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ELECTROSTATIC DISCHARGE (ESD) SIMULATOR EXPERIMENT

(Testing of Some Switches/Relays for Application to an ESD Simulation Circuit)

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For:

Naval Sea Systems Command
NAVSEA 06C31
Washington, DC 20362

October 1983

NOTICE

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INTRODUCTION

Over the past few years, many models have been proposed in an attempt to accurately simulate the human electrostatic discharge using lumped passive networks. The complexity of these models range from a simple R-C network [1,2,3,4] to networks incorporating inductance and multiple discharge effects [2,5,6]. It has been generally accepted to simulate the human touch by a "bounceless" switch that will provide a consistently reproducible output waveform for device ESD sensitivity testing.

This paper presents the results of an investigation/testing conducted to evaluate different types of relays/switches used as the switching mechanism for an ESD simulator test set-up. The network used is the simplest, human body model consisting of a single 100 pF capacitor discharging via a single 1.5 KΩ resistor [3].

EXPERIMENTAL SET-UPS

The technical specifications of the relays/switches that were selected for this experiment are summarized in Table I.

The figure below shows the basic test set-up used:

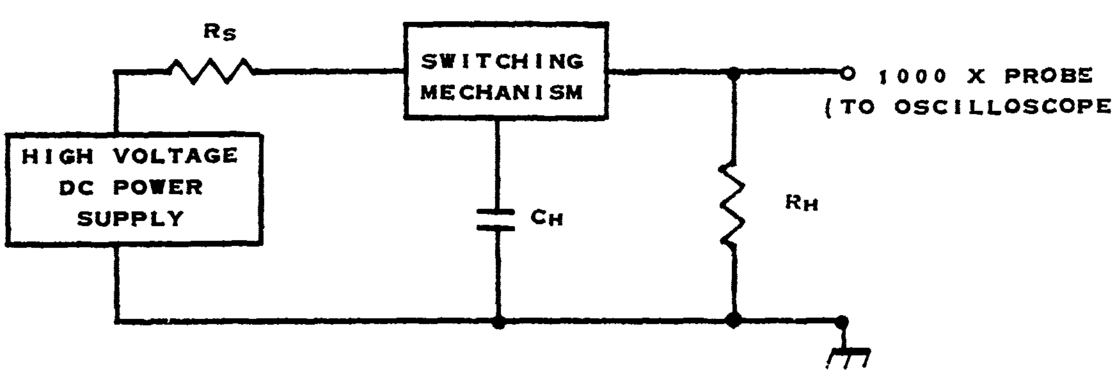


TABLE I

SPECIFICATION	RELAY/SWITCH TYPE					
	VS-6 VACUUM RELAY (EIMAC INC.)	W102HVX-2 REED SWITCH (MAGNECRAFT INC.)	8621 (NO) MERCURY WETTED (H&B INST.)	M35AB-12D 2-POLE MERCURY (MAGNECRAFT INC.)	100NO-120ARH-6X MERCURY SWITCH (MERCURY DISPLACEMENT INDUSTRIES INC.)	GP-92 SPARK GAP (EG&G)
DIELECTRIC STANDOFF	22 KV	12.5 KV	3.5 KV	2.65 KV	3.5 KV	SBV: 25 KV (RANGE: 8-20 KV)
INSULATION RESISTANCE	--	10^9 OHMS (MIN)	--	CLASS B (130°C)	--	--
COIL	12 VDC 30 OHMS	12 VDC 100 OHMS	115 VAC 180 OHMS	12 VDC 28 OHMS	120 VAC 130 mAMPS	USE WITH TR-148A TRIGGER TRANSFORMER
CONTACT RESISTANCE	50 MOHMS (MAX)	150 MOHMS	--	3 MOHMS	1 MOHM (TYPICAL)	--
INDUCTANCE	--	--	--	--	--	5-30 nH
CAPACITANCE	--	2 pF (ACROSS OPEN CONTACTS)	--	--	--	--
OPERATE TIME	--	20 MSEC	80 MSEC (TYPICAL)	50 MSEC (TYPICAL)	50 MSEC	--
RELEASE TIME	--	15 MSEC (WITH DIODE)	100-120 MSEC (TYPICAL)	80 MSEC (TYPICAL)	80 MSEC	--
DELAY TIME	--	--	--	--	--	100 NSEC (AT 75% SBV) 1000 NSEC (AT 40% SBV)
CONTACT CLOSING TIME	20 NSEC (MAX)	--	--	--	--	--
BOUNCE	--	10 MSEC (TYPICAL)	--	NONE. ± 10% OF RATED COIL VOLTAGE	--	--
LIFE EXPECTANCY (OPERATIONS)	--	10^6	8×10^6 (MIN)	--	5×10^6 (MIN)	50×10^6

--: NO DATA AVAILABLE

R_S = 1.1 MΩ, high voltage type

C_H = 100 pF, 20 KV (H200-SD6-K-101-K, K&D Component Inc.)

R_H = 1.5 KΩ, non-inductive, high voltage (106AS152J, Carborundum Co.)

Power Supply = 0 to ± 10 KV (Model 410B, Fluke Inc.)

Storage Oscilloscope: TEK 466 with P-6015 High Voltage Probe

During preliminary measurements, a number of important observations, discussed below, were made that should be considered when implementing an ESD simulator circuit.

a. Errors Introduced by the measuring equipment.

Usually a storage oscilloscope is used for recording the ESD waveform and measuring its rise time. The actual rise time of the waveform is given by

$$t_r \approx \sqrt{t_s^2 - t_p^2 - t_o^2} \quad \text{where}$$

t_s = rise time measured on the screen

t_p = rise time of the scope's probe

t_o = rise time of the scope = $\frac{\ln 9}{2\pi(BW)} = \frac{0.35}{BW}$

(For the TEK 466 Scope: BW = 100 MHz, t_o = 3.5 nsec, $t_p \approx$ 4.7 nsec)

If, for example, the rise time measured on the screen was t_s = 10 nsec, then the actual rise time of the waveform is:

$$t_r = \sqrt{10^2 - 4.7^2 - 3.5^2} \approx 8 \text{ nsec}$$

This indicates that approximately 20% error is introduced for this case by the scope and probe. In addition, in order to be able to capture (store), say, a 5 nsec rise time waveform, the minimum writing speed of the scope must be:

$$\text{Writing speed} = \frac{0.8A}{t_r} \geq 1152 \text{ cm}/\mu\text{sec where}$$

A = number of screen divisions (A = 8, 0.9 cm/div. for the TEK 466 scope)

b. <u>Problems associated with charge/discharge switches and type of capacitor used</u>.

An output voltage loss was observed on an ESD simulator set-up that uses separate switches to perform the charging and discharging operations. These switches were energized using an ON-OFF-ON switch to activate the corresponding coil voltage. This indicated that the leakage resistance, which relates directly to the insulation resistance of the discharge switch and the dielectric leakage resistance of the capacitor, is an important parameter for this circuit. As high as practically possible, values of this resistance are desirable.

Consider, for example, a 100 pF capacitor initially charged to 4,100 Volts. If the effective leakage resistance is assumed to be $\approx 10^{12}$ Ohms and the coil switch is left in the OFF position for 5 seconds, then the output voltage after 5 seconds will be:

$$V(t) = 4{,}100\ e^{-t/RC} = 4{,}100\ e^{-5/100} \approx 3{,}900 \text{ Volts}$$

Note that failure of a device during such test will classify the device as being Class 3 of DOD-HDBK-263 (>4,000) while the actual voltage that the device is tested at is 3,900 Volts, i.e., Class 2.

Another observation made during preliminary measurements related to the type of capacitor used. A disc ceramic capacitor (rated at 6 KV), charged to 500 Volts, did not completely discharge under momentary short-circuit conditions but a voltage recovery ("reappearing voltage") was observed. This was considered to be due to the dielectric adsorption effect, a little known but significant effect for some types of capacitors such as Polyestyrene, paper and ceramic. Typical values of dielectric adsorption range from 0.05% to 5% at 25°C. This effect,and the fact that dielectric constant itself may show significant non-linear changes with applied voltage for some types of capacitors, should also be considered when implementing an ESD simulator circuit.

TESTING AND RESULTS

1) Vacuum Relay (22KV, VS-6, Varian Inc.)

The ESD simulator implemented with a vacuum relay exhibited bounce and, above 1000 Volts, output waveform repeatability was difficult to obtain. In addition, it was noted that the decay time of the discharge waveform did not agree, for some tests, with the values of the resistor and capacitor used. Excessive "parasitic capacitance" was considered to be the cause of this. The capacitance of the relay was measured to be in the order of 20 pF across open contacts.

Various modifications were attempted on this circuit such as: reversing relay contacts, using high voltage diodes across contacts, and using different types of capacitors. However, no essential improvement was observed.

Figures 1 to 6 show typical discharge waveforms obtained with this relay.

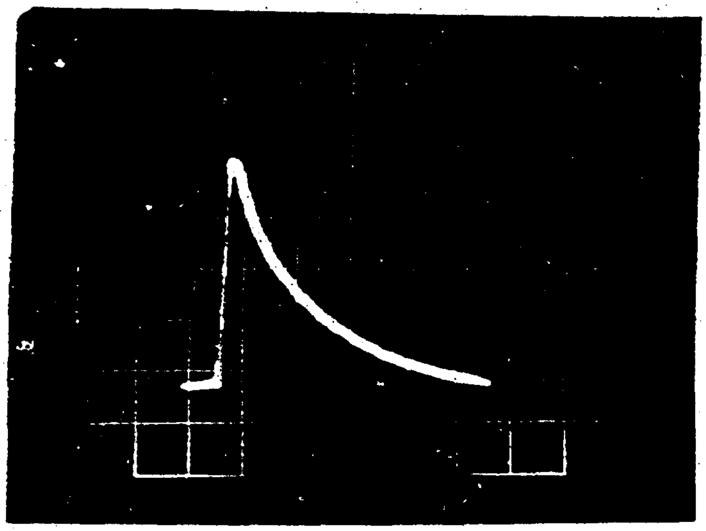


Figure 1: (Charging Voltage: 450 Volts)
50 mV/small div., 50 nsec

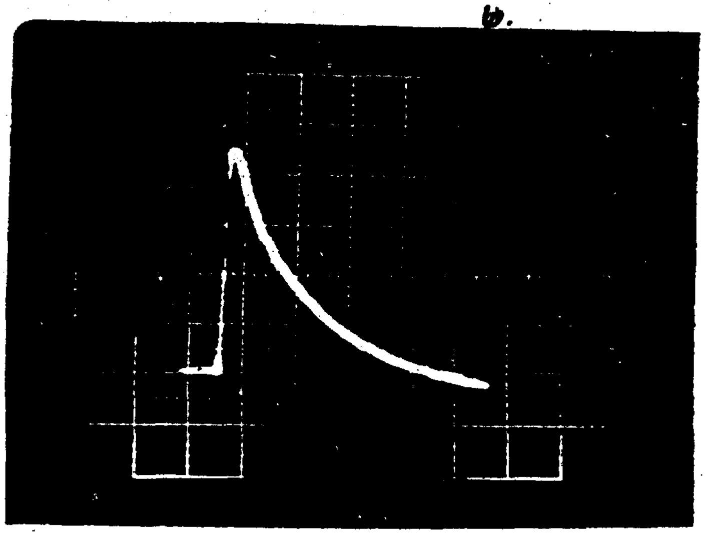


Figure 2: (Charging Voltage: 1000 Volts)
0.1 V/small div., 50 nsec

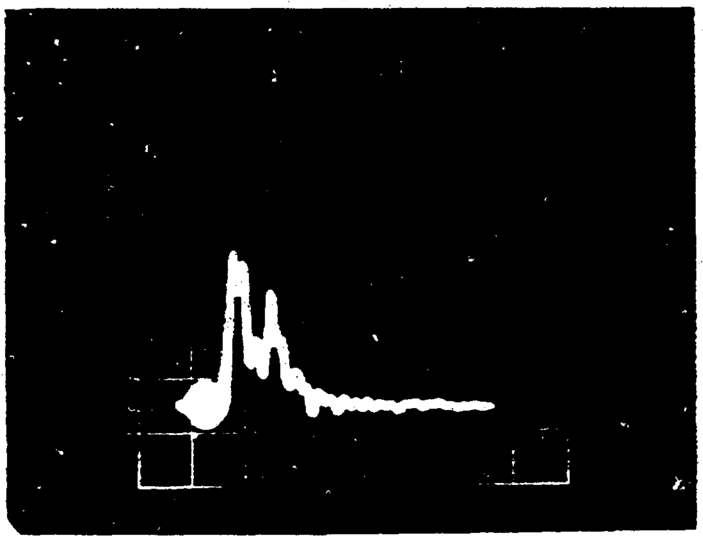


Figure 3: (Charging Voltage: 3000 Volts)
0.5 V/small div., 50 nsec

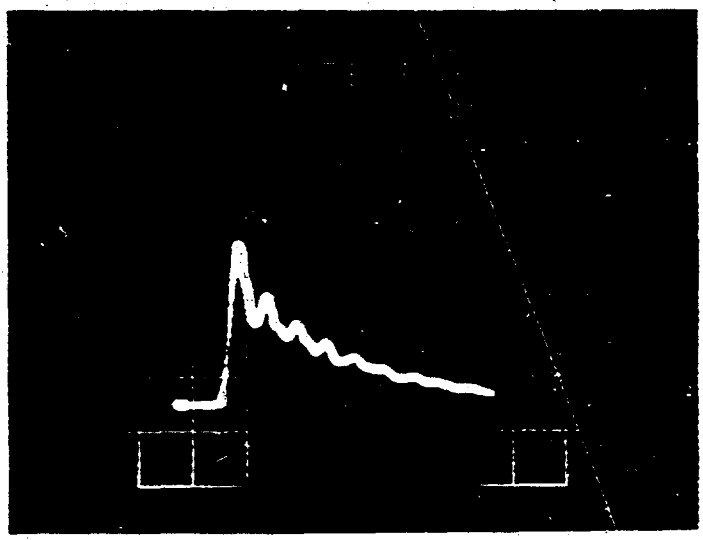


Figure 4: (Charging Voltage: 3000 Volts)
0.5 V/small div., 50 nsec

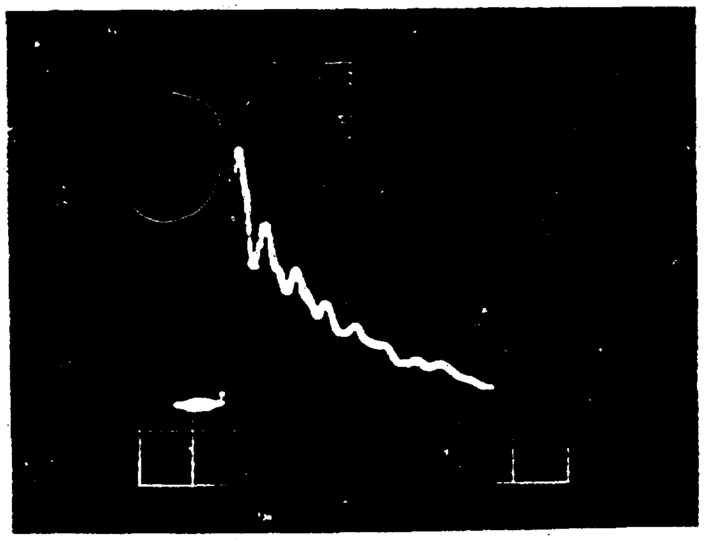


Figure 5: (Charging Voltage: 5000 Volts)
0.5 V/small div., 50 nsec

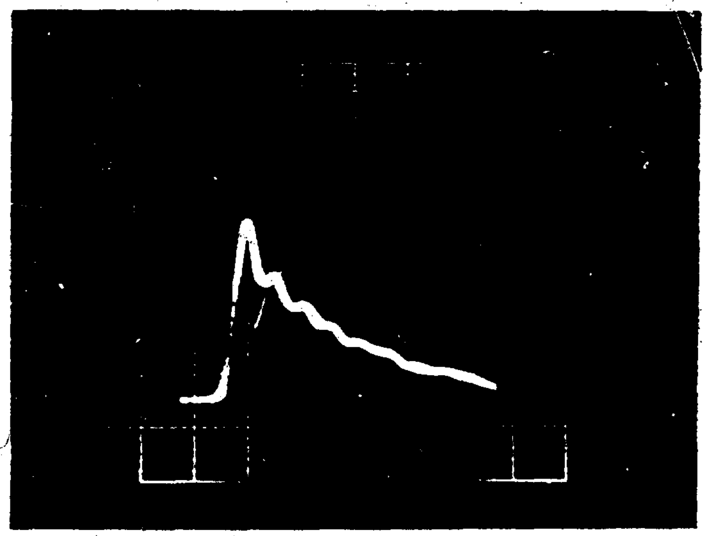


Figure 6: (Charging Voltage: 7000 Volts)
1 V/small div., 50 nsec

2) <u>Reed Switches (10 KV, W102HVX-2, Magnecraft, Inc.)</u>

The ESD simulator implemented with two reed switches (for the charging and discharging operations) exhibited problems similar to case of the Vacuum Relay (i.e., parasitic capacitance effects) for voltages less than 3000 Volts. Above 4000 Volts, output waveform repeatability improved considerably.

Typical discharge waveforms obtained with these switches are shown in Figures 7 to 10.

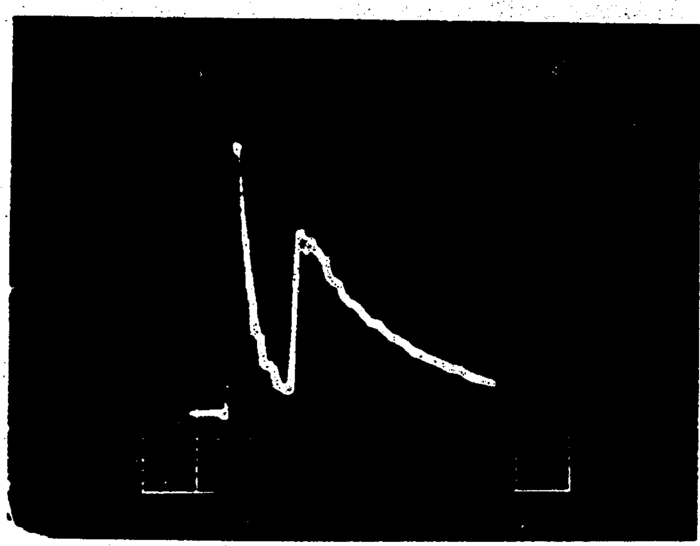


Figure 7: (Charging Voltage: 200 Volts)
20 mV/small div., 50 nsec

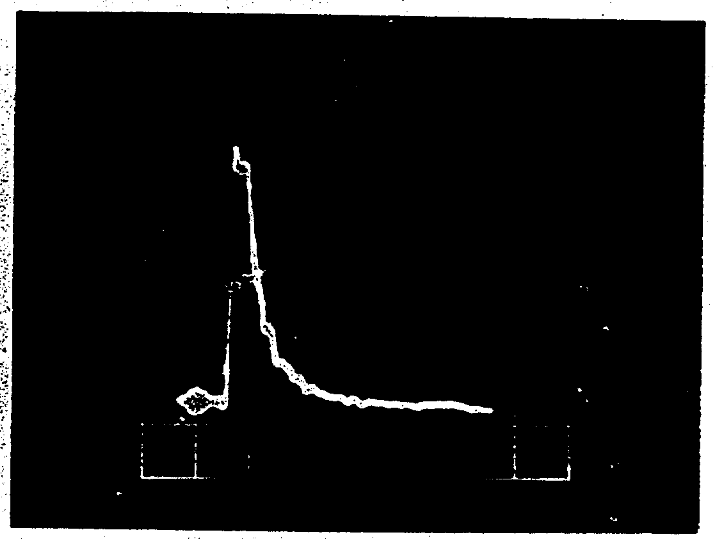


Figure 8: (Charging Voltage: 2000 Volts)
0.2 V/small div., 50 nsec

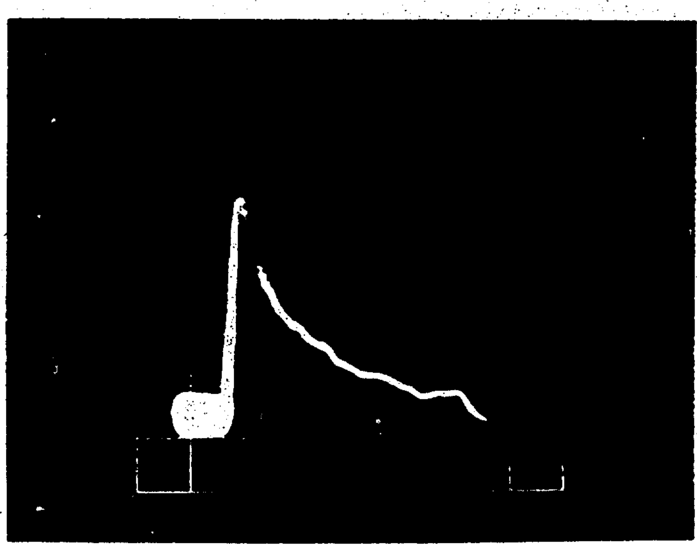


Figure 9: (Charging Voltage: 4000 Volts)
0.5 V/small div., 50 nsec

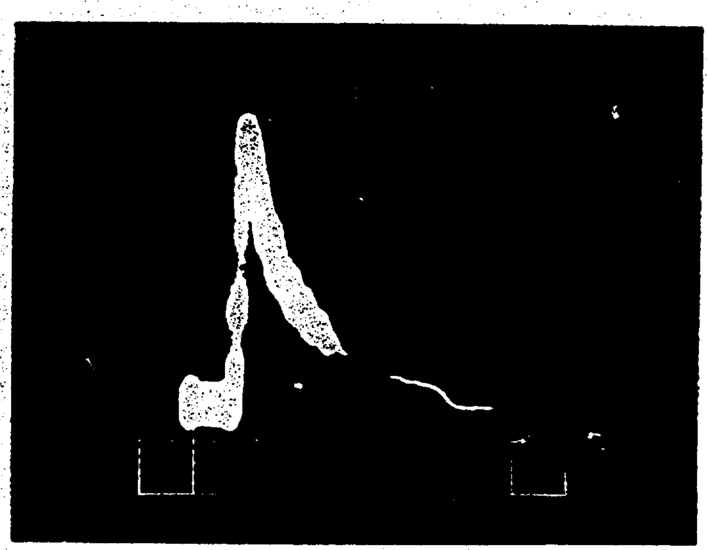


Figure 10: (Charging Voltage: 6000 Volts)
0.5 V/small div., 50 nsec

3) <u>Mercury Displacement Switches (3.5 KV, 8621-N.O., H&B Instrument Co.)</u>

Two mercury displacement switches were used to implement the charging and discharging operations. The circuit exhibited good output waveform repeatability over the voltage range of 0 to ± 3000 Volts with no bounce. Typical waveforms obtained in this voltage range are shown in Figures 11 to 14.

Although switches used were rated at 3.5 KV (dielectric standoff voltage), repeated measurements were taken from ± 4 KV up to ± 10 KV with very good repeatability. However, the discharge waveform exhibited "noise" believed to be due to partial breakdown of the switch dielectric material. The measurement set up may have also contributed to this problem. Waveforms obtained in this voltage range are shown in Figures 15 to 19.

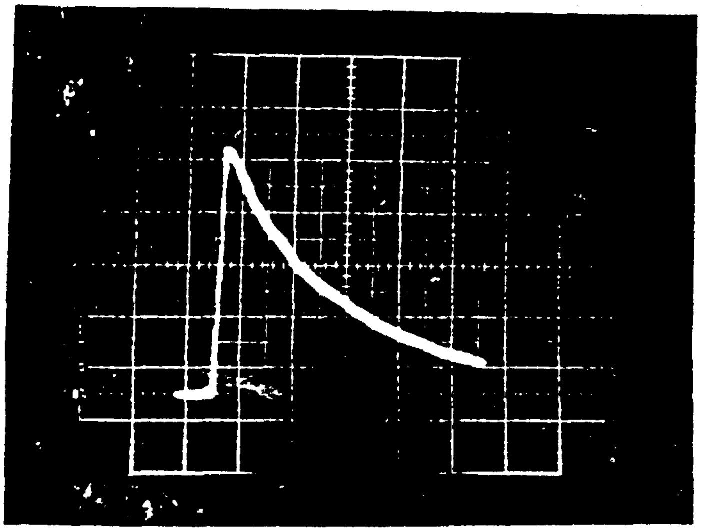


Figure 11a: (Charging Voltage: +500 Volts)
50 mV/small div., 50 nsec

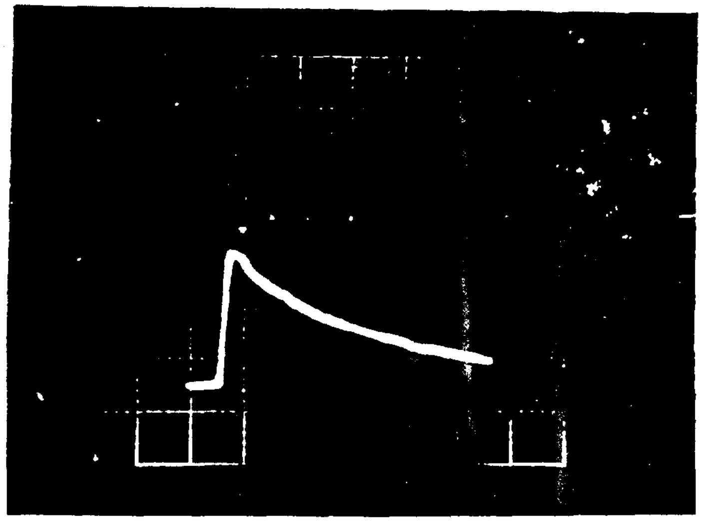


Figure 11b: (Charging Voltage: -500 Volts)
0.1 mV/small div., 50 nsec (Inverted)

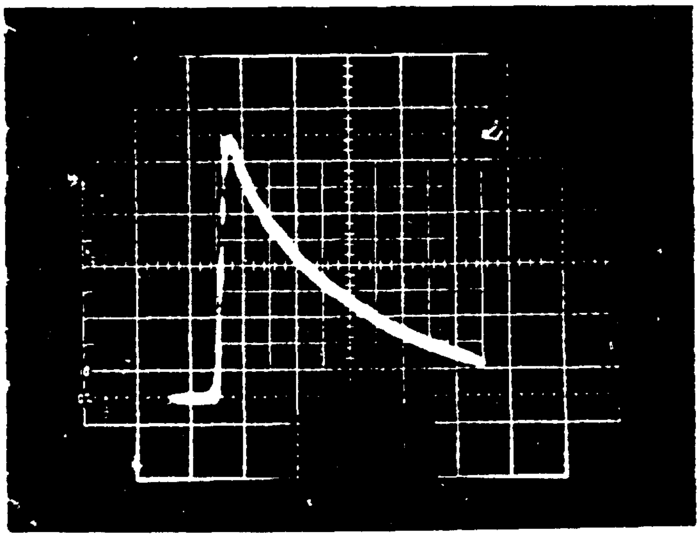


Figure 12: (Charging Voltage: +1000 Volts)
0.1 mV/small div., 50 nsec

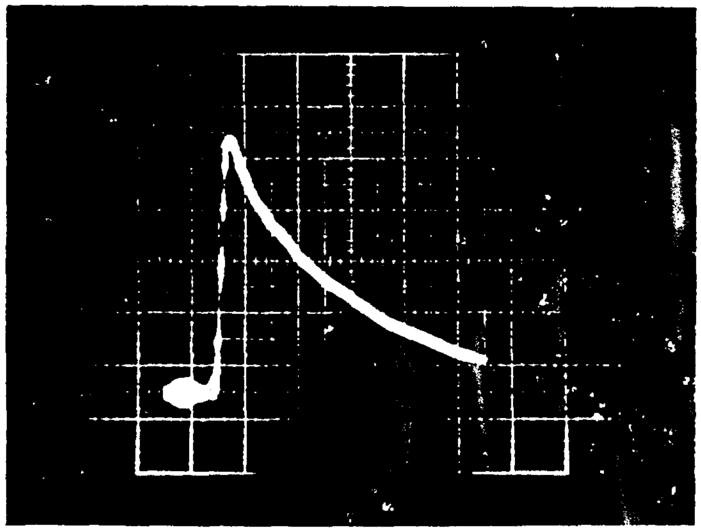


Figure 13: (Charging Voltage: +2000 Volts)
0.2 mV/small div., 50 nsec

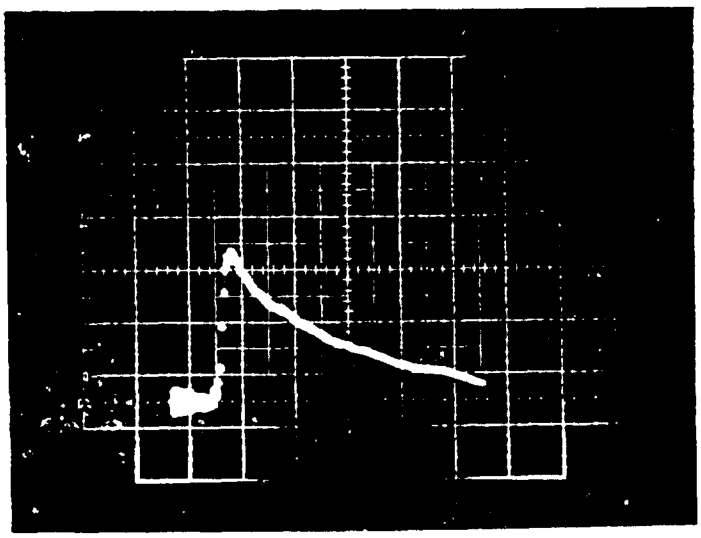


Figure 14a: (Charging Voltage: +3000 Volts)
0.5 mV/small div., 50 nsec

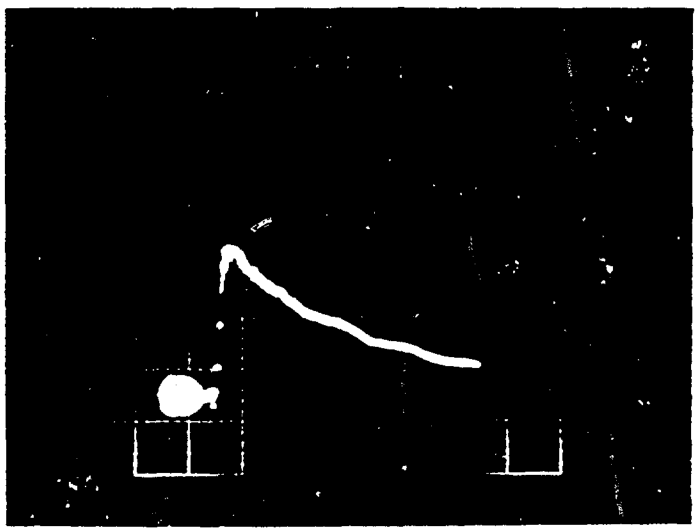


Figure 14b: (Charging Voltage: -3000 Volts)
0.5 mV/small div., 50 nsec (Inverted)

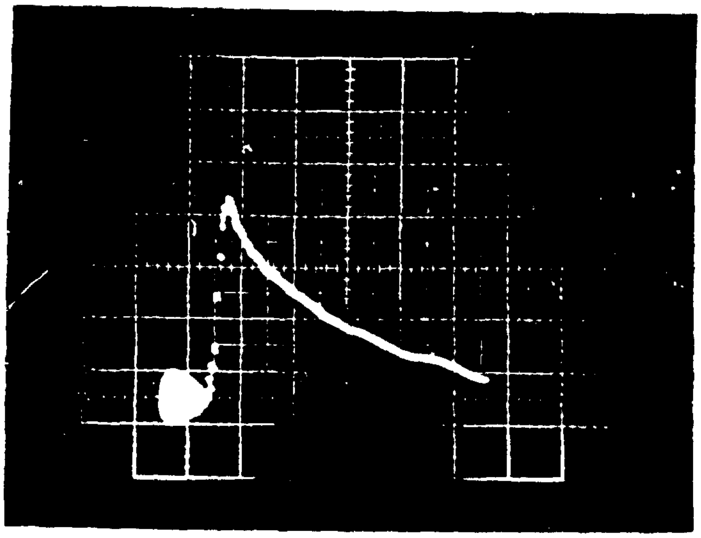


Figure 15: (Charging Voltage: +4000 Volts)
0.5 mV/small div., 50 nsec

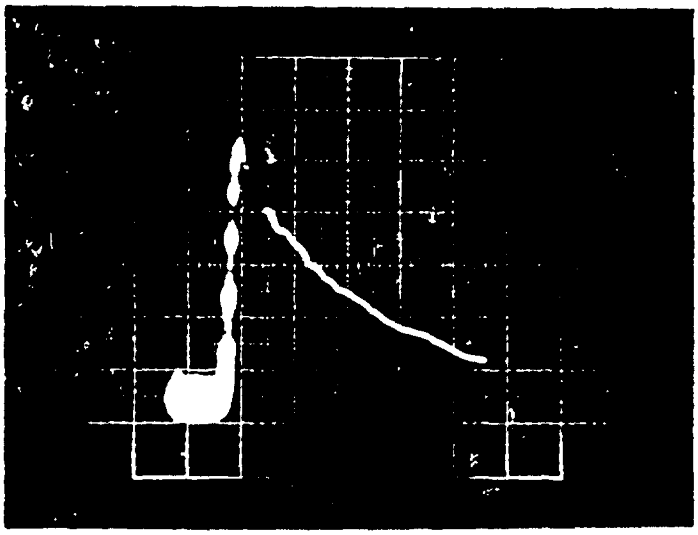


Figure 16a: (Charging Voltage: +5000 Volts)
0.5 mV/small div., 50 nsec

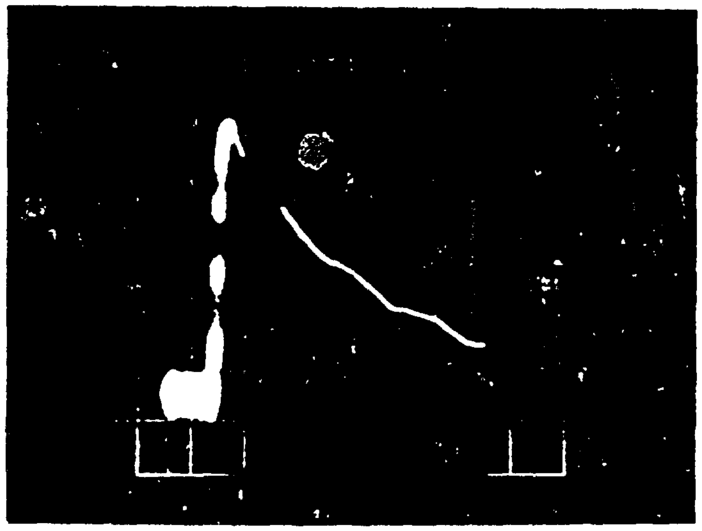


Figure 16b: (Charging Voltage: -5000 Volts)
0.5 mV/small div., 50 nsec (Inverted)

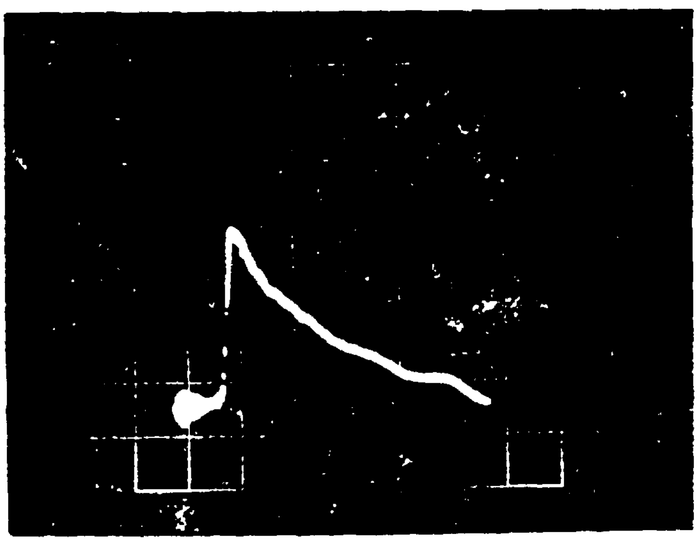


Figure 17a: (Charging Voltage: +7000 Volts)
1 V/small div., 50 nsec

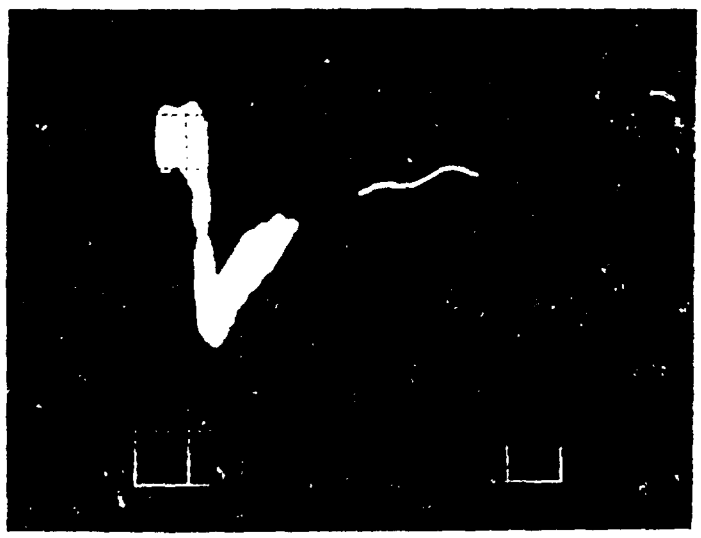


Figure 17b: (Charging Voltage: -8000 Volts)
1 V/small div., 50 nsec

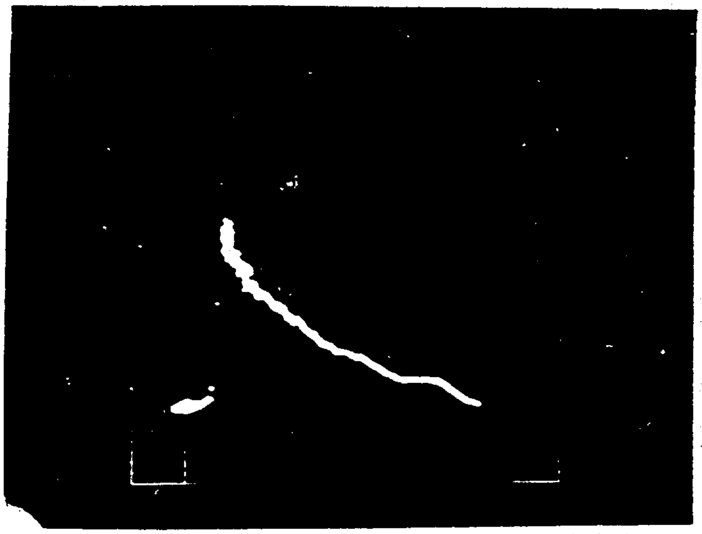


Figure 18a: (Charging Voltage: +9000 Volts)
1 V/small div., 50 nsec

Figure 18b: (Charging Voltage: -9000 Volts)
1 V/small div., 50 nsec

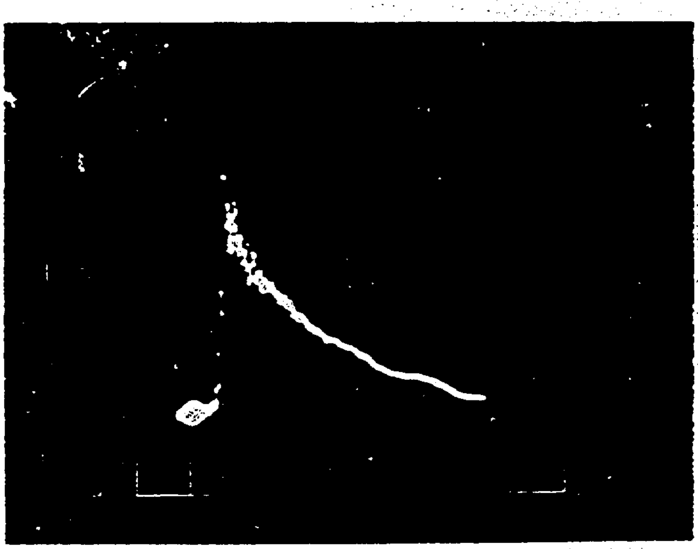


Figure 19a: (Charging Voltage: +10000 Volts)
1 V/small div., 50 nsec

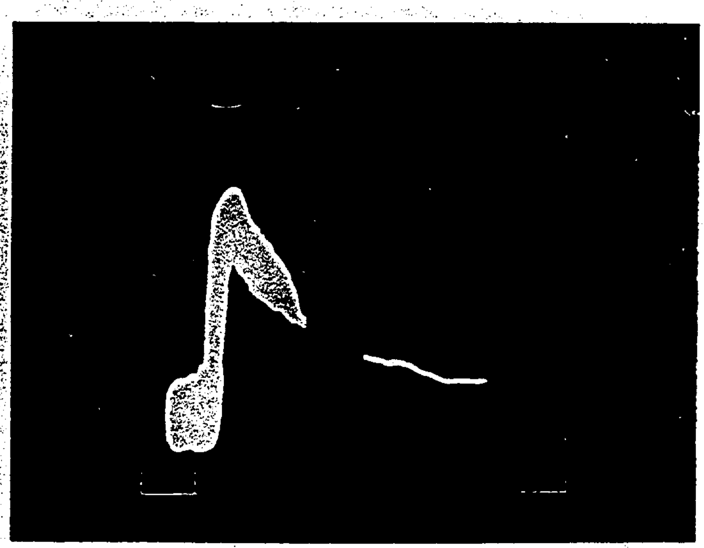


Figure 19b: (Charging Voltage: -10000 Volts)
1 V/small div., 50 nsec

4) Mercury Displacement Relay (M35AB-12D, Magnecraft, Inc.)

Discharge waveforms obtained with this relay are shown in Figures 20 to 27. The mercury relay used was rated 600 VAC, 25 Amps with dielectric strength (across open contacts and contact to frame) of 2,650 Volts (RMS, 1 sec). However, even at ± 10,000 Volts, no problems were experienced other than the "noise" on the waveform believed to be due to dielectric breakdown as in the previous test.

Over the 200 to 10,000 Volts range, the output waveform exhibited very good repeatability for both positive and negative voltages, with rise time less than 15 nseconds.

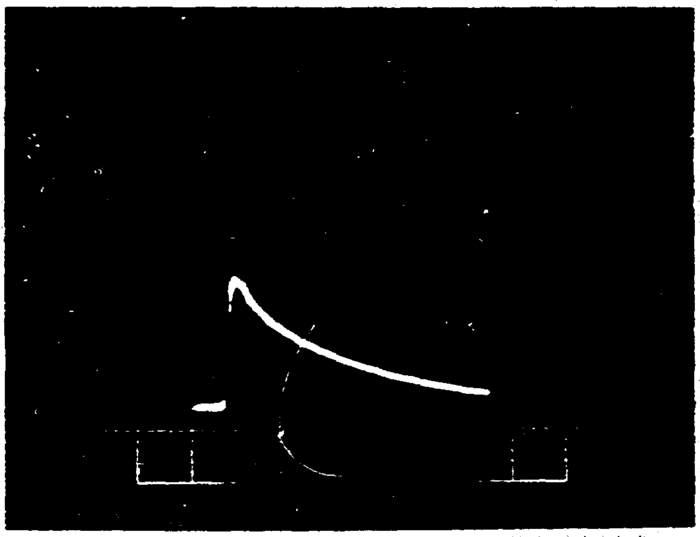


Figure 20a: (Charging Voltage: +500 Volts)
0.1 V/small div., 50 nsec

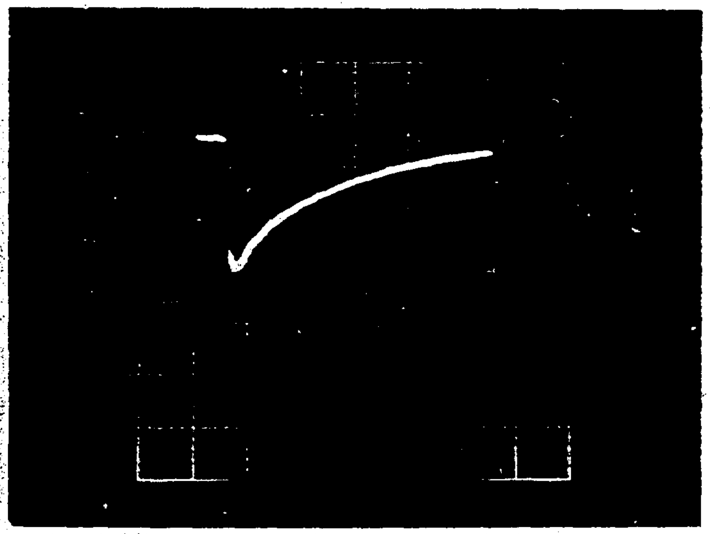


Figure 20b: (Charging Voltage: -500 Volts)
0.1 V/small div., 50 nsec

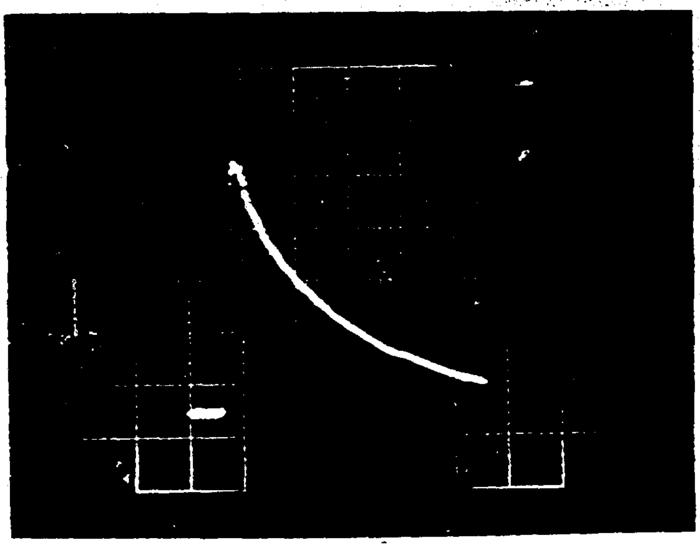


Figure 21a: (Charging Voltage: +1000 Volts)
0.1 V/small div., 50 nsec

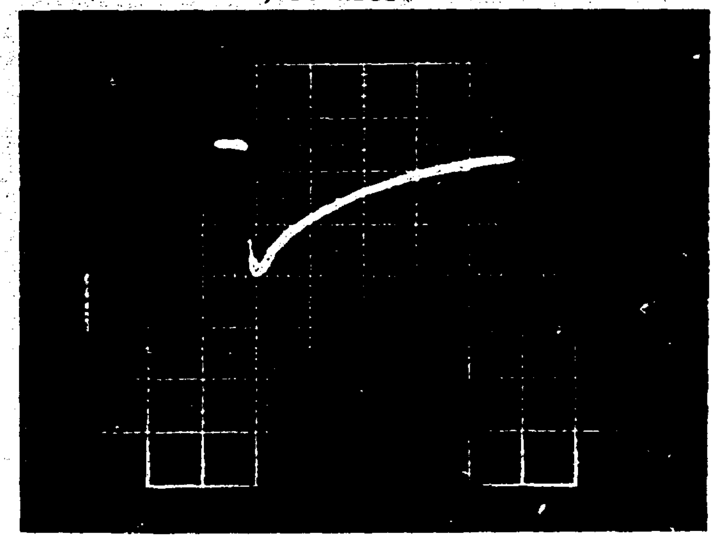


Figure 21b: (Charging Voltage: -1000 Volts)
0.2 V/small div., 50 nsec

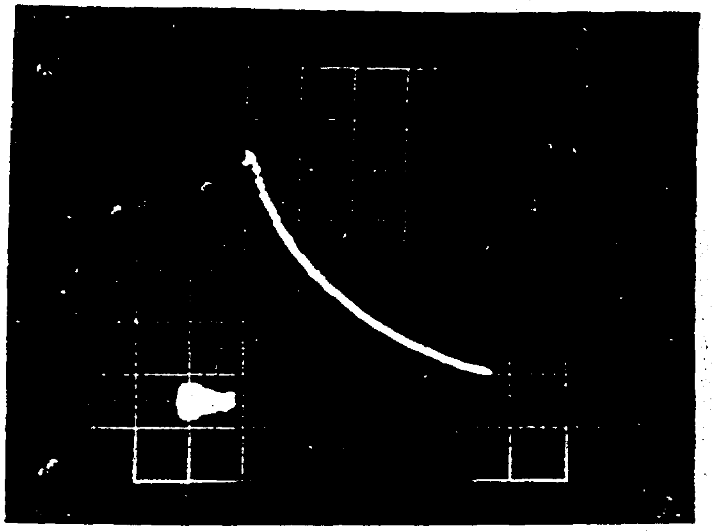


Figure 22a: (Charging Voltage: +2000 Volts)
0.2 V/small div., 50 nsec

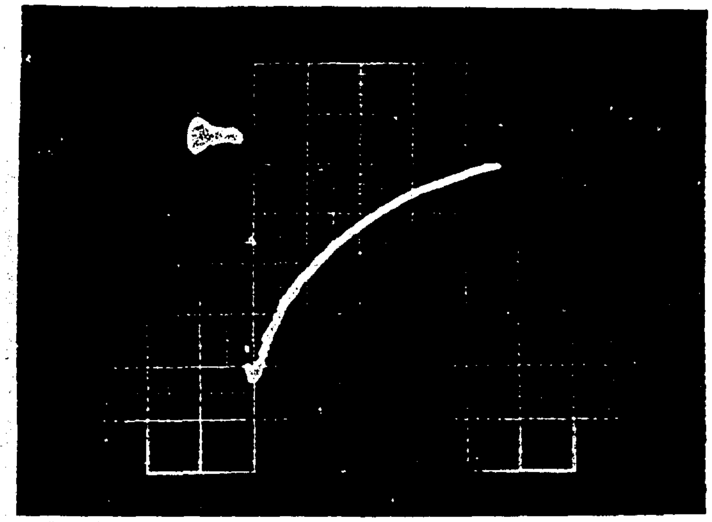


Figure 22b: (Charging Voltage: -2000 Volts)
0.2 V/small div., 50 nsec

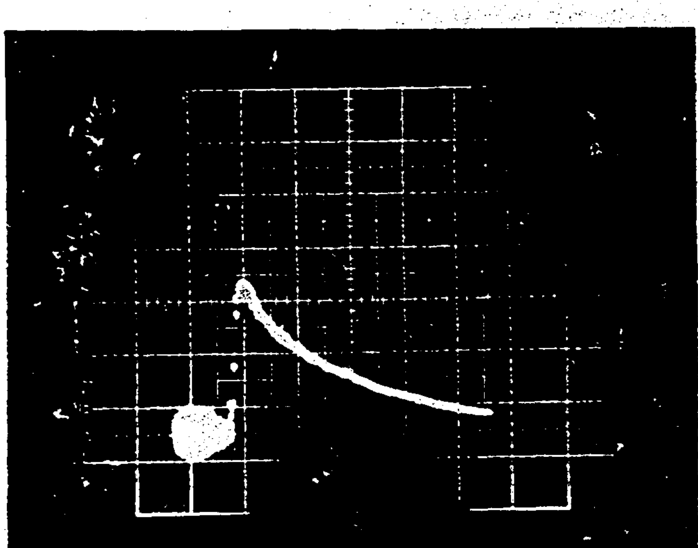


Figure 23a: (Charging Voltage: +3000 Volts)
0.5 V/small div., 50 nsec

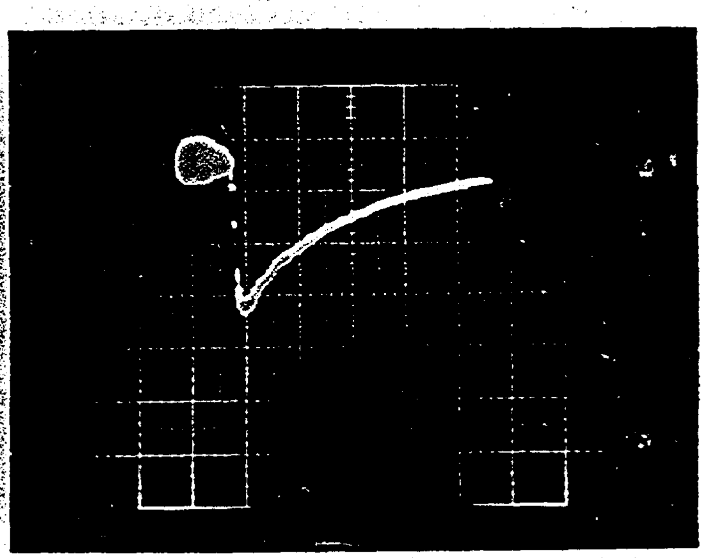


Figure 23b: (Charging Voltage: -3000 Volts)
0.5 V/small div., 50 nsec

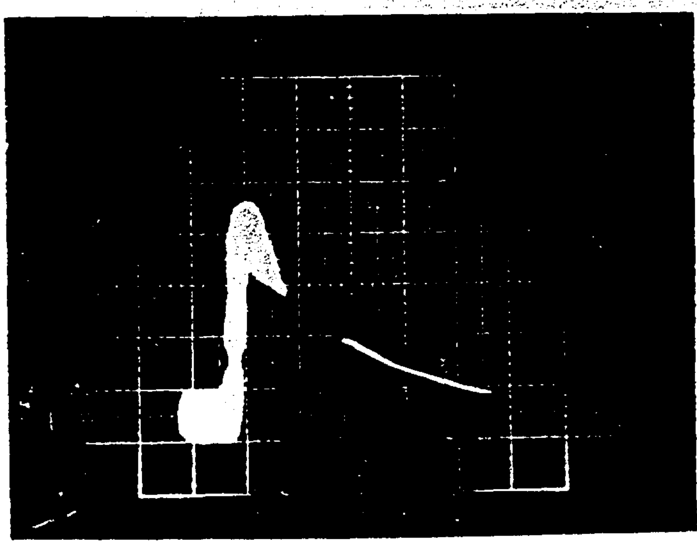


Figure 24a: (Charging Voltage: +4000 Volts)
0.5 V/small div., 50 nsec

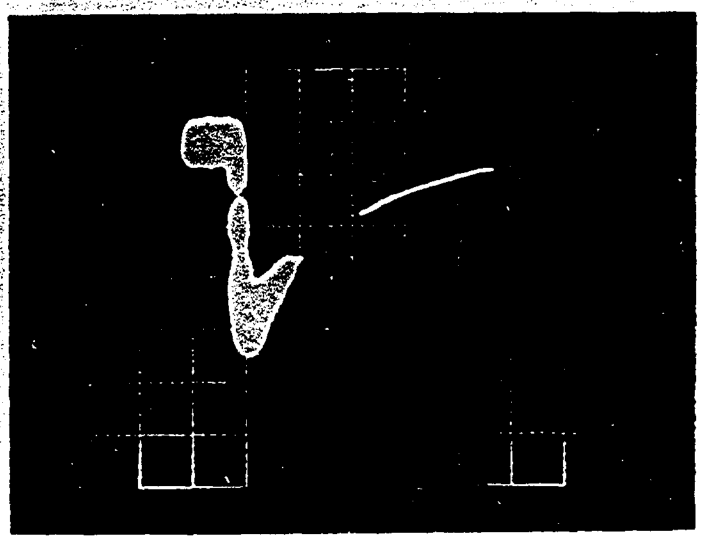


Figure 24b: (Charging Voltage: -4000 Volts)
0.5 V/small div., 50 nsec

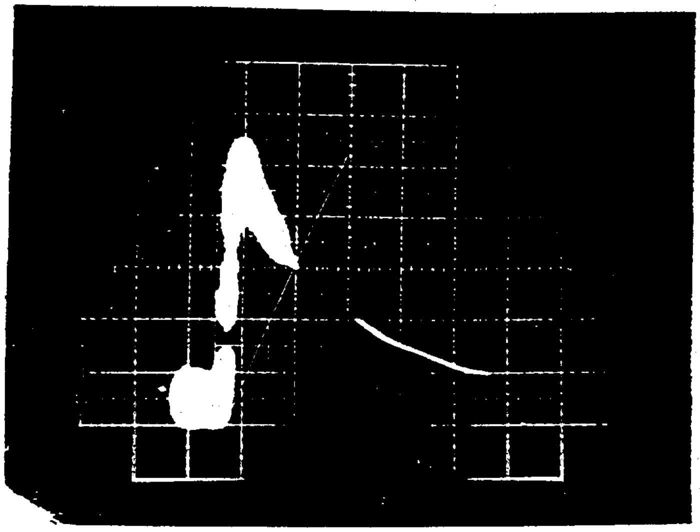


Figure 25a: (Charging Voltage: +5000 Volts)
0.5 V/small div., 50 nsec

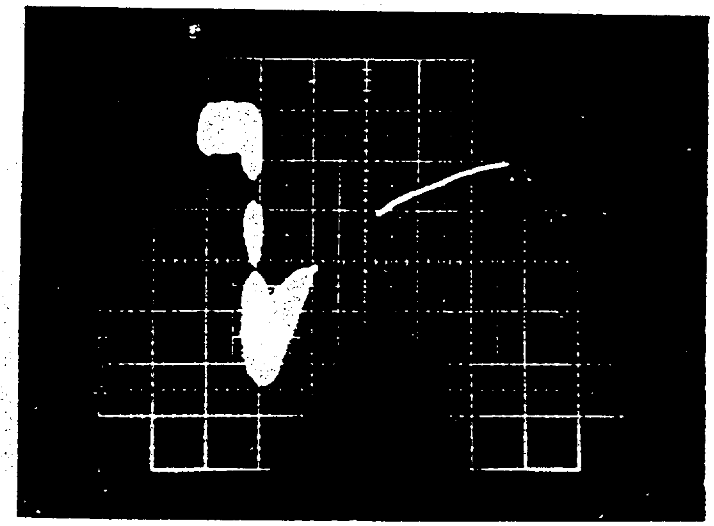


Figure 25b: (Charging Voltage: -5000 Volts)
0.5 V/small div., 50 nsec

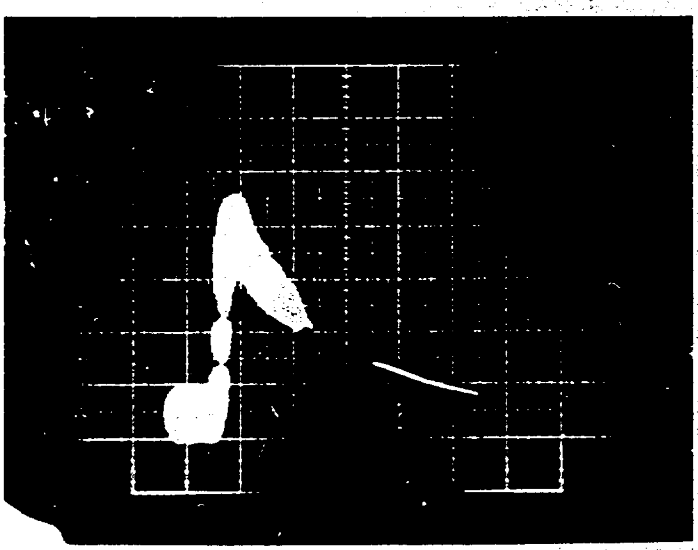


Figure 26a: (Charging Voltage: +8000 Volts)
1 V/small div., 50 nsec

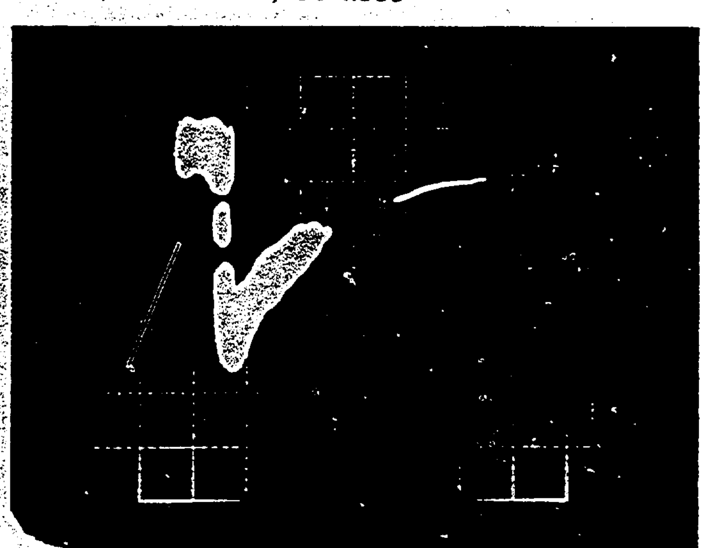


Figure 26b: (Charging Voltage: -8000 Volts)
1 V/small div., 50 nsec

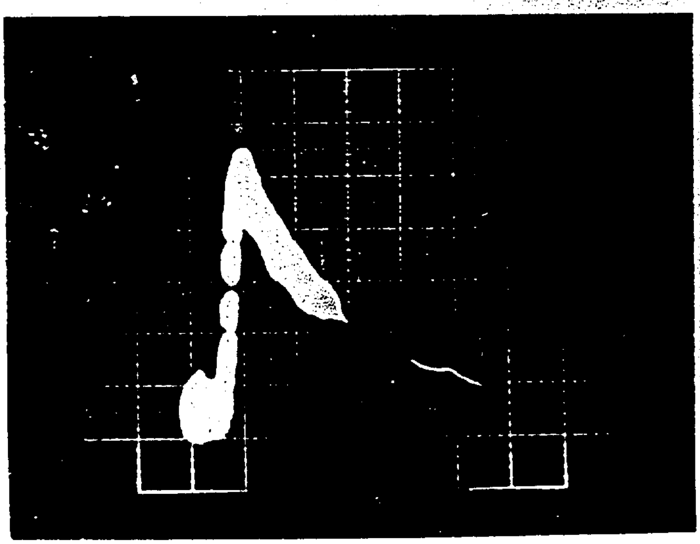


Figure 27a: (Charging Voltage: +10000 Volts)
1 V/small div., 50 nsec

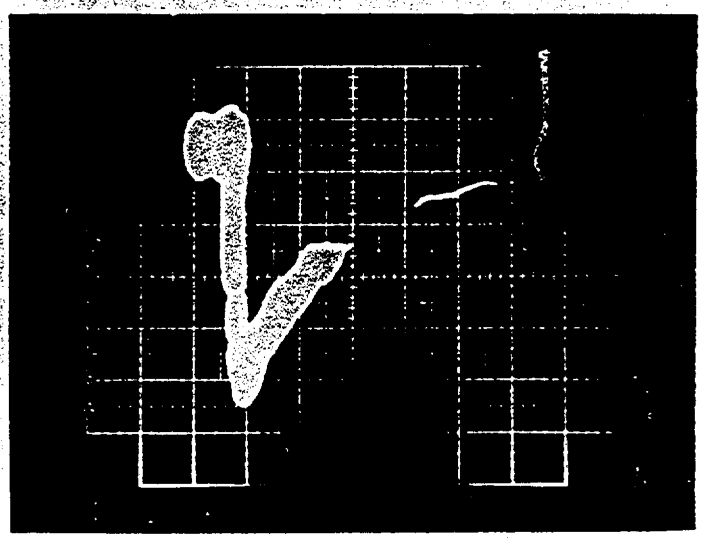


Figure 27b: (Charging Voltage: -10000 Volts)
1 V/small div., 50 nsec

5) Mercury Displacement Contactors (3.5 KV, 100NO-120ARH-6X, Mercury Displacement Industries Inc.)

As in the case of Test #3, separate switches were used to implement the charging and discharging operations. Waveforms with very good repeatability were obtained in the 0 to ± 10 KV voltage range and are shown in Figures 28 to 38. It is noted that these switches were also rated at 3.5 KV.

Observations made regarding waveform behavior above 1,000 Volts were similar to Test #3.

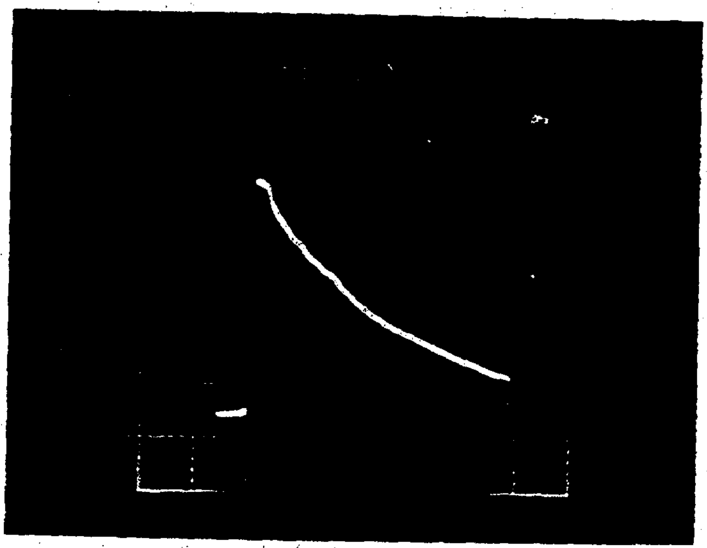


Figure 28: (Charging Voltage: + 450 Volts)
50 mV/small div., 50 nsec

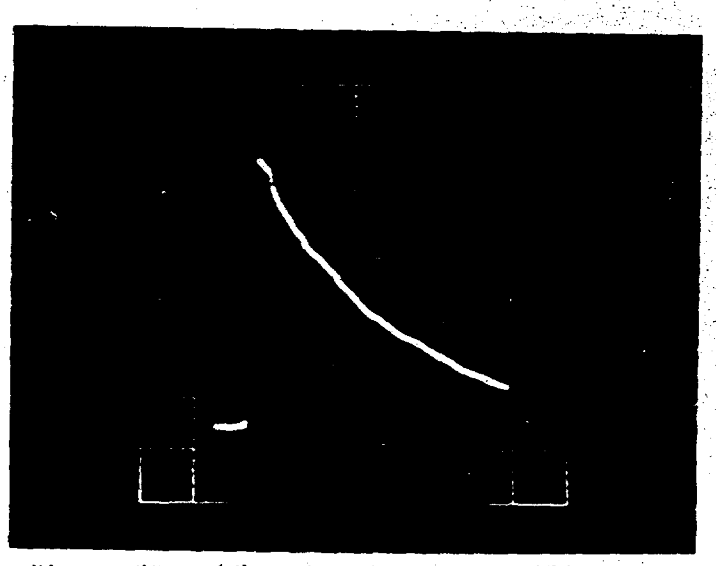


Figure 29a: (Charging Voltage: +1000 Volts)
0.1 V/small div., 50 nsec

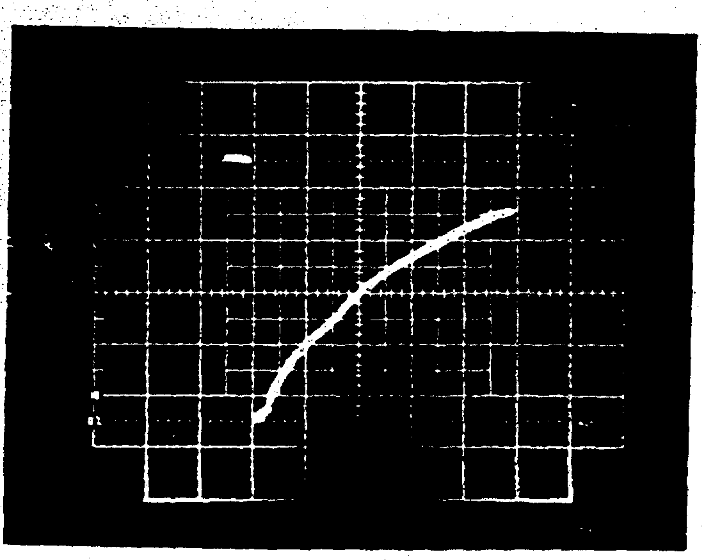


Figure 29b: (Charging Voltage: -1000 Volts)
0.1 V/small div., 50 nsec

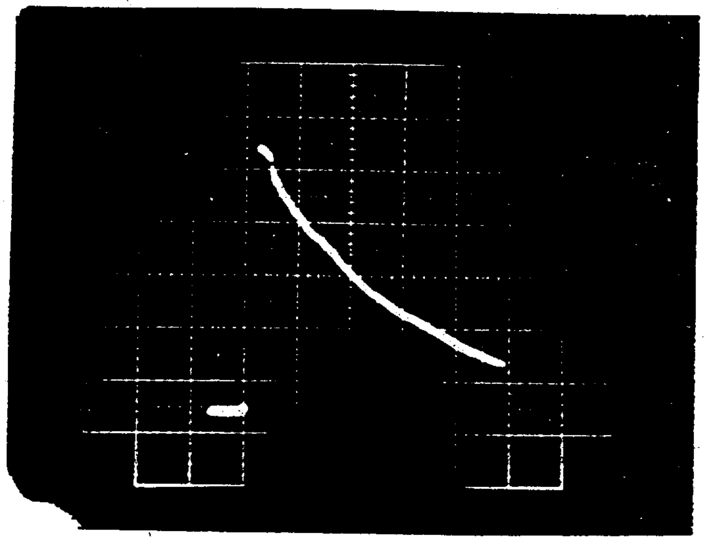


Figure 30: (Charging Voltage: +2000 Volts)
0.2 V/small div., 50 nsec

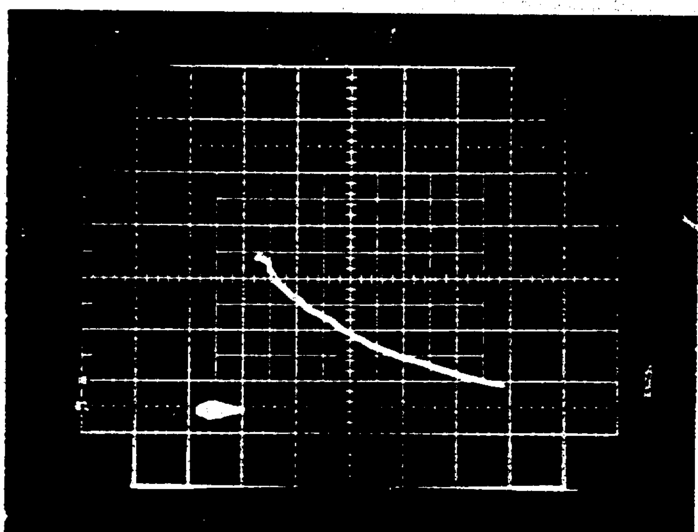


Figure 31a: (Charging Voltage: +3000 Volts)
0.5 V/small div., 50 nsec

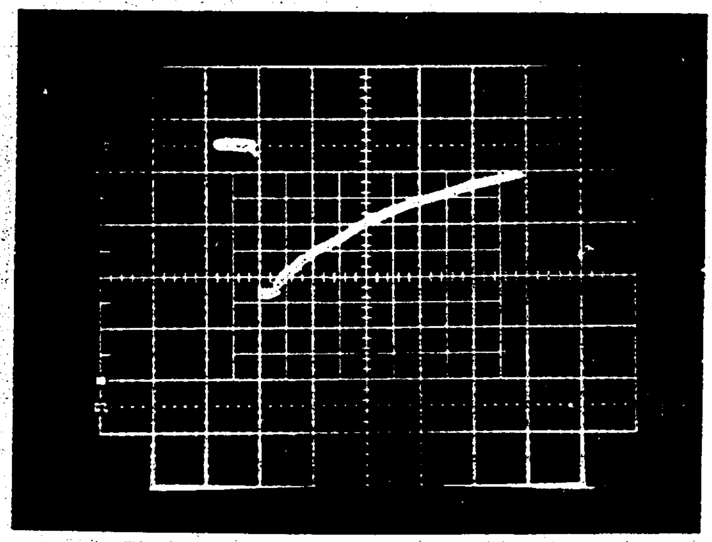


Figure 31b: (Charging Voltage: -3000 Volts)
0.5 V/small div., 50 nsec

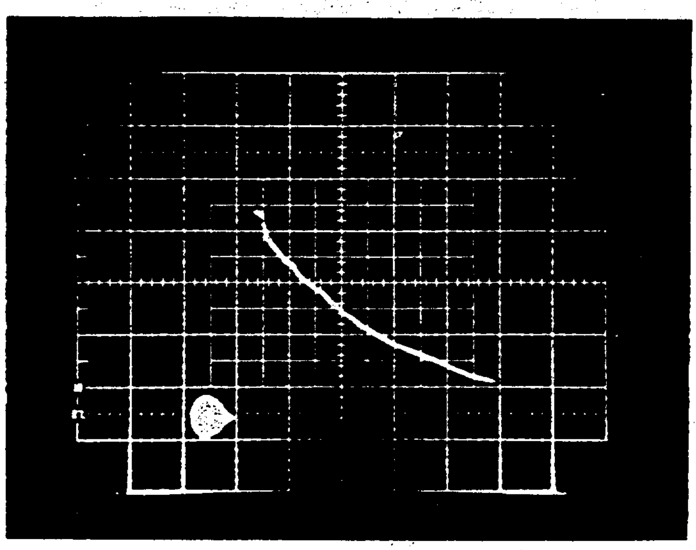


Figure 32: (Charging Voltage: +4000 Volts)

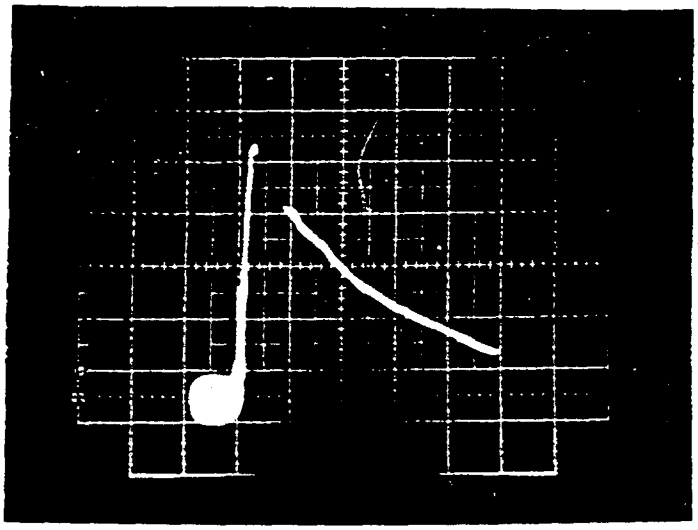


Figure 33a: (Charging Voltage: +5000 Volts)
0.5 V/small div., 50 nsec

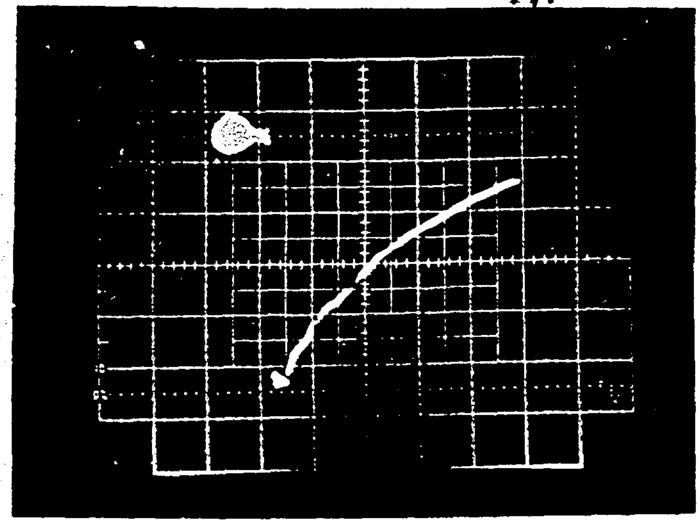


Figure 33b: (Charging Voltage: -5000 Volts)
0.5 V/small div., 50 nsec

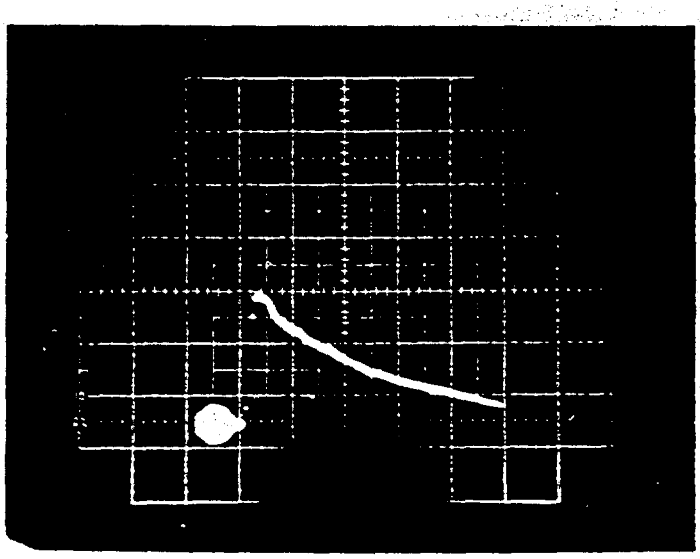


Figure 34a: (Charging Voltage: +6000 Volts)
1 V/small div., 50 nsec

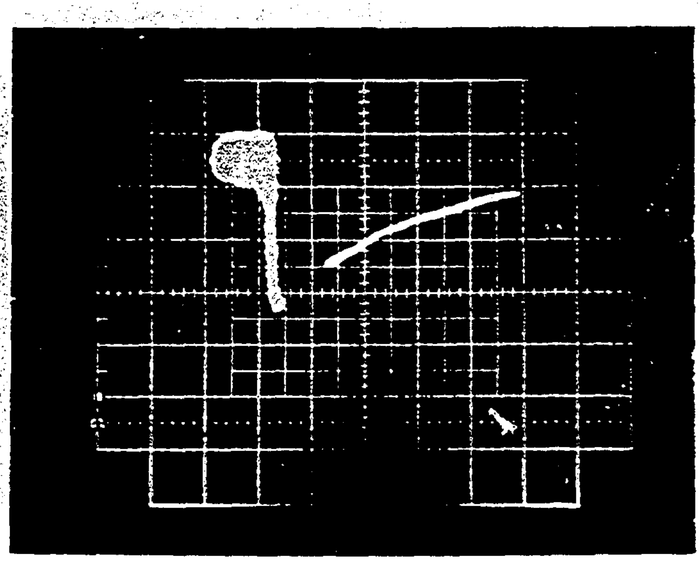


Figure 34b: (Charging Voltage: -6000 Volts)
1 V/small div., 50 nsec

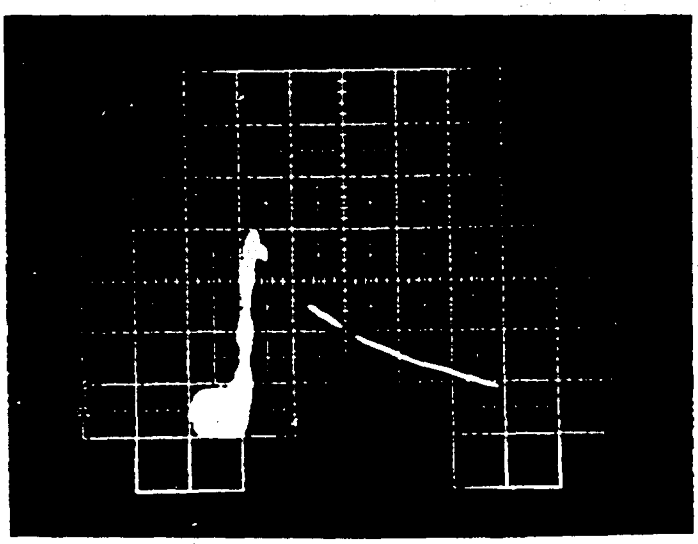


Figure 35a: (Charging Voltage: +7000 Volts)
1 V/small div., 50 nsec

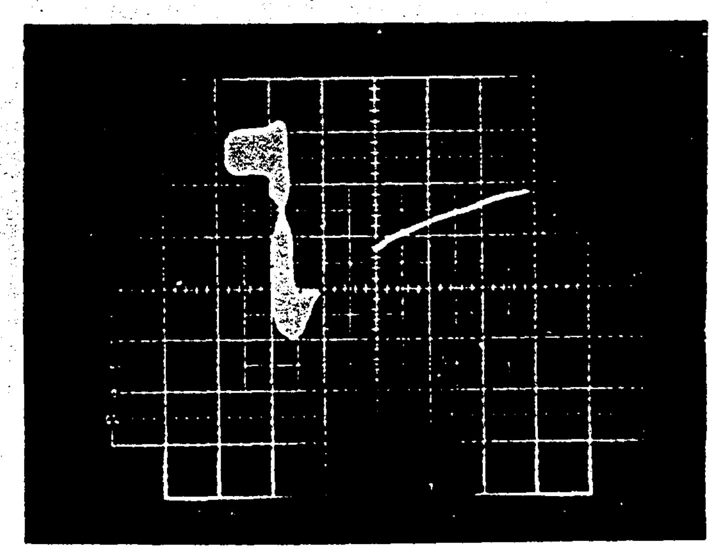


Figure 35b: (Charging Voltage: -7000 Volts)
1 V/small div., 50 nsec

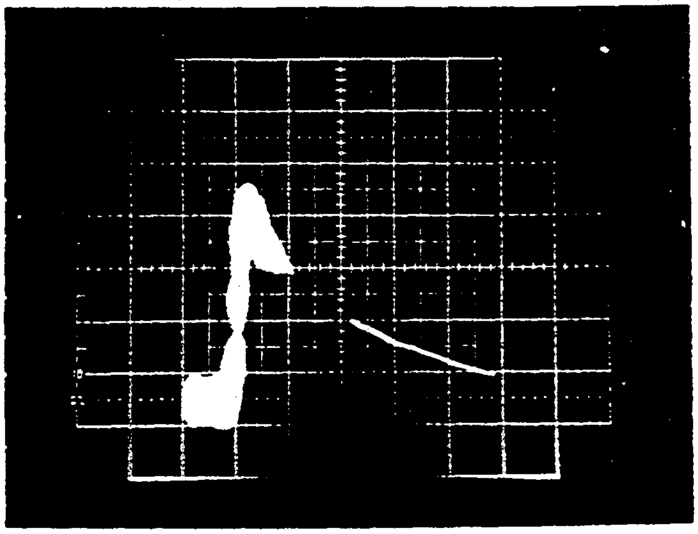


Figure 36: (Charging Voltage: +8000 Volts)
1 V/small div., 50 nsec

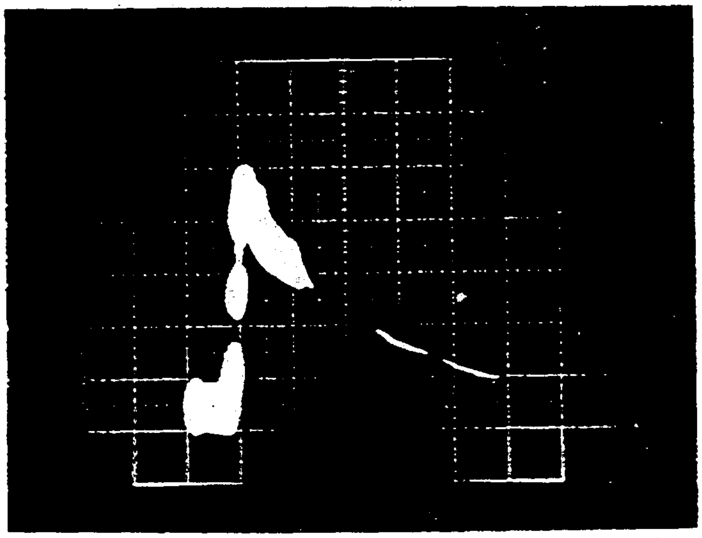


Figure 37: (Charging Voltage: +9000 Volts)
1 V/small div., 50 nsec

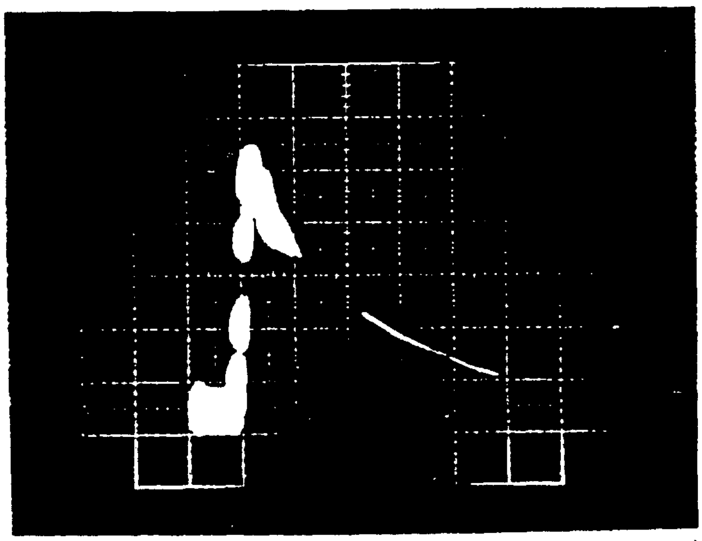


Figure 38a: (Charging Voltage: +10000 Volts)
1 V/small div., 50 nsec

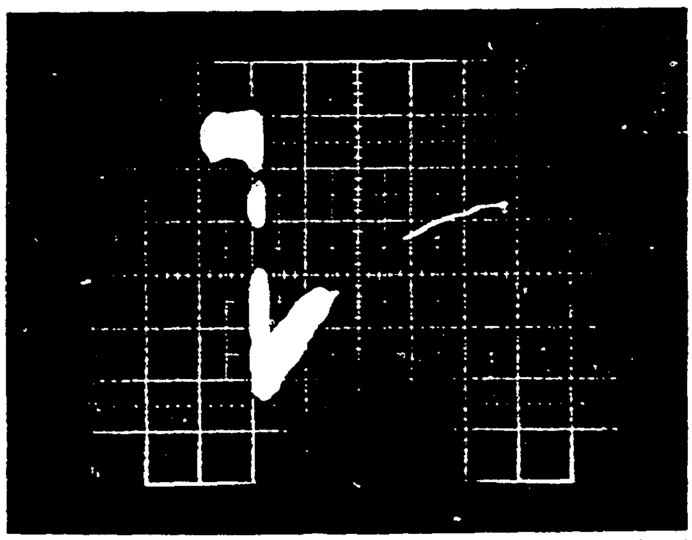


Figure 38b: (Charging Voltage: -10000 Volts)
1 V/small div., 50 nsec

6) Triggered Spark-Gap (GP-92, EG&G)

The ESD simulator implemented using a triggered spark-gap as the switching element was the most complex one of the circuits implemented as shown in Figure 39. The spark-gap is triggered using the circuit of Figure 40 which produces the indicated triggering pulse.

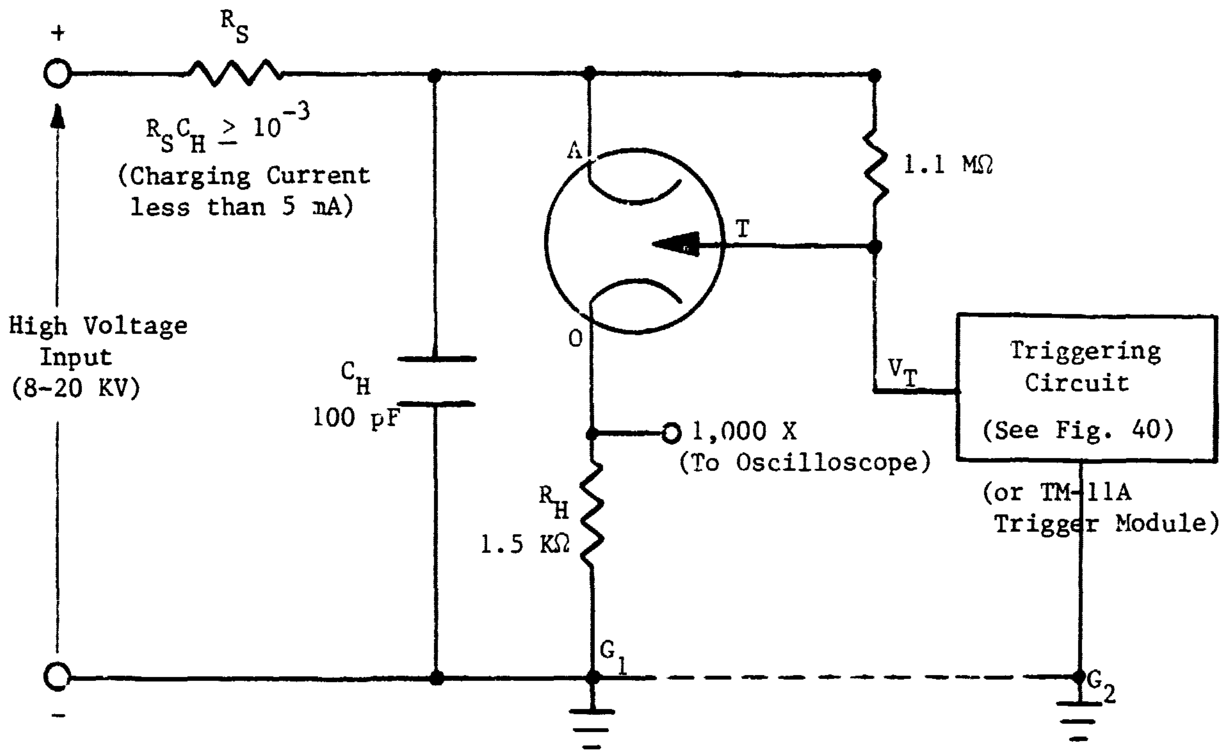
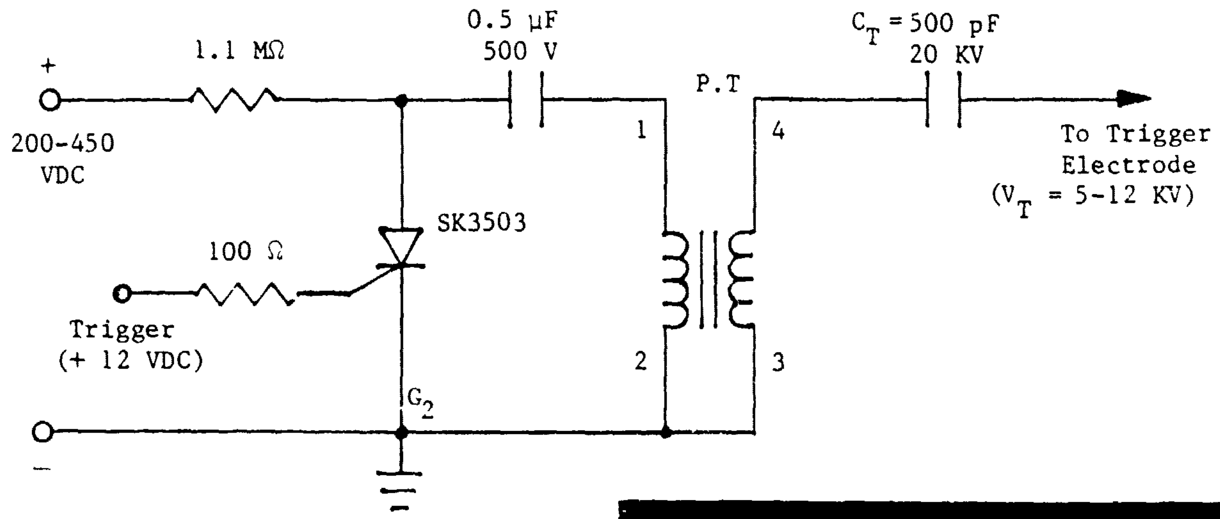


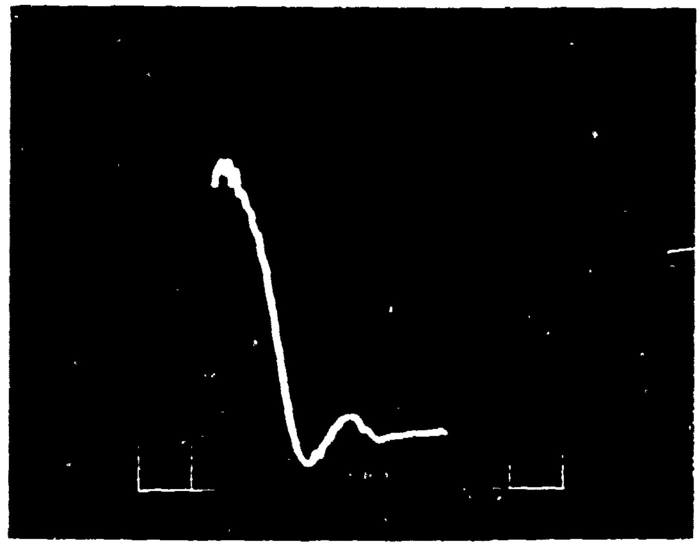
Figure 39: ESD Simulator Using a Triggered Spark-Gap

The operation of this ESD simulator is as follows:

Capacitor C_H (representing the human body equivalent capacitance) is charged through a high value resistance (R_S). The spark-gap is then triggered by applying the pulse of Figure 40 which causes the gap to switch from a non-conducting to a conducting state (in a few nanoseconds), thus discharging C_H through R_H that represents the human body equivalent resistance.



P.T = Pulse Transformer
TR-148A, EG&G Inc.
C_T = 30DK-T5, Sprague Elec. Inc.



(1 V/small div., 0.5 μsec/small div.)

Figure 40: Spark-gap Triggering Circuit and Trigger Pulse

The spark-gap used had a Self-Breakdown Voltage (SBV) of 25 KV, therefore, optimum operating range was 8 to 20 KV (60 to 80% of SBV). Below 8 KV, erratic triggering was experienced. Above 20 KV, self-triggering of the spark-gap will occur. The minimum required trigger voltage was $V_T \approx 7$ KV. However, for reliable triggering and in order to minimize jitter, this voltage was set well above 7 KV with trigger pulse rise time less than 0.5 μsec and pulse width of more than 1.5 μsec (see Figure 40).

Typical waveforms obtained with this set up are shown in Figures 41 to 44. It can be seen that the discharge waveform is dominated by the characteristics of the spark-gap (possibly the delay time that is in the order of 100 ηsec), resulting in an output waveform having time constant much greater than the $R_H C_H$ = 150 ηsec expected.

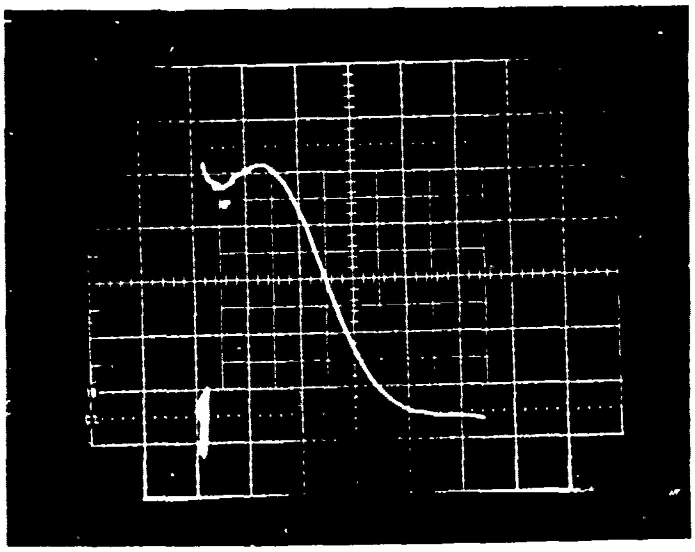


Figure 41: (Charging Voltage: 9000 Volts)
1 V/small div., 0.2 μsec

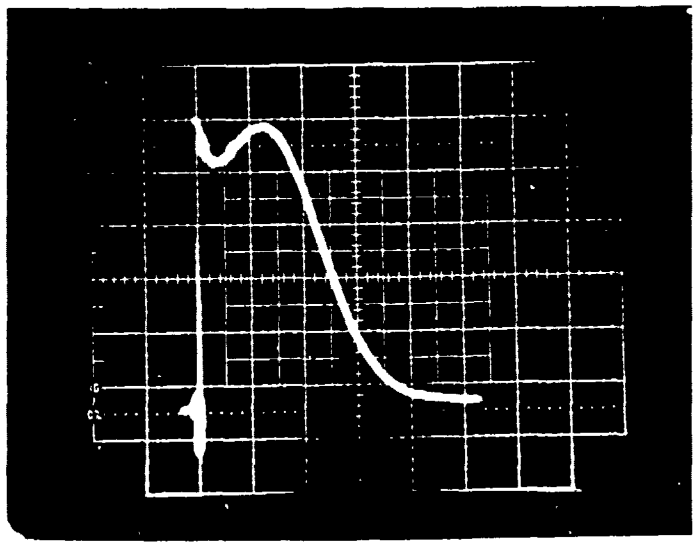


Figure 42: (Charging Voltage: 11000 Volts)
1 V/small div., 0.2 μsec

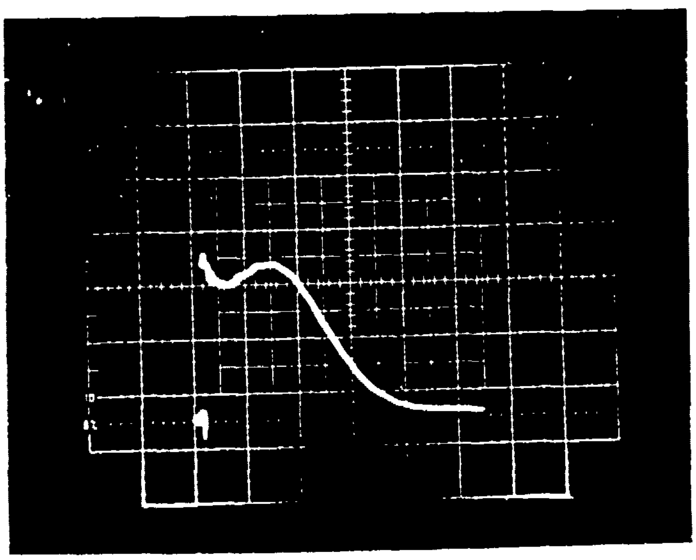


Figure 43: (Charging Voltage: 12000 Volts)
2 V/small div., 0.2 μsec

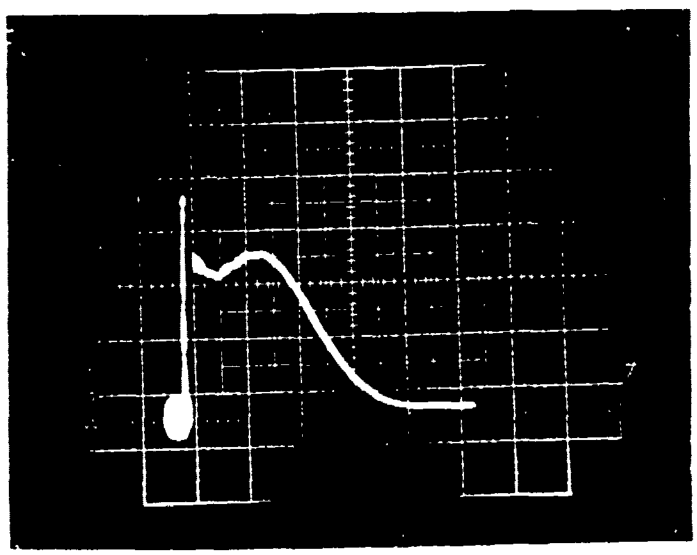


Figure 44: (Charging Voltage: 16000 Volts)
2 V/small div., 0.2 μsec

FURTHER TESTING

a. Mercury Relay (Test #4) and Mercury Switches (Test #5) at Charging Voltages above 10 KV

Measurements were taken on these set-ups in the voltage range of 10 KV to 15 KV (charging source: HV150-152M, High Voltage Module, Plastic Capacitors, Inc.).

Figures 45 to 47 and 48 to 51 show waveforms obtained with the Mercury Switches (Test #5) and the Mercury Relay (Test #4) respectively.

It can be seen that arcing and dielectric breakdown mentioned earlier is more pronounced in this voltage range.

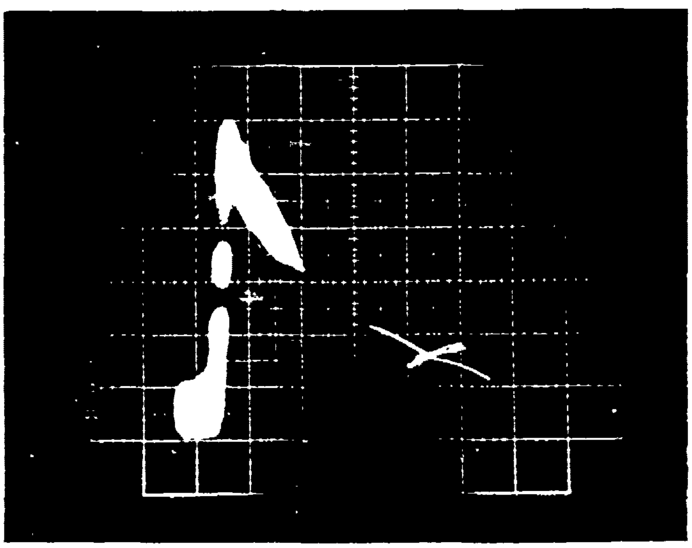


Figure 45: (Charging Voltage: +11000 Volts)
1 V/small div., 50 nsec

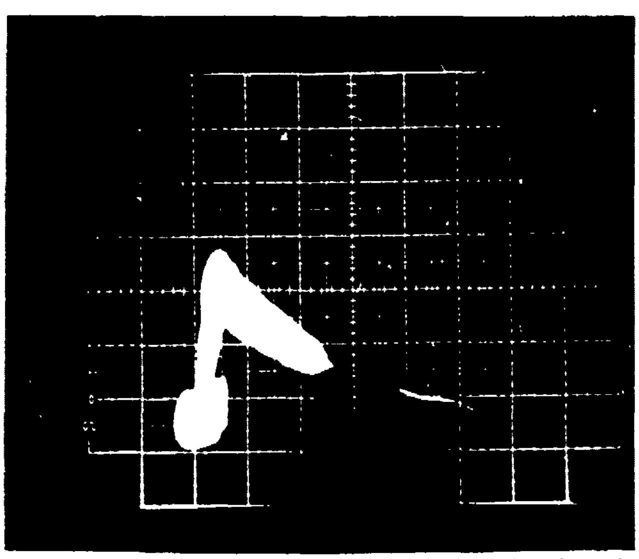


Figure 46: (Charging Voltage: +13000 Volts)
2 V/small div., 50 nsec

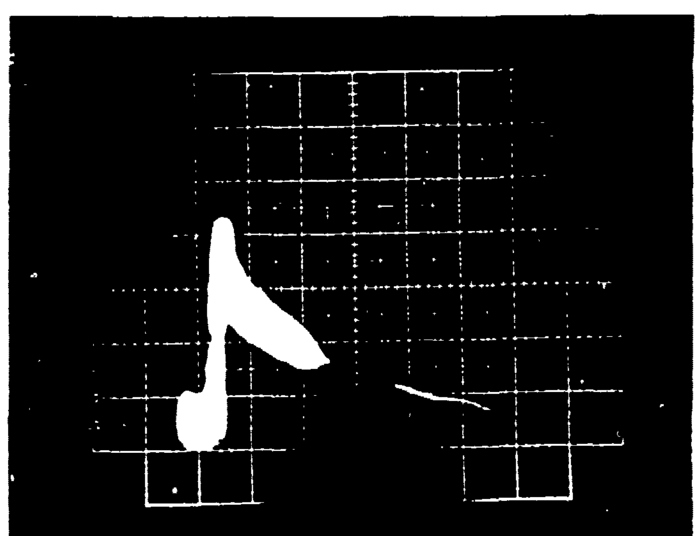


Figure 47: (Charging Voltage: +15000 Volts)
2 V/small div., 50 nsec

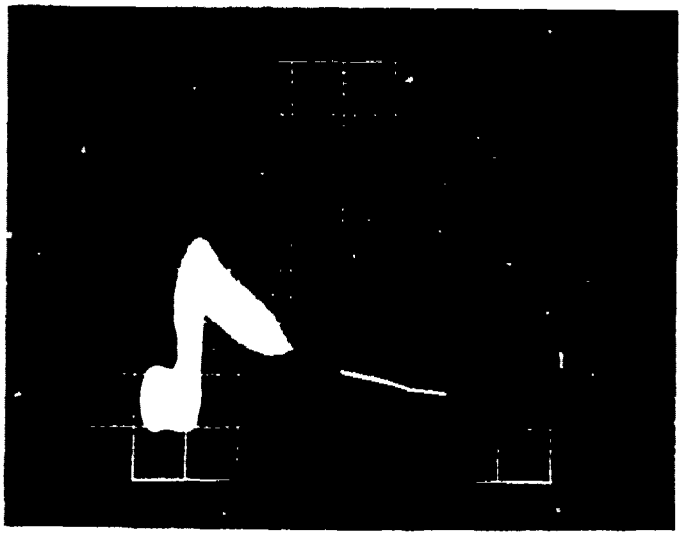


Figure 48: (Charging Voltage: +11000 Volts)
2 V/small div., 50 nsec

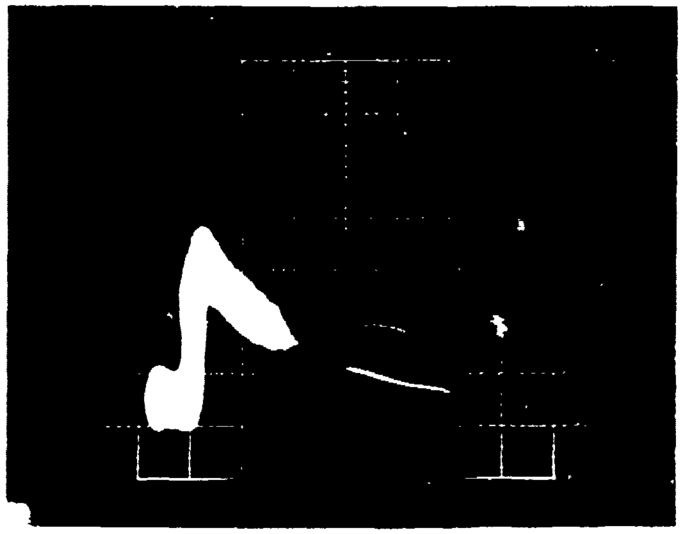


Figure 49: (Charging Voltage: +12000 Volts)
2 V/small div., 50 nsec

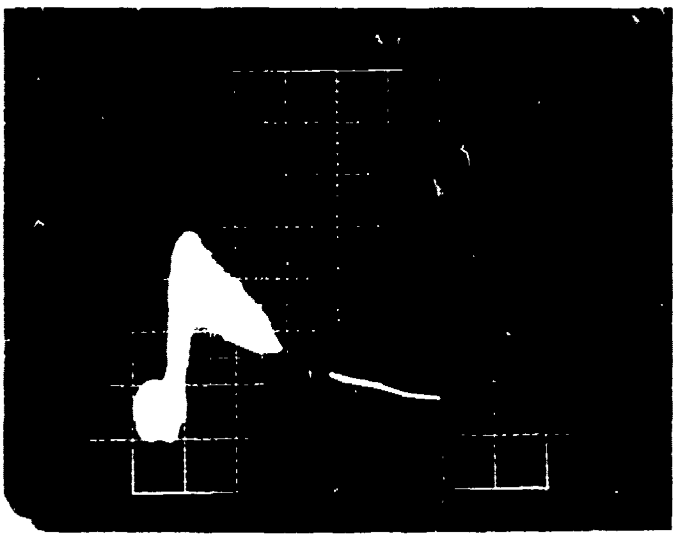


Figure 50: (Charging Voltage: +13000 Volts)
2 V/small div., 50 nsec

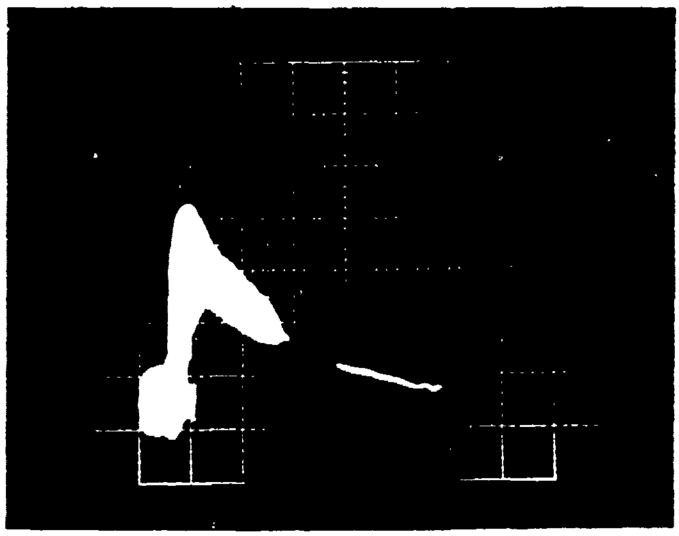
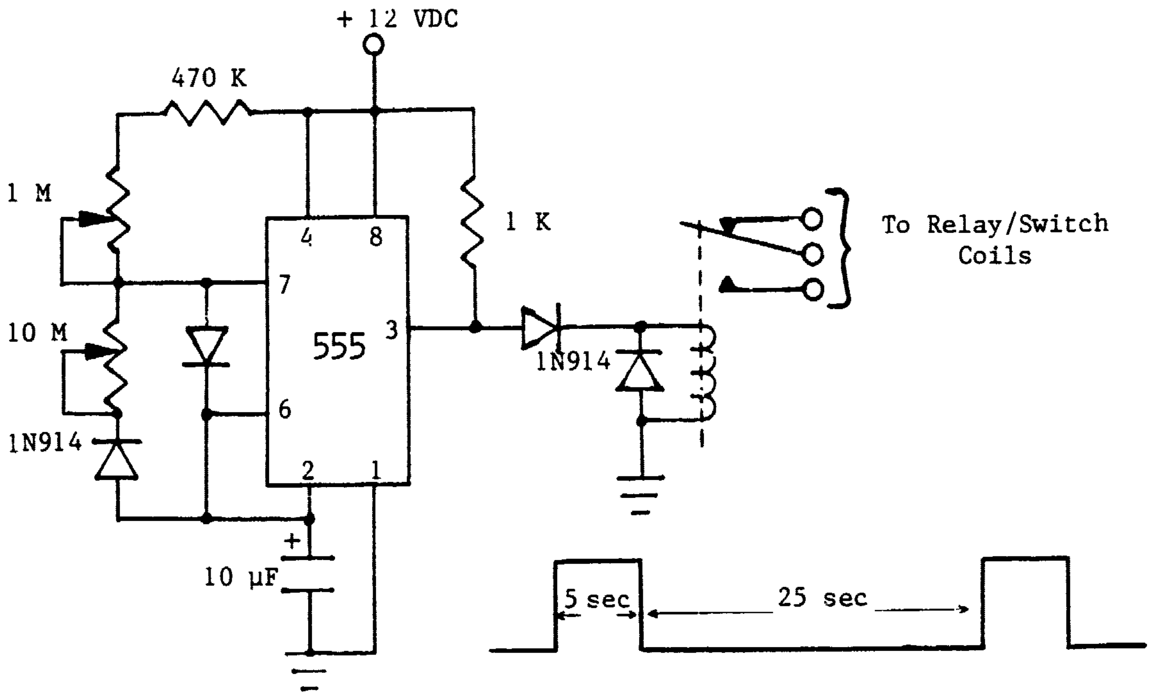


Figure 51: (Charging Voltage: +15000 Volts)
2 V/small div., 50 nsec

b. <u>100-Hour Cycling</u>

Since the Mercury Relay (Test #4) and the Mercury Switches (Tests #3 and 5) were used well above their rated voltage, it was considered necessary to determine the effects of charge/discharge cycling on their behavior.

Using the timing circuit shown below, over 100-hour cycling was performed with each set-up being in the "Charge" position for 5 seconds and in the "Discharge" position for 25 seconds, resulting in 120 cycles/hour.



The Mercury Relay was cycled 6,000 times at + 10 KV, 6,000 times at - 10 KV and 1,200 times at + 15 KV. Similar cycling was performed for the Mercury Switches. Output waveforms were recorded periodically and at the end of cycling.

For both test set-ups, no detrimental effects were observed as a result of the extended cycling at these high voltage levels. Figure 52 and 53 show discharge waveforms obtained at the end of 15 KV cycling for the Mercury Relay and Mercury Switches respectively.

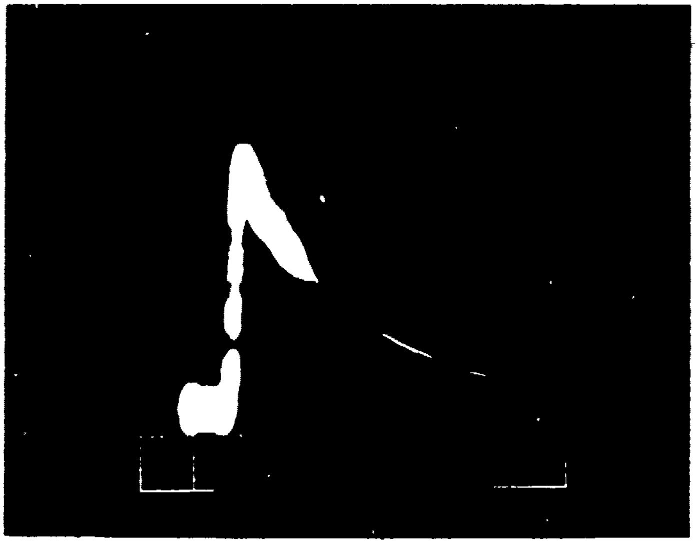


Figure 52: (Charging Voltage: +10000 Volts)
1 V/small div., 50 nsec

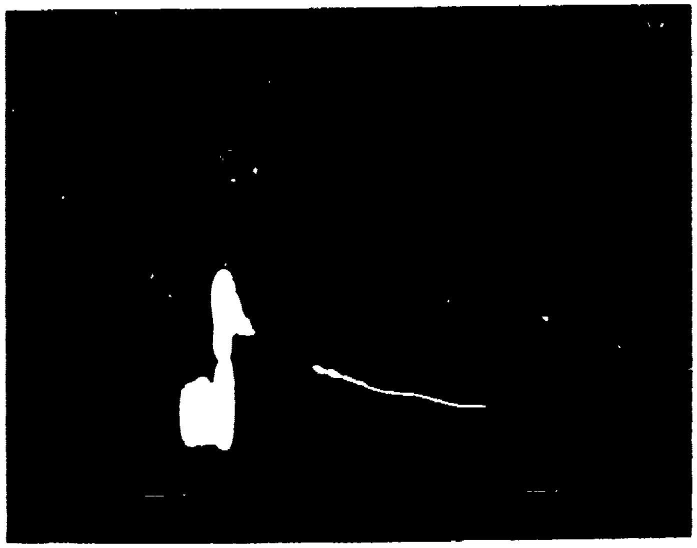


Figure 53: (Charging Voltage: +10000 Volts)
2 V/small div., 50 nsec

CONCLUSIONS

Of the six experimental set-ups investigated in this report, the following three can be considered suitable for ESD simulation:

- Mercury Switches -- Test #3: Up to ± 5,000 Volts
- Mercury Relay -- Test #4: Up to ± 4,000 Volts
- Mercury Switches -- Test #5: Up to ± 7,000 Volts

These set-ups can also be used for test voltages as high as ± 15 KV with good output waveform repeatability; however, above the indicated voltage level, the waveform will show signs of partial dielectric breakdown becoming more pronounced at higher voltages.

REFERENCES

[1] "Module Electrostatic Discharge Simulator," T.M. Madzy, L.A. Price II, EOS/ESD Symposium, 1979.

[2] "Dynamic Waveform Characteristics of Personnel Electrostatic Discharge," W. Michael King, EOS/ESD Symposium, 1979.

[3] DOD-HDBK-263 and DOD-STD-1686

[4] International Electrotechnical Commission (IEC), Technical Committee 65 (TC65), Working Group 4 (WG4), Part 5, Electrostatic Discharge

[5] "Measurement of Fast Transients and Application to Human ESD," H. Calvin, H. Hyatt, H. Mellberg, D. Pellinen, EOS/ESD Symposium, 1980.

[6] "A Closer Look at the Human ESD Event," H. Hyatt, H. Calvin, H. Mellberg, EOS/ESD Symposium, 1981.