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THE MOLECULE, A COMPACT, HIGH-DENSITY, HIGH-PRECISION MARX GENERATOR

Daniel M. Strickland, Capt, USAF
William L. Heatherly, Capt, USAF

November 1973

Final Report for Period July 1971 to June 1973

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FOREWORD

This research was performed under Program Elements 64711F and 64747F, Projects 3763 and 1209, Tasks 01 and 02.

Inclusive dates of research were July 1971 through June 1973. The report was submitted 4 September 1973 by the Air Force Weapons Laboratory Project Officer, Captain Daniel M. Strickland (ELS).

This technical report has been reviewed and is approved.

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ABSTRACT

(Distribution Limitation Statement B)

A Marx generator with the highest energy density ever achieved (39j/pound) is described. The unit, which operates at 2 MV in atmospheric SF_6, is 2 m long, stores 18 kj, and weighs 460 pounds. The design incorporates several novel features: the stage capacitors are 100-kV plastic-cased units with a density of 100 joules per pound; grading is achieved by split grading rings; and a conductive elastomer charges and triggers the resistors. Its compactness, light weight, and atmospheric gas insulation ideally suit this Marx design for a variety of applications such as bounded-wave and radiating EMP simulators, plasma devices, laser systems, and electron-beam devices. The modular nature allows the design voltage to be increased or decreased as necessary. The unit has a demonstrated erection jitter (1 σ) of less than 10 nsec over a 7:1 voltage range and consequently can be precisely time-tied to test sequences or to other hardware.

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SECTION I

INTRODUCTION

This report presents the results of an Air Force Weapons Laboratory (AFWL) program to develop a compact, high-density energy storage system to satisfy various EMP simulation requirements. Such requirements range from small, 1-MV ground-based simulators to elevated or air-supported simulators producing tens of megavolts. Based on studies performed during the HAS program and reported in the EMP-HAS report series (ref. 1) it was concluded that the most versatile and promising pulse generator system for matching this broad range of requirements would utilize a Marx generator and "distributed" peaking capacitor circuit.

The two main constituents of such a system are:

1) A Marx generator which is necessary to generate initially the very high voltage required and to provide a store of energy that will produce the low-frequency components of the final ouput wave.

2) A peaking capacitor, which is a small but very fast energy store, provides the high-frequency content of the wave and enables achievement of the required very fast rise time.

The Marx generator is a method of storing energy at a relatively low initial voltage and by very fast gas switching to connect many parallel capacitors in series to generate a short impulse of extremely high voltage. The advantages of an impulse generating system such as the Marx generator are that advantages can often be taken of the fact that flashover or voltage breakdown within a system is absolute voltage dependent and time dependent. Therefore, it is possible for some applications to impulsively generate very high voltages and remove the voltage from the load or test object prior to the occurrence of a flashover. This phenomenon is principally due to the finite transit time of the streamers that initiate the conducting currents which result in system flashover. See references 2 and 3 for a more detailed discussion of the Marx generator theory.

The "distributed" peaking capacitor is unique in that it is matched to the general shape of the system into which the pulse is to be launched and, in effect, becomes a part of the "wave guide" (ref. 4). Therefore, if the impedance of the "distributed" peaking capacitor is sufficiently low to pass the wave front, then transit time effects within the peaking capacitor itself will not affect the basic rise time observed on the generated wave shape A smooth transition between the fast or high-frequency components of the wave and the tail or low-frequency components is accomplished by initially charging the peaking capacitor with the Marx generator. During the course of the charging of the peaking capacitor, the inductance of the loop formed by the Marx generator and the peaking capacitor is charged to the desired output peak current level at the time the minimum output voltage of the system appears on the peaking capacitor. When this condition is achieved, that is, the voltage on the peaking capacitor is equal to the desired output voltage, and the desired output current is flowing in the loop inductance, the main output switch is closed and the wave is launched into the system.

This circuit is shown in a pseudo-electrical/physical schematic in figure 1. This configuration shows a single pulser module driving a parallel plate transmission line simulator. Figure 2 shows how this module might look physically. If one needed more voltage and/or energy the modules could then be configured into a distributed source array of n series and m parallel elements. Figure 3 shows a 2x2 array of modules producing twice the voltage and four times the energy of a single module. Figure 4 shows the idea carried even further to a 6x5 array of modules driving a parallel plate transmission line.

For driving a radiating simulator with a single module the peaking capacitor arms are simply arranged into a conic geometry as shown in figure 5, for a vertical dipole over a ground plane. However, to drive a radiating simulator with a distributed array the modules are best configured as dihedral horns shown in figure 6. The horns are then arranged to simulate a cylindrical source geometry and phased to approximate the wavefront of a biconic antenna. Figure 7 illustrates a 2x4 array of horns configured to drive a radiating simulator. Figures 8 and 9 illustrate a 2x4 array of modules driving horizontal and vertical dipoles.

The key element in such a distributed source module is the Marx generator which not only must be of ultra-high time precision to allow the modules to be properly time phased, but which also must be compact, lightweight, and low-inductance, especially for the large elevated systems. The other elements of the system are certainly important but the technology for such items as the output switches and peaking capacitors has been fairly well advanced by other programs. The module structure which must also be lightweight is unique to the particular system and cannot be designed universally. Consequently, the bulk of our development effort was directed towards the Marx generator for a compact, high-density, distributed source module.

The result has been named the "Molecule" Marx to indicate that it is a building block for assembly of larger systems. Although the system described here was designed for 2 MV, the modular nature of the Marx itself allows for variation of design output and energy storage. The 2 MV, 18 kj Marx weighs 460 pounds for a density of 39 joules per pound, the highest ever achieved. The Marx operates at a stress of 1 MV/m in ambient atmospheric pressure SF_6, has an inductance of 800 nh/MV, and can be erected with a jitter (1σ) of less tha 10 nsec over a 7:1 voltage range.

The design details presented in this report are intended to enable the reader to fully understand one philosophy and practice of building compact, high-density Marx generators. The "Molecule" design is extremely flexible allowing for many different choices of stage voltage and energy, number of stages, types of capacitors and resistors, and construction materials. Since individual requirements differ it is most likely that the reader will adapt the Molecule design to his particular needs rather than produce a carbon copy. Indeed, the Marx described here is only a prototype; it is not a polished, production-engineered unit. Consequently, a detailed drawing package does not exist which could be used to exactly reproduce this Marx with no other information. However, if any group wishes to obtain details of the Molecule Marx design which could not be included in this report, additional drawings are available for reference at the Air Force Weapons Laboratory.

SECTION II

DESIGN

1. CIRCUIT

The 2-MV Molecule Marx is shown schematically in figure 10. Table I gives the component parameters with respect to the schematic. The Marx consists of 20 stages, of 100 kV each, which are balance charged; i.e., the two capacitor terminals are charged to plus and minus 50 kV respectively. The balance charging requires that the first and last capacitors be isolated from ground during charging and one technique for doing so is to use untriggered "half-gaps" or switches which operate at half the voltage on the full, triggered switches. In figure 10 the half-gaps are those marked S_1 and S_{21}. The triggered switches operate with a total gap spacing of 0.243 inch and a trigger electrode is positioned one third of the total gap distance from one electrode. Thus there are effectively two gaps formed by the three electrodes and the "long" gap is twice the length of the "short" gap.

Table I

COMPONENT PARAMETERS

Stage Voltage	100 kV
Stage Capacitance (C_1, C_2, etc.)	0.18 μfd
Charging Resistance, R_c	10,000 ohm
Trigger Coupling Resistance, R_t	1500 ohm
Biasing Resistance	
R_{b1}	200 meg-ohm
R_{b2}	400 meg-ohm
Input Trigger Resistance	
R_1	1000 ohm
R_2	3000 ohm
R_3	1000 ohm
R_4	2000 ohm
R_5	1000 ohm

The trigger pins are connected in an M = 3 configuration, i.e., the pins of each switch are resistively connected to the pins of switches three stages away. This technique has been called a "Martin" Marx after J. C. Martin of the Atomic Weapons Research Establishment, Aldermaston, England who developed the technique (ref. 3). The Martin technique has been adopted in all the passively coupled, ultra-high precision Marx generators known to the author.

2. STRUCTURE

The Molecule Marx is assembled on a rigid skeleton. All components can be installed or removed without disassembly of the skeletal structure which consists of four basic units: stage trays, stage spacers, tie rods, and end plates.

a. Trays

The tray shown in figure 11 is formed by sandwiching a 1/4-inch sheet of phenolic between two 1/8-inch sheets of Kydex. The sheets are glued together with an adhesive such as Cadco BA 460 to form a rigid unit. The phenolic has a rectangular section milled out which produces a slot in the tray after laminating. This slot accepts the tongue on the stage switch discussed in section II. Clearance holes for the tie rods and grading ring support rod holes are drilled into the plastic sheets.

b. Spacers

The stage spacers (figure 12) are acrylic rods drilled with tie rod clearance holes. Their cross-sectional area is dictated by the amount of pretensioning desired on the tie rods--the greater the pretensioning, the more rigid the structure. The materials and dimensions used for the Molecule Marx structural components allow the entire unit to be lifted vertically from either end, horizontally with lift points at both ends, or even cantilevered from one end. The cantilevered position, however, is more a demonstration of conservatism than a real operational configuration.

c. Tie Rods

The tie rods are 1/2-inch diameter Nuplaglass rods fitted with specially designed end fittings. Figure 13 shows an assembled rod. Specifications for the end fittings are shown in figure 14 and a cross section of an assembled fitting is shown in figure 15. Tie-rod assembly details are given in Appendix I. The modified wedge shown in figure 15 is a standard wedge manufactured for 1/2-inch Nuplaglass rod which has been shortened to the specified length. Three tie-rod specimens with fittings on both ends were pull-tested to failure. In all three cases failure occurred in the rod at no less than 17,000 pounds tension and none of the fittings separated from the rod.

d. End Plates

The end plates shown in figure 16 are aluminum angle-iron weldments. This particular shape was chosen because it provided a convenient way to make other mechanical connections to the top and bottom of the Marx. In general, however, the end plates could be simple metal plates, thick enough to impart required rigidity to the structure. The Marx is essentially clamped between the two end plates by the tie rods.

3. GRADING RINGS

A novel split-ring technique is used for grading the Molecule Marx generator. While conventional rings are electrically continuous and operate at a single potential on each ring, the split rings are divided into two sections separated by insulating spacers (figure 17). One section is electrically connected to the top of its associated stage switch, and the other section is connected to the bottom of that switch. Thus, one full-stage voltage appears between the sections during charging, but after switch closure (during erection) the sections equalize in voltage.

The ring sections (figure 17, piece No. 1) can be fabricated from any material suitable for conventional rings, e.g., electrical conduit, aluminum tubing, or copper pipe. The shape can either be rectangular, as shown, or circular depending upon the particular Marx design. The cross-sectional dimensions are chosen to provide adequate spacing between the rings and the Marx core.

The section spacers (piece No. 2, figures 17 and 18) can be fabricated from any high-dielectric strength material; and they can either be molded as one piece or formed by gluing several pieces together, taking necessary care in the positioning of glue seams. In the prototype Molecule Marx, for example, the spacers are made by gluing two rubber cane tips to a polyethylene disc. The spacers must provide a snug, friction-fit around the grading ring. Piece No. 3 in figure 18 is simply a metal plug inserted to terminate the tubing in a round end to shield the sharp edges which could cause an arc through the spacer. The rings are supported on the Marx structure in any desired position by dielectric rods. Electrical connections to the rings are made by appropriate techniques such as soldering, clamping, or with threaded inserts such as "Molynuts" or "Rivnuts." Appendix II discusses further applications of the split-ring technique.

4. RESISTORS

Two types of resistors are presently used in the Molecule Marx: wirewounds and a conductive silicone elastomer tubing (Appendix III presents a preliminary test data on the conductive elastomer). The wirewounds are used as primary charging resistors. Five, 2,000 ohm Dale RS-10 wirewounds are soldered into a string, fitted with brass end terminals, and slipped inside a plastic tube. A Panduit strap is clamped around each end of the tube to hold the string of resistors in place. The brass resistor terminals have holes drilled in them which mate onto banana plugs attached to the grading rings. Figure 19 illustrates how the resistor strings look when they are mounted between the grading rings. Since the rings are split, they provide convenient attachment points for both the positive and negative charging chains. The stage capacitors are then either hardwired to the grading rings or connected through another resistor string. This sideways resistor connection is preferable because it damps erection transients which might otherwise overvoltage the inter-ring capacitance and produce an arc between grading rings. However, the sideways resistance must be small compared to the main stage charging resistance so that proper grading of the Marx is maintained after erection.

In the Molecule Marx the sideways resistance connection is made through a short piece of the conductive elastomer tubing with 1/4-inch ID, and 3/8-inch OD and a nominal resistance of 1000 ohms. Each end of the tubing is fitted with a female receptacle electrode held in place with a Panduit strap, one electrode of which mates to a grading ring plug and the other of which mates to the pin on the capacitor connector.

The trigger resistors are also constructed of silicone elastomer tubing and utilize similar electrodes which mate with banana plugs on the switch buss bars. The manufacturer can produce the elastomer in almost any shape desired with resistivities from 10 ohm/cm up 100,000 ohm/cm. Both the sideways resistors and charging resistors in the Molecule Marx utilize a 10-ohm/cm material but a higher resistivity is required for the main charging resistors. Although the wirewounds are satisfactory for the main charging resistors, it is intended that they too be replaced by the resistive tubing as soon a suitable material is received.

5. SWITCHES

a. Housing

The original prototype switches utilized an acrylic tube housing with end caps held on by nylon screws. After some use at high pressure, these screws would shear and have to be replaced. Additionally the electrodes were held in position by threaded rods which screwed into matching holes in the housing. These threads were sealed with epoxy and tended to develop leaks. These mechanical problems were compounded by an electrical problem. In order to prevent external flashover from the main electrode connections to the trigger connection it was necessary to cement acrylic barriers to the outside of the housing. These joints were troublesome and had a propensity to arc through tiny bubbles in the cement. Consequently a new set of switches was fabricated with an injection-molded Lexan housing, shown in the assembly drawing of figure 20. In this new design the external insulation is part of the housing, eliminating glue-joint problems; the end caps are simple plugs which are set in with PS-30 acrylic cement; and the housing is molded with internal flats for O-ring or gasket sealing of the electrode connections. In addition the capacitor connections are insulated from adjacent ones by an overlapping portion of the housing, and the switch tongue is cemented into a socket on back of the housing. It is this tongue which fits into the slot in each stage tray, providing mechanical support as well as insulation for the stage switches. Figure 21 shows a bare housing with the tongue glued in place.

b. Electrodes

The main switch electrodes are Mallory-1000 rods with hemispherical ends. They are mounted in the housing with a flathead screw which is countersunk in the capacitor connector and threads into the electrode. A small flat is ground on each side of the electrode for holding with a wrench while tightening. The gas seal is presently provided by a Thredseal O-ring located between the flat end of the electrode and the molded flat on the inside of the switch housing. However, this causes two problems. First, the O-ring will not fully compress to make a metal-to-metal contact between the electrode and the metal part of the Thredseal. This results in an error in gap setting unless the electrodes are ground off slightly. Second the metal part of the Thredseal is electrically floating with a gap between it and the electrode. Consequently, during Marx charging, this gap arcs and reduces the stability of the switches with a reduction in self-breakdown voltage. In addition the lifetime of the switch housing is degraded by the arcing and failure occurs from an internal track around the wall of the switch. The data presented in section III were all taken with switches which had this problem and the results are discussed relative to this problem. At the time of writing, a design modification was being implemented to correct this problem. The Thredseal will be removed completely and an O-ring groove cut in the flat end of the electrode to provide a direct seal with the switch body. The edge of the flat end will also be rounded slightly to reduce field enhancement. This geometry will then be nearly identical to the original prototype geometry which used epoxy to seal the screw threads directly. Internal switch dimensions were the same as in the molded housing and no internal tracks were observed after many thousands of shots.

The trigger electrode is a tungsten-carbide scriber point mounted in a threaded brass rod. Since it is expected to erode more rapidly than the main electrode, it was designed to be quickly removed externally and replace as necessary. Figure 22 (a) shows an assembled buss bar ready to be mounted on the switch. Figure 22 (b) shows a new trigger pin in closeup, and figure 22 (c) shows trigger pin erosion after 500 shots.

c. Connections

The electrical connection between switch and capacitor is made with the connector shown in figure 23. This piece is permanently attached to the switch during assembly and mates with the capacitor by being plugged into the capacitor receptacle discussed in paragraph 6 of this section. In other words during Marx assembly the switches are connected electrically and mechanically by simply being plugged in. Connection to the charging chain is made through a pin which pressed into the connector. A flexible resistor plugs into this pin and another one located on the grading rings. Connections to the trigger pin are made via the buss bar of figures 22 and 24. The trigger pin is threaded into the buss bar which is mounted to the switch with nylon screws and banana or pin plugs are screwed into the buss bar for resistor connections. Figure 25 shows a completely assembled switch.

6. CAPACITORS

The basic capacitor used in the Molecule Marx is shown in figure 26. It is a 100-kV, 0.18-ufd unit, with a density of 100 joules per pound. The internal construction of a generalized capacitor of this type is shown in figure 27.

Because the head of the capacitor was not designed to hold off 100 kV externally, it was necessary to make the modifications shown in figure 28. First a Celcon or Delrin barrier was hot-air welded to the existing head. This barrier in theory provided all the insulation needed to operate at 100 kV in SF_6. However to ensure against a bad weld joint, which would produce a flash-over and damage the capacitor, the sheet insulation shown in figure 29 was added to each side of the head. One sheet is a piece of 10-mil mylar and the other is a commercial dielectric sandwich of 3-mil polypropylene between 1-mil kraft paper. The dielectric sandwich sheet is placed in contact with the capacitor terminal to allow the paper to grade the static charge distribution near the terminal. Connections to the capacitors were made with the receptacles shown in figure 30 which attach with screws to the existing capacitor rail terminals. The capacitor connector of figure 23, which is attached to the switch body, then plugs into the socket and electrical contact is made through the finger stock.

To prevent the compression of the Marx column from damaging the capacitor bodies, a thin strip of 1/4-inch sponge rubber was glued to the cases. The rubber not only cushions the capacitors but also provides enough friction to hold them in place with no other supports.

Figures 31 and 32 show the Marx generator assembled, with most of the components visible. For clarity, figures 33 and 34 show front and side view drawings of the Marx with all components in place except the resistors and gas line connections.

The generator is assembled in the following manner. First the skeletal structure is assembled. The tie rods are inserted into one of the end phases and the stage spacers and trays are alternately slipped over the tie rods. After all spaces and trays are in position, the last end cap is put on and the nuts are tightened to whatever tension desired (generally 2000 to 4000 pounds). The basic structure is now complete and all additional components can be installed or removed without disassembly of this structure.

Next the capacitors are inserted between the trays and aligned. It is best to insert one switch to determine the proper capacitor position. The rest of the switches are then plugged into position. The switch tongues fit into the tray slots, and the finger stock capacitor connectors plug into the capacitor sockets, all in one motion. Note that the sideways resistors should be plugged into the capacitor connector pins before the switches are pushed all the way in. Also, even after all capacitors and switches are installed, any one of them can be removed without disturbing any other component, except for the grading rings and resistors attached to that capacitor or switch.

The next step is attachment of grading rings. Each tray has four dielectric rods which fit into holes drilled into the rings. The two halves are put in position and the mating ends pushed into the grading ring spacers, which have a tight friction fit to the rings.

Last, the trigger and charging resistors are plugged in, gas lines connected, and high voltage charging and trigger connections are made.

SECTION III

OPERATING DATA

1. AMBIENT INSULATION

The Molecule Marx operates in an ambient environment of atmospheric pressure gas. Up to 50 kV per stage, or 1 MV output, the ambient gas can be air, but above this level a hard gas such as SF_6 or Freon 12 should be used. SF_6 is recommended, however, because some evidence exists which indicates that Freon 12 forms conductive decomposition products in a high corona environment. After sustained operation in Freon-12, a thin layer of a soot-like material (probably a carbon product) builds up on insulator surfaces and can produce a flashover. No such effect is noticed in SF_6.

2. INDUCTANCE

Inductance was determined by measuring the ring frequency of the Marx firing into a short circuit. After subtracting the contribution from circuit loop inductance (calculated by a technique in reference 5) the effective inductance of the Marx was found to be approximately 1.6 microhenries, or 80 nanohenries per stage. This value is consistent with that obtained by calculating the inductance contributions of an individual stage (table II).

Table II

APPROXIMATE CONTRIBUTIONS TO MARX STAGE INDUCTANCE

Capacitor	15 nh
Switch	15 nh
Connections	50 nh

3. JITTER

The jitter of Marx erection is basically a measure of the erection time of the Marx. Although absolute erection time is difficult to measure it can be relatively defined as the time between application of a firing signal and voltage first appearing across a load on the Marx. The technique used to measure Molecule Marx erection jitter is a standard one which involves displaying the trigger signal and the output waveform on the same oscilloscope trace. The trigger signal is used to trigger the oscilloscope, and if the signal is identical from shot-to-shot and the oscilloscope properly adjusted, repetitive displays of the trigger signal should result in perfectly overlapping trigger signal traces. Any nonoverlapping of the Marx output signal then represents jitter.

In the circuit of figure 35 which was used for jitter measurements the net effective delay in the trigger signal circuit was about 5 nanoseconds. That is, if 5 nanoseconds are added to the time between the trigger signal and Marx output as measured on the oscilloscope, a measure of the erection delay can be obtained. Figures 36 through 43 show five shot overlays of the trigger signal and the Marx output for various charging voltages and switch pressures. The first, short, triangular signal is the trigger signal to the Marx differentiated by the trigger probe. The second, slowly rising signal is the Marx output measured by the voltage probe. In all cases the Marx output was negative and the trigger signal was positive (trigger cable charged negative). The trigger signal is displayed negative because it was inverted by the B input of the 1831A direct access plug-in.

Using figure 36 as an example, the delay on the scope trace is approximately 70 nsec, and adding 5 nsec yields an erection delay of 75 nsec. In figure 37 the total erection delay is only about 35 nsec because the switches are being operated at a higher voltage and fire more quickly than at the lower voltage. This relationship, however, does not necessarily hold if a different gas is used at the higher voltage.

The series of eight traces show representative performance of the Marx between 14 kV and 100 kV per stage, or in total voltage between 280 kV and 2 MV. (In reality the Marx will erect reliably as low as 4 kV per stage, or 80 kV total with 0 psig air in the switches, but the erection jitter is quite high.) The worst jitter is indicated in figures 41 and 42 which show a $\pm$ 10 nsec spread about the mean value of delay. The jitter in figures 37, 38, 39, and 41 is unmeasurable and even in figure 36 is quite low (about $\pm$ 5 nsec).

As mentioned previously, these data were taken with the switches which used a Thredseal to seal the main electrode connections. Because of the instability produced by arcing between the electrode and the metal part of the Thredseal it was necessary to heavily pressurize the switches and use a high percentage of SF_6 to achieve voltages above 70 kV. Consequently the jitter increased. It is felt that once this problem is rectified the low jitter performance can be maintained over the full operating range. Even so, the Marx presently operates with better than 10 nsec jitter over a 7:1 voltage range (14 kV to 100 kV) which is adequate for many requirements. A new set of switches which will correct the top-end instability is presently being fabricatcd, and new data will be published when they are available.

APPENDIX I

TIE-ROD ASSEMBLY PROCEDURES

1. Degrease wedges and end fittings.
2. Carefully grind or sand white protective coating from rod, 2 inches back from each end.
3. Clean all parts with alcohol.
4. Slip acrylic spacers on rod.
5. Seize each end of rod with nylon electrical lacing cord. Start 2 inches from end and finish at 2 1/2 inches from end.
6. Start splits at each end.
7. Slip end fitting on rod.
8. Start wedge in rod end to open cracks in rod.
9. Douse liberally with Epon 828 epoxy mixture (60 parts Epon 828, 40 parts Versamid 140). Make sure epoxy gets in splits.
10. Push wedge about 1/2 to 2/3 of the way in.
11. Wrap end with a layer of glass cloth.
12. Soak thoroughly with epoxy.
13. Slip end fitting into position.
14. Align rod and end fitting in a holding fixture.
15. Drive wedge home.
16. Fill end of fitting with epoxy.
17. Cure
18. Do other end.

APPENDIX II

APPLICATIONS OF SPLIT-RING MARX GENERATOR GRADING

The split-ring grading technique provides several conveniences to the Marx designer. In addition to providing the same field grading of conventional rings, the split-rings provide attachment points for charging resistors as discussed in section II.6 and illustrated in figure 19.

The split-ring technique also provides assistance in the quest of that golden fleece, sometimes called the "Self-Healing Marx." Two promising concepts for stage fuse, utilizing split grading rings, are presently being investigated (ref. 6). These fuses would sense a failed capacitor during charging and disconnect it from the charging chain to allow operations to continue without the necessity of capacitor replacement. Ultimately, the same fuse might short out the corresponding stage switch to ensure continuation of optimum erection performance. One fuse concept utilized in a split-ring Marx is shown in figure 44. The fuse is a small carbon resistor, under tension, which breaks apart under short circuit charging currents and disconnects the capacitor from the grading ring. To ensure that normal erection transients do not open the fuse, the resistor is shunted by a surge arrestor.

A second fuse concept, shown schematically in figure 45, utilizes a current-imbalance detector to disengage the failed capacitor from the charging chain. This concept places several constraints on [illegible]x design. First, it must be balance charged, i.e., the capacitor termi[illegible] charged plus and minus with respect to ground. Second, the stage capac[illegible] must have a ground or neutral terminal. Third, the neutral terminals must be connected with a resistor chain (called the balance chain) which is similar to the two charging chains.

Neutral terminals on capacitors can be obtained in several ways. For metal-cased units with two insulated terminals, the can is usually neutral when the capacitor is balance charged. If metal-cased units with a single insulated terminal are used, the cans of two capacitors must be connected, and the two terminals charged plus and minus, the cans then becoming neutral.

For a compact Marx, metal-cased capacitors are awkward to use and dielectric-cased units are preferable. If a single dielectric-cased capacitor is used per stage, the manufacturer must provide a neutral terminal. However, a convenient scheme utilizing two capacitors is shown in figure 46. Each capacitor is relatively thin compared to its length and width and has a rail terminal on each end. For convenience it has been called a double-ended flat-pack, to distinguish it from those units with two rails at one end. At least three manufacturers, Maxwell Laboratories, Aerovox Corporation, and High Energy, Inc., now produce such units. One version is pictured in figure 47. As shown in figure 46 two of the units are stacked with one or more sheets of insulating material between them. The terminals at one end are bussed together, connecting the two units in series (for increased capacitance, parallel connections can also be made). The common end becomes neutral and the opposite terminals are connected to the charging chains. The insulating material between the capacitors not only serves to insulate the high-voltage terminals but it can be utilized as insulation between adjacent Marx switches.

One scheme for utilizing an imbalance detector to disconnect a capacitor is illustrated in figures 48 and 49. Following the detector circuit of figure 45 the relay is adjusted so that normal balance charging currents do not trip it. However, if a capacitor fails the balance current becomes an "imbalance" current which is high enough to engage the relay. The relay in turn connects the photoflash battery across the fuse wire, which melts and releases a spring-wound spool. As the spoon recoils it retracts two dielectric leads which are routed through plastic guide tubes and attached to disconnect fittings at the front of the capacitors. Retraction of the leads disconnects the capacitor from the charging chain.

SUMMARY

The split-ring grading technique provides a particularly well-defined and convenient interface (electrical and mechanical) between the charging chain and the stage capacitors. All aspects of Marx design, fabrication, and operation can potentially benefit from the technique. The Molecule 2-MV Marx generator, which uses split rings, operates at 1 MV/m in atmospheric pressure SF_6 or Freon 12, has a density of nearly 40 joules per pound, and can be assembled by one man in a few hours. In fact, any component can be removed and replaced without disassembling the Marx. Admittedly, all of these features are not unique to the Molecule, nor do they all accrue from the use of split rings. The combination, however, of compactness, density, and ease of handling is substantially benefited by the split rings. In addition, the design provides broad flexibility

to investigate such technology advancements as fault-correction devices without the necessity of building a special Marx for each device. Almost any device can be added as an afterthought.

APPENDIX III

PRELIMINARY TEST DATA ON CONDUCTIVE SILICONE ELASTOMER

This appendix presents preliminary test data (ref. 7) on the conductive silicone elastomer being used as charging and trigger resistors in the Molecule Marx. Although the data are incomplete they do indicate that the material has extremely attractive possibilities as an alternative to more conventional resistors.

The material, called SC-CONSIL, is manufactured by Tecnnical Wire Products, Inc. Test data are presented on samples of the material in the form of tubing, 1/8 inch ID, 1/4 inch OD, with a nominal resistivity rated at 10 ohm/cm, the lowest achievable by the manufacturer (ref. 8). Electrical connections to the sample were made by inserting a small cylindrical stainless steel electrode with a hemispherical end and clamping it in place with a Panduit strap.

Figure 50 shows the effect of stress and pulse length on the quality of the tubing for use as a high-voltage resistor. It should be noted that the effective pulse length is defined as the time during which the pulsed voltage is no less than 88 percent of the peak applied voltage. The region marked "bad" is one in which flashover will always occur after several hundred shots. The region marked "marginal" is accompanied by visible streamer activity but no bulk flashover. The "good" region is one in which the resistor can be operated with no streamers or flashovers. It is postulated that these regions will be affected by the size of tubing tested because the data seem to indicate a current or energy density effect on the quality of the resistor. Consequently, a larger diameter tube with more cross-sectional area might be expected to remain good at higher combinations of stress and pulse length, however, no data presently exist to verify this hypothesis.

Figures 51 through 54 show a decrease in resistivity with increasing number shots for those samples operated in the good region, although stabilization is indicated after a certain amount of "burn in." Figures 55 and 56 indicate that the material is ohmic, although the non-zero intercept is yet unexplainable. Figure 57 shows how stretching the tubing affects the resistance. (R_0 an l_0 are unstretched resistance and length, respectively.) These measurements were taken with a low-voltage bridge and within reasonable limits the stretching does not seem to affect the resistance at the higher stresses (> kV/cm), but this effect requires further investigation.

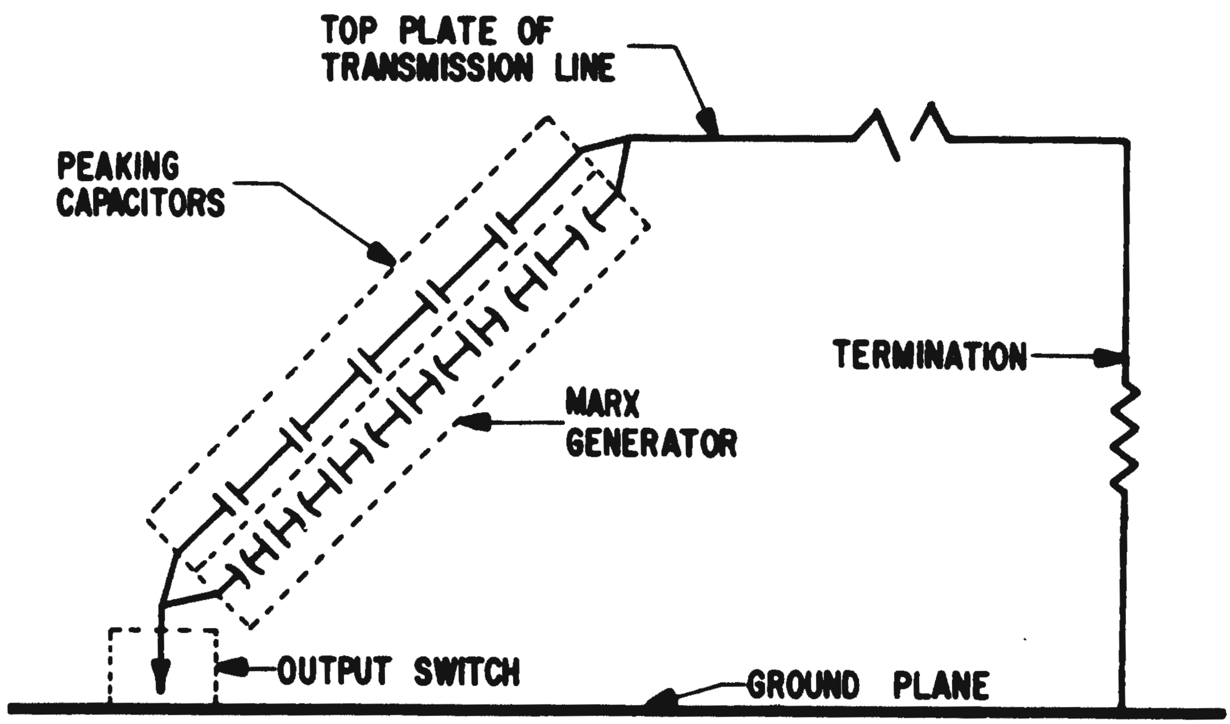


Figure 1 Schematic of Distributed Peaking Generator Configured to Drive a Parallel Plate Simulator

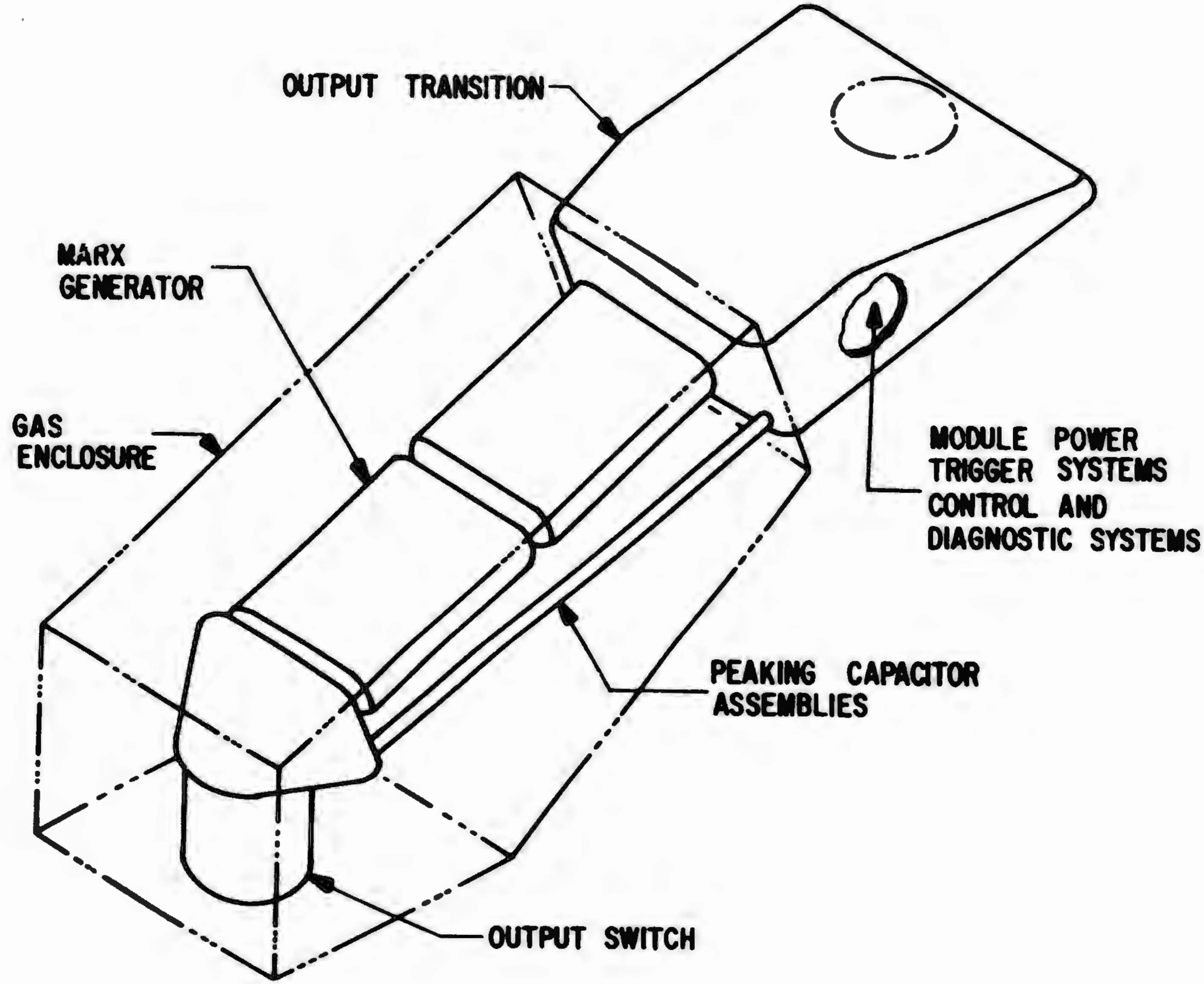


Figure 2. Generalized Physical Layout of a Distributed Peaking Generator for Parallel Plate Simulators

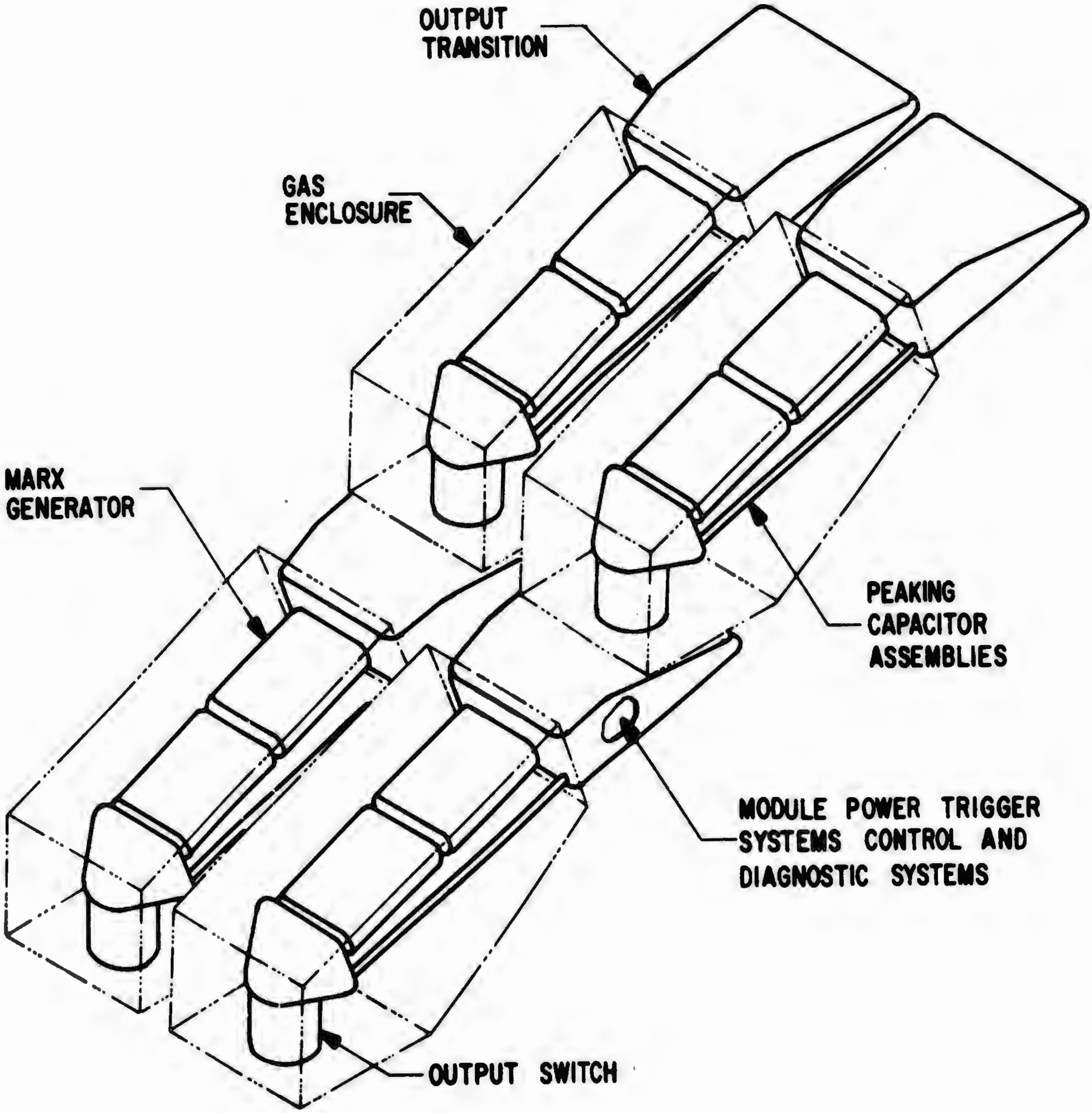


Figure 3. 2 x 2 Array of Distributed Peaking Generator Modules for Driving a Parallel Plate Simulator

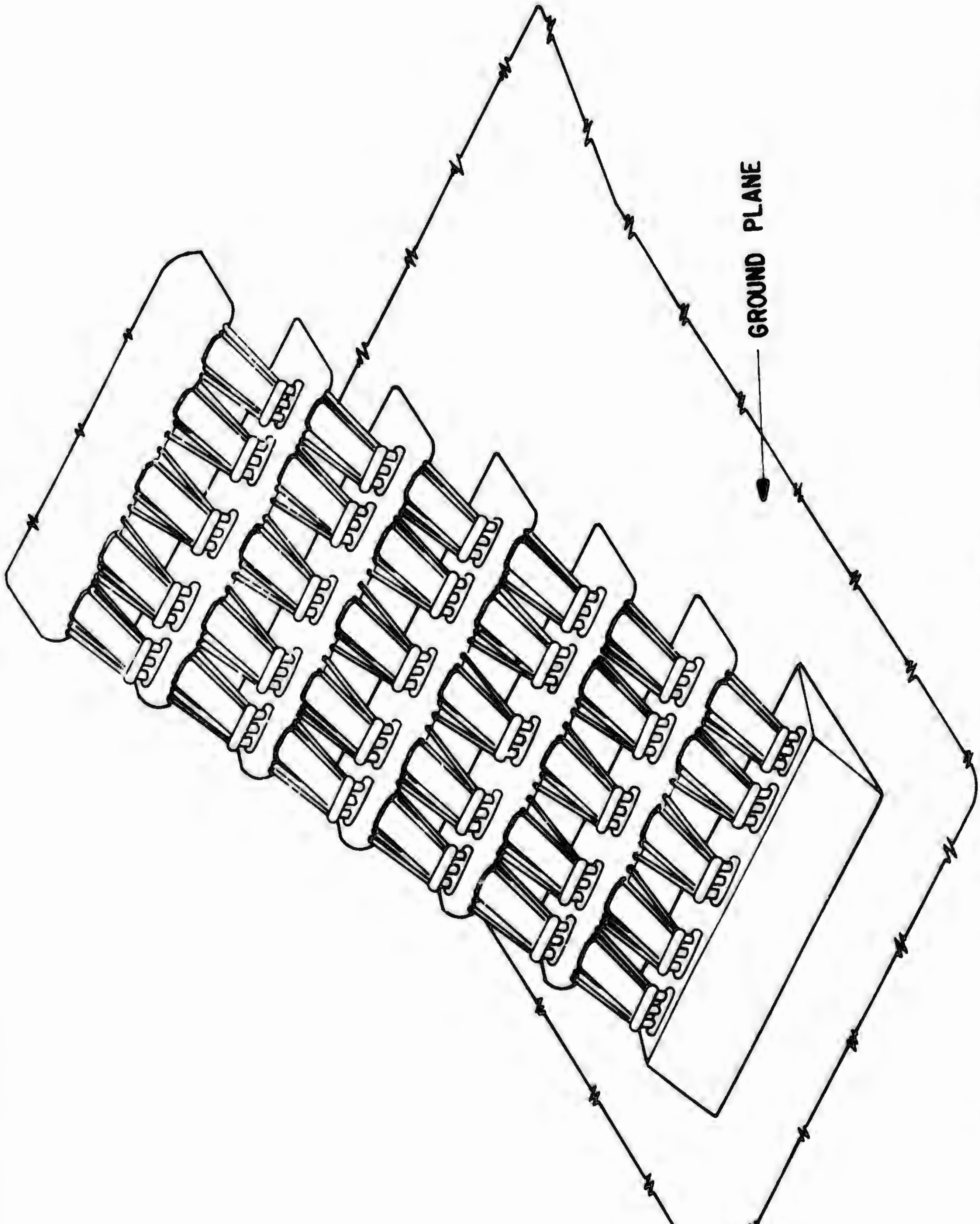


Figure 4. 6 x 5 Array of Distributed Peaking Generator Modules for Driving a Parallel Plate Simulator

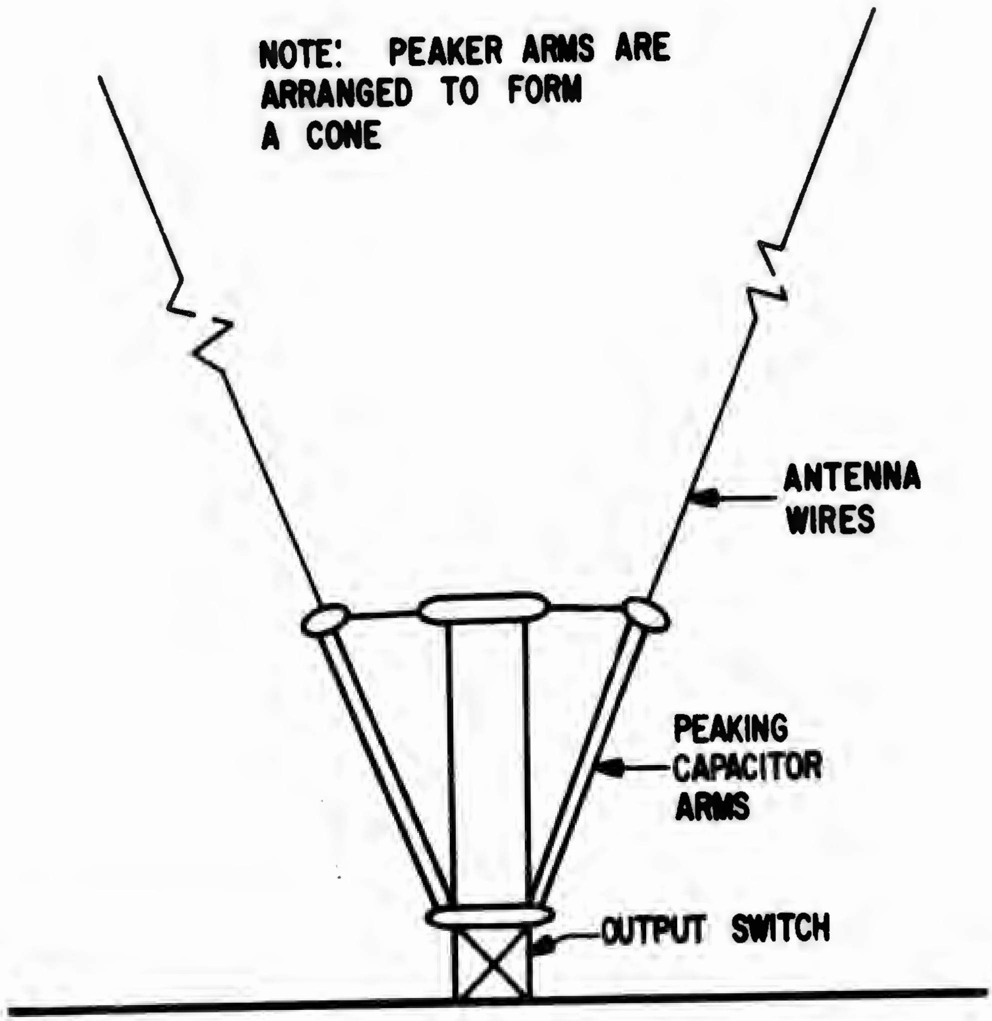


Figure 5. Distributed Peaking Generator Geometry for a Vertical Dipole over a Ground Plane

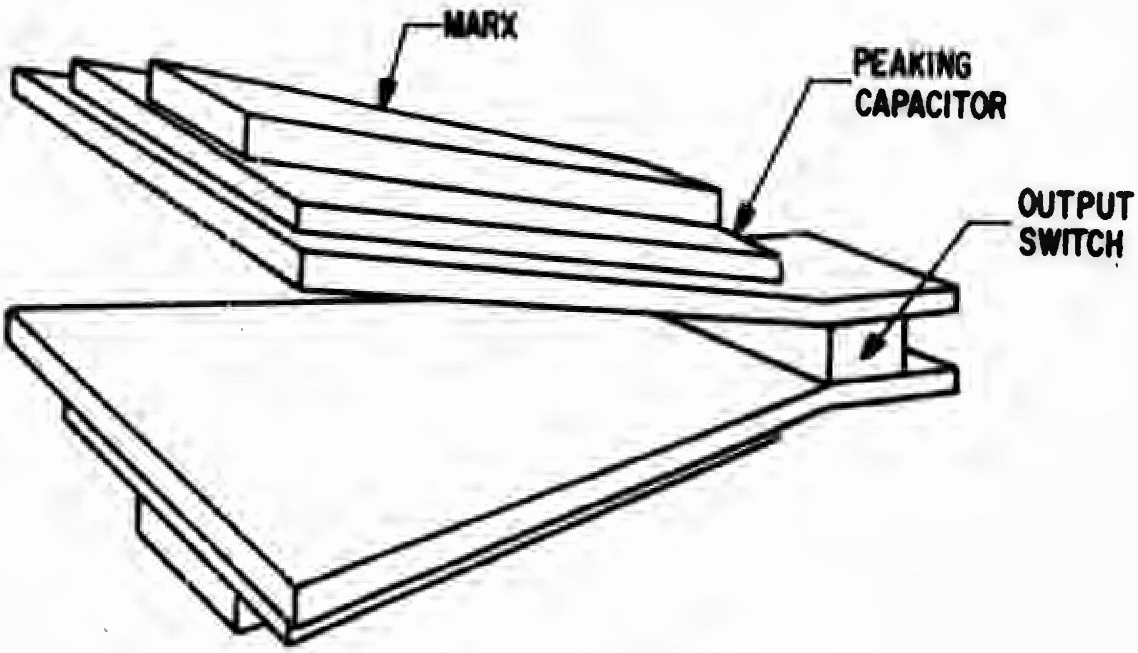


Figure 6. Dihedral Horn Pulse Generator

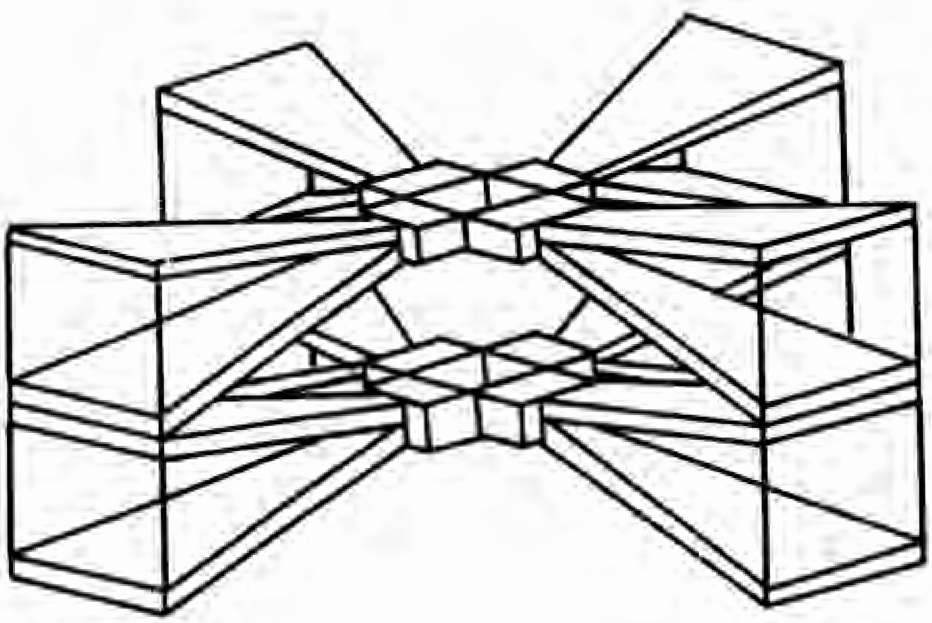


Figure 7. 2 x 4 Array of Distributed Peaking Generators for Radiating Simulators

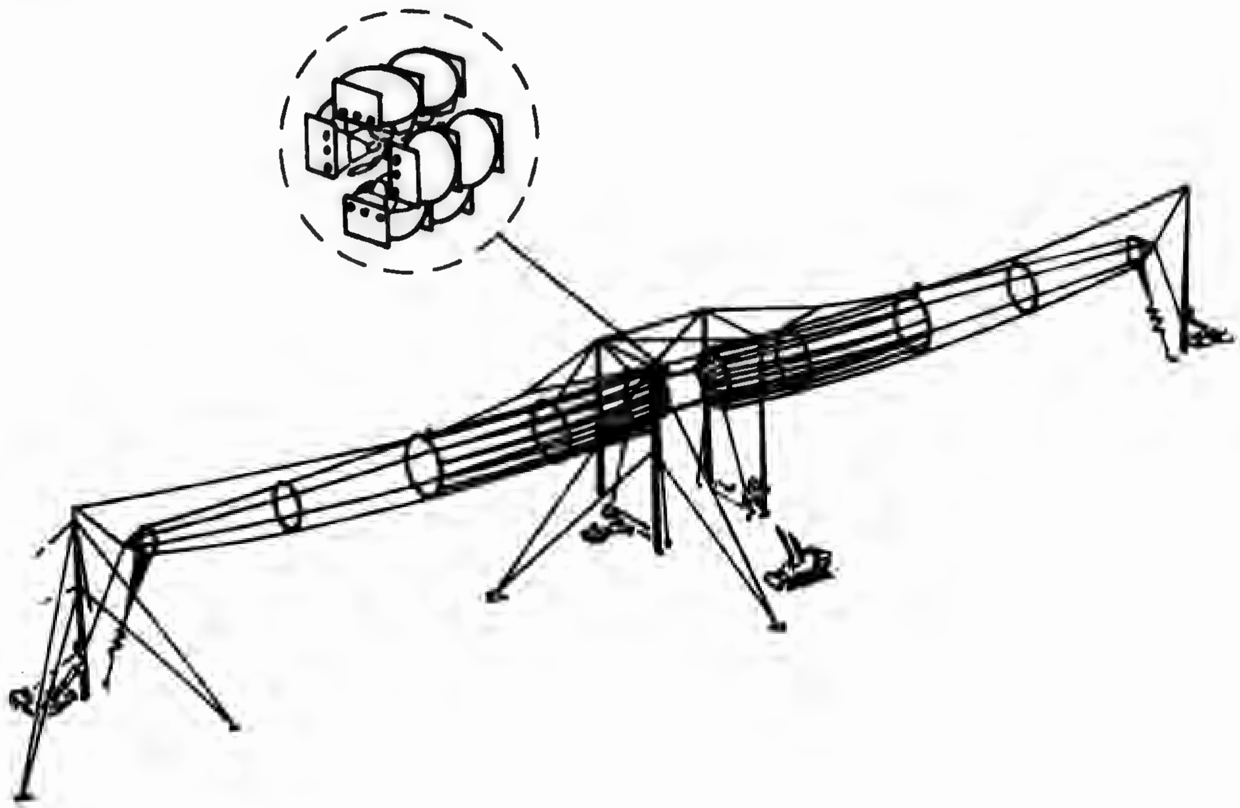


Figure 8. 2 x 4 Array Driving a Horizontal Dipole
(More correctly termed a hybrid)

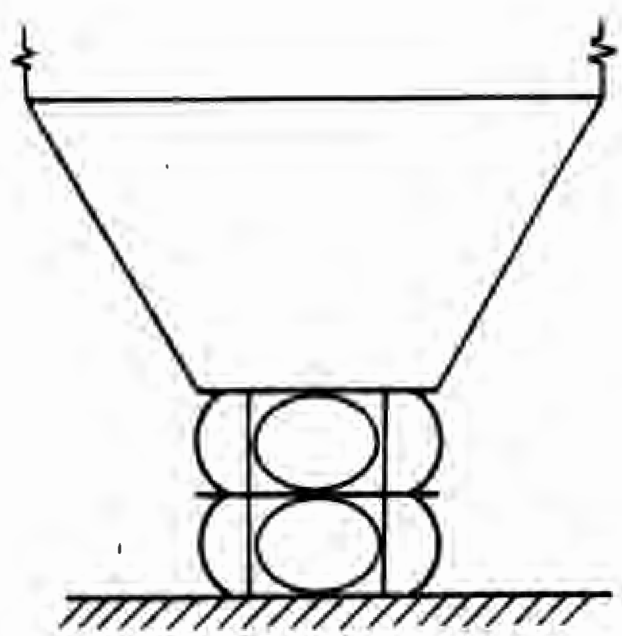


Figure 9. 2 x 4 Array Driving a Vertical Dipole

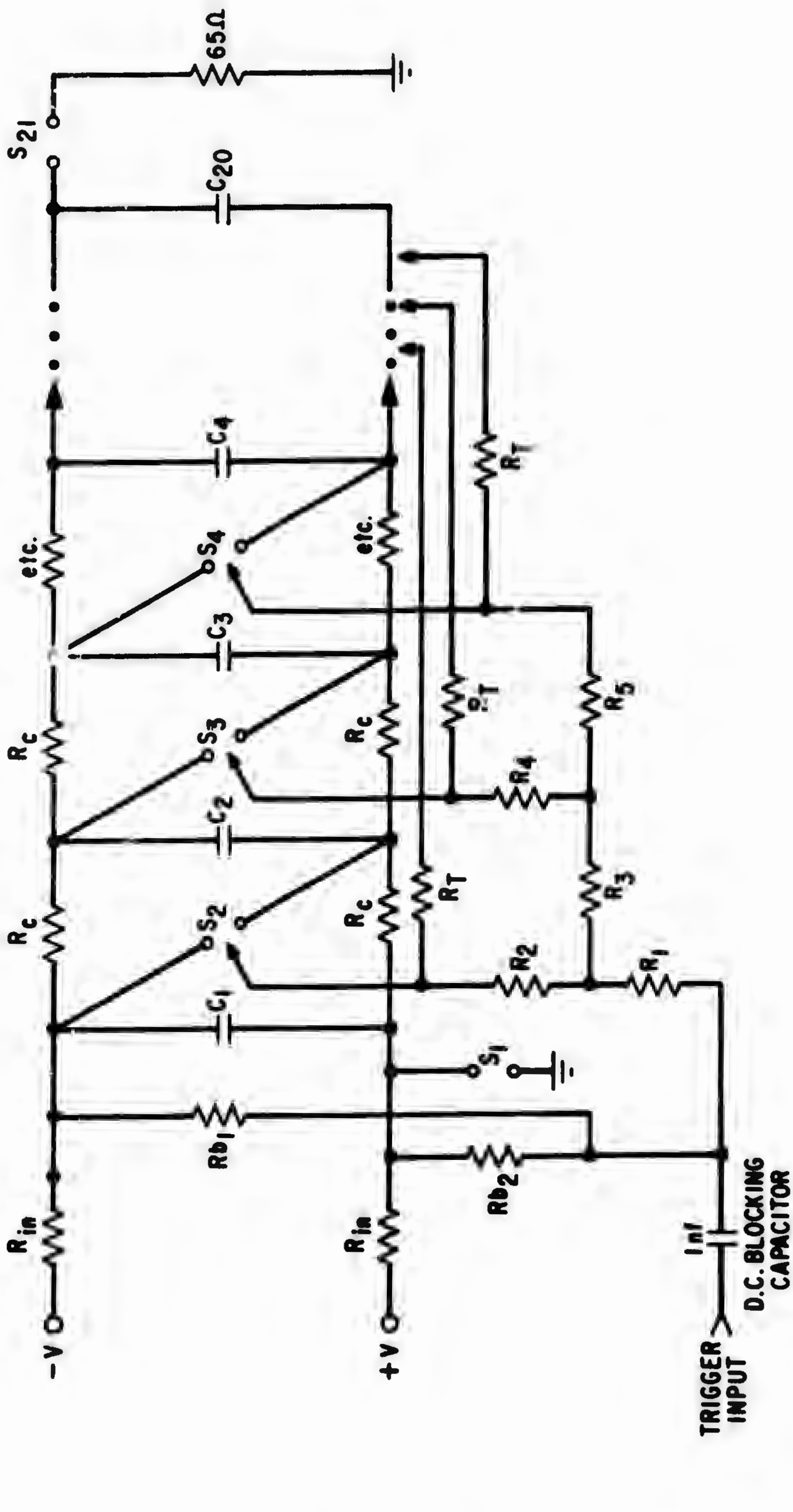


Figure 10. Schematic of the 2 mV Molecule Marx Generator

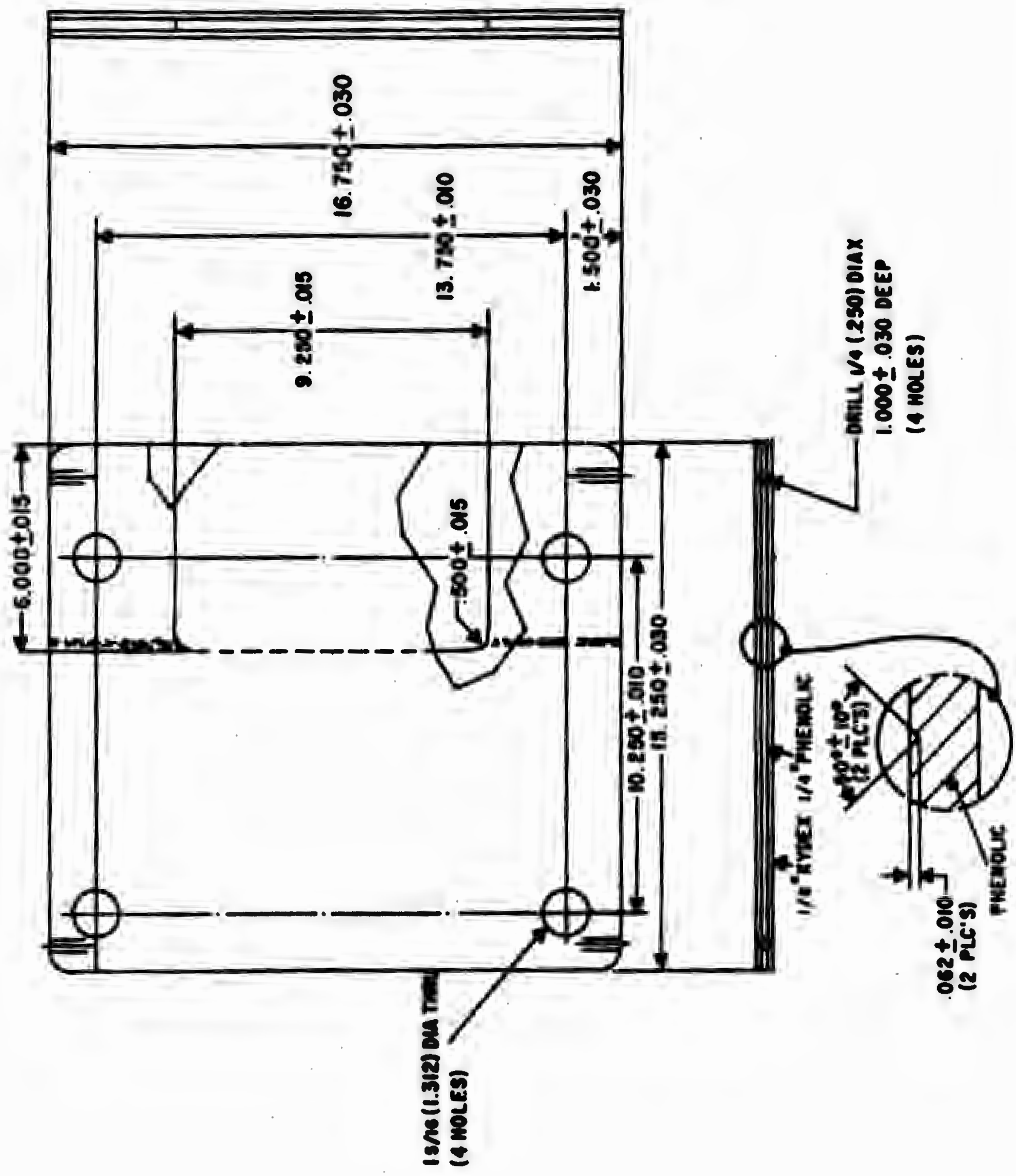


Figure 11. Marx Stage Tray

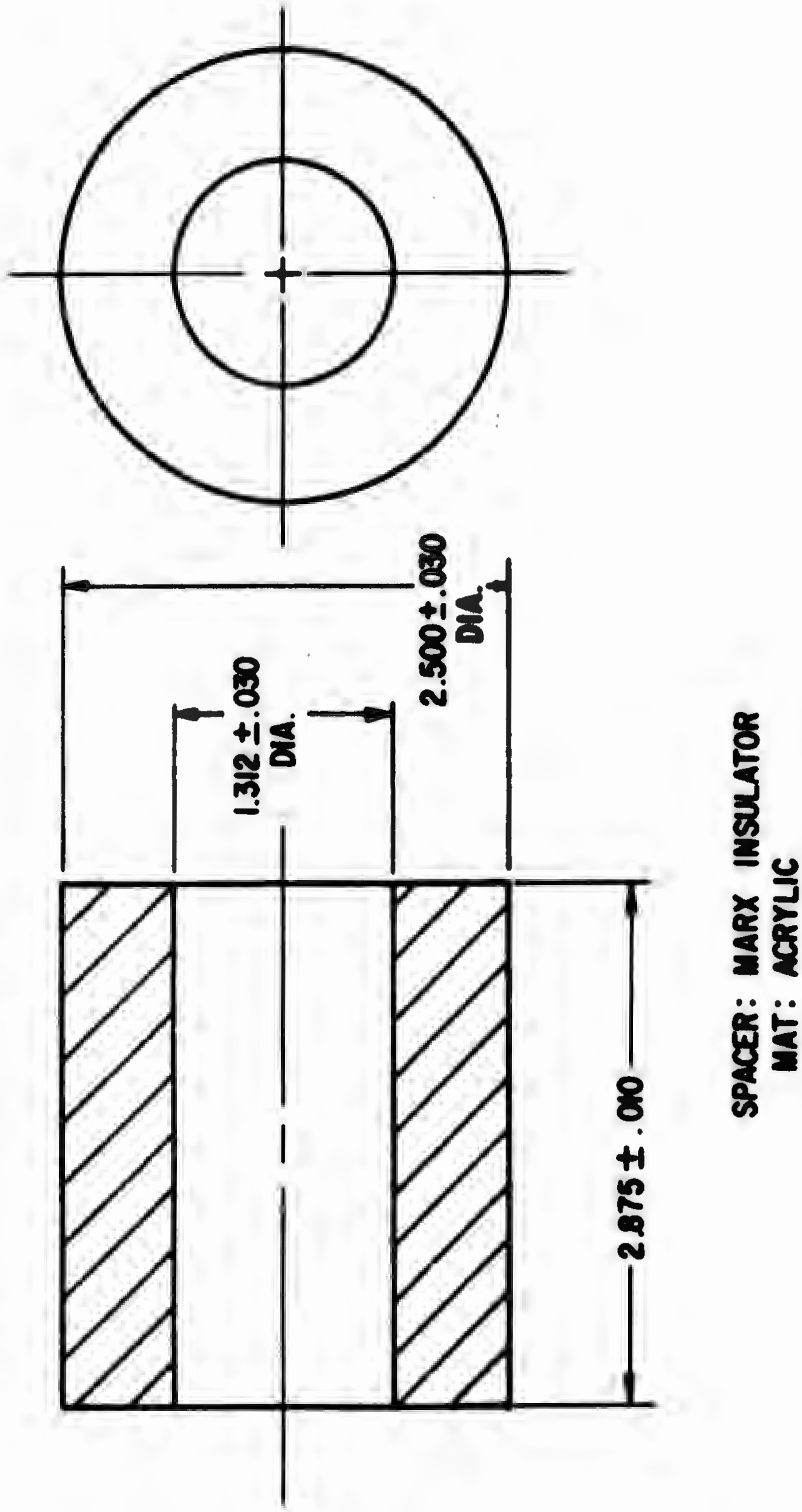


Figure 12. Stage Spacer

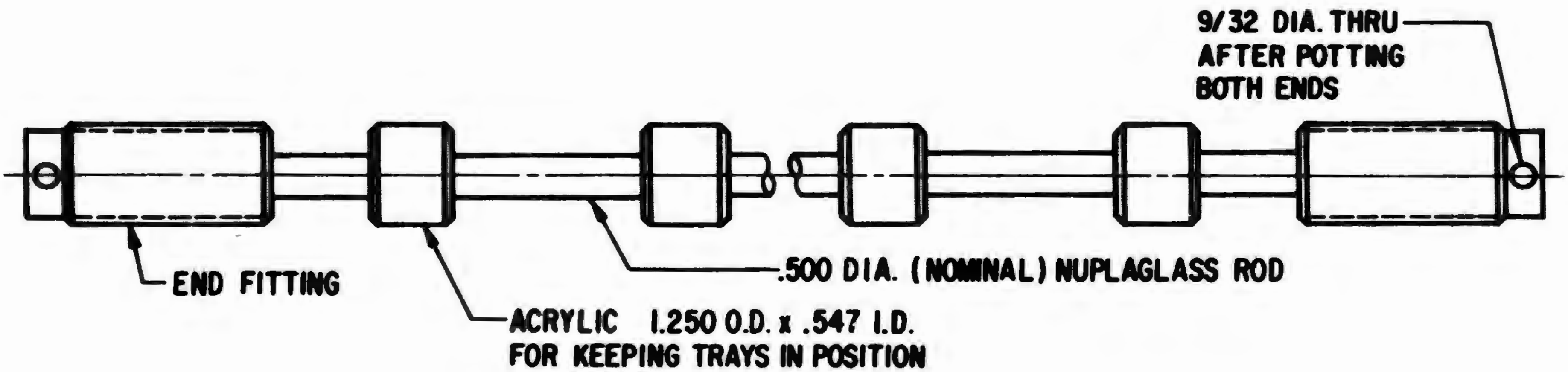


Figure 13. Assembled Tie Rod

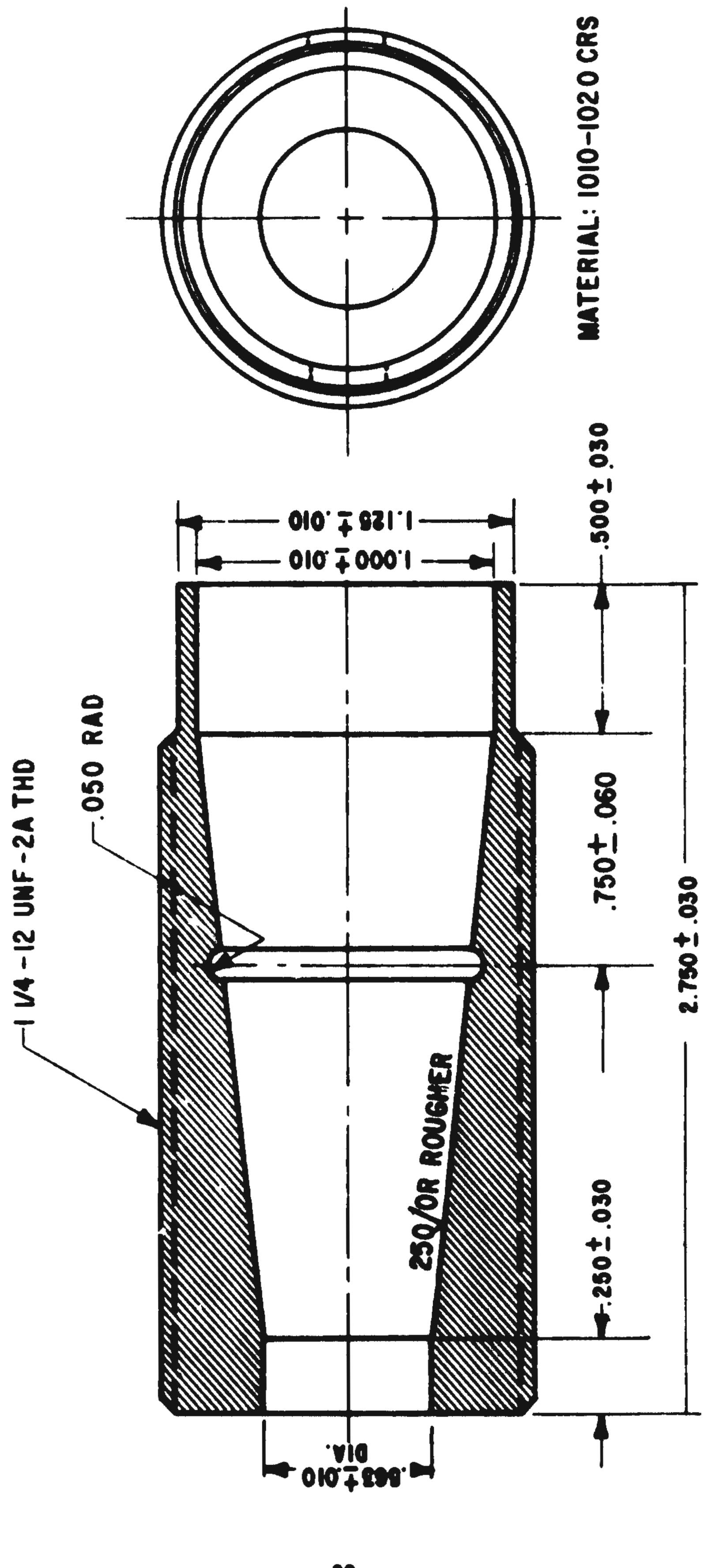


Figure 14. End Fitting Detail

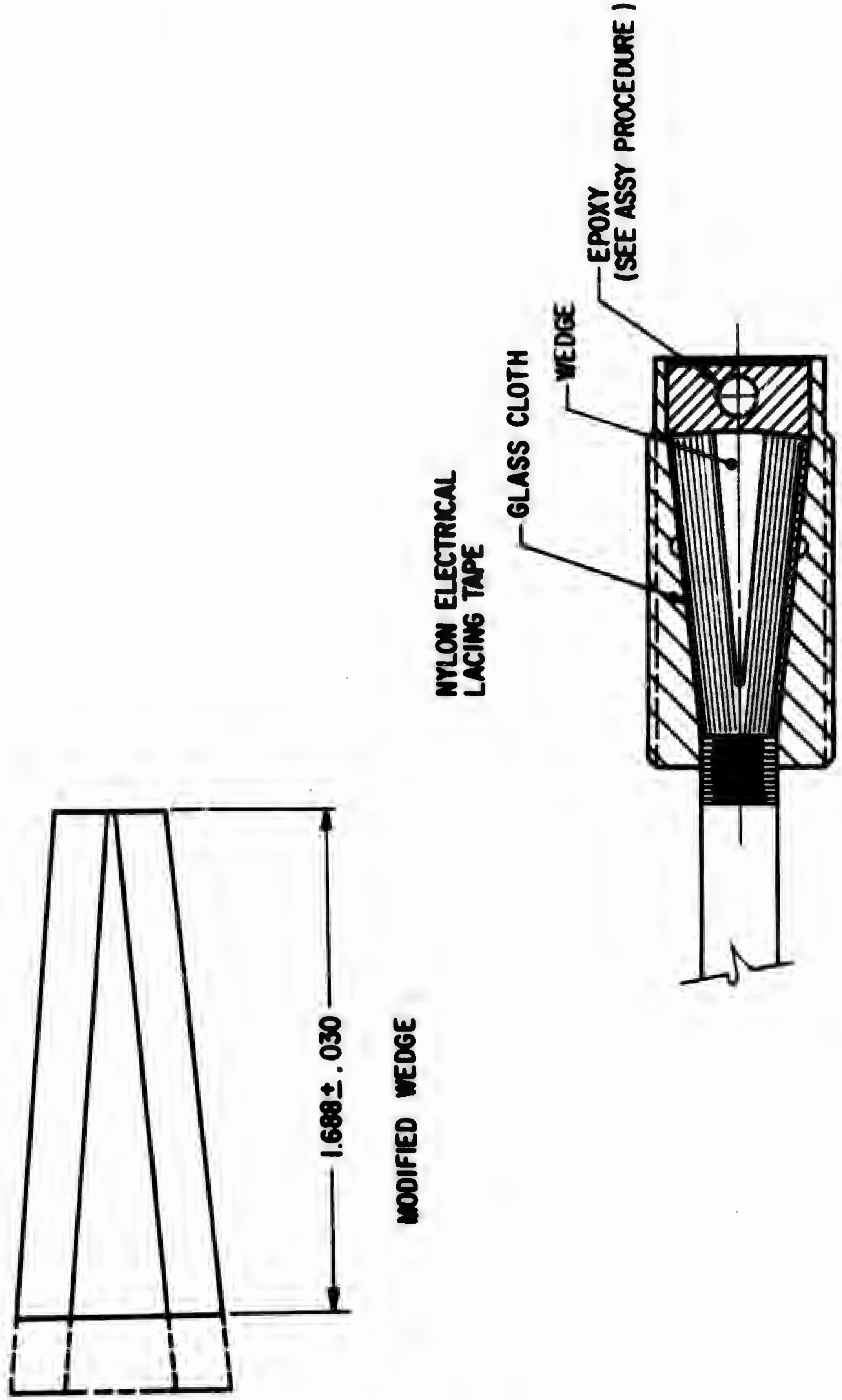


Figure 15. Cross Section of Assembled End Fitting

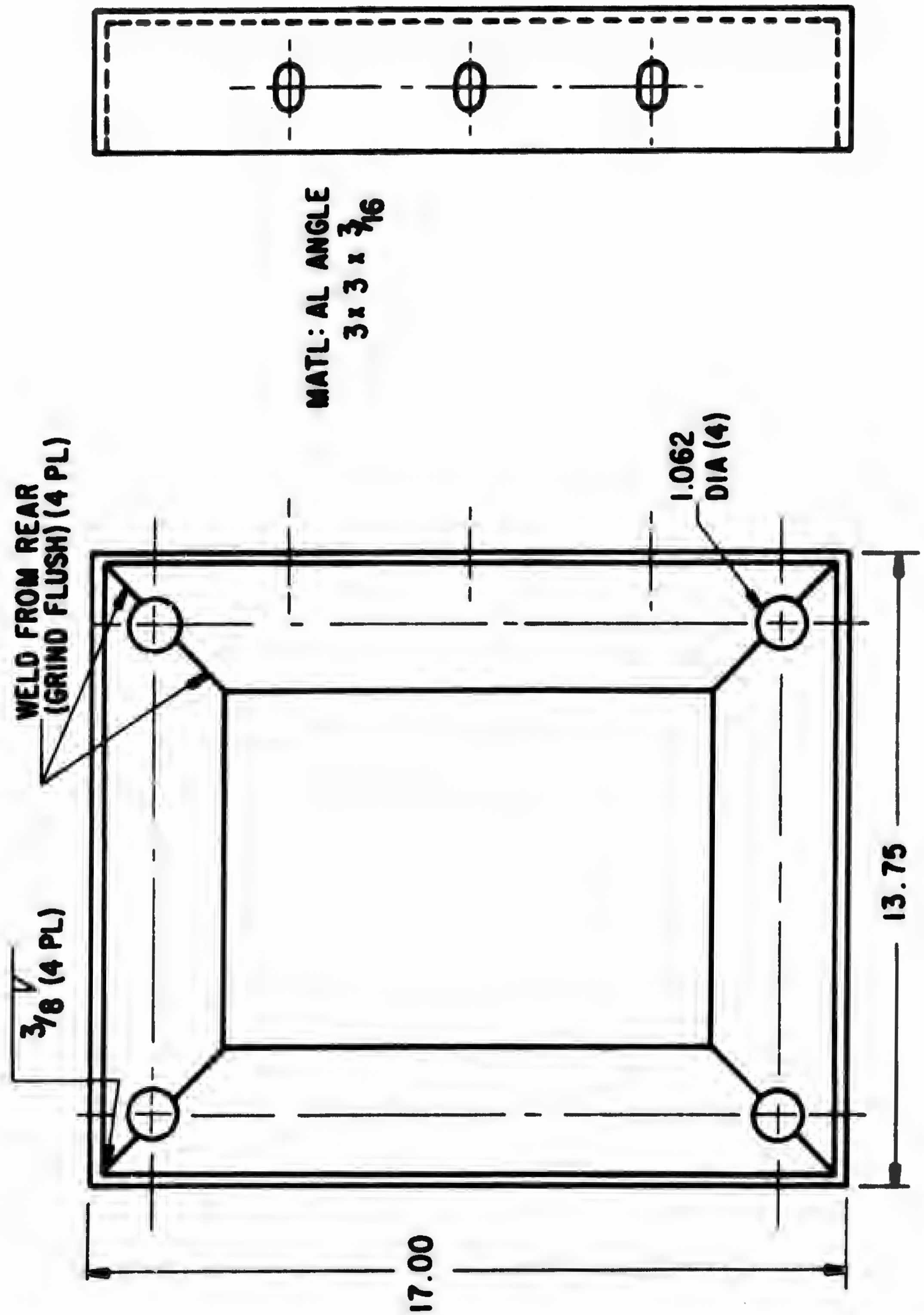


Figure 16. End Plates

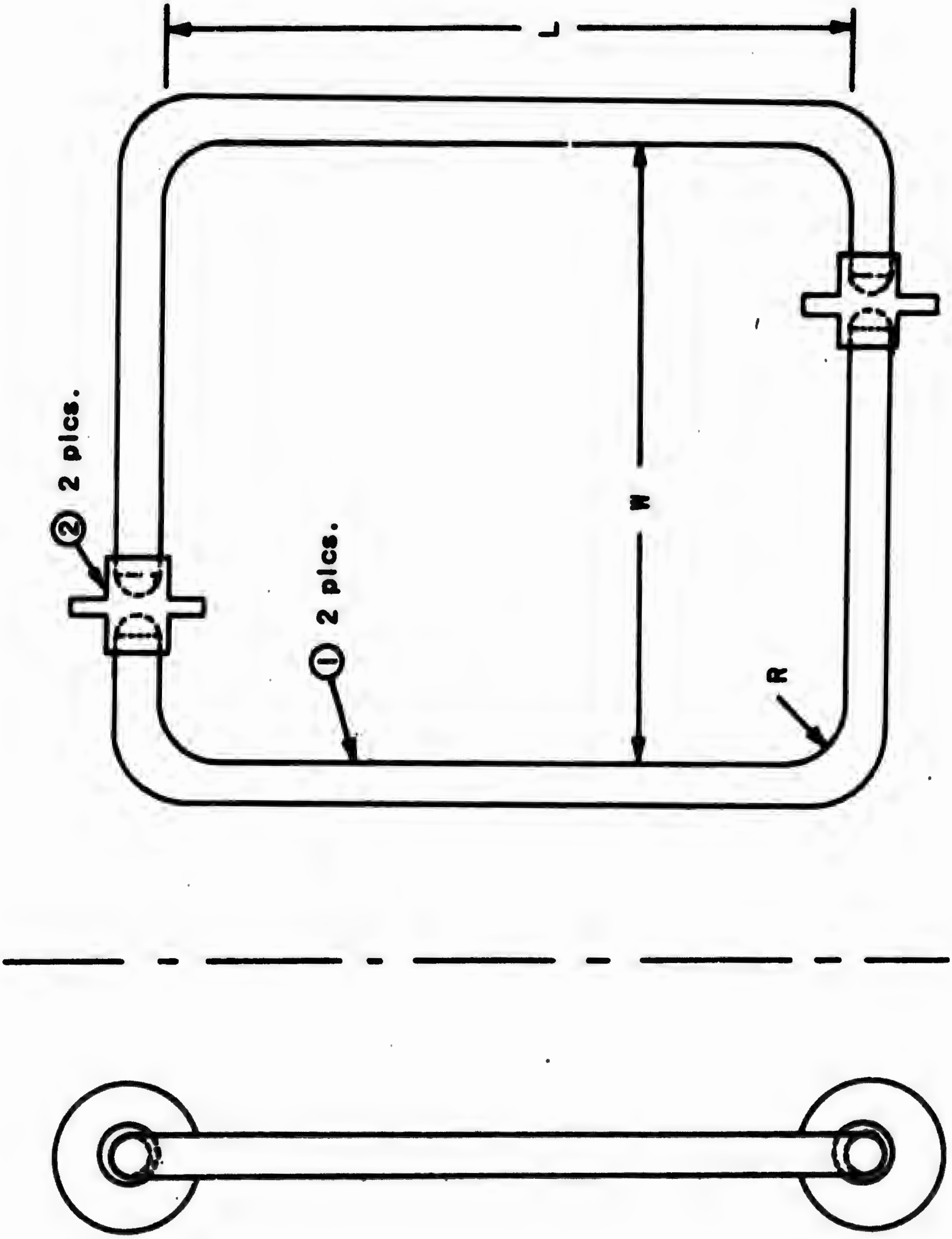
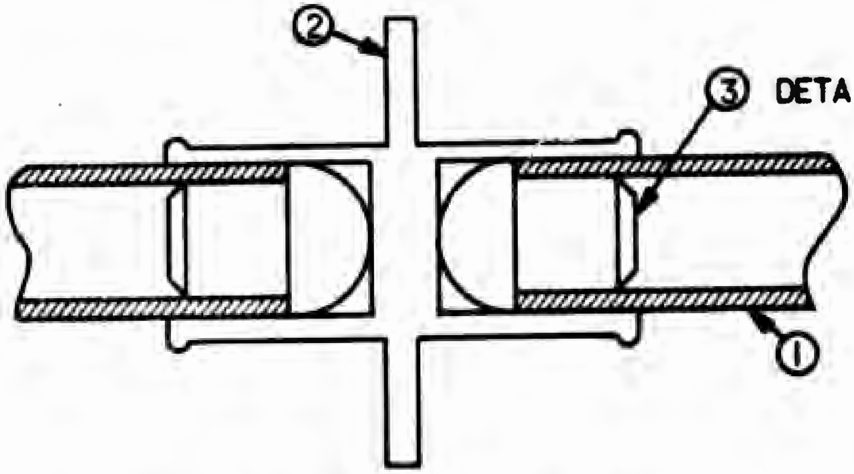
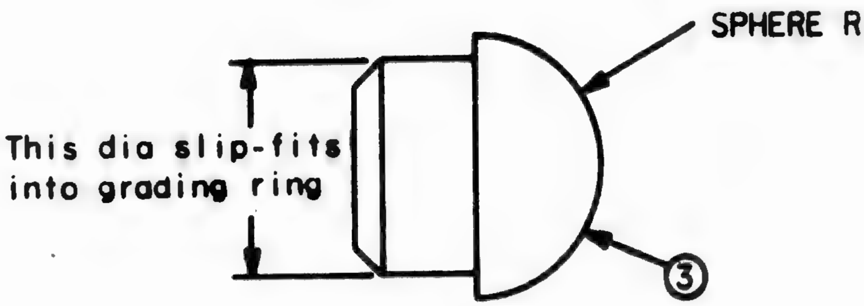


Figure 17. Grading Ring Profile



DETAIL A - SPACER (X-SECTION)



DETAIL B - PLUG

Figure 18. Detail of Plug and Spacer

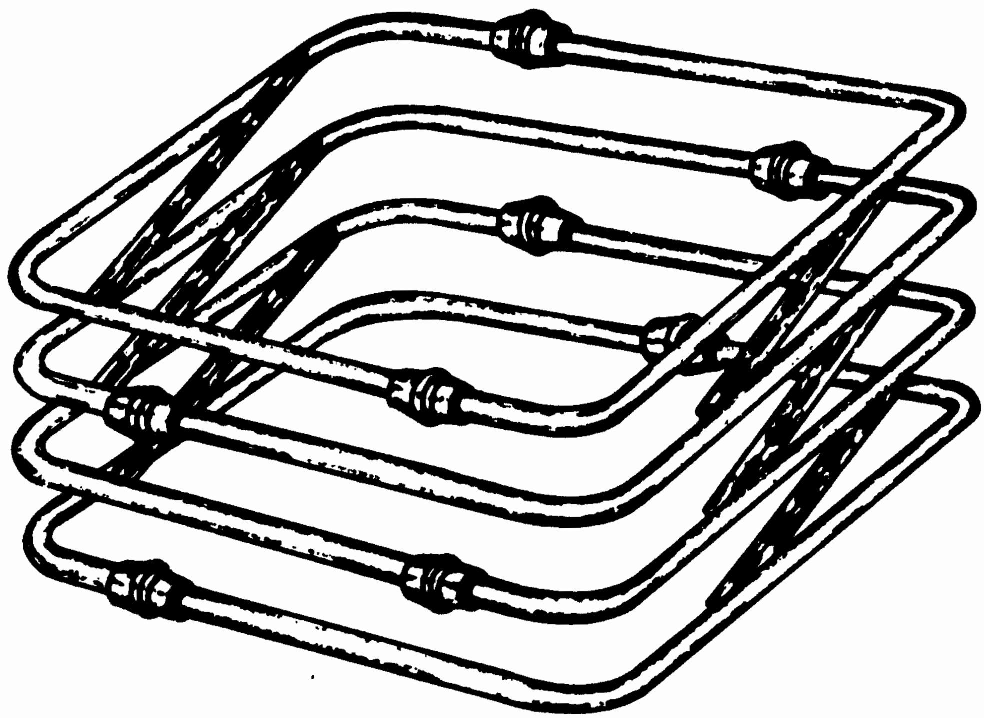
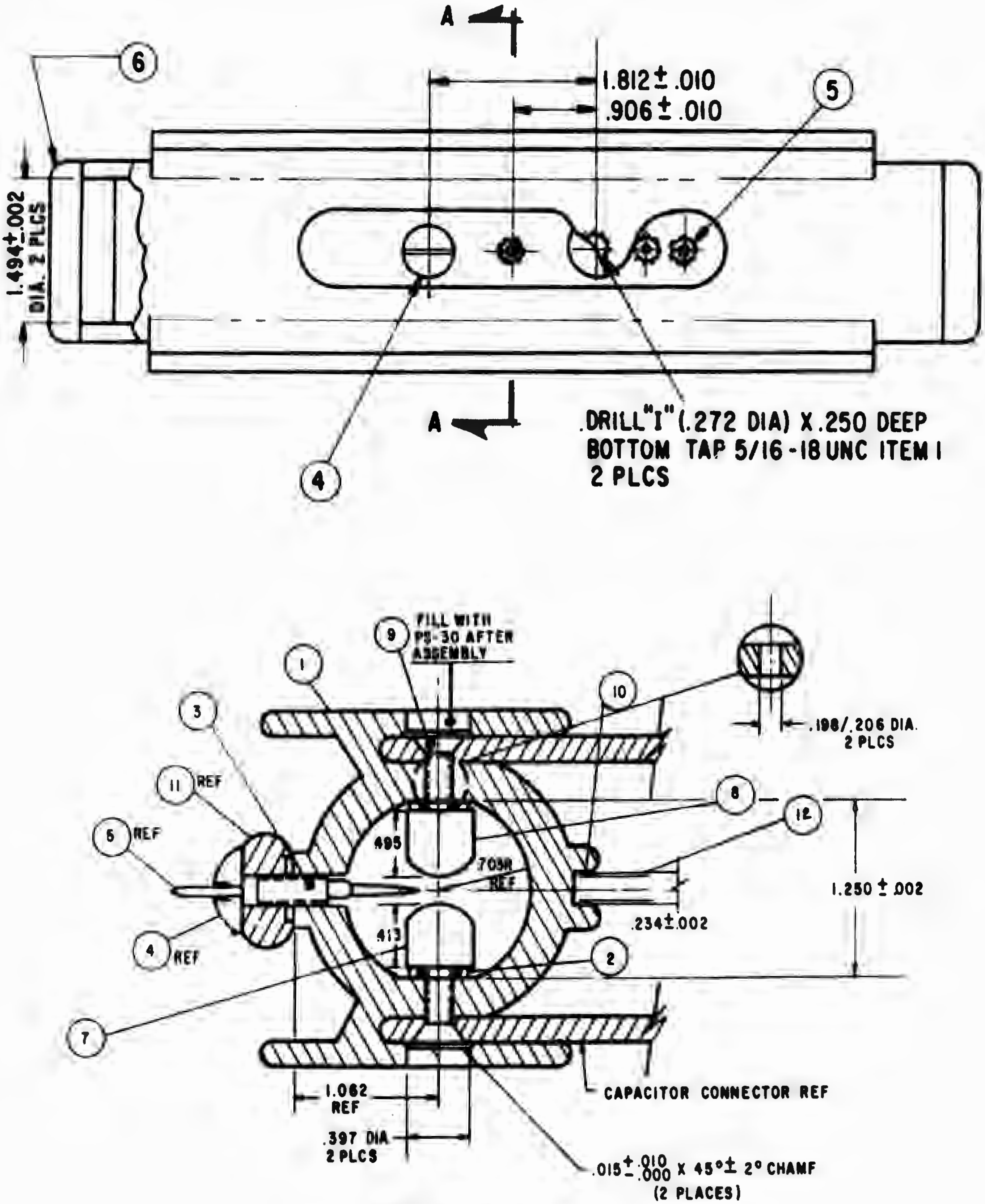


Figure 19. Charging Resistors Mounted on Split Grading Rings



SECTION A - A

Figure 20. Marx Switch Drawing

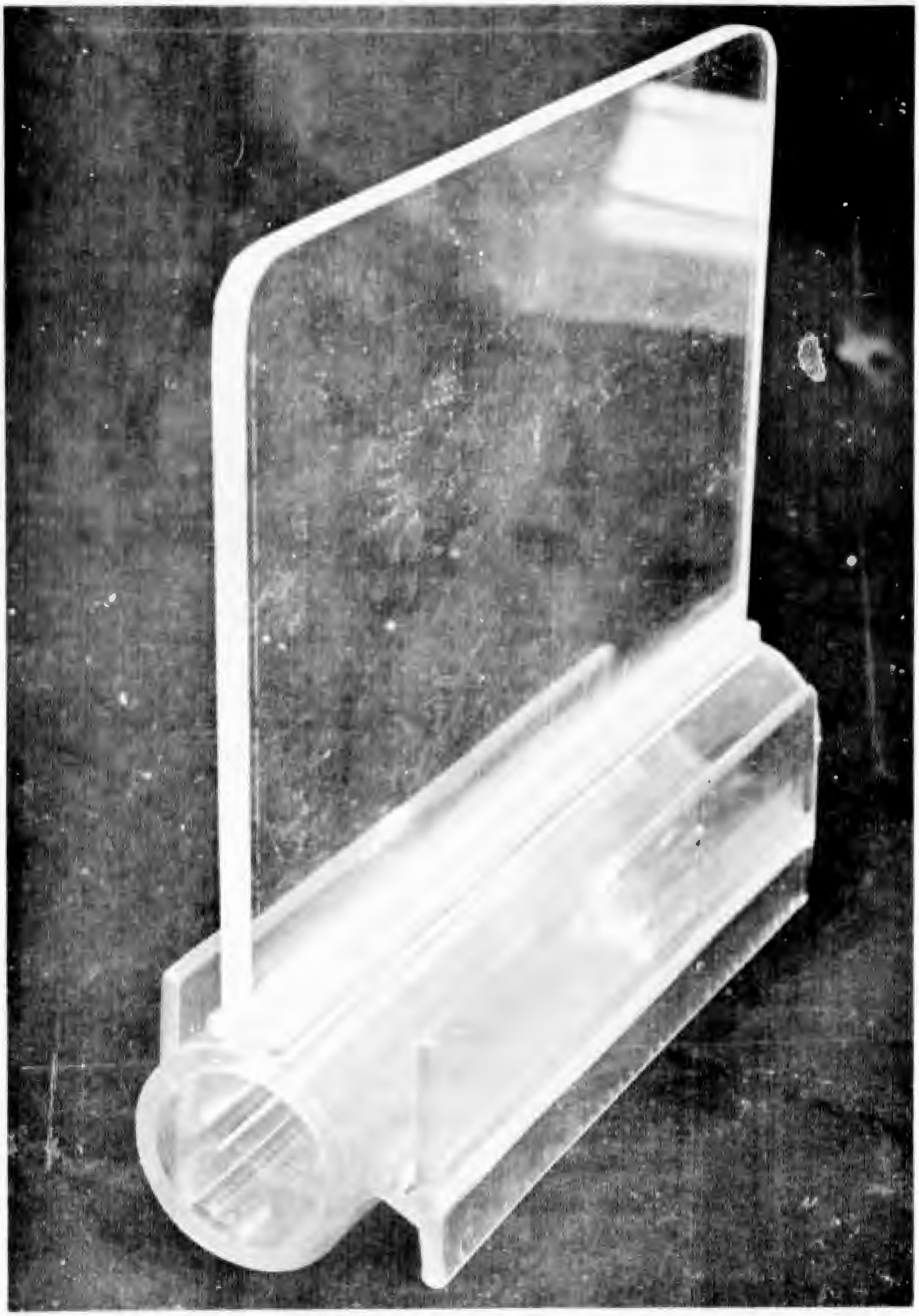
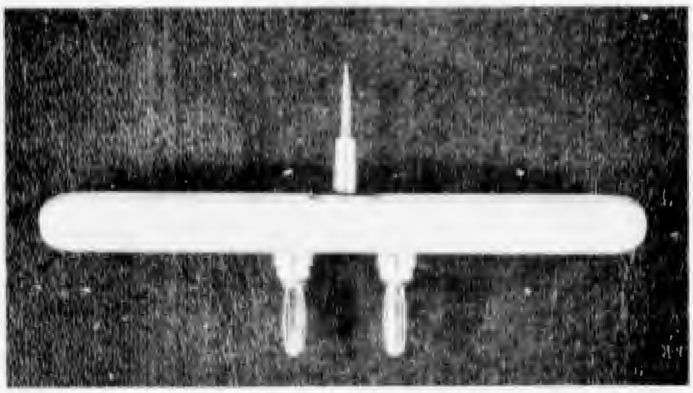
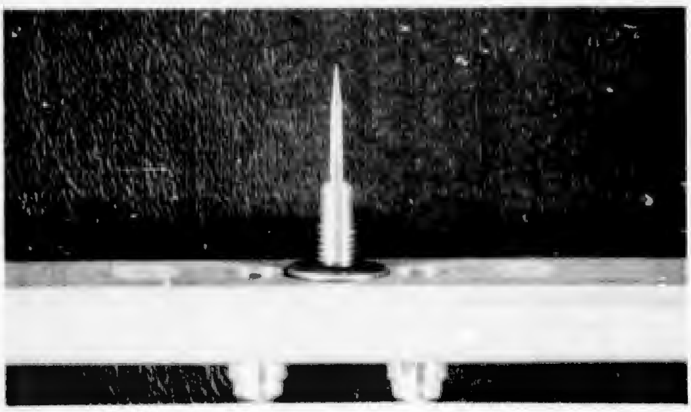


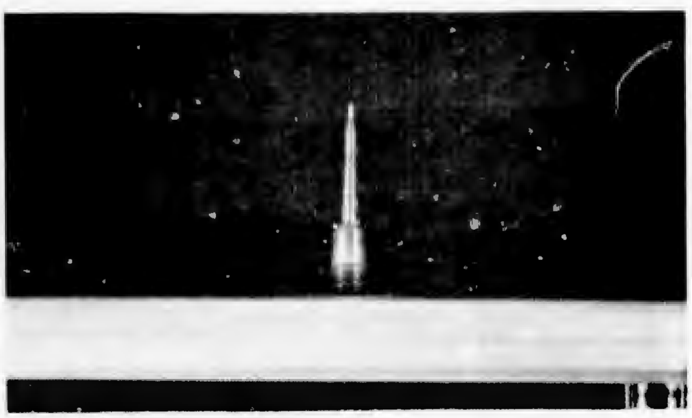
Figure 21. Marx Switch Housing with Tongue Glued in Place



(a) Buss Bar with Trigger Pin and Banana Plug Resistor Connections



(b) Closeup of New Trigger Electrode



(c) Erosion of Trigger Electrode after 500 Shots

Figure 22. Buss Bar

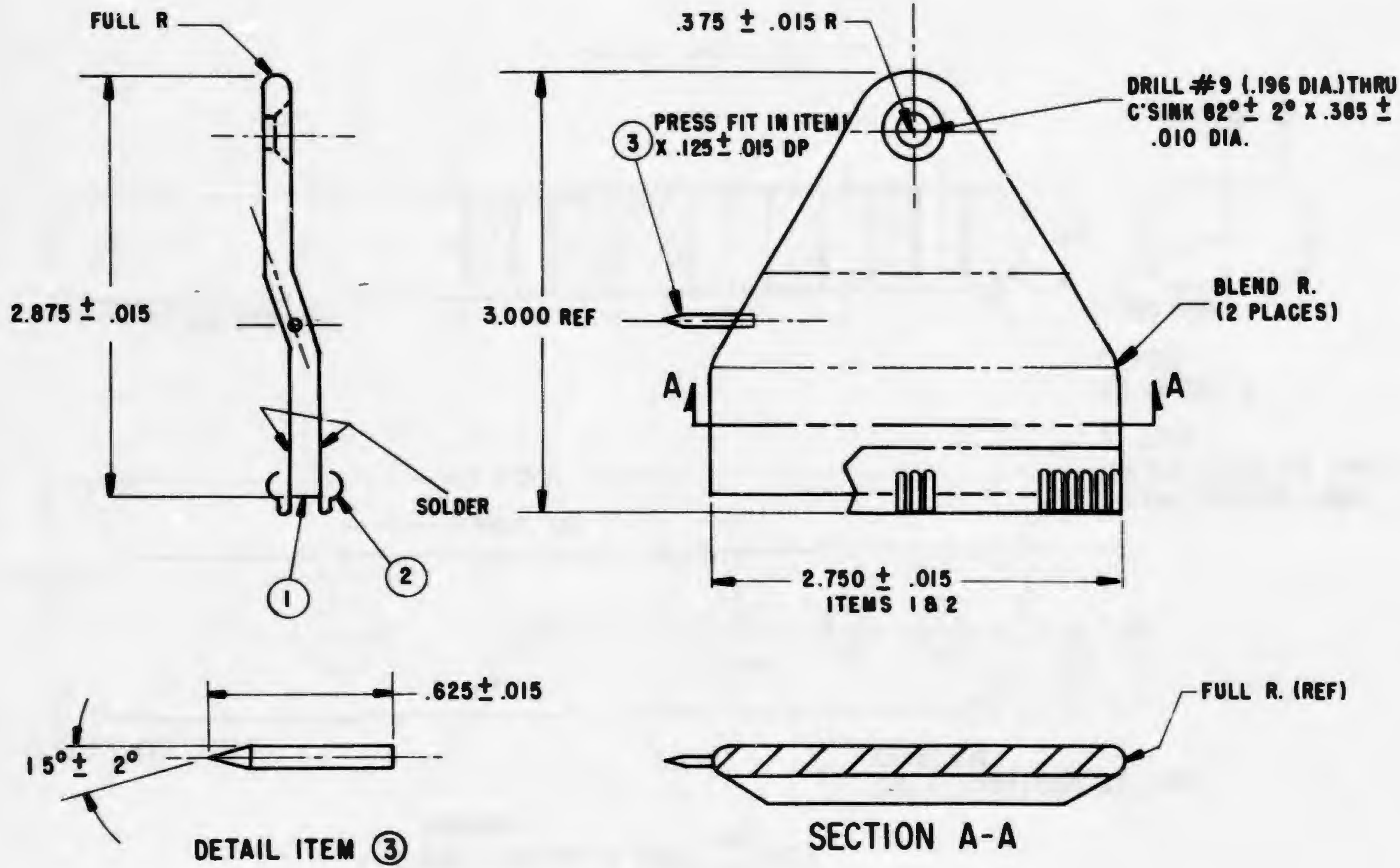


Figure 23. Capacitor Connector

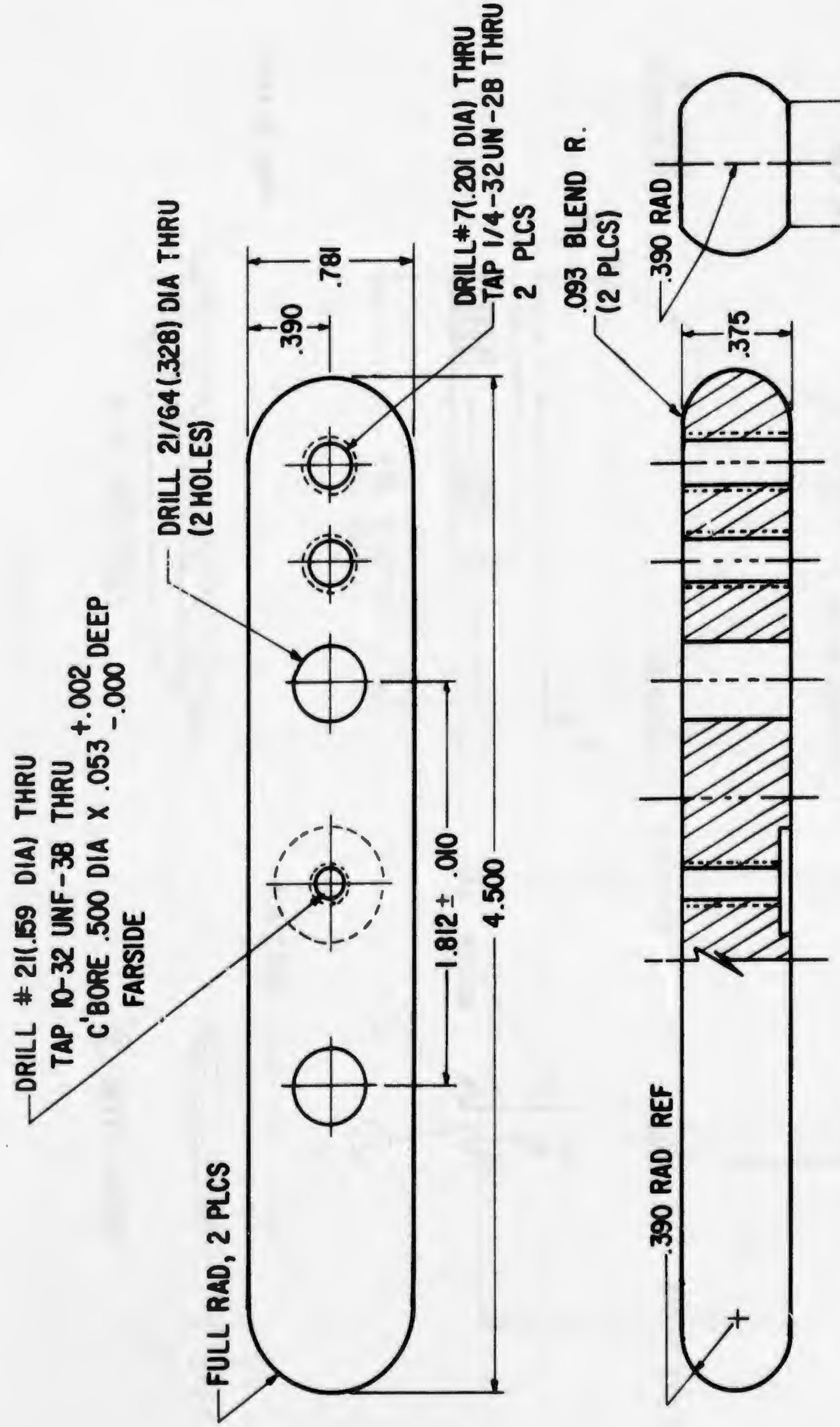


Figure 24. Switch Buss Bar

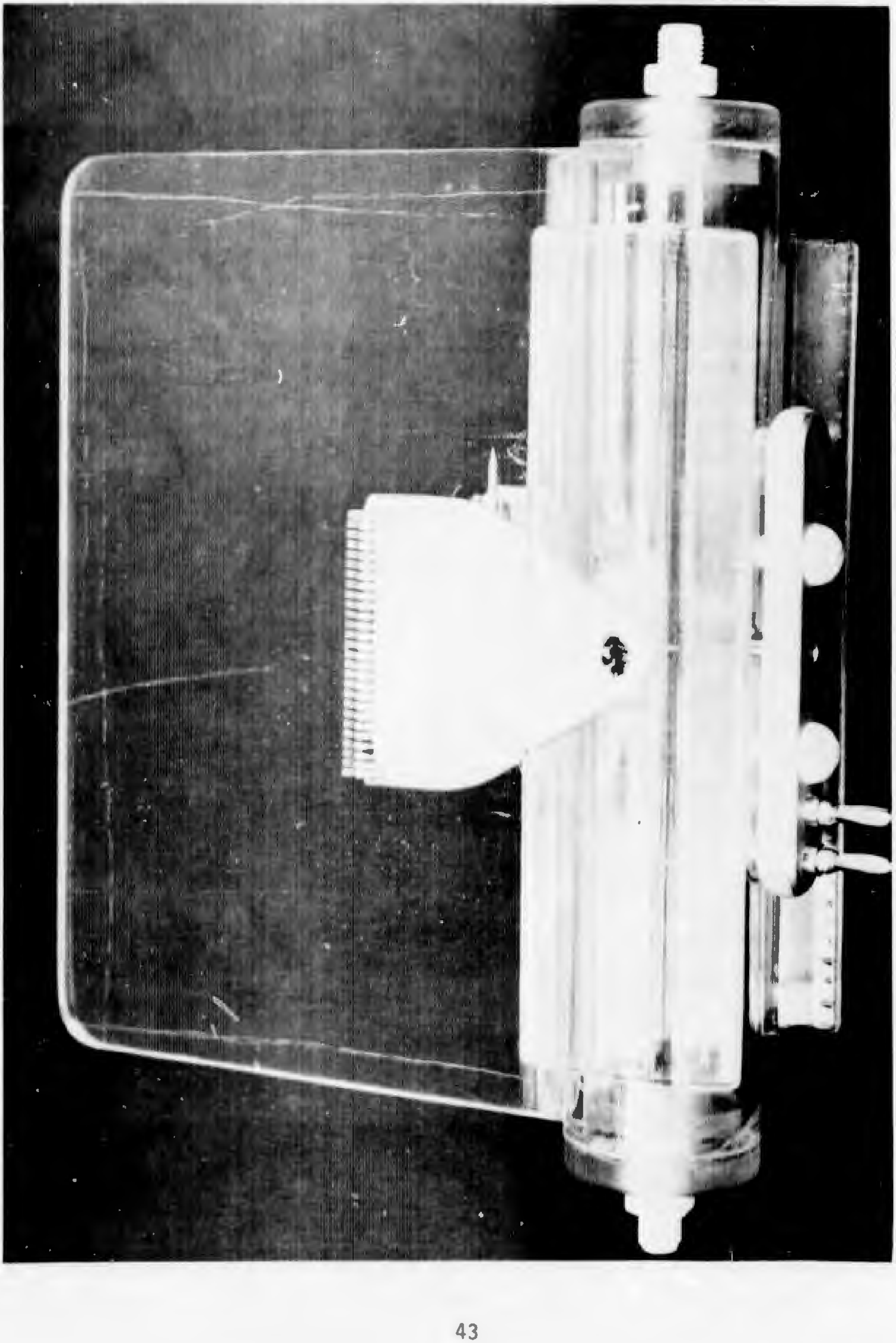


Figure 25. Assembled Marx Switch

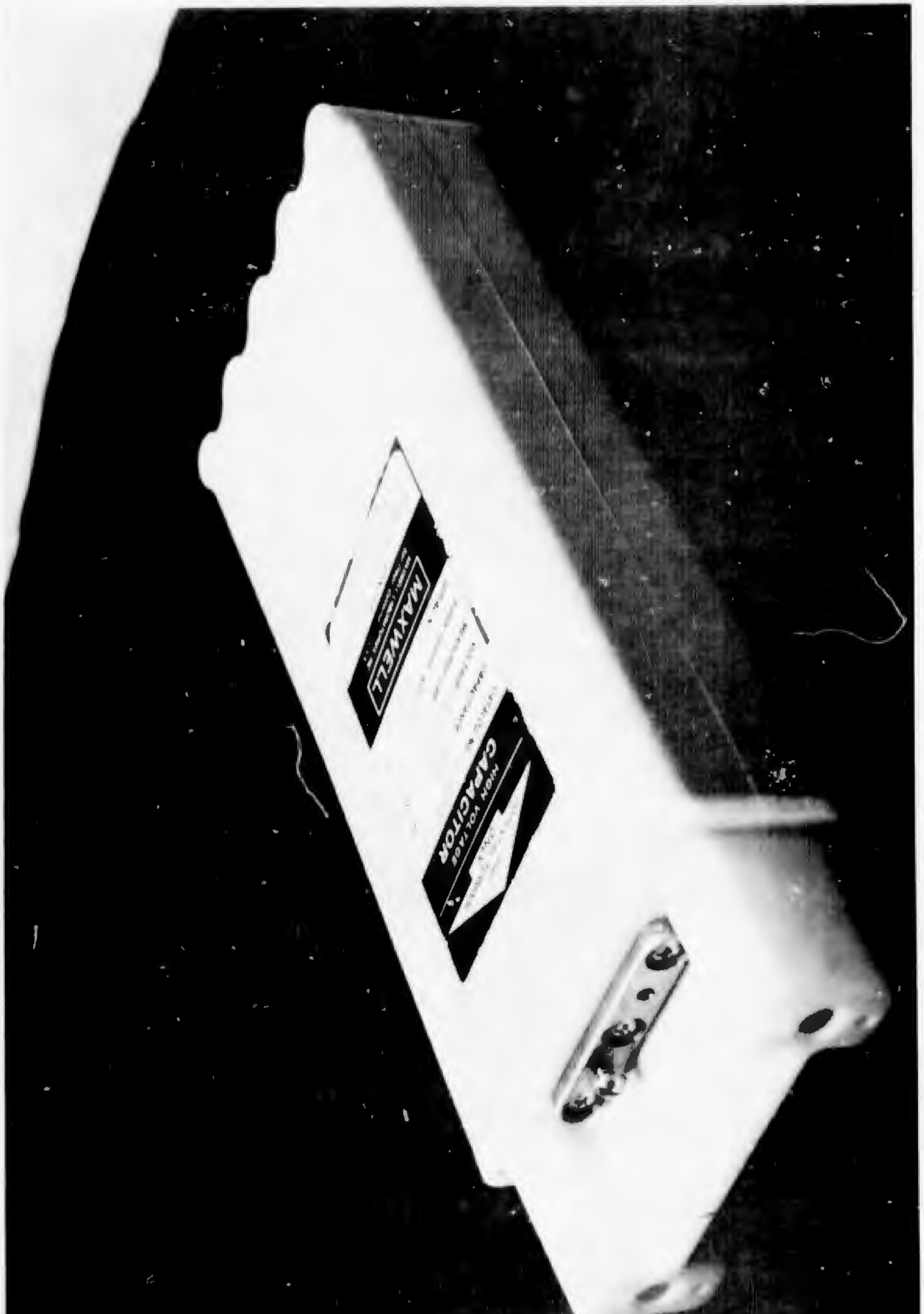


Figure 26. 100 kV Stage Capacitor

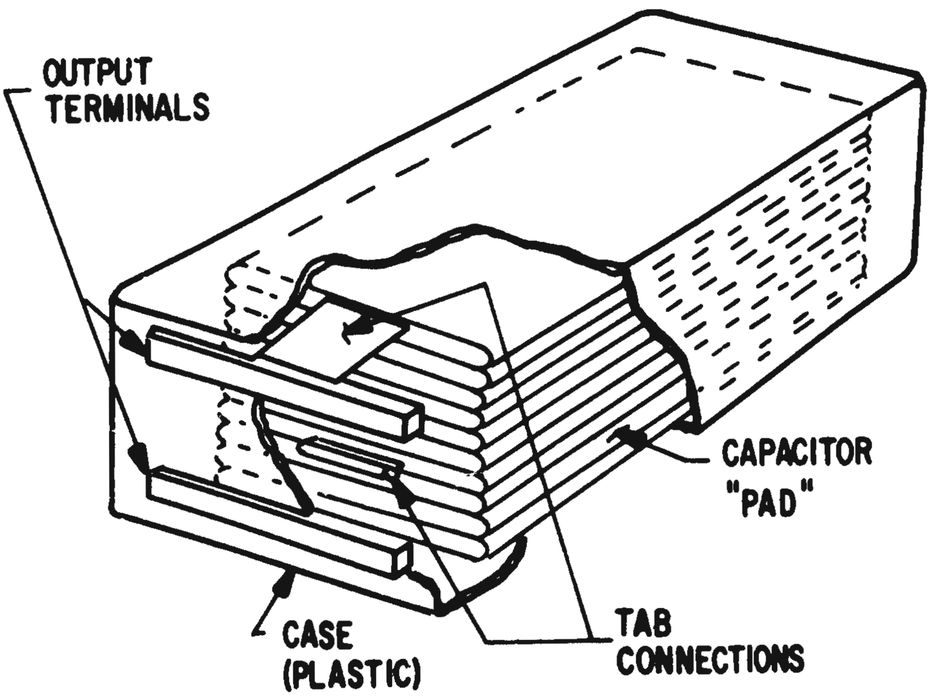


Figure 27. Construction of Generalized Plastic Cased Capacitor

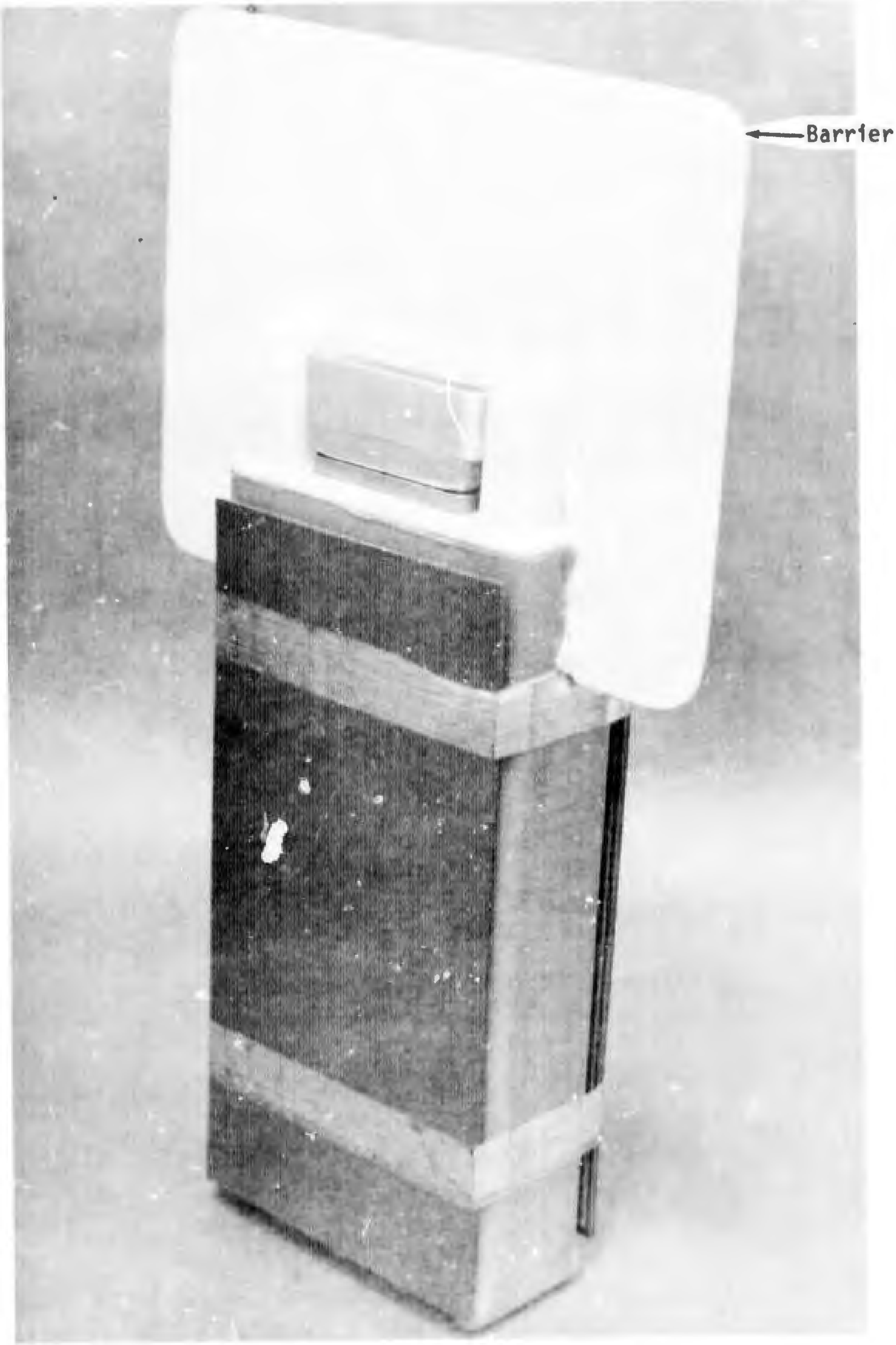


Figure 28. Head Barrier Added to Stage Capacitor

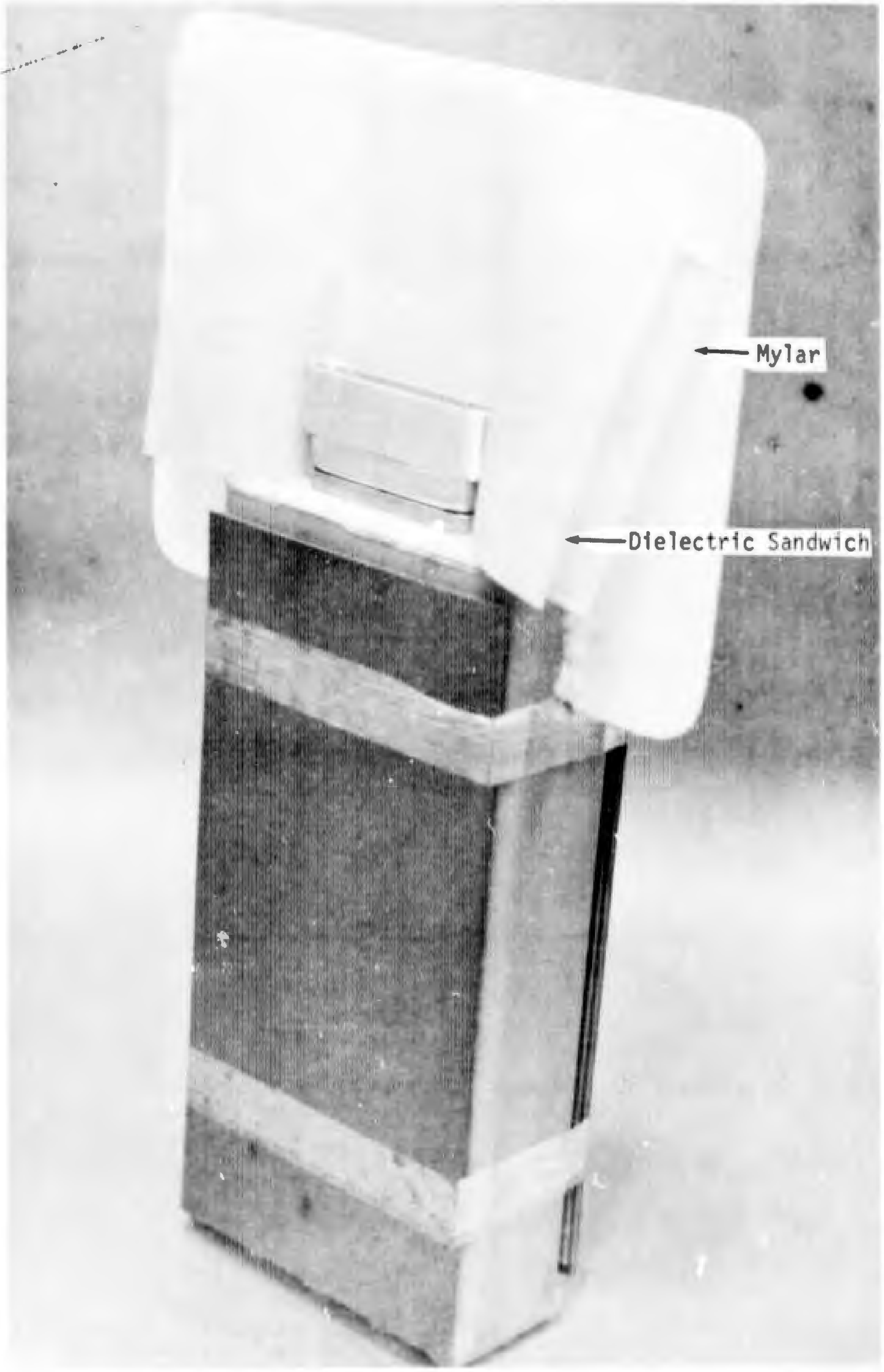


Figure 29. Sheet Dielectric Added to Capacitor Head

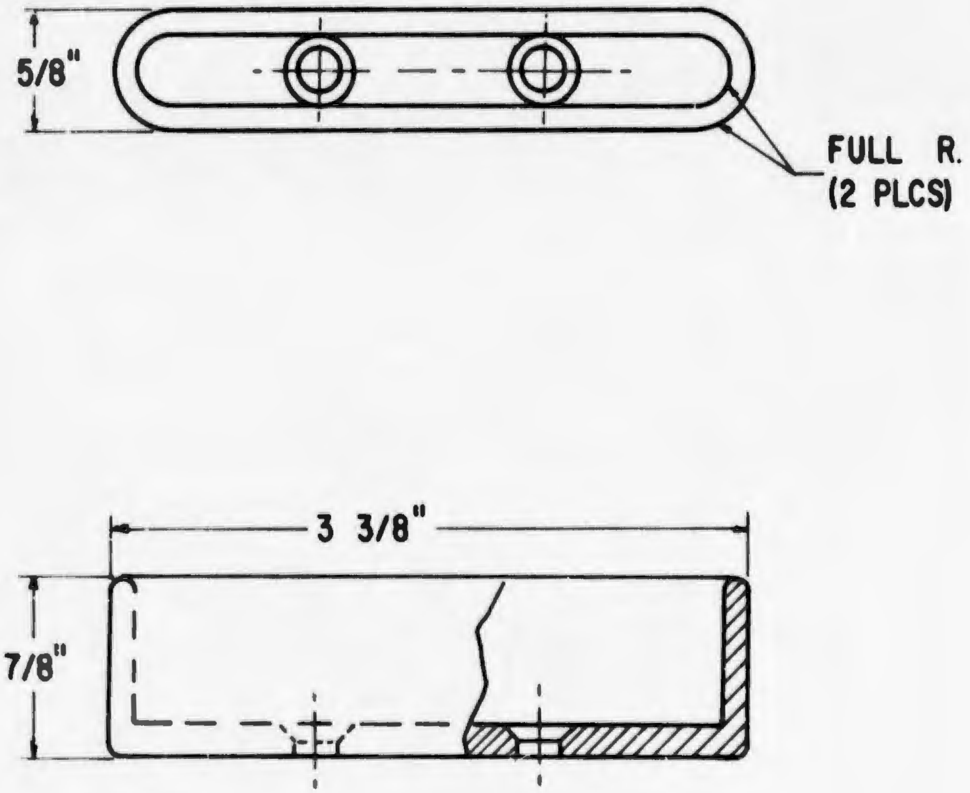


Figure 30. Capacitor Connector Receptacle

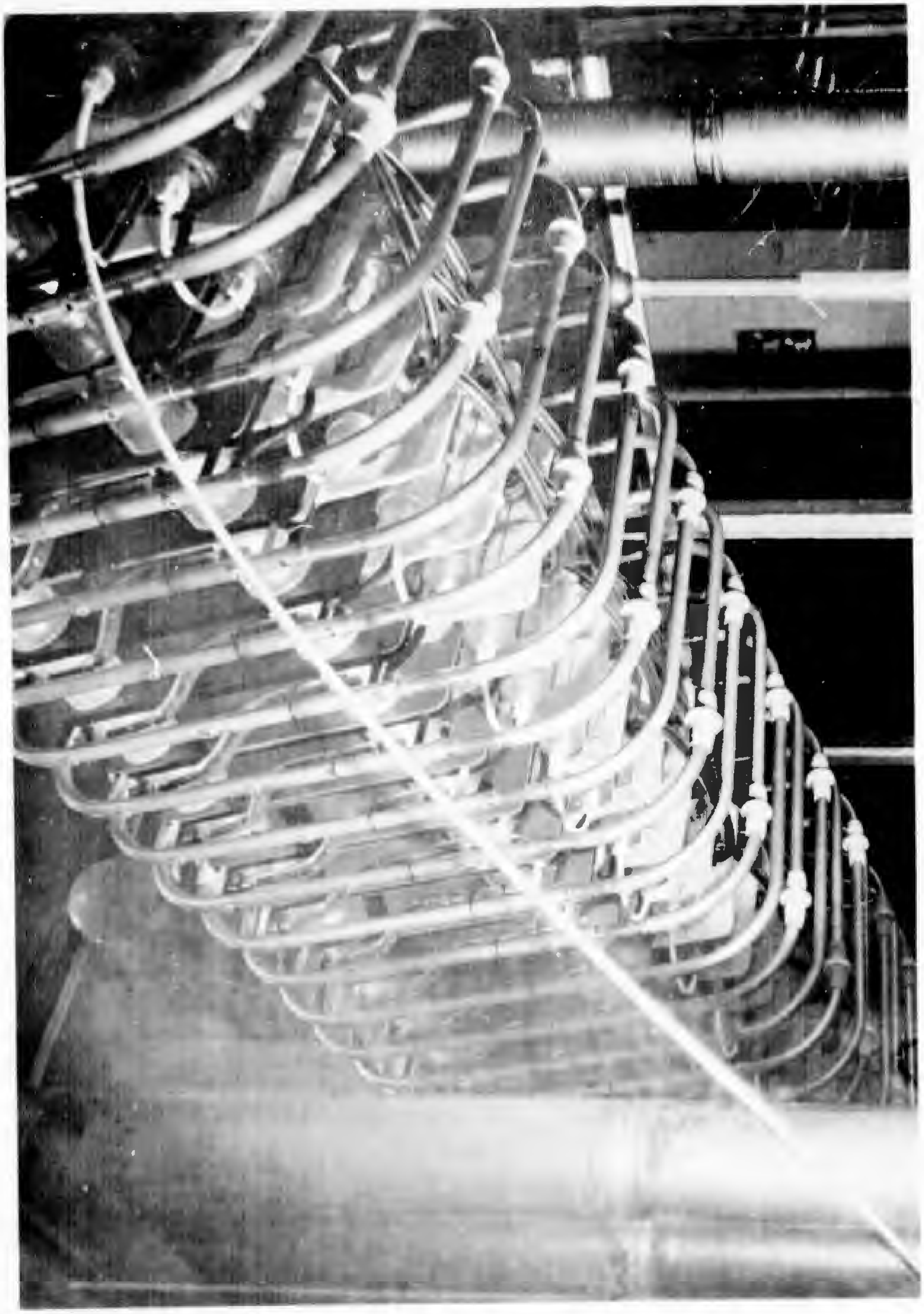


Figure 31. Bottom View of Marx

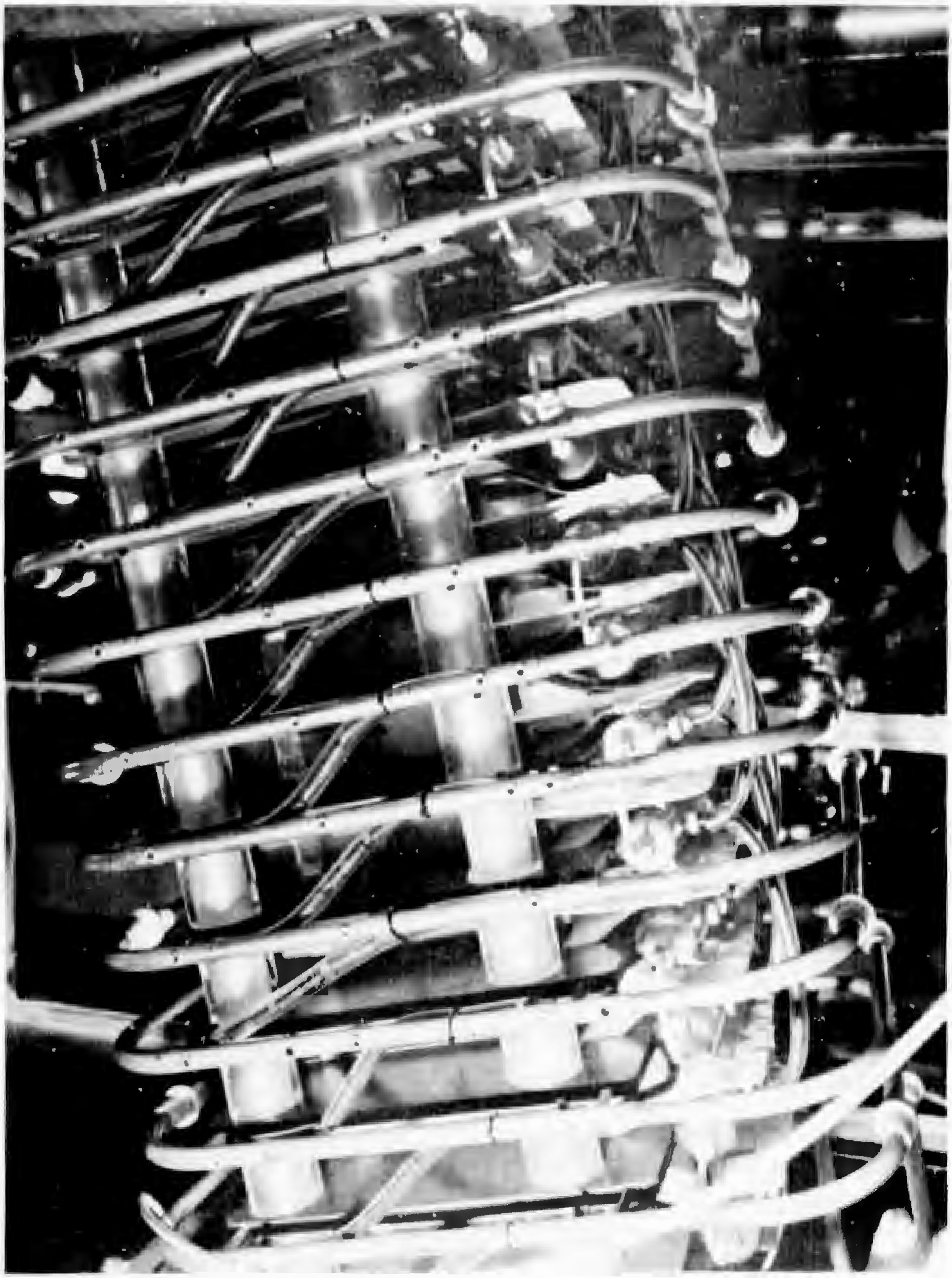


Figure 32. Side View of Marx

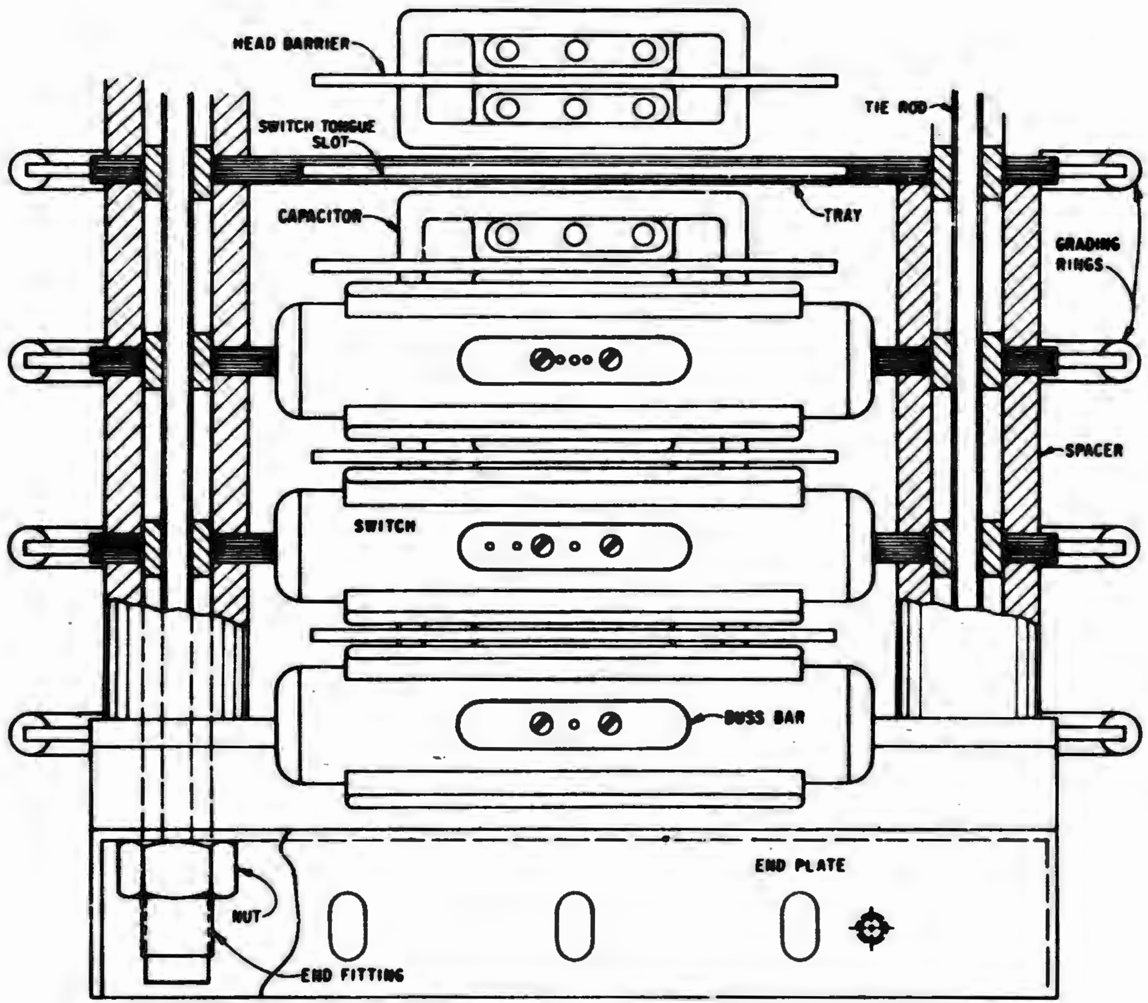


Figure 33. Front View Drawing of Marx

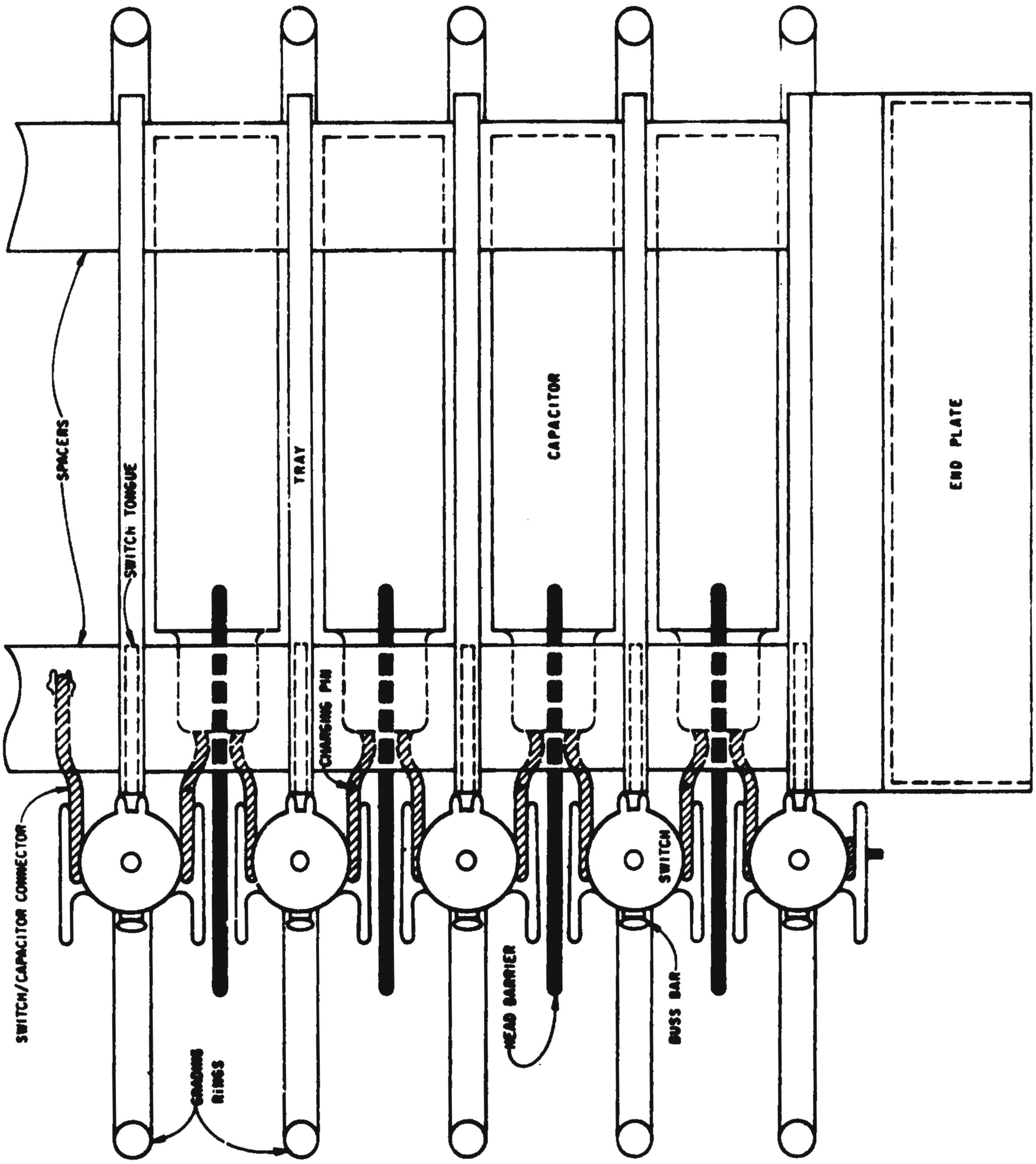


Figure 34. Side View Drawing of Marx

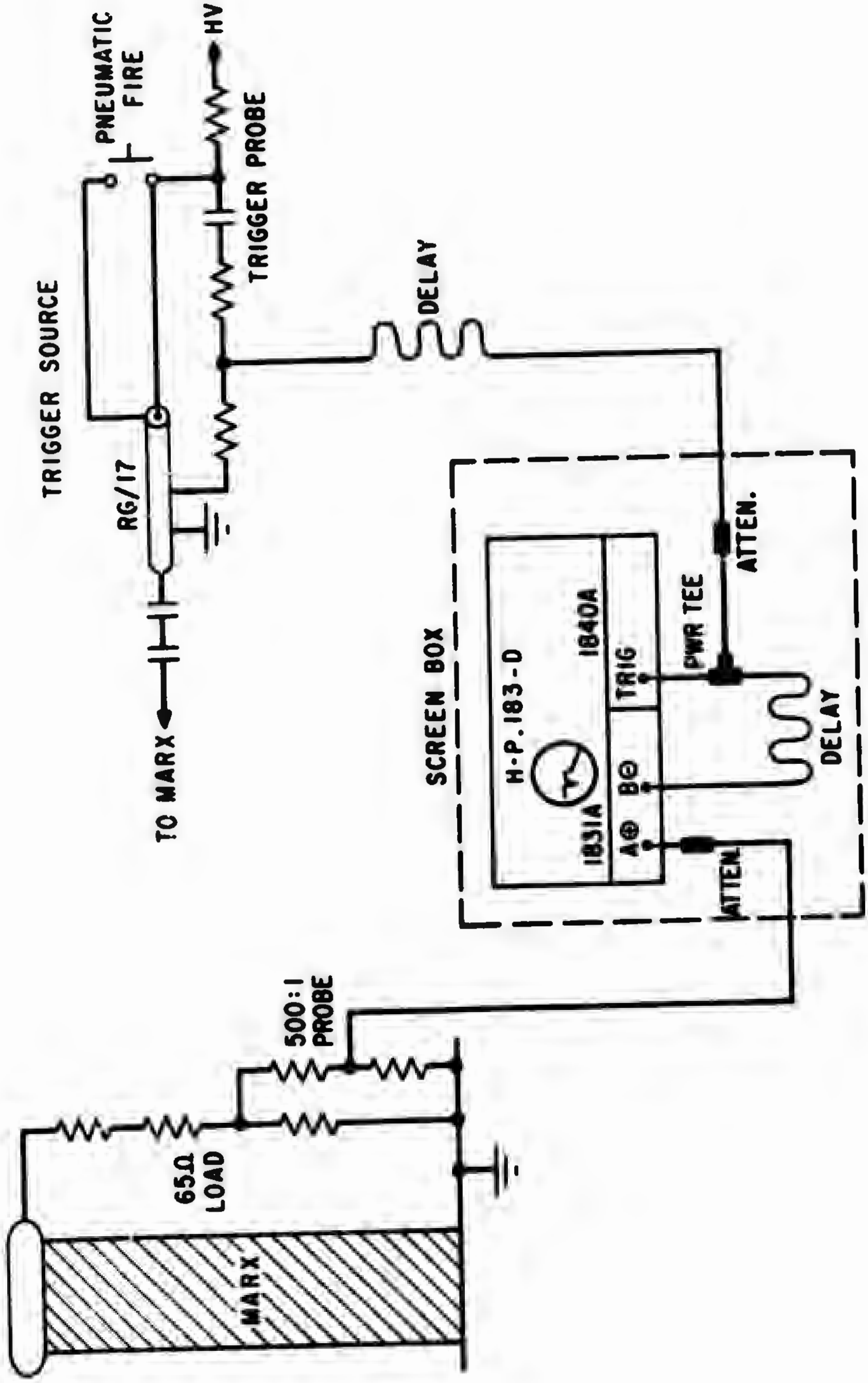
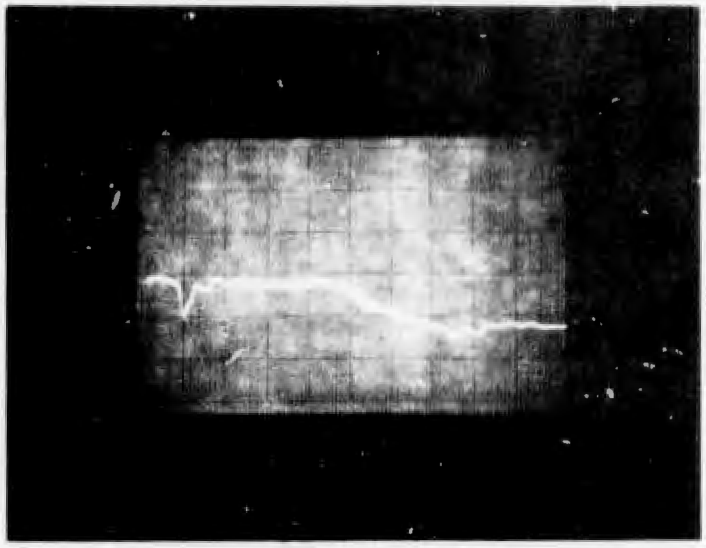


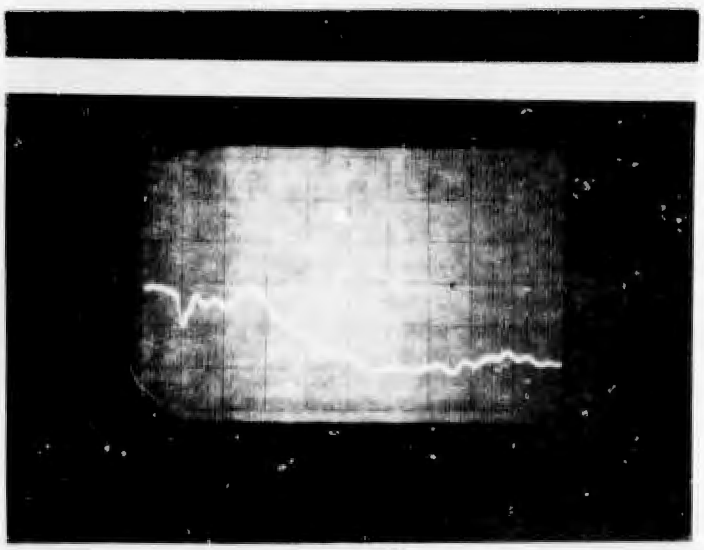
Figure 35. Diagnostic Circuit for Marx Jitter Measurement



Marx Stage Voltage: 14 kV Θ
Trigger Charge Voltage: 60 kV
Switch Gas Type: air
Switch Pressure (psig): 0
V_{SB}: 18 kV

Sweep Speed: 20 nsec/cm
5 Shots Superimposed

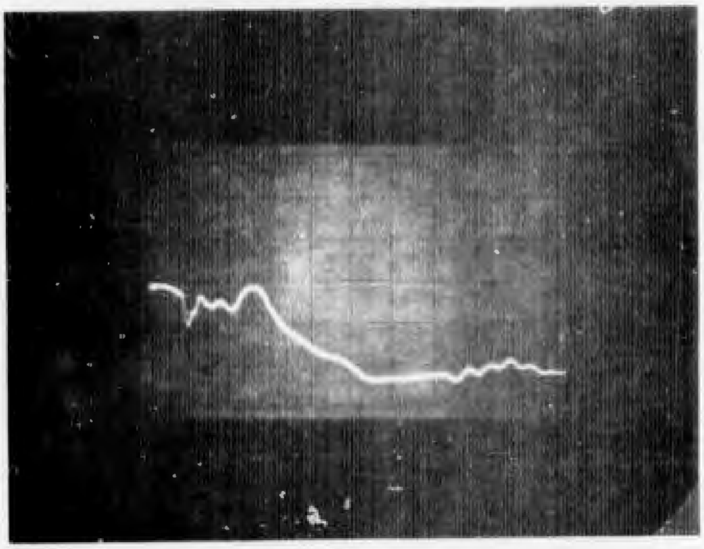
Figure 36. Jitter Measurements
(14 kV Θ, Air)



Marx Stage Voltage: 40 kV Θ
Trigger Charge Voltage: 60 kV
Switch Gas Type: air
Switch Pressure (psig): 30
V_{SB}: 48 kV

Sweep Speed: 20 nsec/cm
5 Shots Superimposed

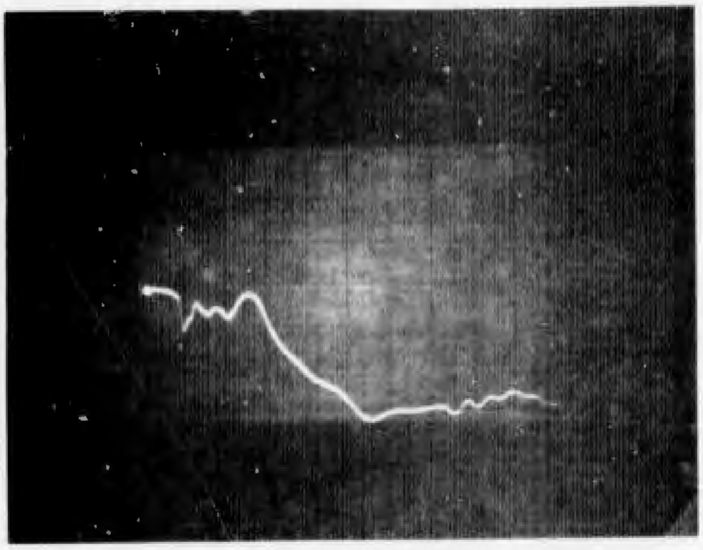
Figure 37. Jitter Measurements
(40 kV Θ, Air)



Marx Stage Voltage: 46 kV ⊖
Trigger Charge Voltage: 60 kV
Switch Gas Type: Air
Switch Pressure (psig): 40
V_{SB}: 56 kV

Sweep Speed: 20 nsec/cm
5 Shots Superimposed

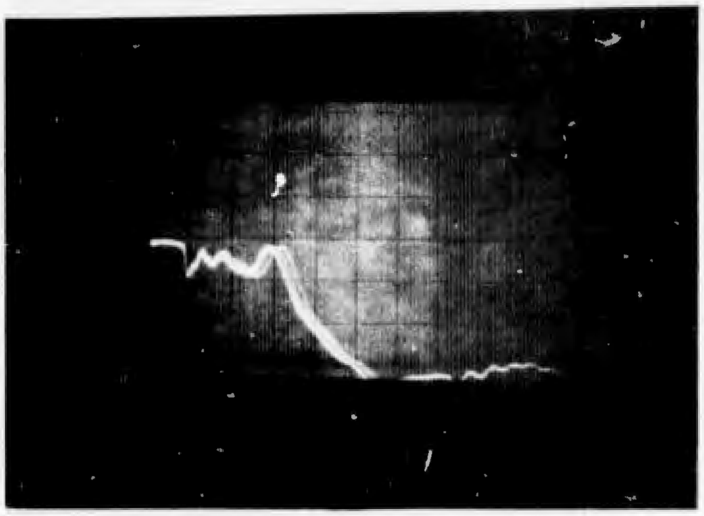
Figure 38. Jitter Measurements
(46 kV ⊖, Air)



Marx Stage Voltage: 60 kV ⊖
Trigger Charge Voltage: 60 kV
Switch Gas Type: Air
Switch Pressure (psig): 60
V_{SB}: 72 kV

Sweep Speed: 20 nsec/cm
5 Shots Superimposed

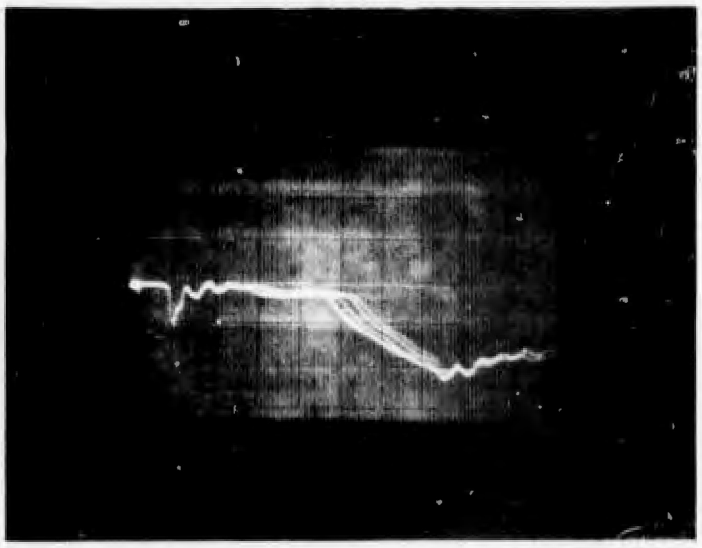
Figure 39. Jitter Measurements
(60 kV ⊖, Air)



Marx Stage Voltage: 70 kV ⊖
Trigger Charge Voltage: 60 kV
Switch Gas Type: Air
Switch Pressure (psig): 80
V_{SB}: 80 kV

Sweep Speed: 20 nsec/cm
5 Shots Superimposed

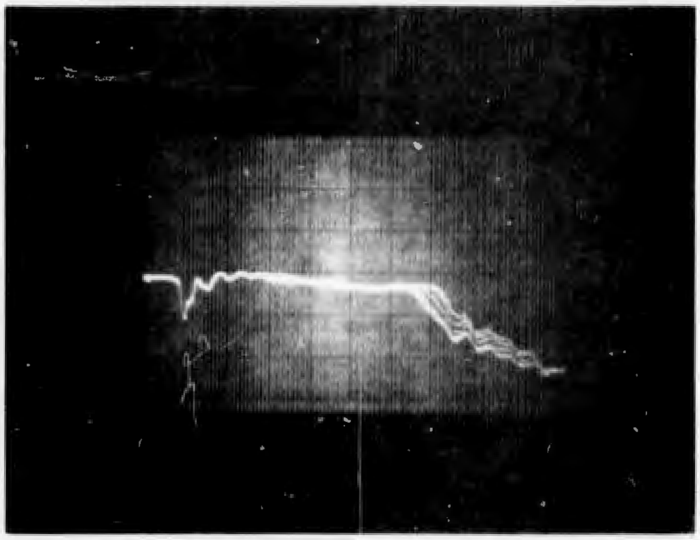
Figure 40. Jitter Measurements
(70 kV ⊖, Air)



Marx Stage Voltage: 90 kV ⊖
Trigger Charge Voltage: 80 kV
Switch Gas Type: 10% N_2/90% SF_6
Switch Pressure (psig): 46
V_{SB}: >100 kV

Sweep Speed: 20 nsec/cm
5 Shots Superimposed

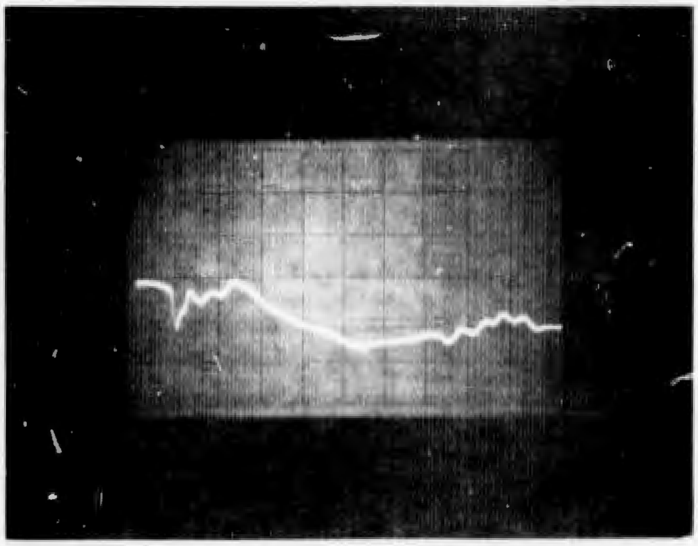
Figure 41. Jitter Measurements
(90 kV ⊖, 10% N_2/90% SF_6)



Marx Stage Voltage: 100 kV Θ
Trigger Charge Voltage: 80 kV
Switch Gas Type: 10% N_2/90% SF_6
Switch Pressure (psig): 70
V_{SB}: >100 kV

Sweep Speed: 20 nsec/cm
5 Shots Superimpc: :

Figure 42. Jitter Measurements
(100 kV Θ, 10% N_2/90% SF_6)



Marx Stage Voltage: 70 kV Θ
Trigger Charge Voltage: 80
Switch Gas Type: 90% N_2/10% SF_6
Switch Pressure (psig): 62
V_{SB}: 75 kV

Sweep Speed: 20 nsec/cm
5 Shots Superimposed

Figure 43. Jitter Measurement
(70 kV, 90% N_2/10% SF_6)

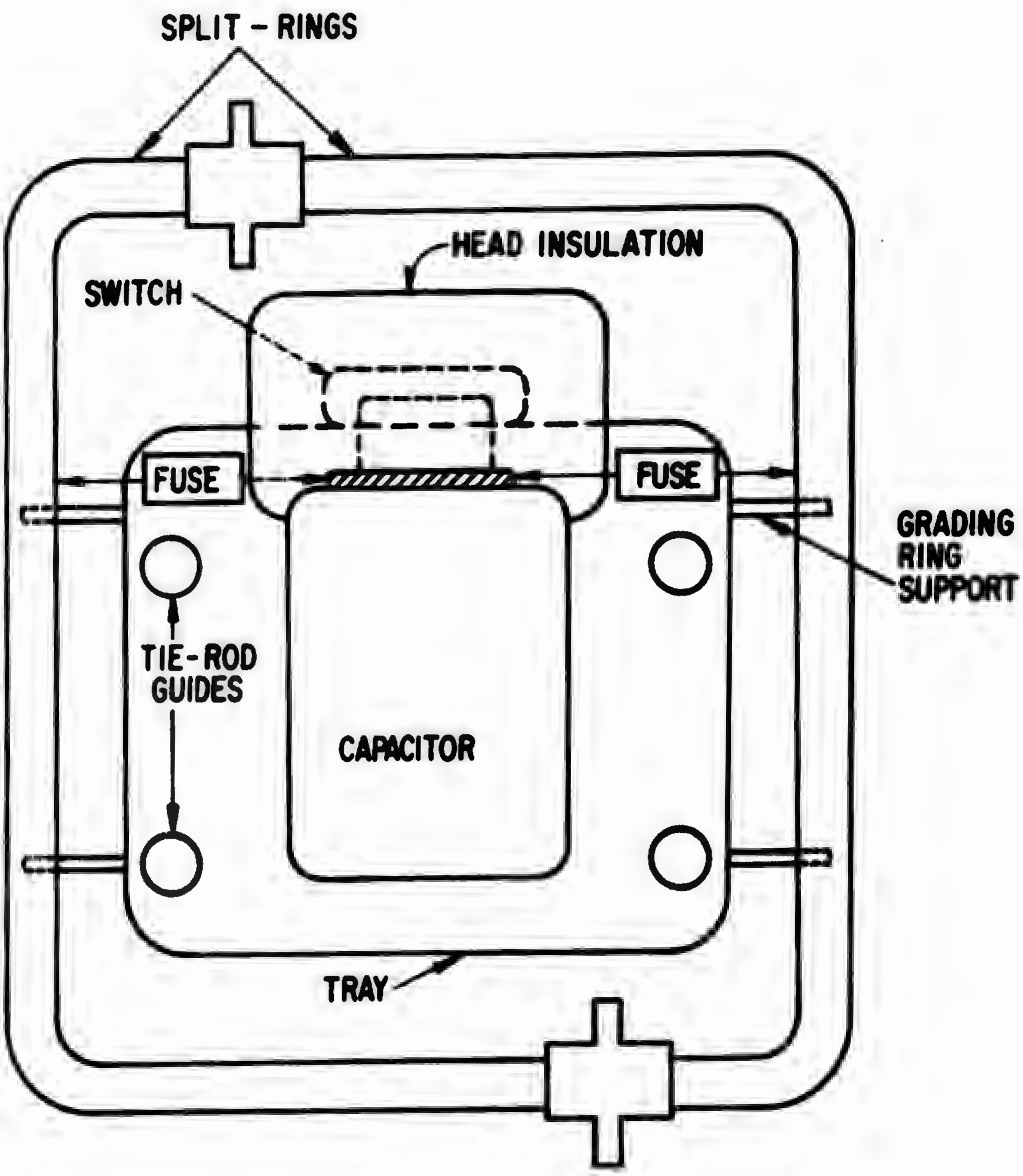


Figure 44. Carbon Resistor Fuse Connected Between Grading Ring and Capacitor

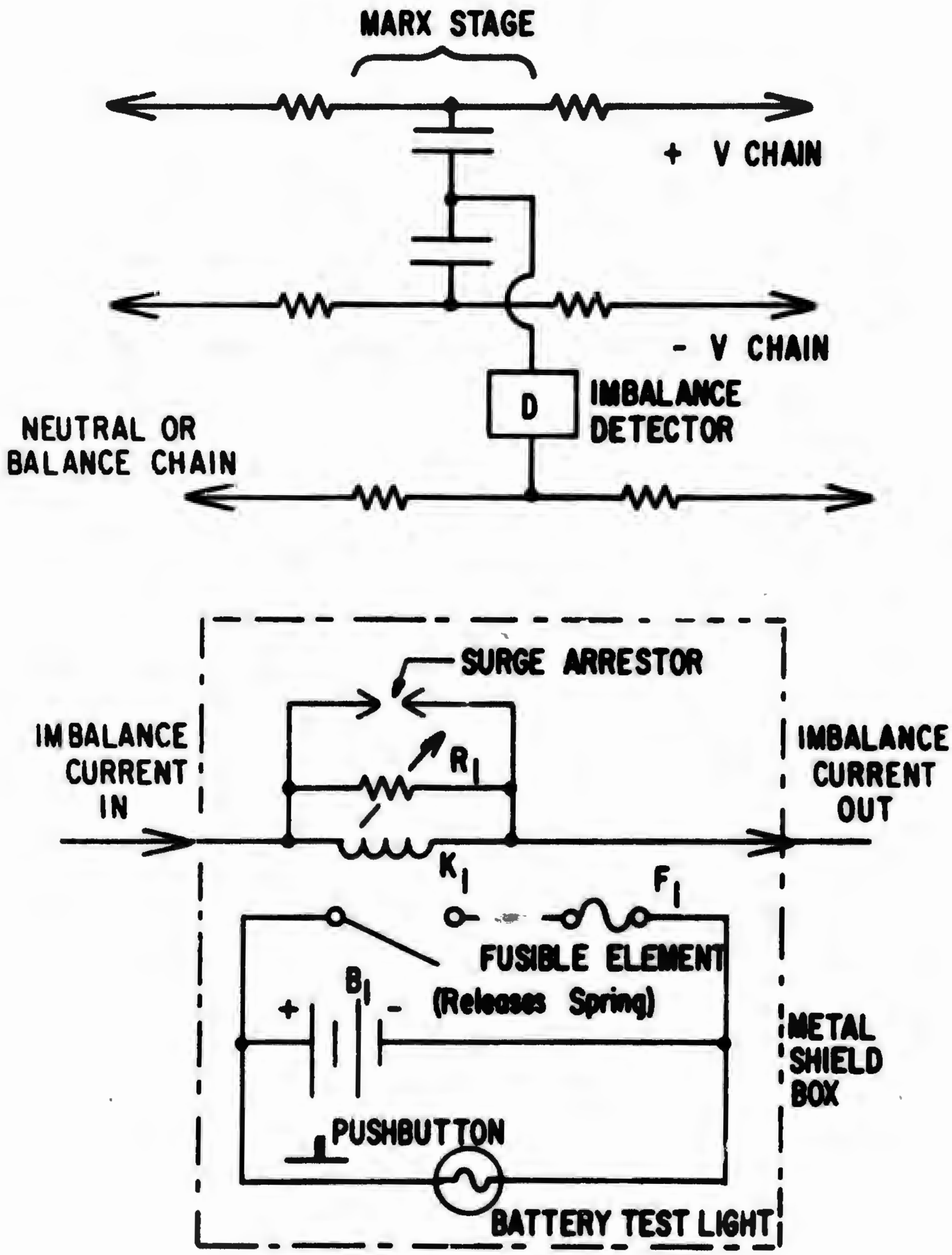


Figure 45. Schematic of Current Imbalance Detector

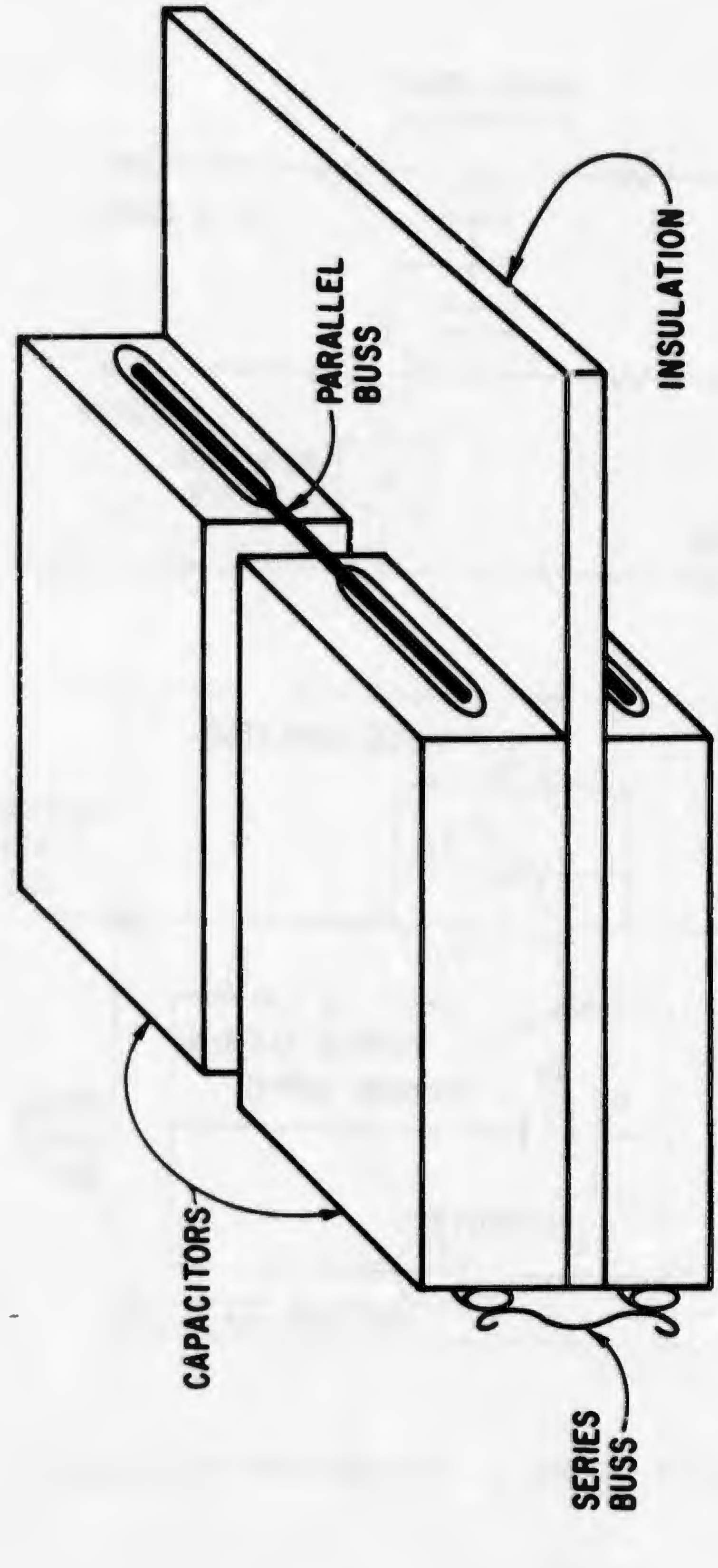


Figure 46. Connection of Double-Ended Flat-Pack Capacitors

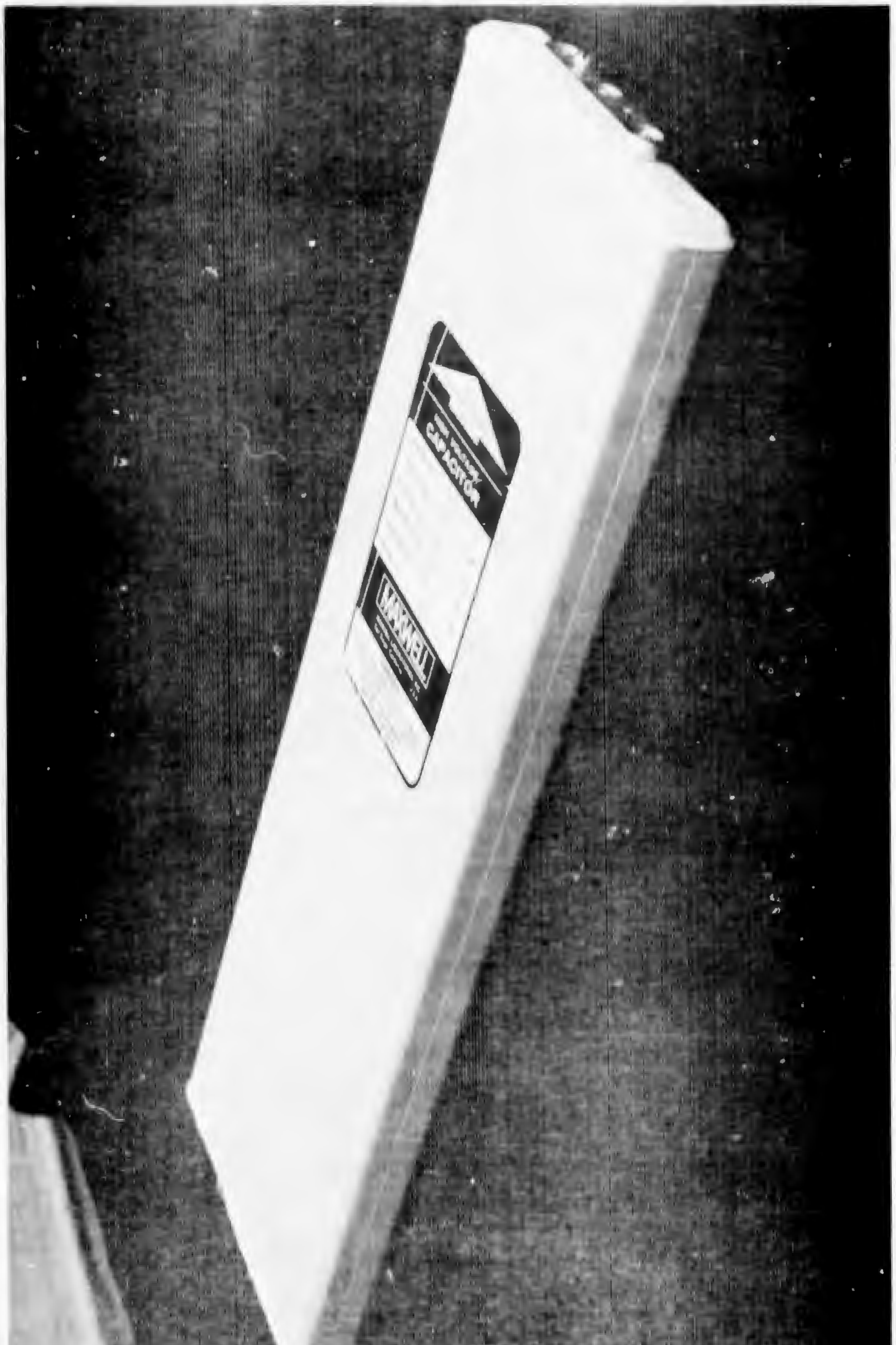


Figure 47. One Version of a Double-Ended Flat-Pack Capacitor

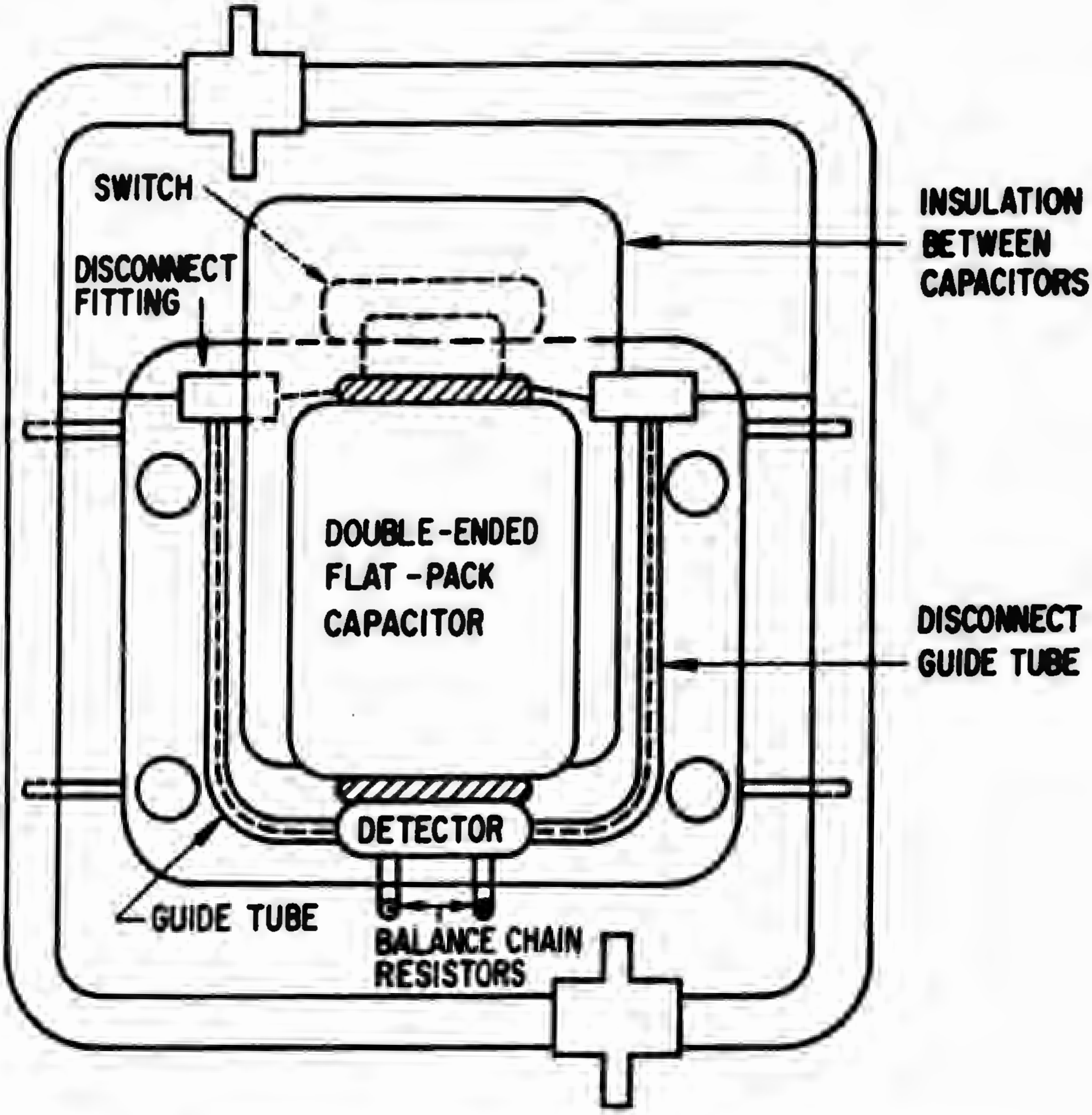


Figure 48. Imbalance Detector Scheme for Disconnecting Capacitors

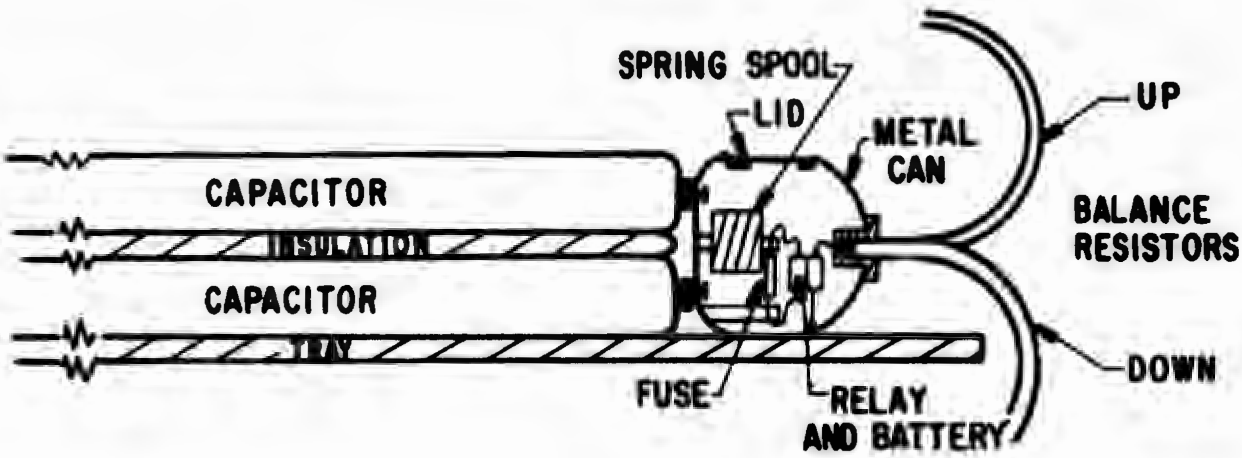


Figure 49. Detector Detail

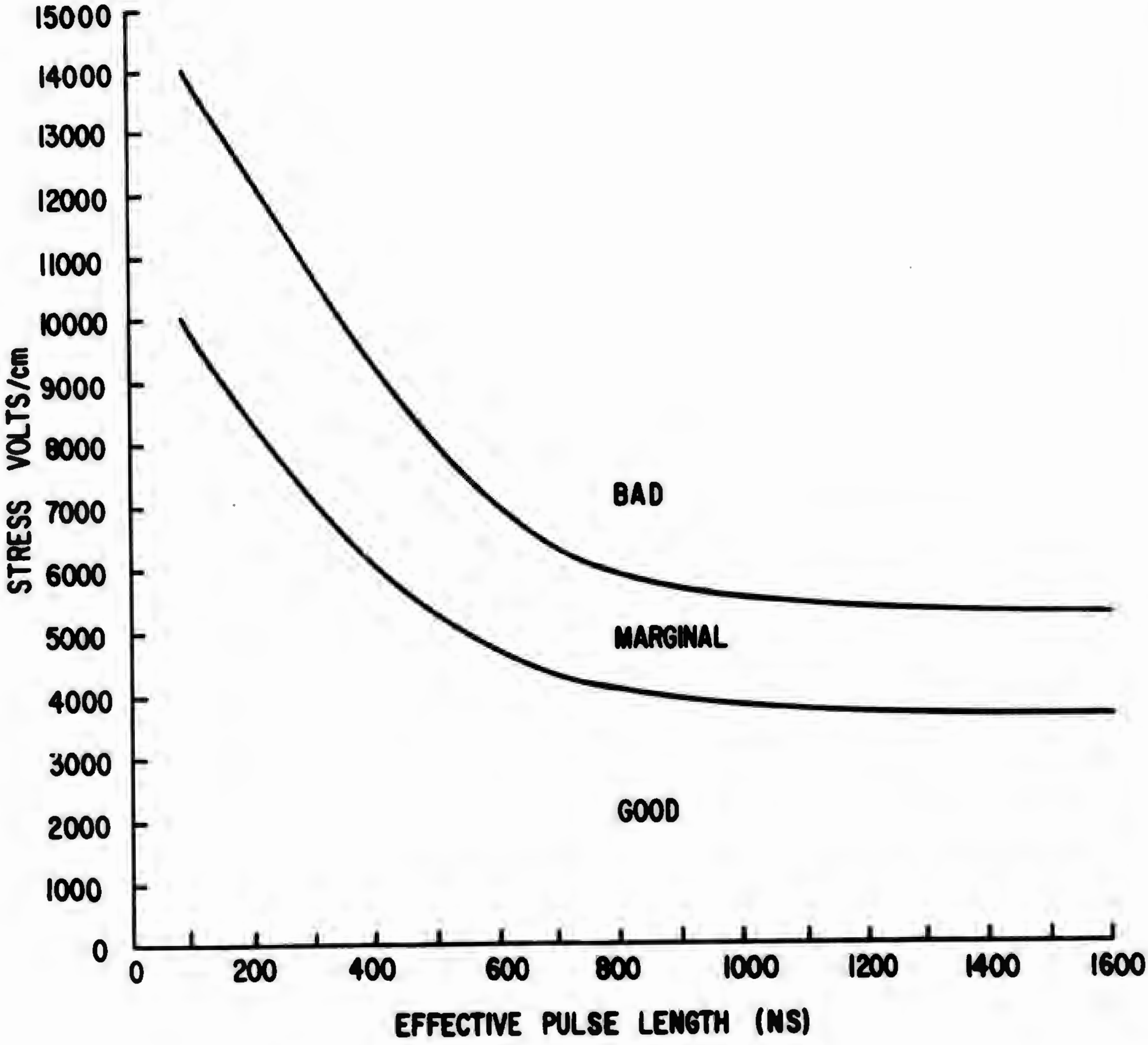


Figure 50. Quality Curve: Stress versus Effective Pulse Length

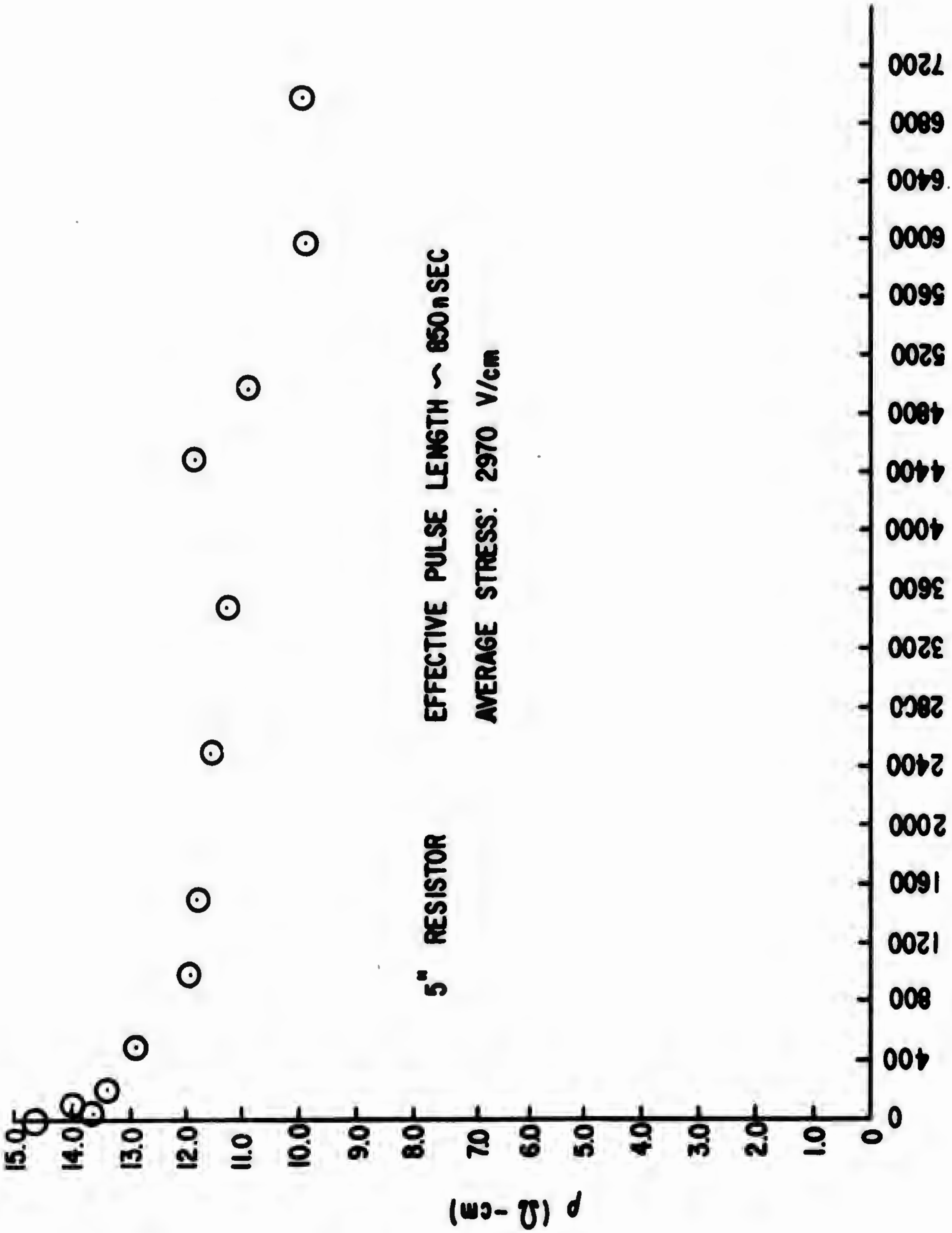


Figure 51. Resistivity versus Shot Number (5-inch resistor, 2970 V/cm)

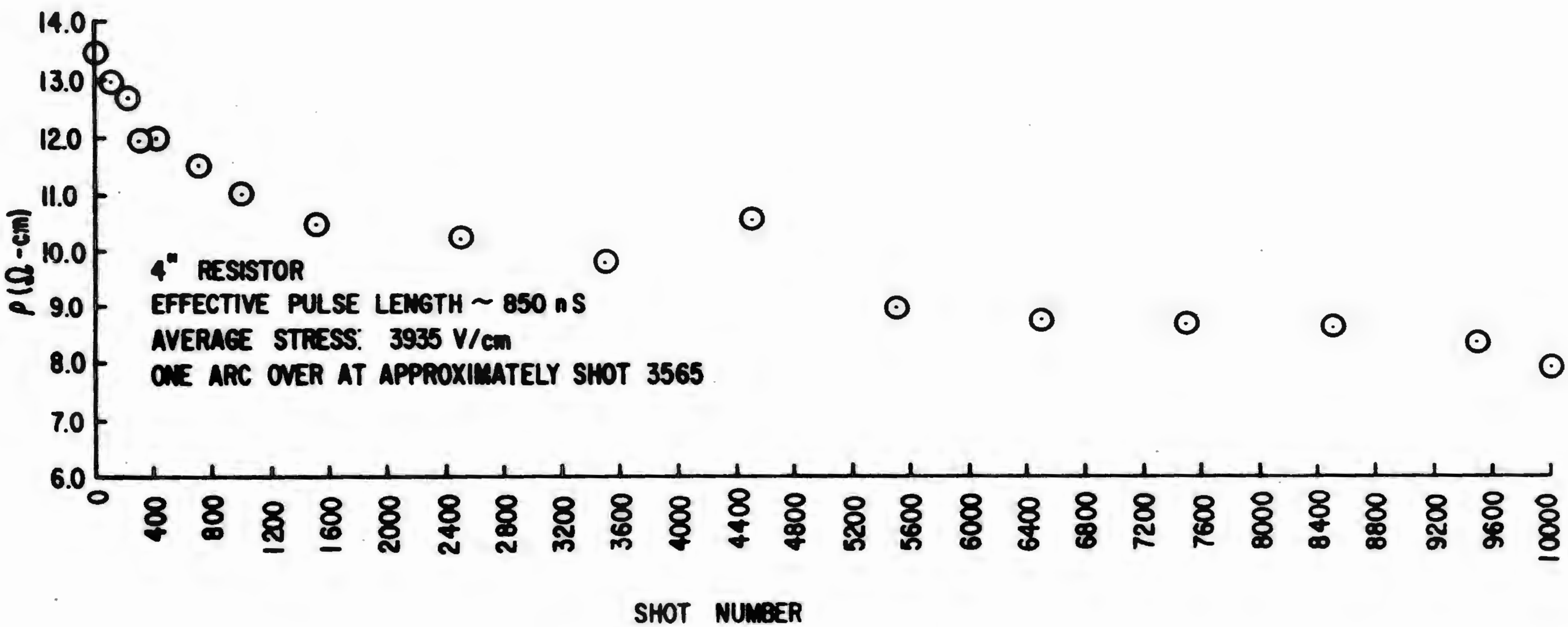


Figure 52. Resistivity versus Shot Number (4-inch resistor, 3935 V/cm)

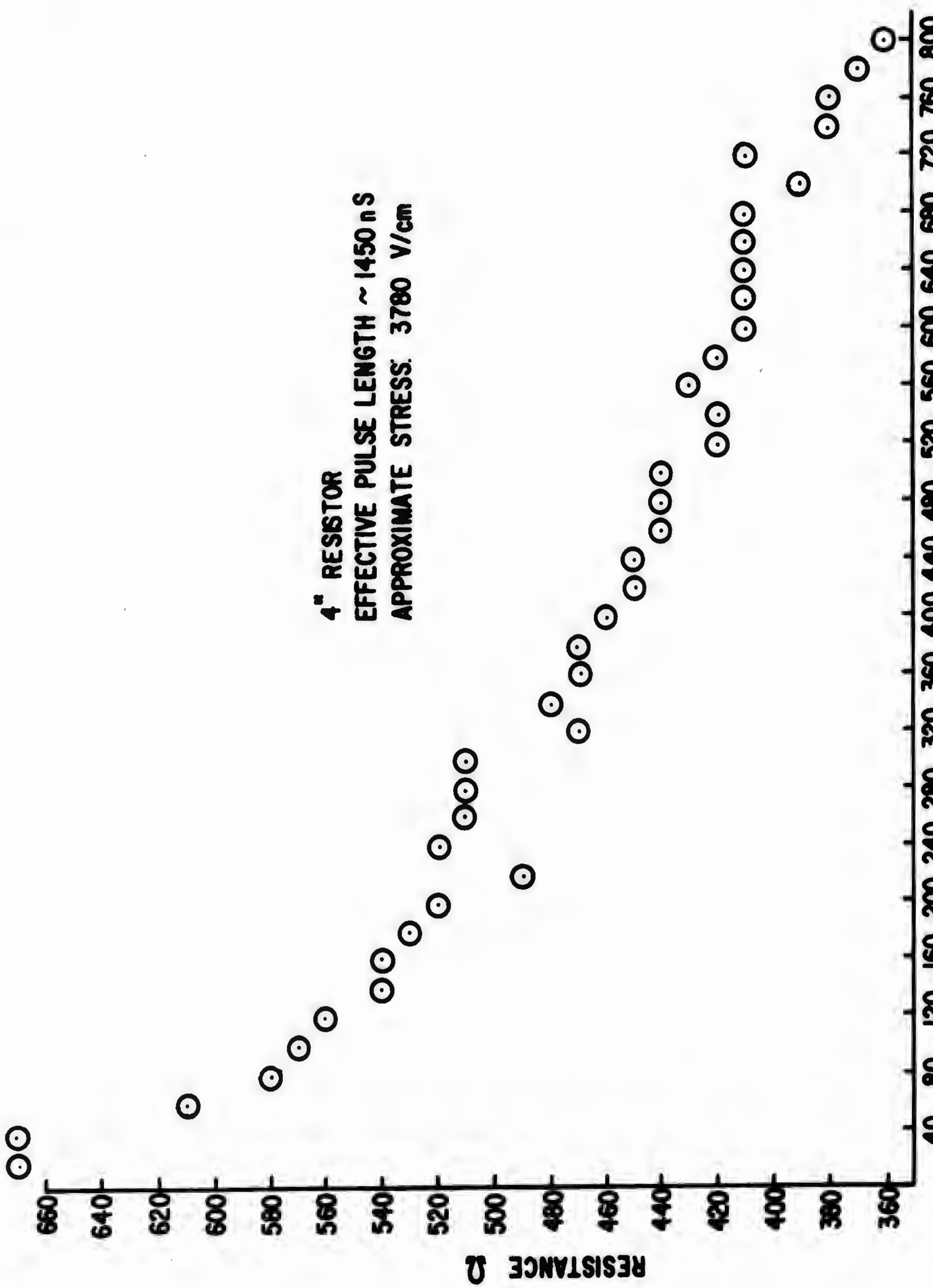


Figure 53. Resistance versus Shot Number (4-inch resistor, 3780 V/cm)

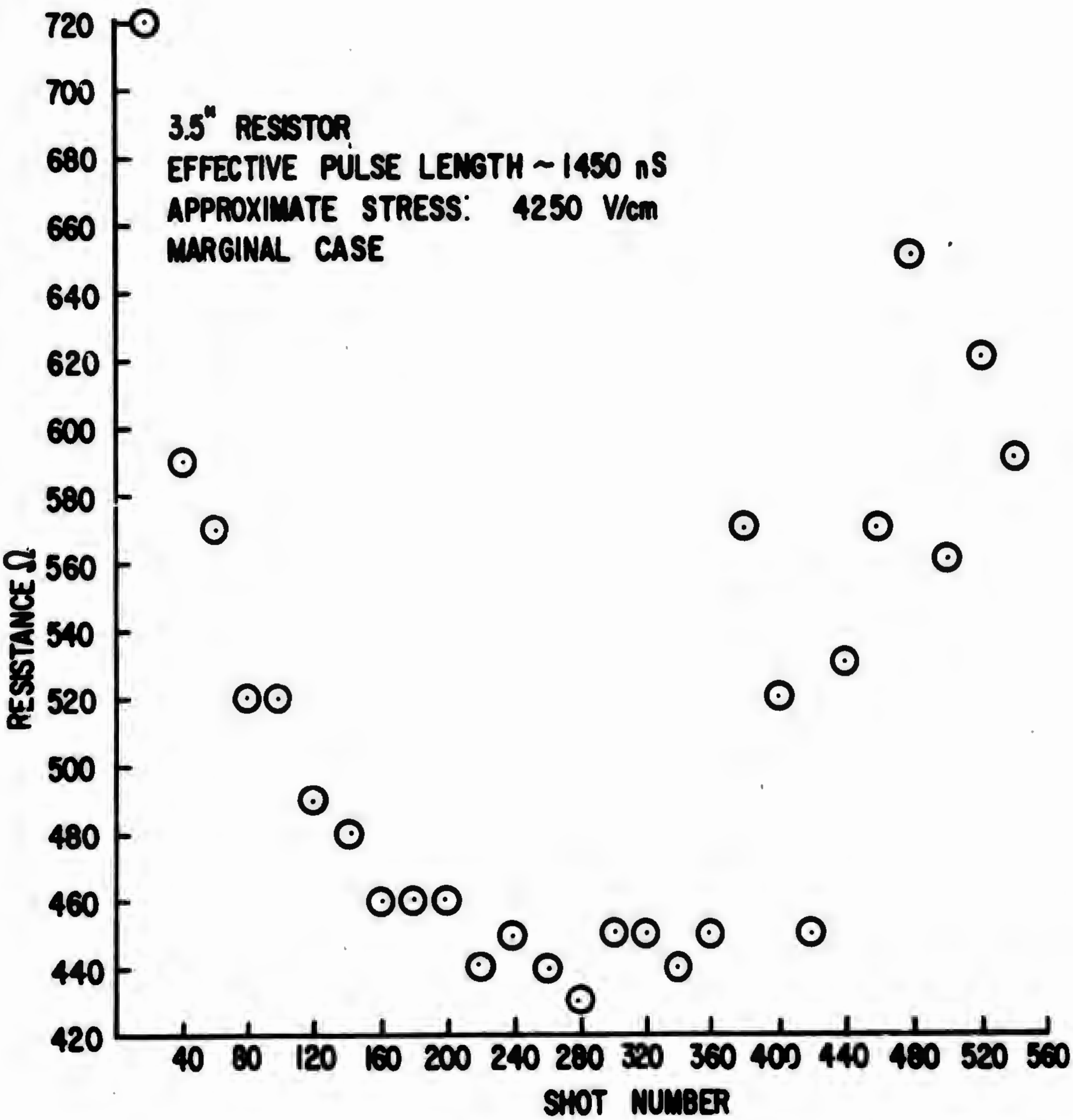


Figure 54. Resistance versus Shot Number (3.5-inch resistor, 4250 V/cm)

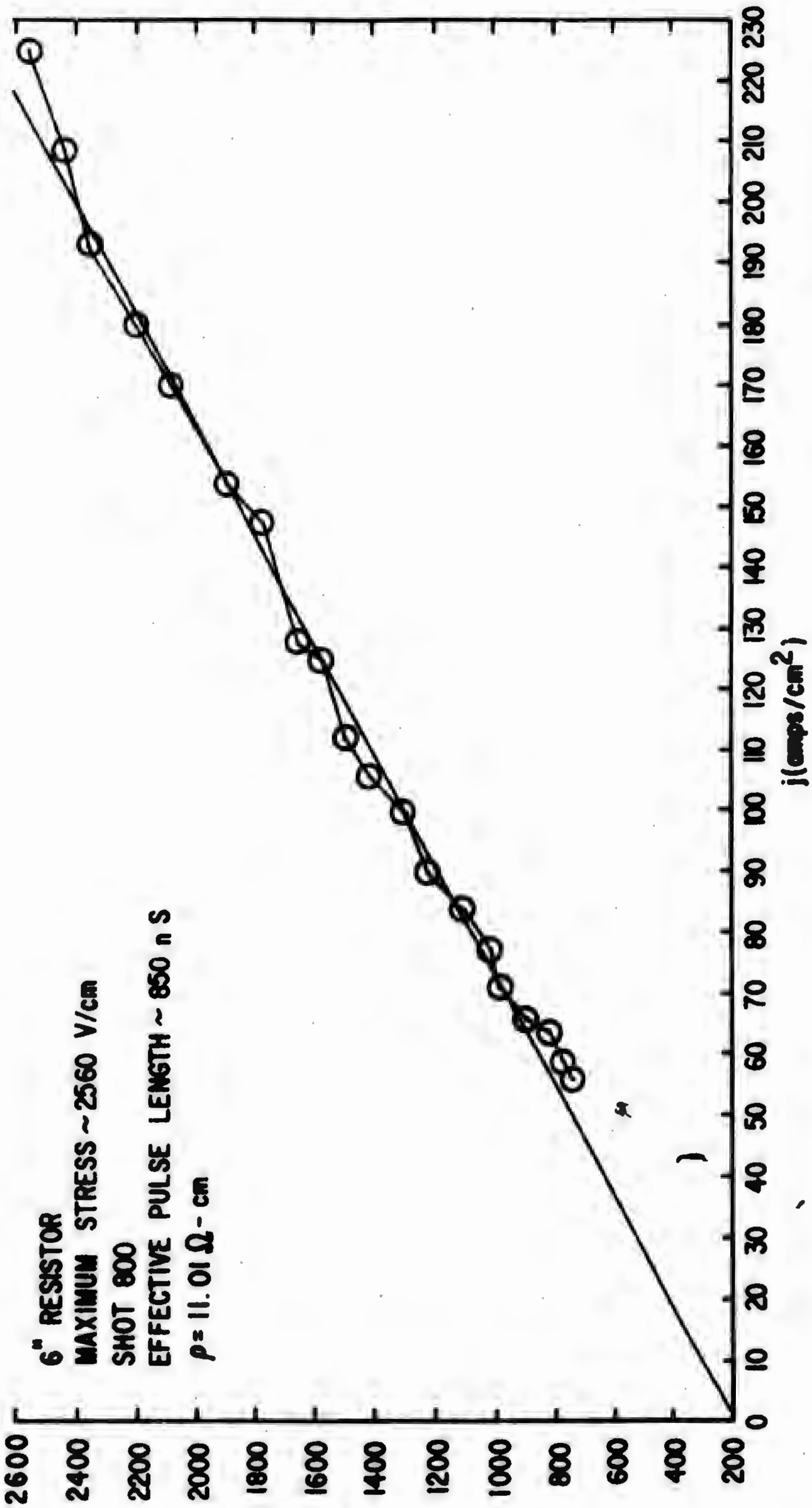


Figure 55. Stress versus Current Density (6-inch resistor, 2560 V/cm)

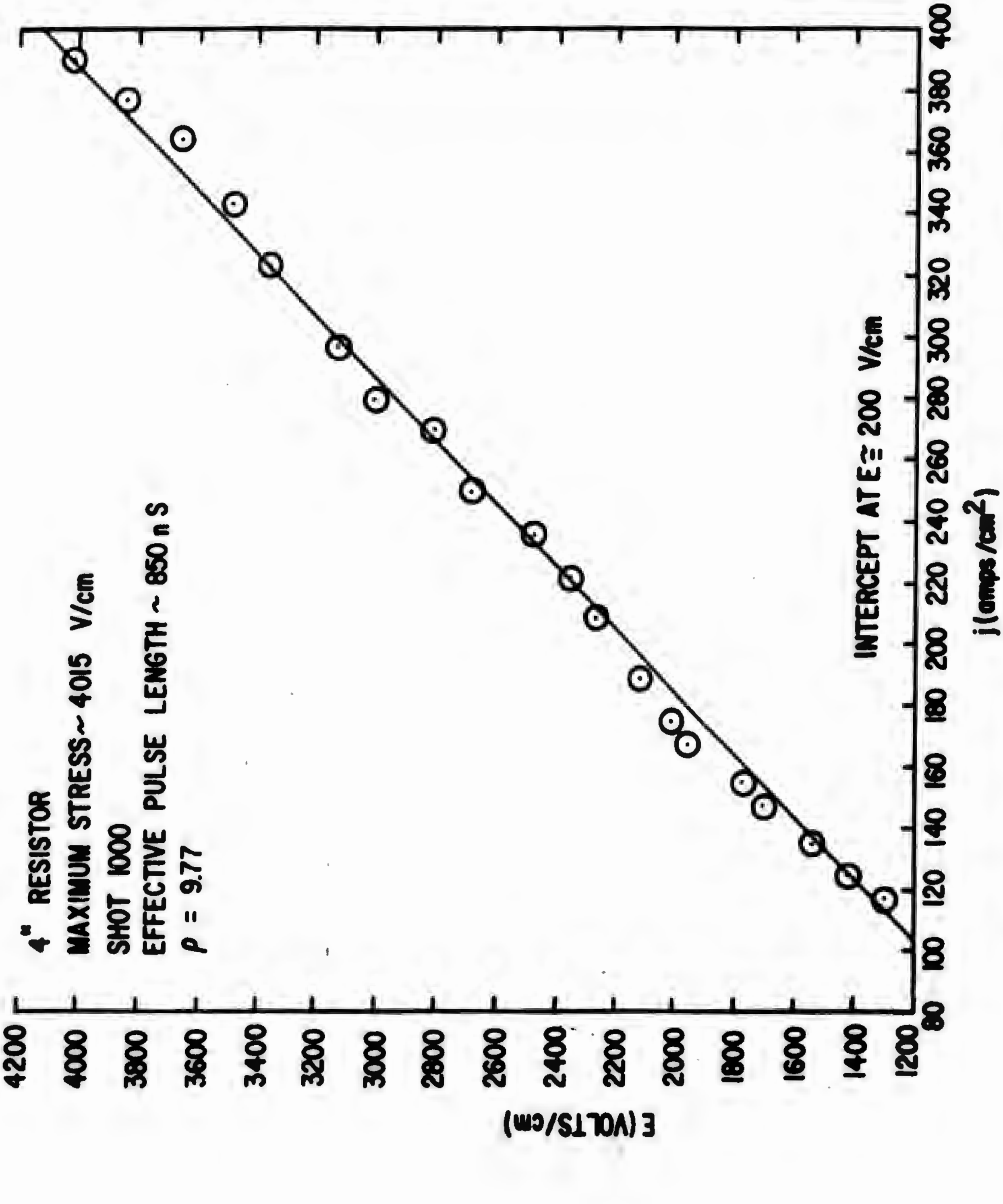


Figure 56. Stress versus Current Density (4-inch resistor, 4015 V/cm)

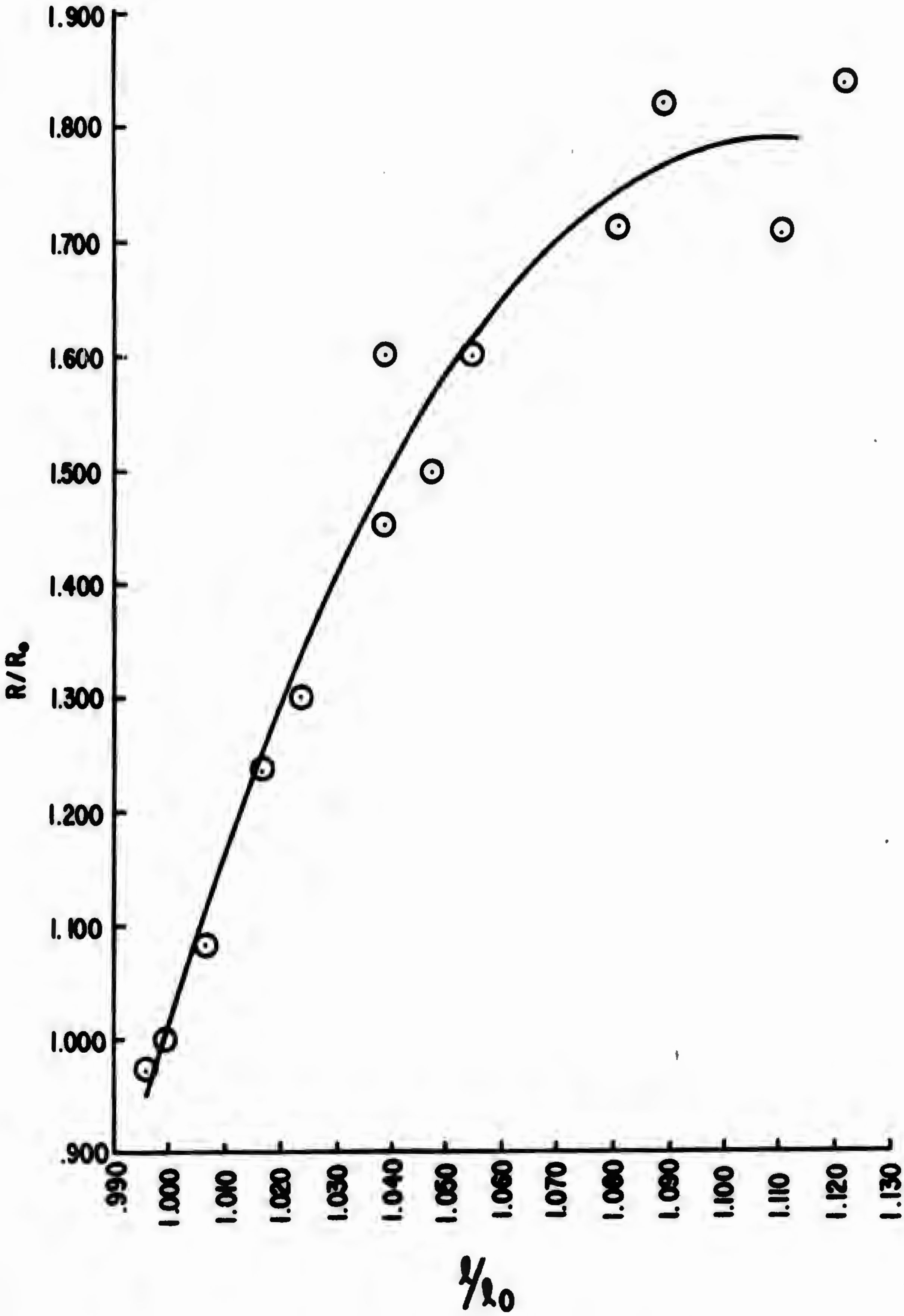


Figure 57. Resistance versus Longitudinal Stretching

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13. ABSTRACT (Distribution Limitation Statement B)

A Marx generator with the highest energy density ever achieved (39j/pound) is described. The unit, which operates at 2 MV in atmospheric SF_6, is 2 m long, stores 18 kj and weighs 460 pounds. The design incorporates several novel features: the stage capacitors are 100-kV plastic-cased units with a density of 100 joules per pound; grading is achieved by split grading rings; and a conductive elastomer charges and triggers the resistors. Its compactness, light weight, and atmospheric gas insulation ideally suits this Marx design for a variety of applications such as bounded-wave and radiating EMP simulators, plasma devices, laser systems, and electron-beam devices. The modular nature allows the design voltage to be increased or decreased as necessary. The unit has a demonstrated erection jitter (1 σ) of less than 10 nsec over a 7:1 voltage range and consequently can be precisely time-tied to test sequences or to other hardware.

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