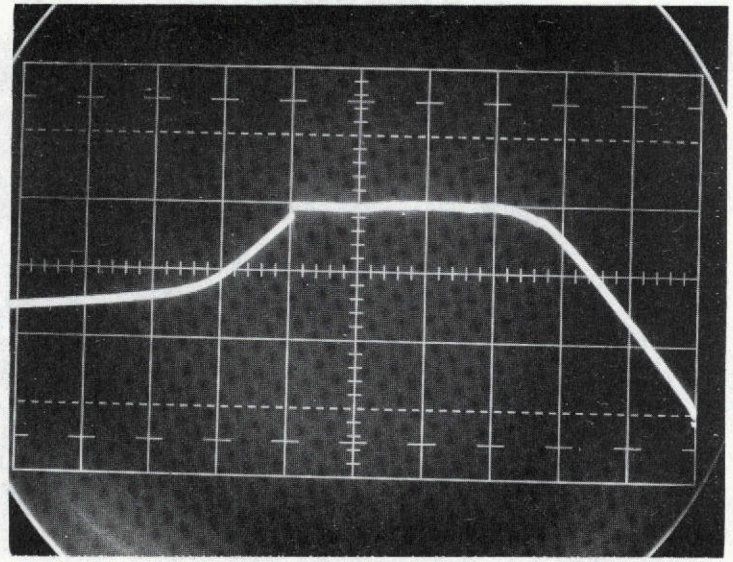

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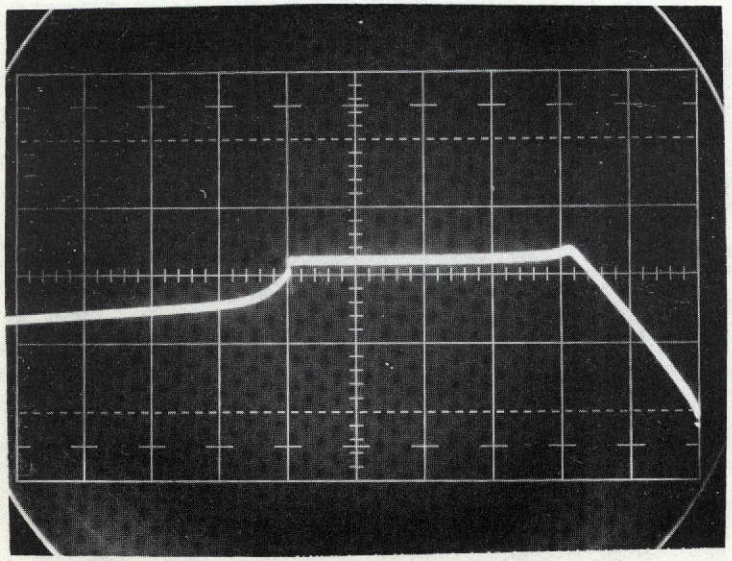

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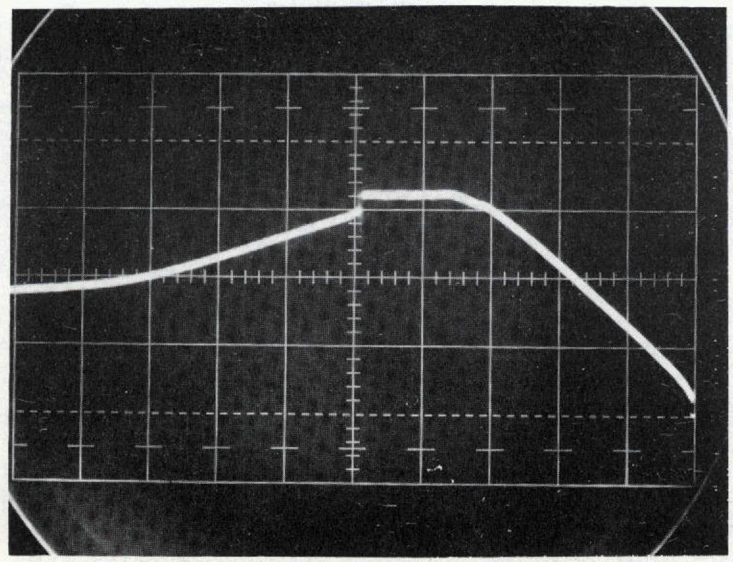

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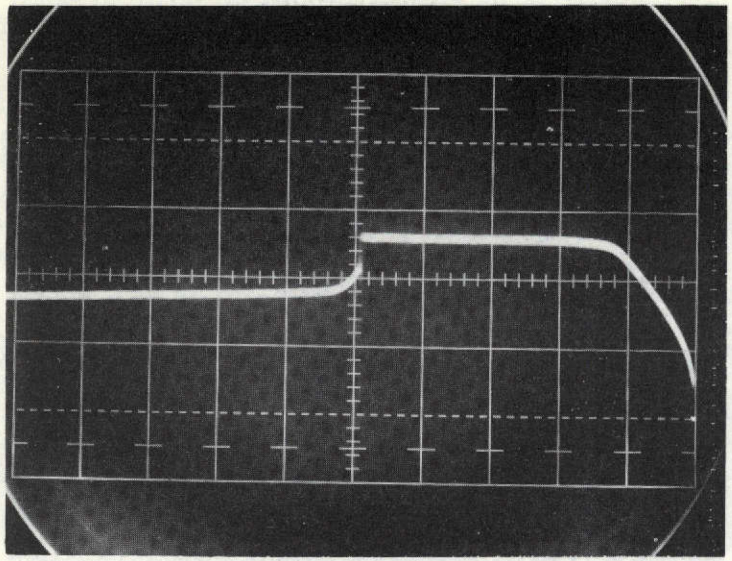

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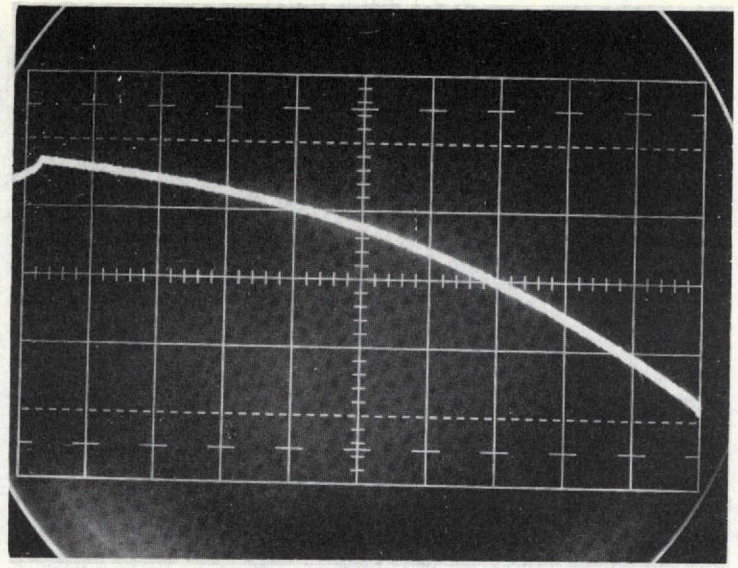

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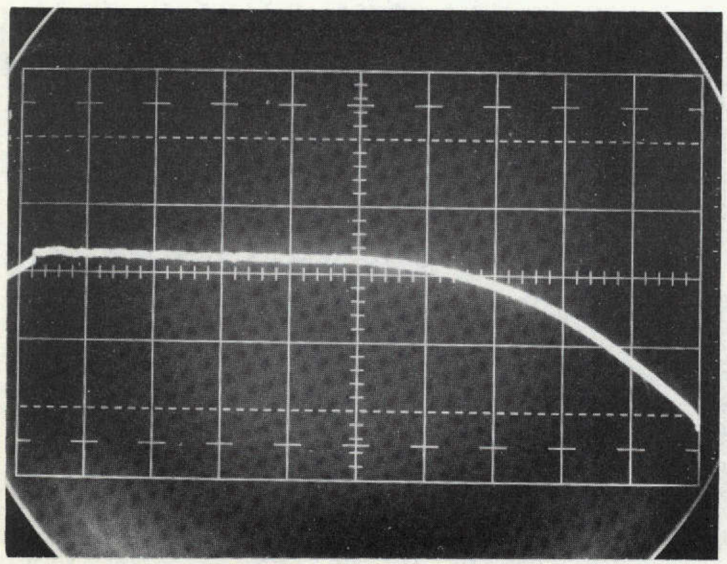

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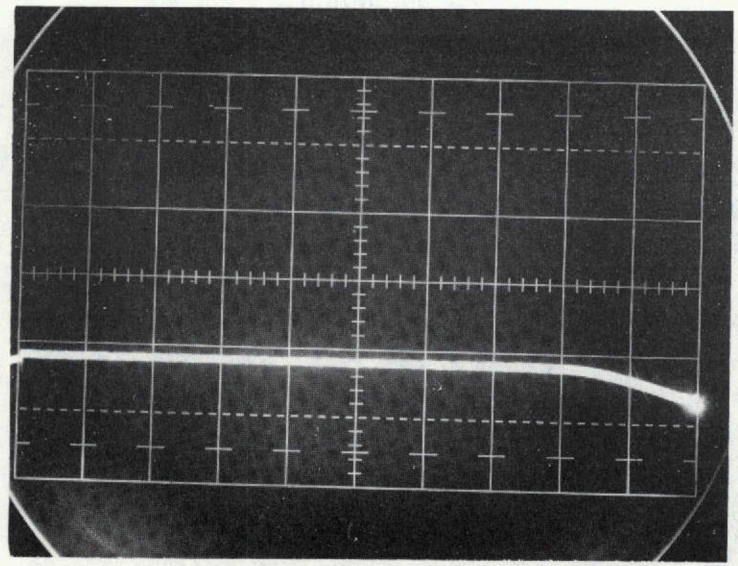

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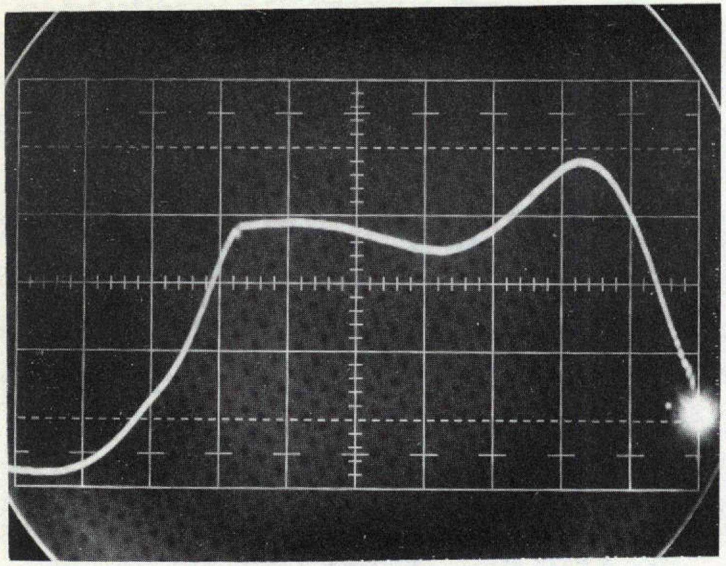

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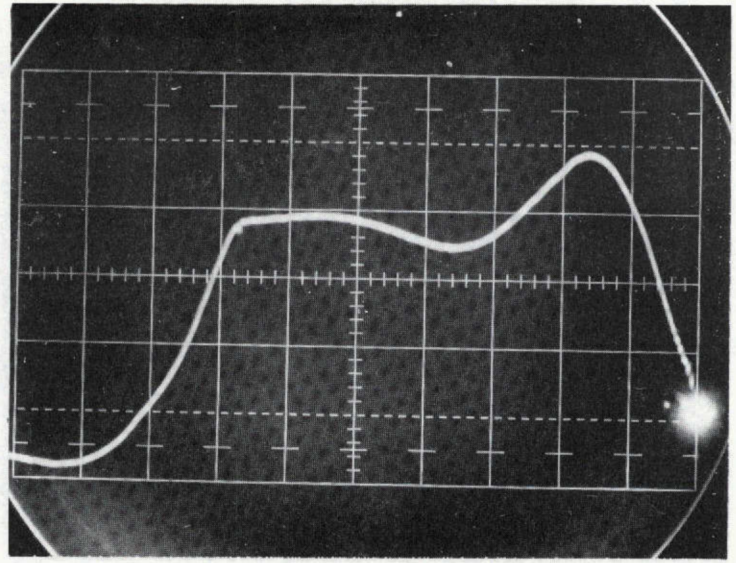

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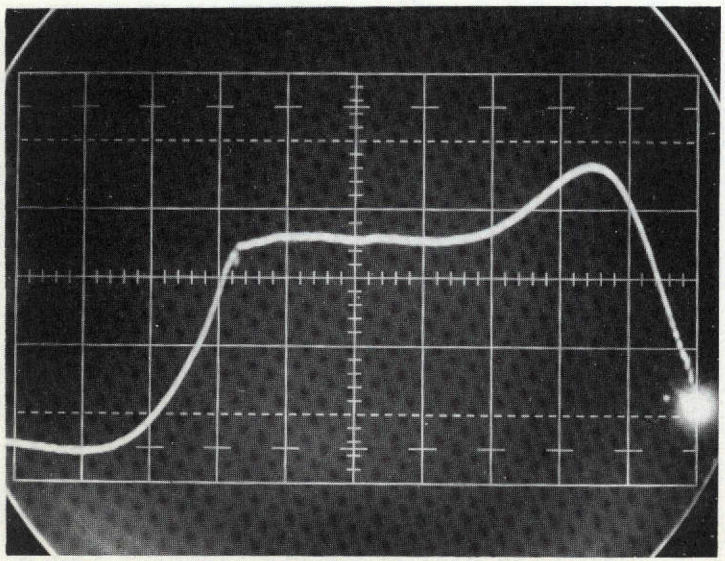

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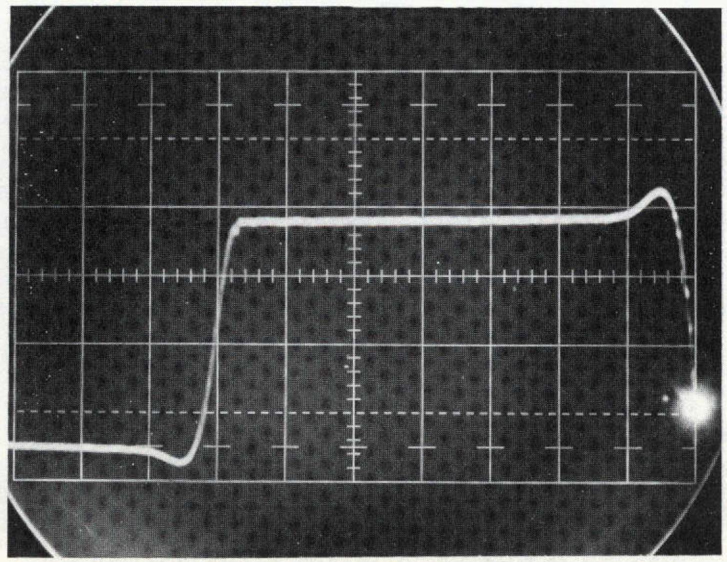

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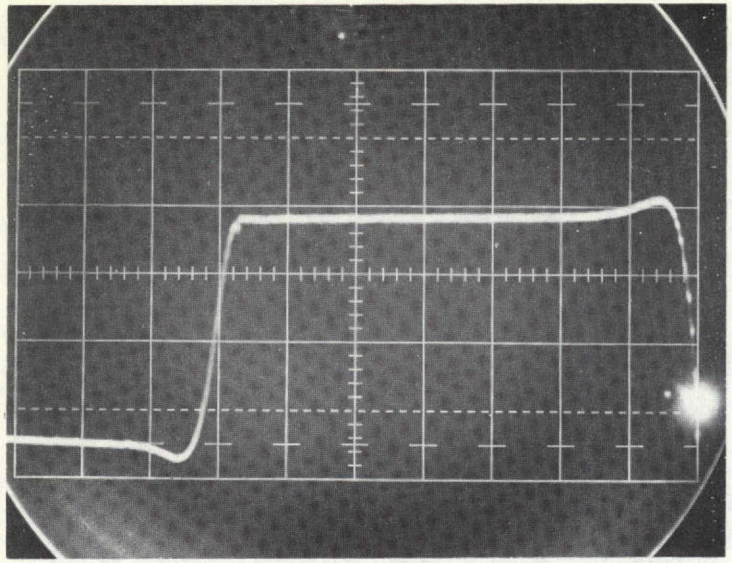

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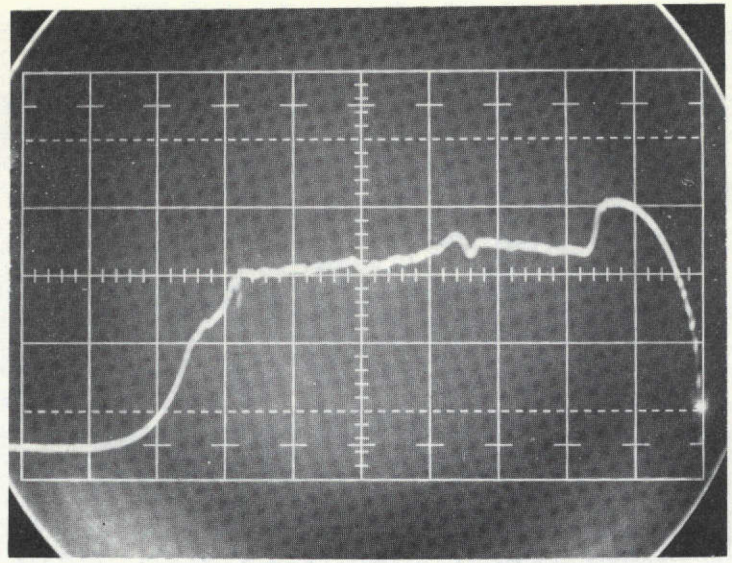

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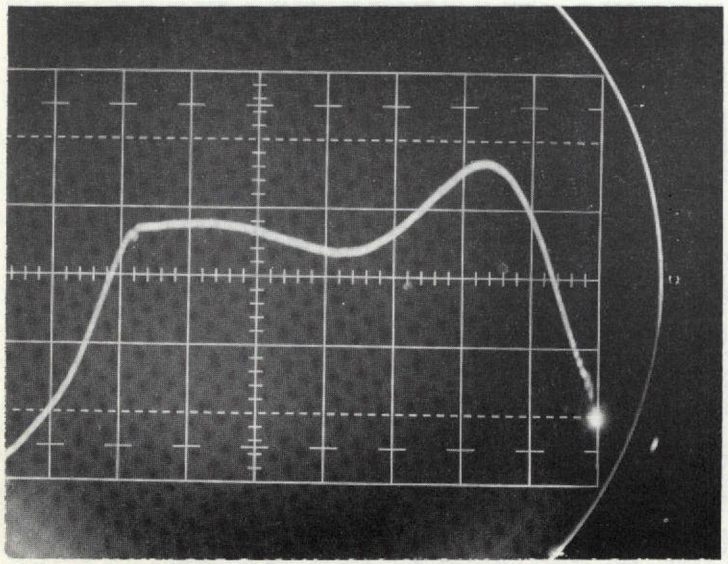
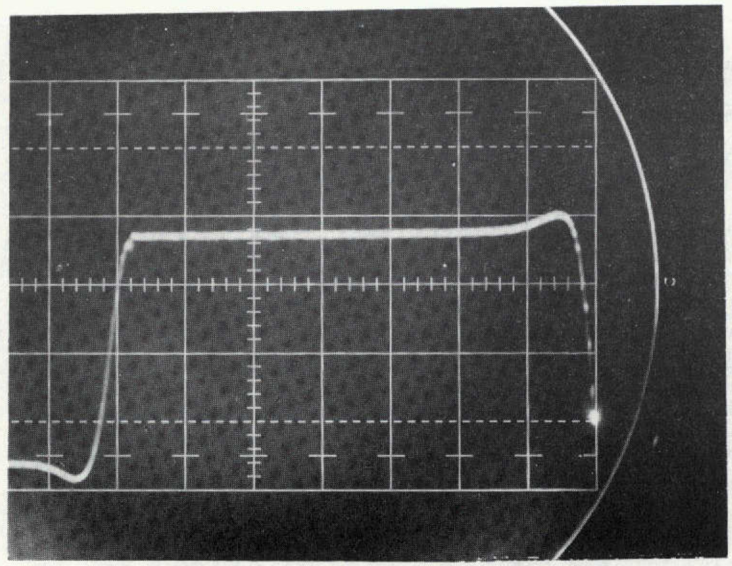
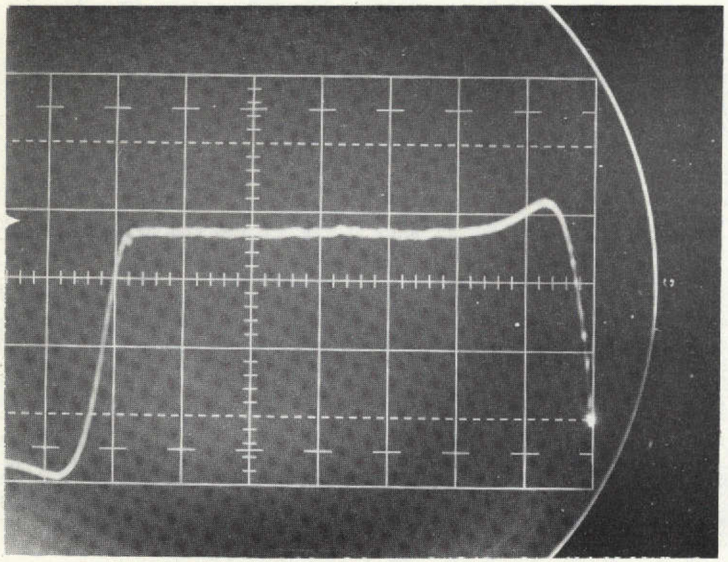


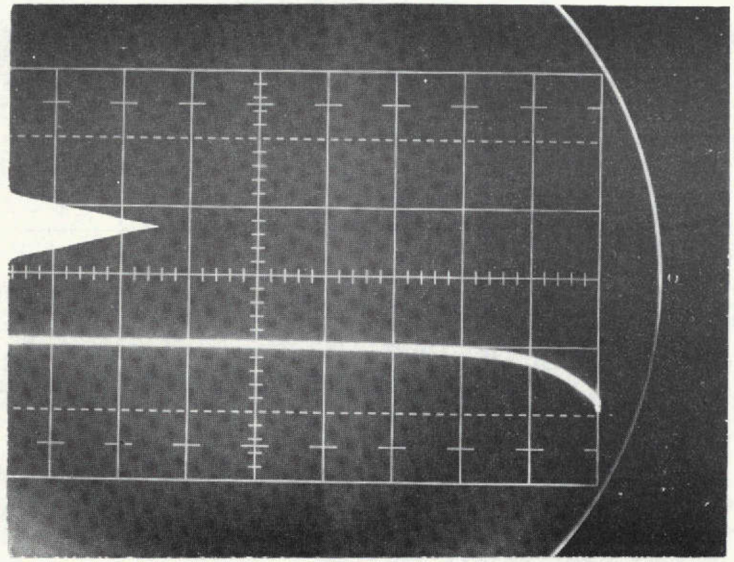
Photograph 35



Photograph 36



Photograph 37



Photograph 38

TABLE II.- POST-TEST CAPACITOR LEAKAGE

Capacitor sequence no. (a)	Leakage, μA at -			
	30 sec	45 sec	1 min	10 min
1 and 2	0.9	0.5	0.3	--
3	.5	.6	.6	--
4	1.0	.9	.8	--
5	1.1	1.0	1.0	--
6	2.0	2.0	1.7	--
7	1.1	1.3	1.4	--
8	1.5	1.7	1.7	--
9 to 13	25	25	23	16
14 and 15	30	30	30	26
16 and 17	17.5	17	16.8	15
18 and 19	95	90	80	50
20 and 21	.2	.3	.1	--
22	.2	.1	.1	--
23	.2	.1	.1	--
24	.2	.1	.1	--
25	1.0	.4	.2	--
26 to 28	2.5	2.0	1.5	1.0
29	.8	.5	.4	--
30	.8	.7	.6	--

[a]Sequence number corresponds to photograph number. Some capacitors were pulsed more than once, resulting in several numbers for a given capacitor.

TABLE II.- POST-TEST CAPACITOR LEAKAGE - Concluded

Capacitor sequence no. (a)	Leakage, μA, at -			
	30 sec	45 sec	1 min	10 min
31	3	2.6	3	--
32	0.1	0	0	--
33	.1	0	0	--
34	5.6	5.2	5	5
35	2	2	1.8	1.3
36	.2	0	0	--
37	.5	.4	.1	--
38	.2	.1	.1	--

[a]Sequence number corresponds to photograph number. Some capacitors were pulsed more than once, resulting in several numbers for a given capacitor.