FINAL REPORT

on

DEVELOPMENT OF A MICROMETEROID ACCELERATOR

by

G. M. Pjerrou
J. F. Farnham

October 1968

prepared for
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

Contract No. NAS8-21103

MBA

MBAssociates
Electrosciences Division
San Ramon, California 94583

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ABSTRACT

An arc plasma micrometeroid accelerator system has been developed by MBAssociates for the National Aeronautics and Space Administration. The principal components of the system are an arc plasma accelerator, a 200-kJ capacitor bank and its associated controls for energizing the system, a spark-gap and delay line subsystem for switching, a vacuum system containing the accelerator, a target and an electrical interface vacuum seal assembly. Design, fabrication, assembly and testing of individual components and the entire system were performed during this contract. Velocities in excess of 10 km/sec for 2.6 mil glass projectiles were obtained during the tests. Comprehensive descriptions of the system design and operation and of the test results are included in the report.

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1.0 INTRODUCTION

The arc plasma accelerator consists of a pair of parallel conducting rails separated by an open channel containing the plasma and the particles to be accelerated, as illustrated in Figure 1. The plasma is accelerated by the $\vec{J} \times \vec{B}$ Lorentz force due to the magnetic field in the channel induced by the current flow in the rails. The particles are accelerated by aerodynamic drag of the plasma medium. Velocities as high as 15 km/sec for 2.6 mil diameter glass spheres have been attained using this method. Particles of this size and velocity are used to stimulate micrometeoroid impacts on material targets.

The plasma between the rails is initiated and maintained by the ringing discharge of the capacitor bank. This bank is charged initially to a level of 20 kV. The discharge is initiated by a -15 kV pulse from a thyratron trigger circuit. This pulse in turn fires a set of spark-gap switches followed by the bank discharge. This sequence may be followed in Figure 2 which shows a pictorial sketch of the entire system. The bank discharge current is directed through a coaxial cable array transmission line to prevent quenching of the switch action. The current is collected, from the various cables, at an interface assembly which in turn transmits the current to the conducting rails. The rail assembly is located inside a vacuum system. During system operation the peak current may reach several million amperes producing very large repulsive forces between the rails. It is for this reason, as well as to confine the plasma discharge that the rails are housed in a massive nonconducting jacket. Particles emerge from the accelerator in a wide angle. Only a small fraction of these are propelled directly towards the target at the opposite end of the vacuum enclosure. The plasma created in the accelerator also emerges and proceeds toward the target, and since the plasma is highly luminous, its flight time may be recorded by light monitors

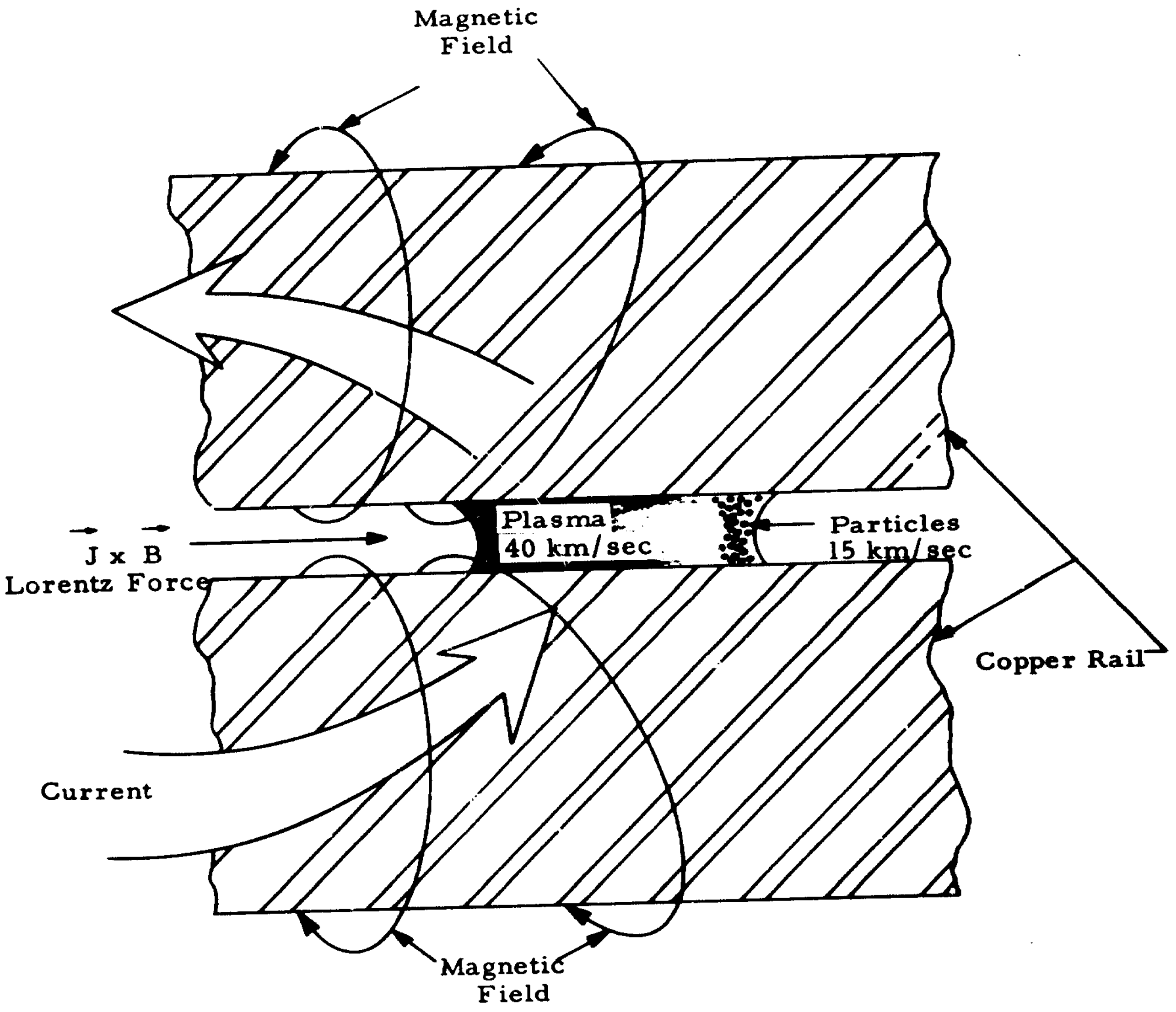

Figure 1. Arc plasma accelerator operation

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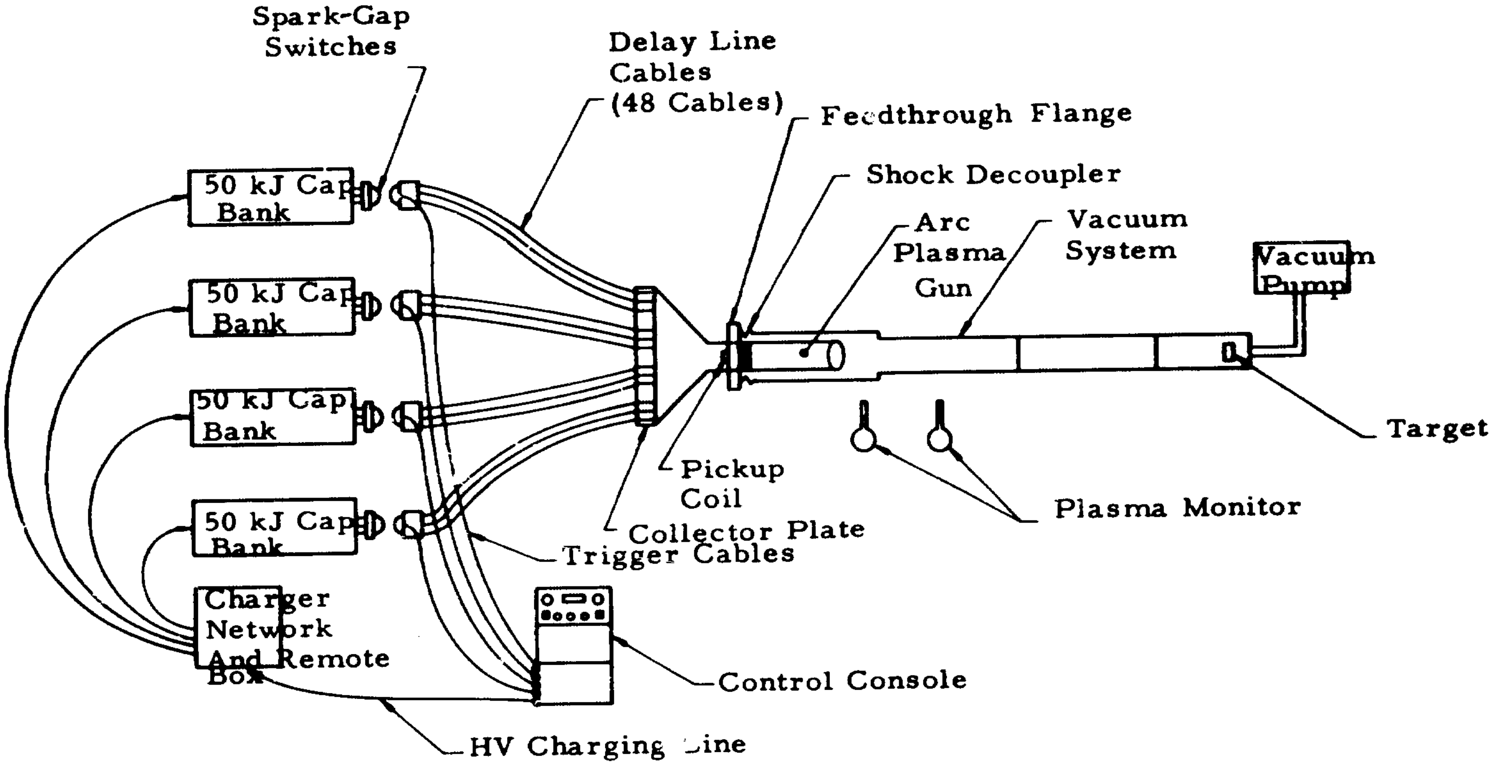

Figure 2. 200-kJ arc plasma accelerator charge/discharge system sketch

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placed along the vacuum tube. Particle flight time was measured using the apparatus shown in Figure 3. A thin target of aluminum sheet is used to form one end of a light tight box which is coupled to a photomultiplier tube. Upon penetration of the target by the particles a signal is produced by the photomultiplier which is recorded on an oscilloscope. This system yields very positive and easily identifiable, flight time measurements. The target is placed as far from the accelerator as possible to increase the accuracy of the velocity measurements and too minimize the interference by the plasma.

It should be noted that this method of measurement to determine particle velocity is dependent upon penetration of the target by the acclerated particles. Care must be exercised to reduce the possibility of a false velocity measurement due to the plasma tearing the target. To protect against this occurrence, a graticular target support was designed to provide target strength and still allow for easy particle penetration. This support is illustrated in Figure 4.

The major portion of work under this contract was devoted to the design, fabrication and assembly of a 200 kJ system and components, to preliminary testing and to the solution of the technical problems uncovered during testing. Two major problems were encountered. These were extremely high pressures due to confinement of the plasma and a number of high voltage insulation breakdowns. The high pressure resulted in shock damages which were solved by redesigning the brass feedthrough tabs and a shock decoupler. This allowed more volume for the plasma expansion. The high-voltage problems were solved by using high breakdown threshold materials and by proper maintenance procedures.

With the lower energy 100-kJ system* weighted mean projectile velocities of 8.64, 11.04 and 12.85 km/sec were obtained for 4.8, 2.6 and 2.3 mil mean diameter glass spheres, respectively. The maximum velocity obtained was 14.91 km/sec for the 2.3 mil spheres. These results were obtained during a systematic study of the 100 kJ system velocity capability and by optimization of initial conditions of the system. In the present work, no systematic study of this type

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*Contract NAS8-20295

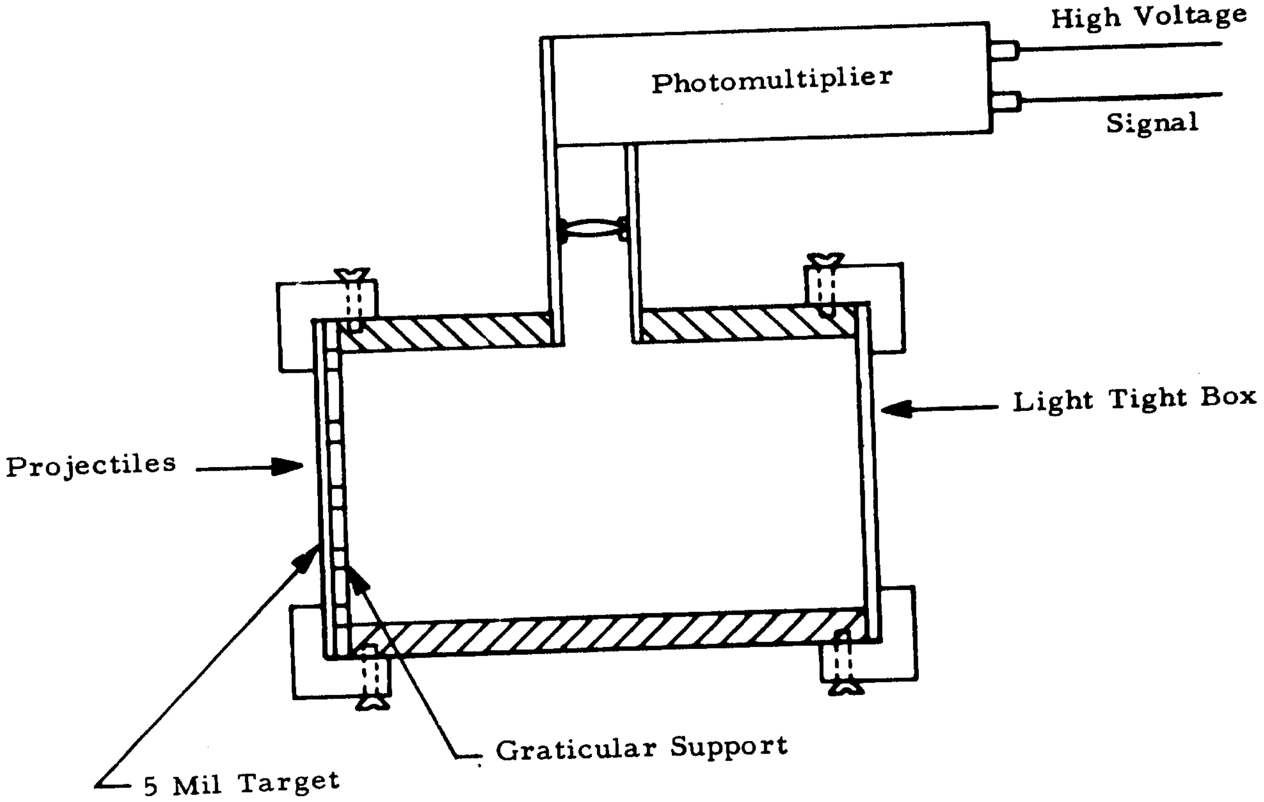

Figure 3. Apparatus for projectile velocity measurements

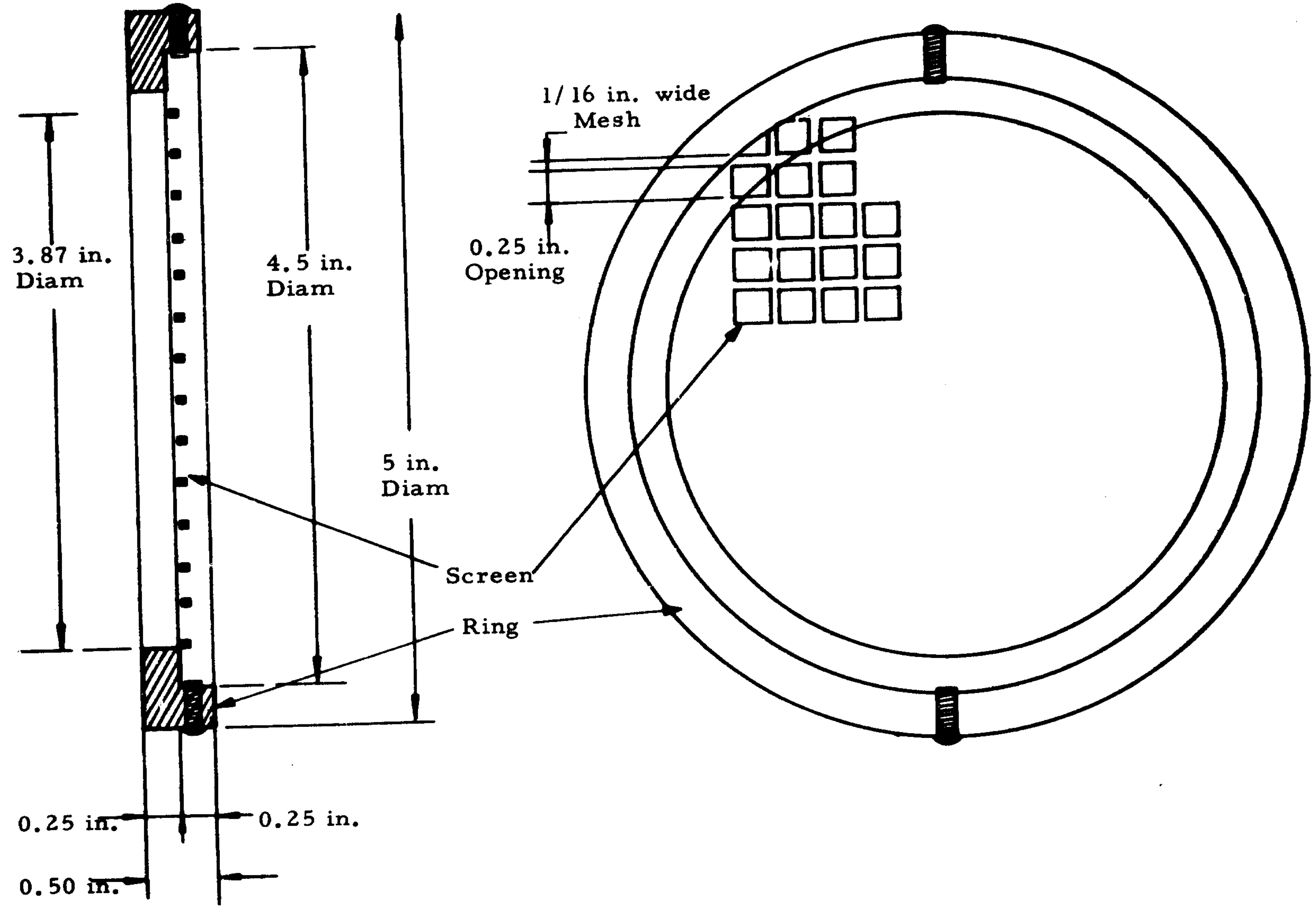

Figure 4. Target retainer and graticular target support

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was possible; however, initial tests of the systems indicated particle velocities in excess of 10 km/sec. These tests will be described in this report along with a comprehensive description of the system, its components, and an operational procedure.

2.0 SYSTEM DESIGN

The design of the various components used in the system and the general principles underlying their design are discussed in the following sections. The components include (1) capacitor bank, (2) spark-gap switches, (3) control console, (4) electrical interface and vacuum seal, and (5) the arc plasma gun. An electrical block diagram of the system is shown in Figure 5.

2.1 CAPACITOR BANK

The capacitor bank was designed to achieve a total maximum nominal energy of 216 kJ in rapid discharge from a charged level of 20 kV. The bank consists of 72 high-energy, low-inductance discharge capacitor units manufactured by Cornell-Dublier. The manufacturer's specifications are given in Table I.

The bank was divided into four separate quarter banks each with its own spark-gap switch for reasons of safety and also to achieve low inductance. These quarter banks are connected in parallel at the electrical interface. In addition, each quarter bank was further divided into six separate modules of three capacitors each. The six modules are connected in parallel at the spark-gap switch for the appropriate quarter bank. The connection between each module and its switch is a transmission line consisting of two parallel coaxial cables. The cables are of the BICC type and were supplied by Sangamo Electric Company. The cable specifications are given in Table I. In the module itself the three capacitors are in close proximity and are connected in parallel by means of copper bus bars in a low-inductance confriguration. The module design is given in Figure 6.

In view of the high currents and voltages employed in the arc plasma system, arcing can cause considerable problems. The module

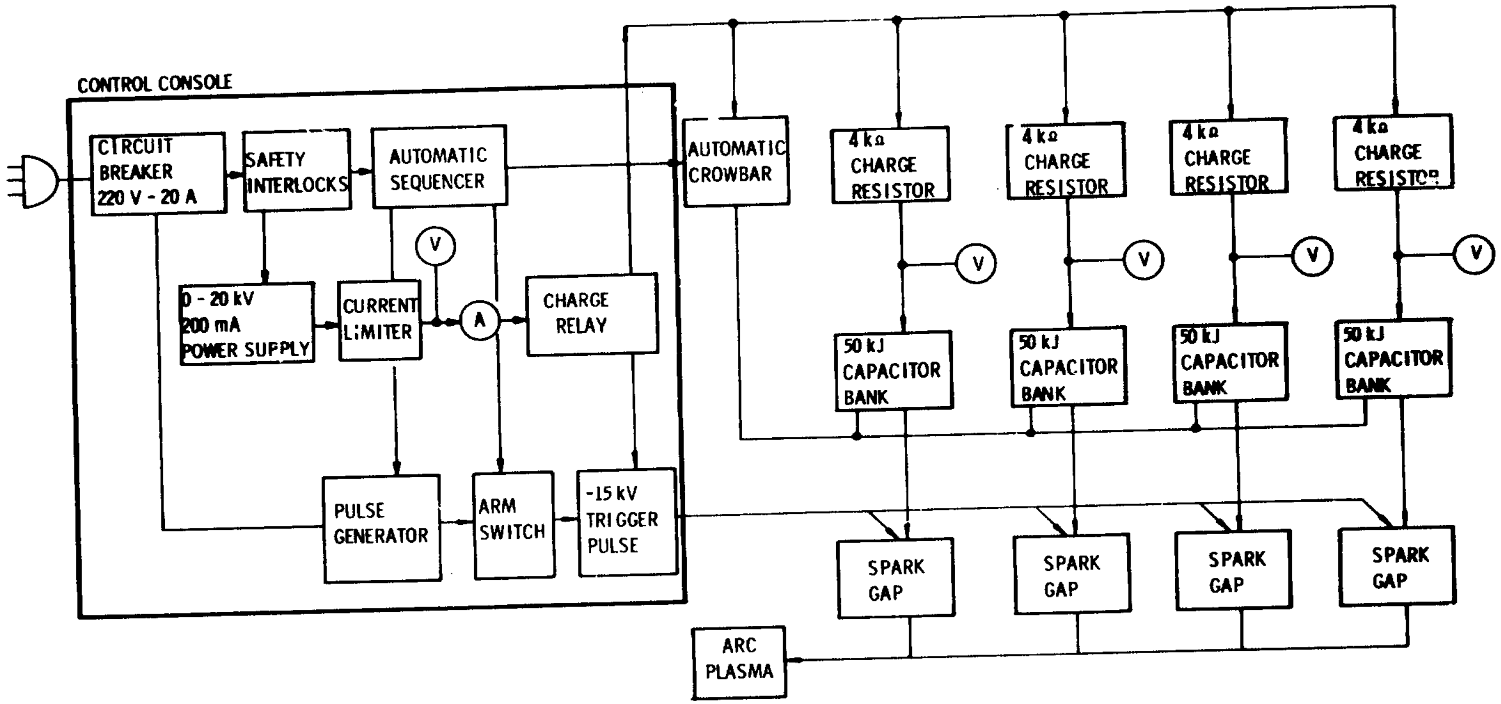

Figure 5. Electrical block diagram of the 200-kJ arc plasma accelerator system

TABLE I

Capacitor and Cable Specifications

Capacitors

Peak dc voltage	20 kV
Capacitance	15 μF + 20%, -10%
Inductance	40 nH (max)*
Energy	~300 J
Voltage Reversal	90%
Peak Current	200,000 A (direct short)
Life Expectancy	100,000 discharges

Cables

Type	20P2
Peak Voltage	20 kV
Reversal level for full nominal life	19 kV
Nominal Life	10^5 pulses
Characteristic Impedance	16 ohms ± 1 ohm
Inductance (@ 200 KCS)	32 ± 2 nH/ft
Delay	2 nsec/ft
Normal DC Resistance	
Inner conductor	0.52 /1000 yards
Outer Conductor	3.05 /1000 yards
Minimum Bending Radius	5 in.
Capacitances	124 pF/ft**

*nH = nanohenry (10^{-9} henries)

**pF = picofarad (10^{-12} farad)

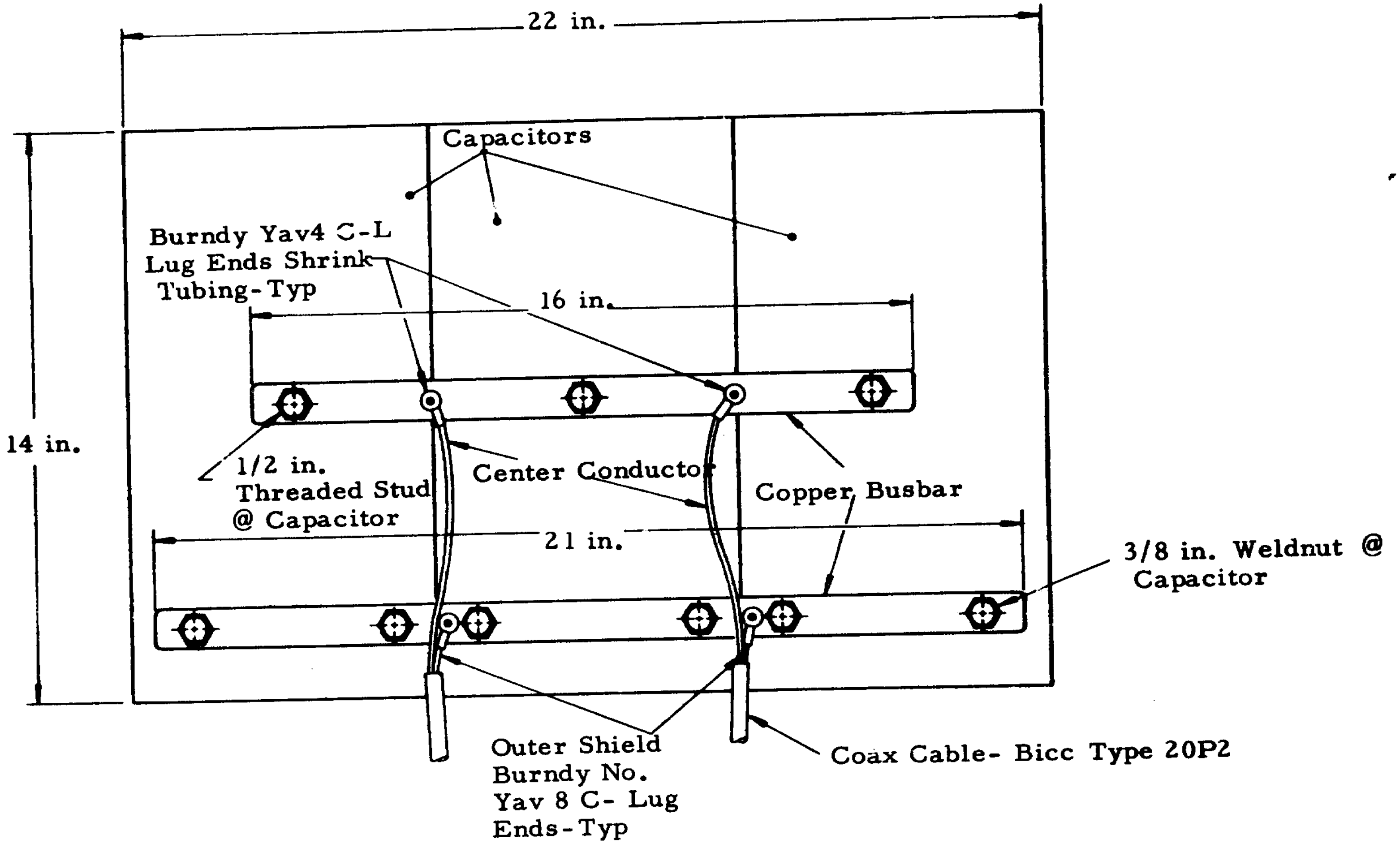

Figure 6. Capacitor module diagram

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design adopted was chosen to reduce these problems. If an internal short develops in a capacitor, there is a small probability of case rupture, due to internal pressure build-up at low currents. However, at high currents this probability is greatly increased (see Figure 7). Furthermore, an internal short in one capacitor will cause a large surge current, due to the discharge of the other capacitors through the short in the other capacitors. This is illustrated in Figure 8. The modular concept tends to minimize these surge currents because of the limiting action of the inductance in the connecting cables. A 4000 Ω resistance was also placed in series with each quarter bank to limit the current in nonshorted quarter banks to 2.5 A.

2.2 SPARK-GAP SWITCHES

Four identical open air spark-gap switches are used in the system. Each switch is in series with the quarter bank and the arc plasma gun. When properly triggered, the four spark-gap switches simultaneously discharge the four quarter banks into the arc plasma gun. In addition to their function as high-voltage, high-current switches, the spark-gap assemblies also serve as collecting points for the delay lines and the connections to the six capacitor modules. The spark-gap switch design is shown in Figure 9a.

The principal design consideration was imposed by a requirement for a low-inductance component. Low inductance was achieved by placing the hemispheres close to the base plate. This reduces the area available to cut the flux lines.

The base plates shown in Figure 9b, provide continuous electrical paths between the shields of the cables from the capacitor modules to the shields of the delay lines. The center conductors of these cables connect the hot center terminal of the modules and are open circuited at the spark-gap switch.

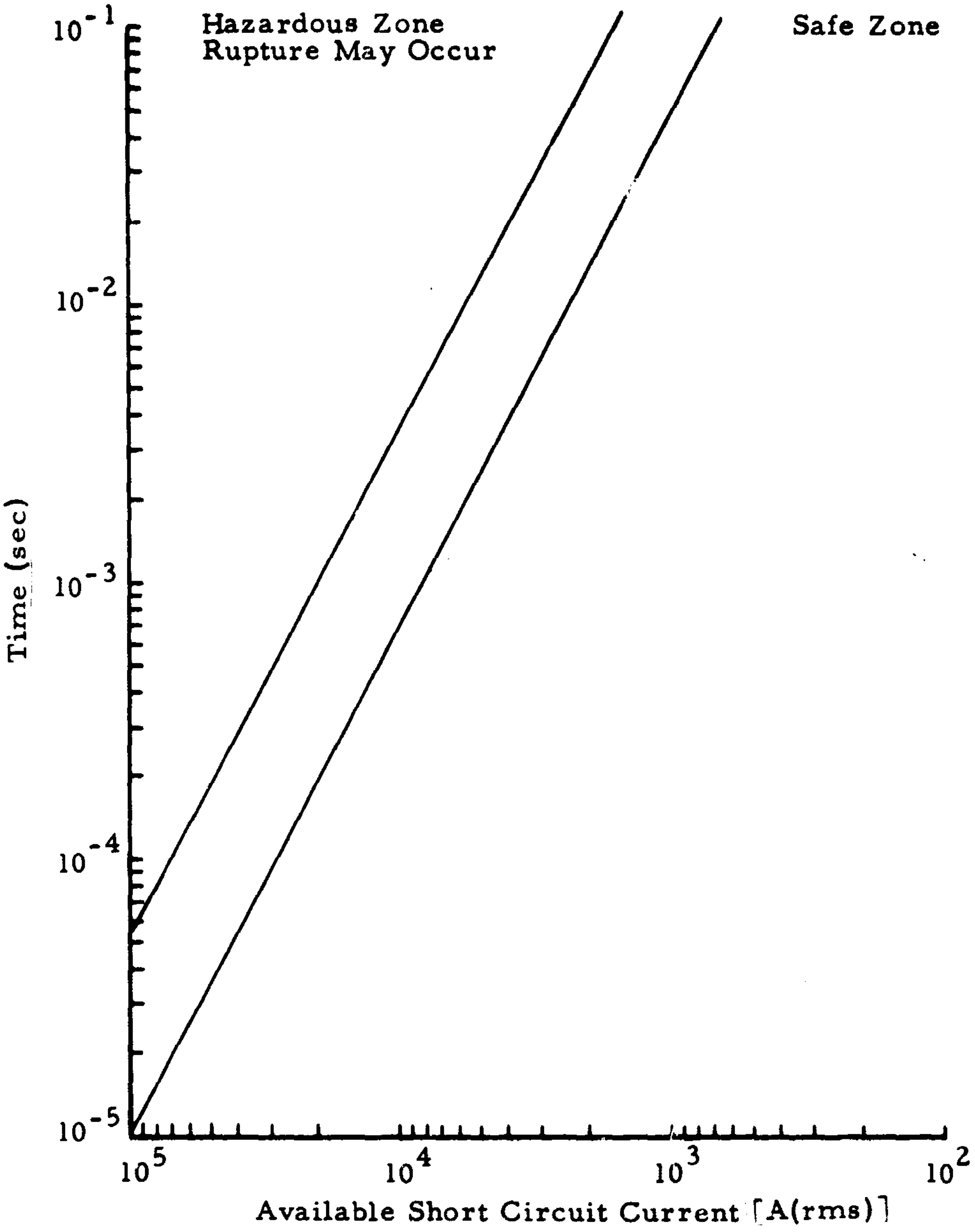


Figure 7. Current versus time for energy storage capacitors to rupture due to gas pressure caused by internal arcing

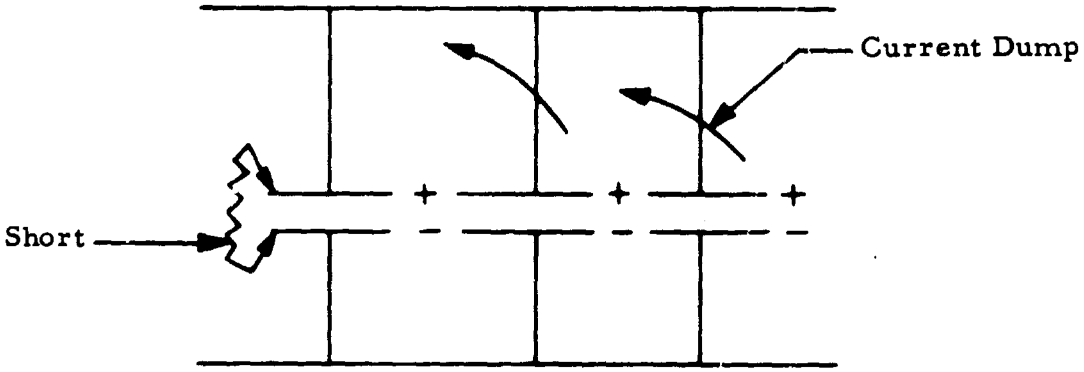
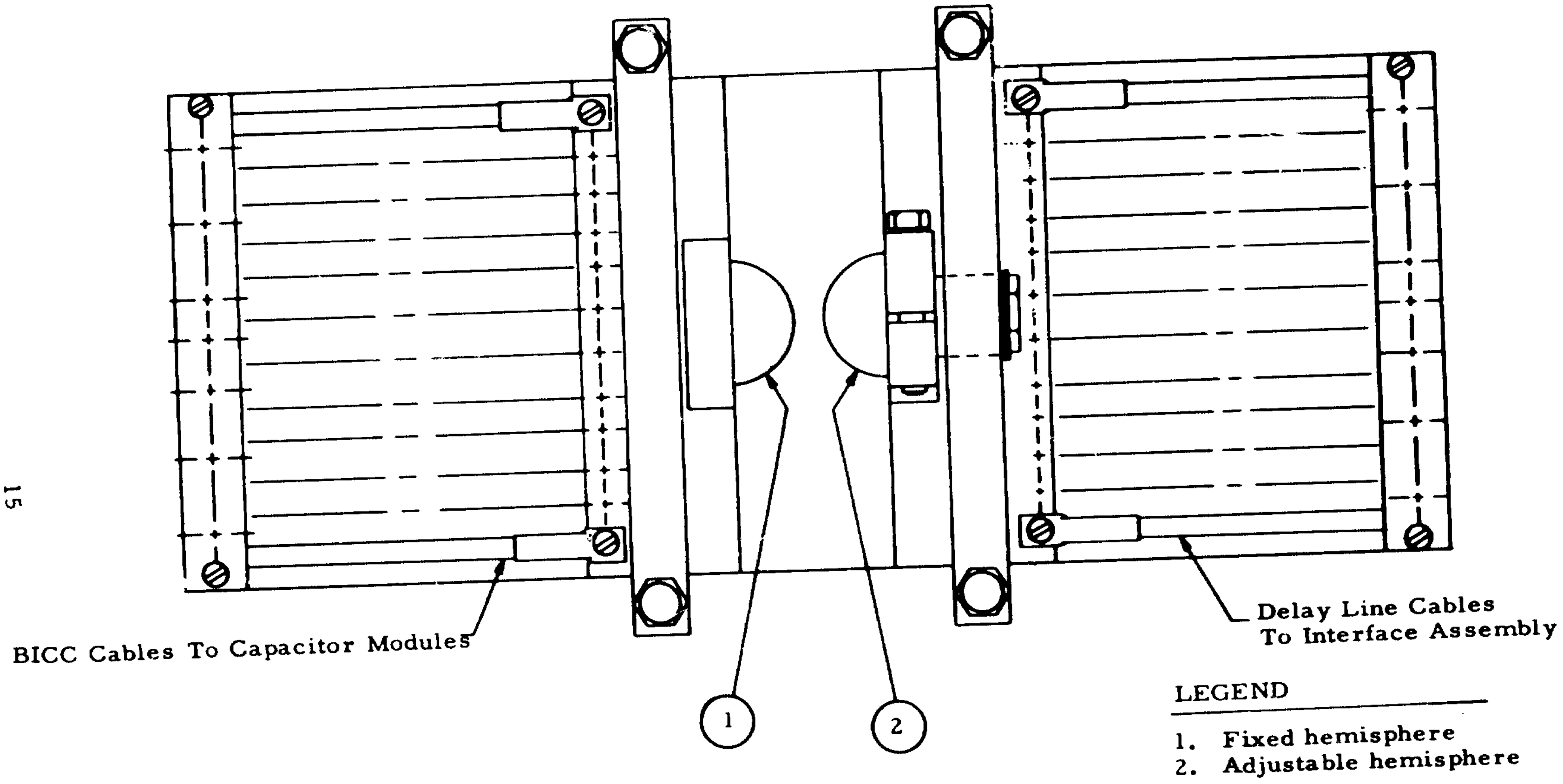


Figure 8. Illustration of capacitor internal short



(a) Top View

Figure 9. Spark gap switch assembly showing top and side views

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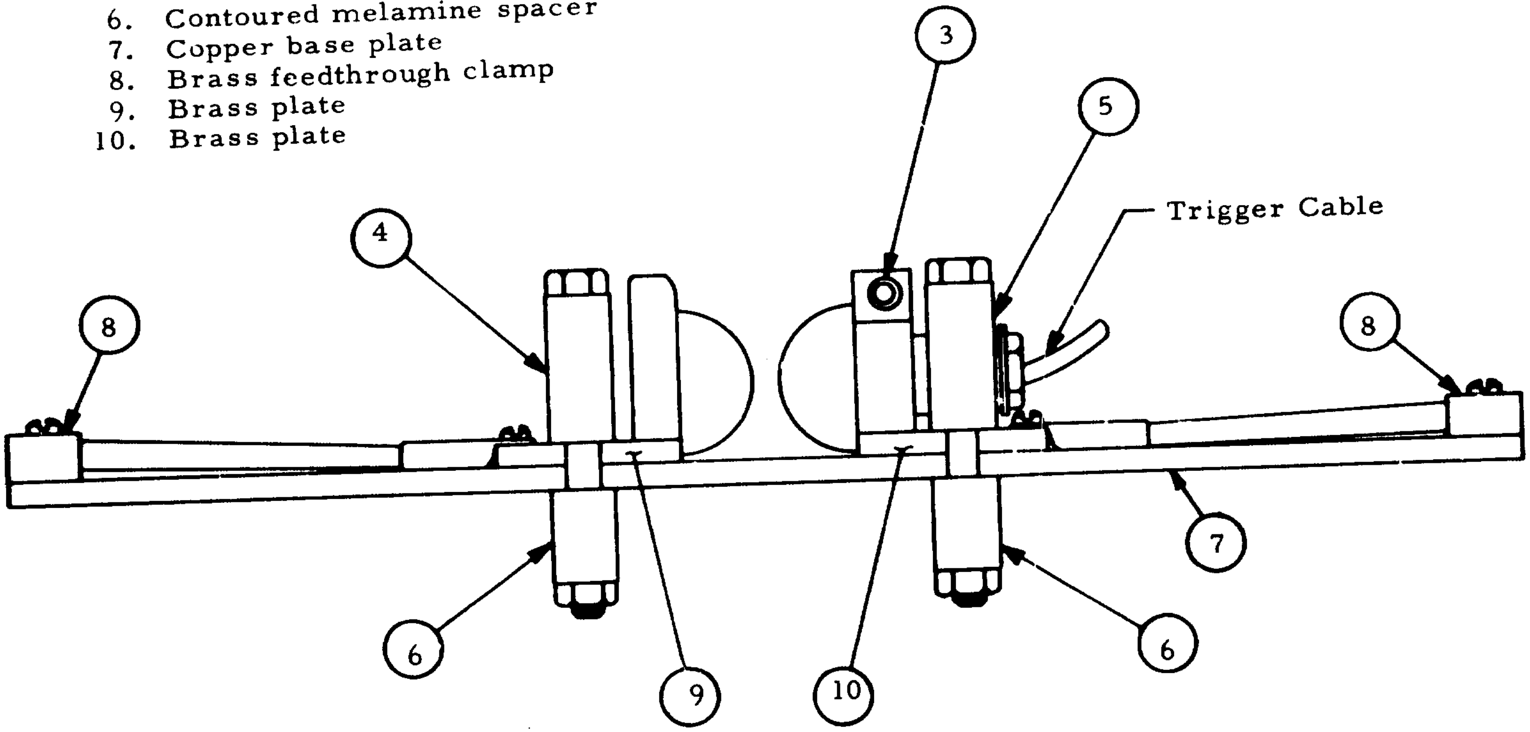
LEGEND

1. Fixed hemisphere
2. Adjustable hemisphere
3. Retainer bolt
4. Stainless steel hold-down bar, fixed spark gap
5. Stainless steel retainer block
6. Contoured melamine spacer
7. Copper base plate
8. Brass feedthrough clamp
9. Brass plate
10. Brass plate



(b) Side View

Figure 9. Spark gap switch assembly showing top and side views

When the capacitor bank is charged, the fixed hemisphere rises to a positive 20 kV potential. The adjustable hemisphere* is at ground potential. A -15 kV puls is applied to a trigger pin, coaxially coupled through the center of the adjustable hemisphere. This raises the potential difference across the gap to 35 kV, thus causing it to break over and discharge the capacitor bank into the arc plasma gun.

The gap between the hemispheres is adjusted to sustain a 20 kV potential and allow a -15 kV trigger pulse to cause a fast firing of the spark gap. A fast firing of the spark gap occurs within 30 nsec if the trigger spark is between the trigger pin and the fixed hemisphere. In contrast to this, a slow firing of the spark gap will occur if the trigger spark is between the trigger pin and the adjustable hemisphere, in which case, all four quarter banks would not discharge simultaneously into the arc plasma gun. Normally, gap spacing of 0.325 in. was used, however, this spacing is very dependent on humidity and the cleanliness of the room.

The time between the arrival of the trigger pulse and the closure of a given spark gap switch is nominally 30 nsec. If the voltage wavefront created by the closure of this switch arrives at another spark-gap switch before it has closed, the potential difference between the hemispheres will be reduced to zero and the switch will not close. Thus, to prevent quenching of the switches that have not closed, it is necessary to delay the wavefront from the closed switch by at least 30 nsec. This delay is achieved by using low-inductance coaxial cable delay lines from each spark-gap switch to the collector plate of the electrical feedthrough assembly.

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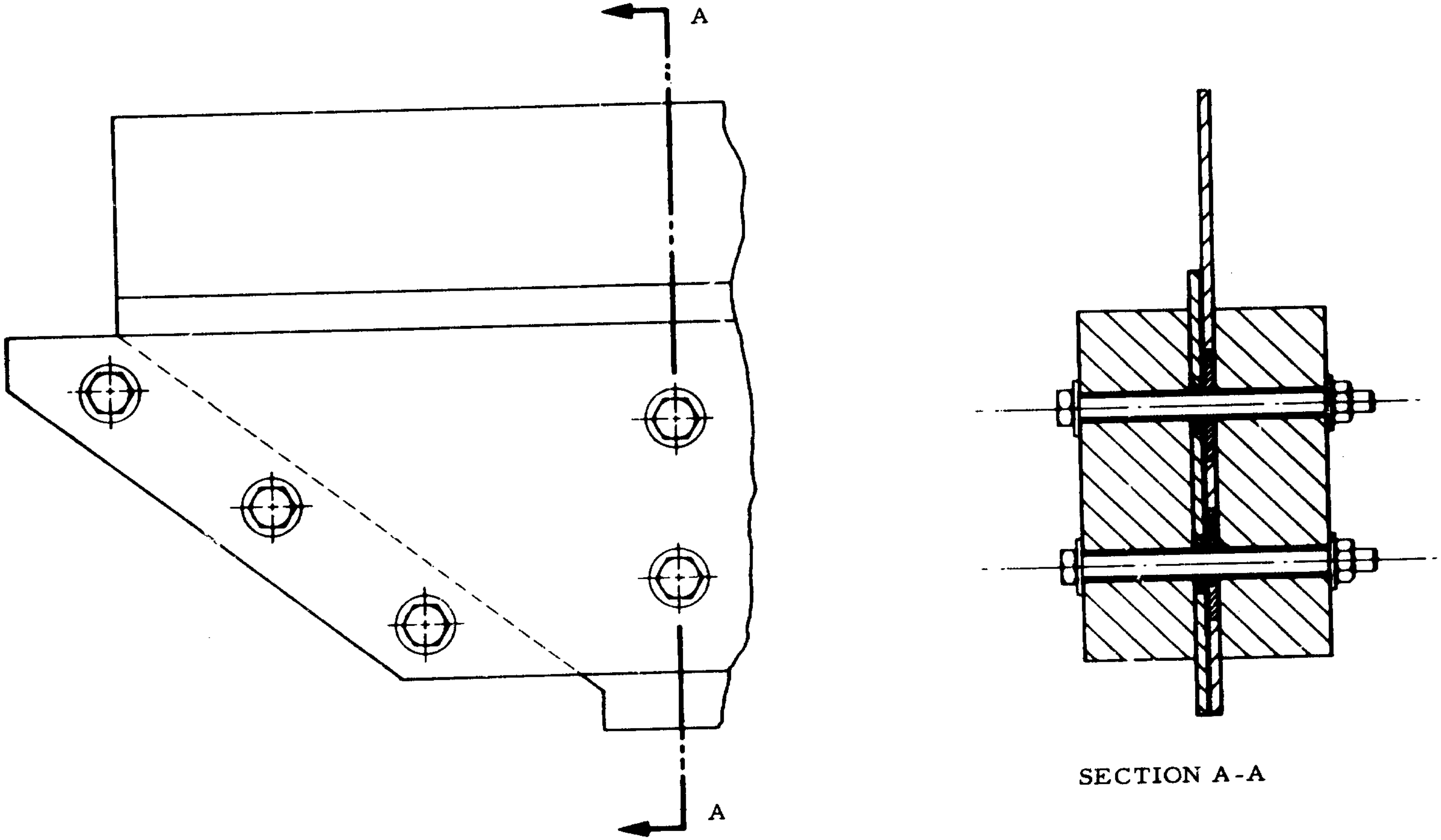
*The position of one hemisphere was made adjustable for ease in setting the air gap.

2.3 ELECTRICAL INTERFACE

The electrical interface consists of two triangular shaped collector plates (which terminate the delay line cables coming from the four spark-gap switches), two clamps for retaining the collector plates, and a set of thick brass feedthrough tabs imbedded in a rectangular block. These brass feedthrough tabs conduct the current surge from the bank discharge from the exterior atmospheric environment into an evacuated tube, which contains the arc plasma gun. Because of the exceedingly high repulsive force acting between the plates at the time of discharge the surrounding rectangular block was formed from very high strength fiberglas material (G-10). The nonconducting fiberglas material was used because of probable breakdown or eddy current problems with conductors.

The collector plate assembly is shown in Figure 10. The triangular shaped collector plates serve two functions. First, they provide a low inductance termination point for the delay line cables. It is at this junction that the full capacitor bank is paralleled. Second, they serve to transform the coaxial feedline into a parallel plate transmission line, thus allowing a gradually tapered entrance into the vacuum system. The insulation between the two conducting plates consists of two 62-mil silicone rubber sheets separated by a 14-mil mylar sheet. The mylar is used because of its high dielectric strength (1000 V/mil). The rubber is used both for its electrical properties and its ability to provide a vacuum seal. Silicone rubber was chosen over neoprene because it has an excellent balance of physical, electrical and chemical properties over a wide temperature range. This material has extremely high resistance to high-voltage ionization (corona resistance approaches that of mica) with the added advantage of flexibility. The silicone rubber used was supplied by Raybestos Manhattan. The characteristics of this material are listed in Table II.



SECTION A-A

Figure 10. Collector plate assembly

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TABLE II

Silicone Rubber Insulation Material Specifications

Raybestos Manhattan type	No. 64
AMS Number	3301 C
Durometer	43
Tensile Strength	1015 psi
Elongation	500%
Tear Resistance	60 lb/in.
Compression Set	9% (22 hr/350 °F)
Brittle Point	-85 °F
Volume Resistivity	$> 10^{15}\ \Omega$
Electric Strength	> 600 V/mil
Dielectric Constant	~ 3.0
Temperature Range	175 to 500 °F

The insulation sandwich between the collector plates is continued between the brass conductors. Pressure is applied to the sandwich at this point by undersizing of the retaining gap. This provides a vacuum seal for the evacuated tube containing the arc plasma gun.

Clamps for retaining the collector plate were formed from thick fiberglas material for reasons mentioned above. Because of the large collector area, two bolts were needed in the interior area of the plate to prevent bulging. These bolts, although conducting, were insulated from the plates by circular teflon guards. Conducting bolts were utilized because of their high-strength properties.

The vacuum system consists of standard 6-in. i. d. pyrex glass pipe and 8 in. i. d. lucite tubing. Supports for the vacuum system, shown in Figure 11, are attached to Thomas linear bearings and are designed to slide along two guide rails. This feature allows rapid turn-around while maintaining alignment between the arc plasma gun and the target plate.

2.4 CONTROL CONSOLE

The control console contains a high-voltage power supply for charging the capacitor bank, and other indicating and control circuits for the operation of the arc plasma system such as the trigger circuit for the spark-gap switches and an automatic sequencer for discharge of the bank. The control console was divided into three major sections (Figure 12) according to function. The top section contains the master control circuits for discharge of the bank. The middle section contains ac power controls and the voltage control for the charging circuit. The bottom section contains the high-voltage power supply and the high-voltage trigger generator for the spark-gap switches.

The major components placed in the master control section were control switches, indicating lights, meters, low-voltage pulser and the automatic sequencer. The control switches allow the operator

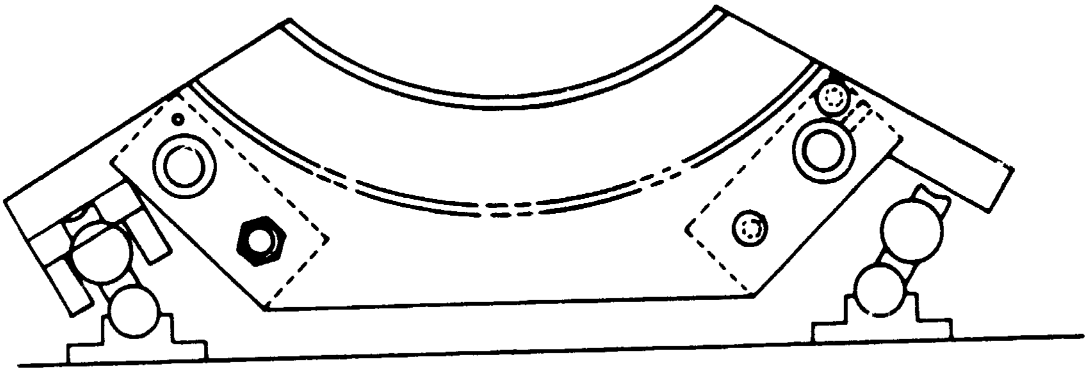

Figure 11. Supports for vacuum system

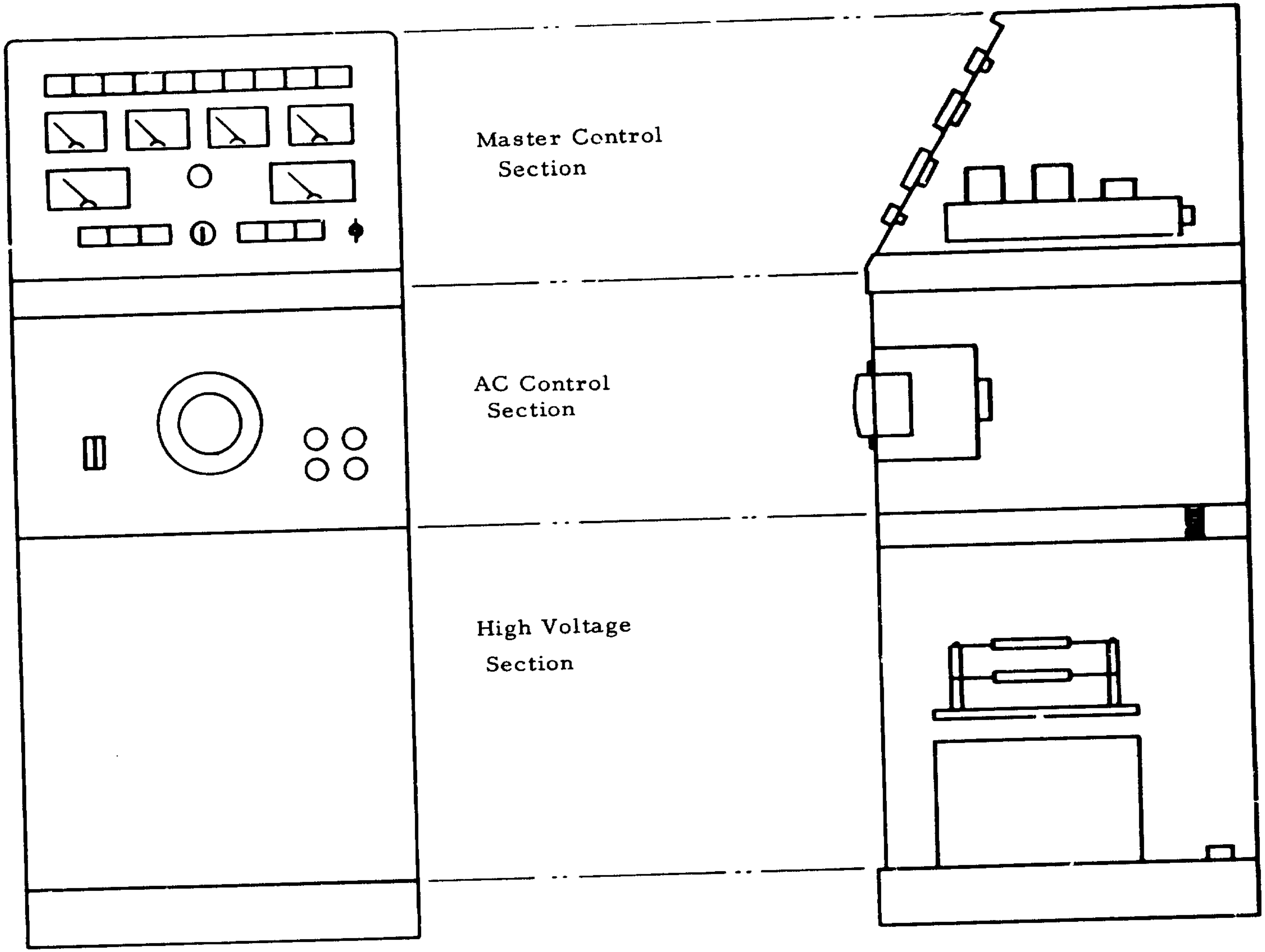

Figure 12. Control console

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to turn on the high-voltage power, charge the capacitor bank, arm and trigger the spark-gap switches and connect a dump circuit across the capacitor bank. The eleven indicating lights were placed on the face of the master control panel and show the operational condition of the arc plasma system. Six panel meters were included to monitor the voltage on each quarter bank and both the voltage and current in the 20 kV power supply.

The low-voltage pulser was designed to develop a pulse a few microseconds wide and several hundred volts in amplitude to initiate the high-voltage trigger generator. This pulse is also available at the front panel as a t=0 pulse. The automatic sequencer was designed to allow the operator to start a 5 sec countdown (refer to Figure 13) including automatic closure of the vacuum valve solenoid, actuation of the camera shutters, arming of the system, firing of the system, crowbarring, actuating a safety circuit for the capacitor bank, and resetting by manual depression of a single switch button.

The ac power controls placed in the middle panel of the control console include the main ON-OFF control for the entire control console. All ac power to the system comes through the circuit breaker for this control. The incoming ac power is further divided into four branches which are protected by separate indicating line fuses.

The voltage control for the charging circuit, which is also contained in the middle panel, is a Variac autotransformer. The Variac supplies 0 to 280 Vac to the primary of a high-voltage transformer in the lower panel which steps it up to a maximum of 22.5 kV. This high voltage is utilized for charging and triggering of the capacitor bank.

2.5 ARC PLASMA GUN

The arc plasma gun design is shown in Figures 14 and 15. The large sheath enclosing the rails prevents their movement under the large repulsive forces present during a shot and provides a rectangular

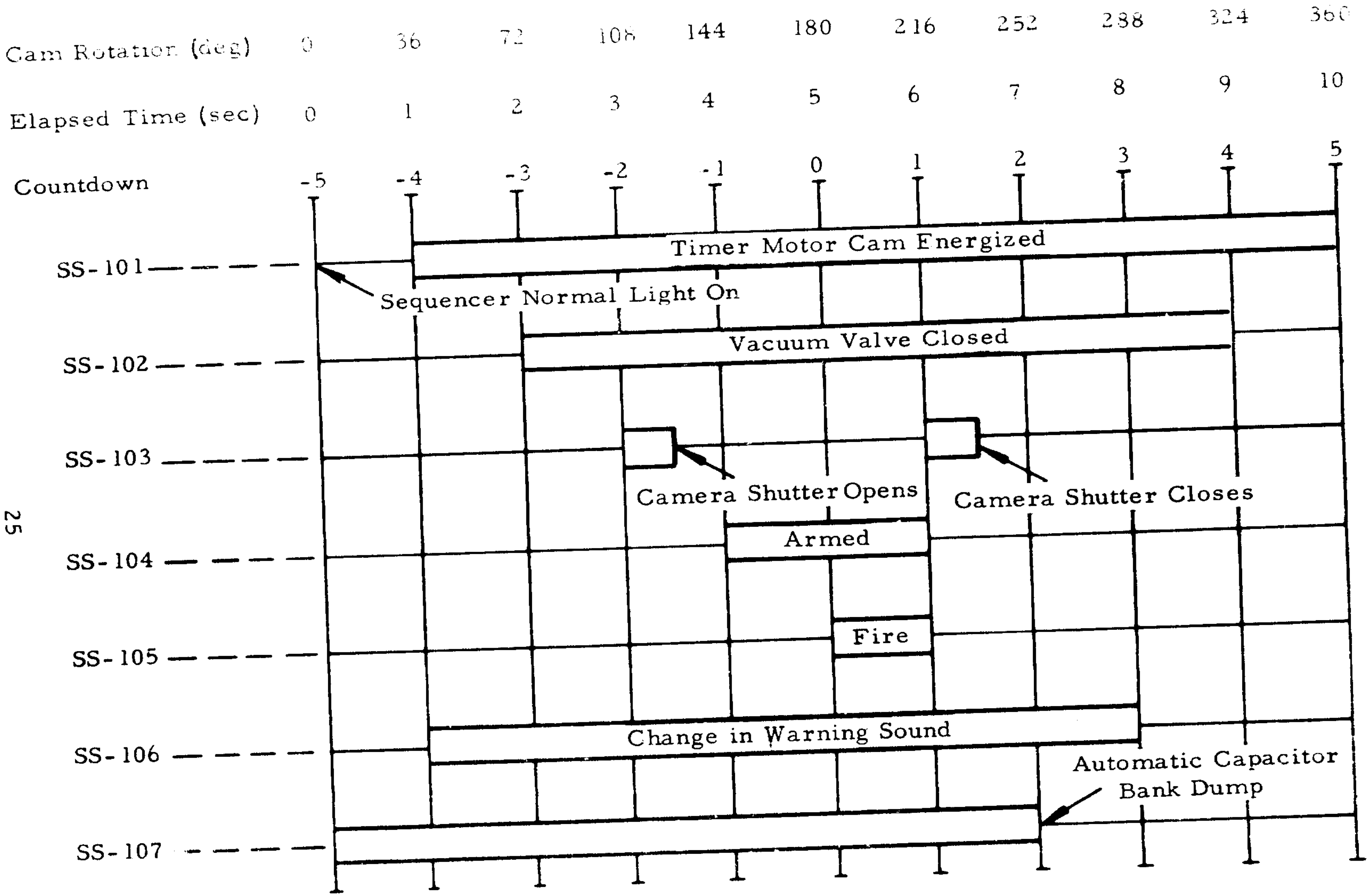

Figure 13. Automatic sequencer

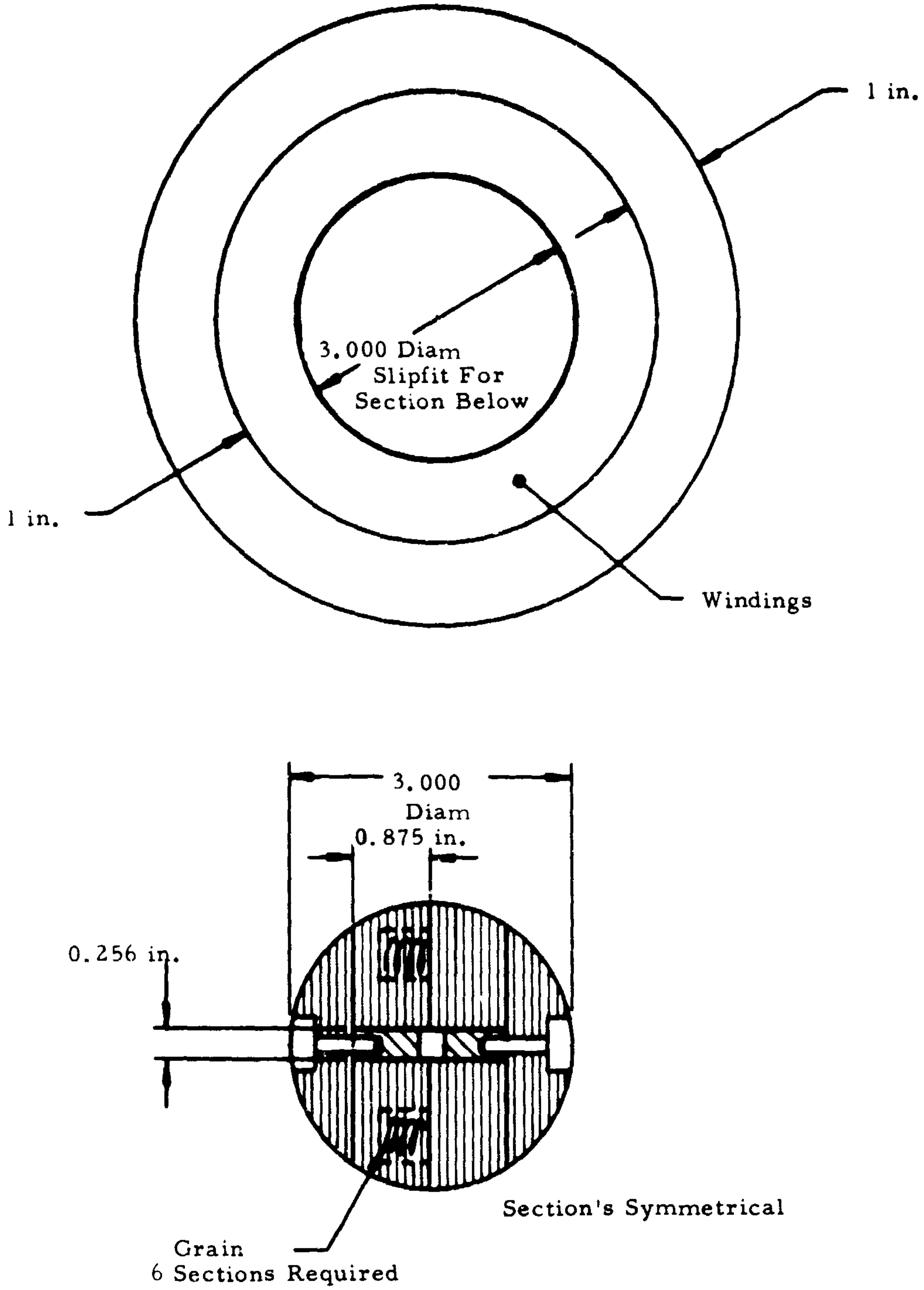

Figure 14. The arc plasma gun design

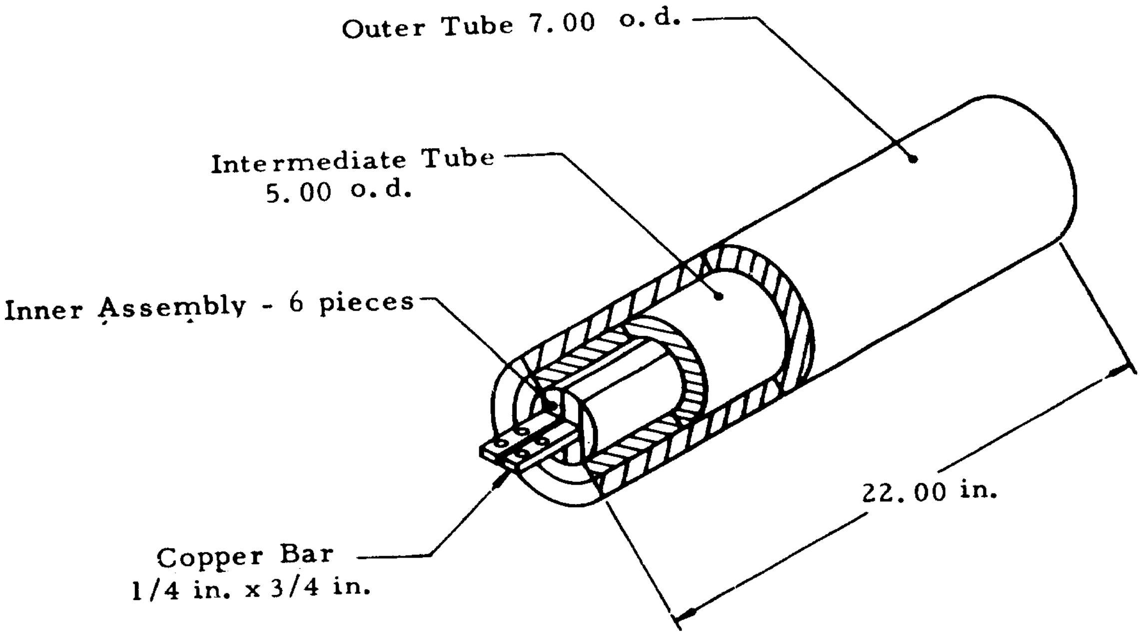

Figure 15. Improved arc plasma gun

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guide for the accelerated particles. The sheath was designed to withstand the reaction force due to the repulsive force between the rails caused by the discharge current and also the sudden expansion force exerted on its walls by the hot plasma. The high-yield strength of the sheath was attained by the use of multiple layers of circularly wound fiberglas. The circular winding prevents shear tears from developing in the sheath. The sheath was divided into an outer shell and inner section for ease in assembly and disassembly of the gun.

3.0 DETAILED DESIGN AND FABRICATION SPECIFICATIONS

The constructional details of the system components and a circuit description of the electrical functions are given in this section. The fabrication drawings used in the construction are identified in this section along with detailed electrical assembly information.

3.1 CAPACITOR BANK

The capacitor bank consists of 72 high-energy, low-inductance discharge capacitors manufactured by Cornell-Dublier (type NRG-204). The manufacturer's specifications are given in Table I. The measured capacitance value for the full bank was 1026 μF. The full bank is divided into four quarter banks mounted on 4 ft by 4 ft wide plywood platforms and are insulated by three layers of 14-mil mylar sheets.

Each quarter bank is further subdivided into six modules of three capacitors each. The three capacitors in each module are connected by copper bus bars 0.25 in. thick and 1.0 in. wide. A 16-in. "hot" bar connects the center terminals and a 21-in. bar connects the case terminals. All corners of these bars are rounded to prevent arcing.

Up to six modules can be paralleled at the spark-gap switch to form a quarter bank by use of a low-inductance transmission line. The module transmission line consists of two paralleled BICC low-inductance coaxial cables. The BICC cables are attached to the copper bus bars and average approximately 5 ft in length.

Each quarter bank is discharged through a separate spark-gap switch. The four quarter banks are paralleled at the collector plate by 48 BICC low-inductance coaxial cables. The modules and quarter banks are paralleled to lower the inductance and therefore to produce faster rise times and higher peak currents.

3.2 SPARK-GAP SWITCHES

The four spark-gap switch assemblies are bolted onto two melamine sheets located above the front row of capacitors. The saprk-gap switch assembly — top and side views — is shown in Figures 9a and 9b, respectively. The spark-gap hemispheres (Items 1 and 2) have a 1-in. radius. The trigger-pin assembly is inserted through the center of the adjustable hemisphere and is connected to the RG8 trigger cable by a coaxial screw-in fitting. The distance between the two hemispheres is set by loosening the retainer bolt (Item 3), inserting a gauge block with the desired thickness between the gap, sliding the movable hemisphere forward until it is pressed tightly against the gauge block and then tightening the retainer bolt (Item 3). The trigger pin should be flush with the front face of the adjustable hemisphere. The hemisphere assemblies are clamped into place by two stainless steel bars (Items 4 and 5), two contoured melamine spacers (Item 6) and four 1/2-in. diameter bolts (torque to 50 ft lb).

The 8-in. wide copper base plate (Item 7) has three wraps of 0.014 in. thick mylar for insulation. An additional sheet of 0.014 in. mylar is placed under the hemisphere assembly. This sheet is easily replaceable if its surface should become damaged. The dielectric strength of the four layers of mylar is 56,000 V.

Each spark-gap switch assembly is in series with twelve BICC coaxial cables. The shields of the coaxial cables are clamped to the copper base plate (Item 7) by the brass feedthrough clamps (Item 8). The base plate provides a continuous electrical path for the shields of the coaxial cables from the capacitor bank modules to the shield of its delay lines. The center conductors of the BICC coaxial cables are lugged and screwed to the brass plates (Items 9 and 10) which are bolted to the hemispheres. The center conductors of the BICC coaxial cables which connect to the hot center terminals of the high-velocity capacitors are therefore open circuited at the spark-gap switch.

The high-voltage charging line from the charging network board is connected to the brass plate (Item 10) which is bolted to the fixed hemisphere. This is the junction point for the center conductors of the coaxial cable going to the hot terminals of the capacitors for each quarter bank. The adjustable hemisphere is referenced at ground potential and the shield of the trigger cable is terminated there. When the capacitor bank is charged, the fixed hemisphere rises to a positive 20,000 V. The adjustable hemisphere is at ground potential. A minimum 15,000-V pulse is applied to the trigger pin inserted in the adjustable hemisphere. This pulse drives the potential difference across the gap to 35 kV causing the pulse to break over thus discharging the capacitor bank into the arc plasma gun.

3.3 ELECTRICAL INTERFACE

The major components of the interface assembly are two triangular shaped copper plates, two thick brass plates, a 3-in. wide G-10 flange and two G-10 hold-down clamps (Figure 10).

The 48 BICC coaxial delay line cables are terminated on the copper plates. The two brass plates are bolted to the opposite end of the copper plates and extend through the G-10 flange into the vacuum system. These two conducting surfaces are insulated by two sheets of 62-mil silicone rubber and one sheet of 14-mil mylar. The height of the rectangular slot in the G-10 flange through which the brass plates are inserted is machined 0.025 in. undersize to compress the silicone rubber providing a vacuum seal on the inner surfaces of the brass plates. The outer surfaces are sealed with a silicone potting compound, RTV-108.

The collector plate hold-down clamps consist of two 3-in. thick sheets of G-10 glass epoxy material on either side of the collector plates, joined by eight 5/8 in. diameter high-strength steel bolts. The bolts are indulated with mylar tape and shrink-tubing. Six bolts, three on either side, are located in an out-board position. The remaining two bolts go through the center of the clamp and are insulated from the copper collector plates by a set of large circular teflon guards. The bolts are torqued to 80 ft lb to obtain maximum strength. The G-10 material was selected instead of melamine because it has greater strength and is easier to machine.

The following procedure should be observed to assemble the interface assembly:

(1) Bolt the brass plates to the collector plates.

(2) Place the three layers of insulation between the two metal plates.

(3) Apply a thin layer of RTV on the rectangular slot, the top of the brass plates and on the insulation directly between the brass plates.

(4) Apply a generous amount of RTV on the side of the brass plates.

(5) Insert the whole assembly through the rectangular slot until the brass extends out 2.5 in. Allow the excess RTV to squeeze out.

(6) Remove all the excess RTV and allow the potted assembly to dry (RTV-108 requires approximately 24 hr per 1/8 in.).

(7) Connect the vacuum system to the feedthrough flange and pump.

(8) While pumping, apply RTV around the area where the brass feedthrough tabs enter the G-10 block. Any leaks will be sealed by the RTV.

(9) Remove the vacuum system and apply RTV to the inside face of the brass feedthrough tabs.

(10) Cover the RTV with a 10-mil teflon sheet to protect it from arc blowback during a shot.

In order to accommodate the arc plasma gun, the first section of the vacuum system was made from 8 in. i.d. lucite tubing with 0.5 in. wall thickness. A sealing flange was placed at one end to provide the stepdown to the 6 in. pyrex glass pipe. A lucite ring is glued at the other end of the 8 in. i.d. lucite tube to help retain the gum rubber of the shock decoupler. The shock decoupler assembly (Figure 16) consists of a lucite flange which is bolted to the G-10 feedthrough block and a 1/4 in. thick gum rubber circlet which spans a 1-in. gap between the lucite flange and the first vacuum section. The first vacuum section is secured to the table by means of a nylon strap pulled tightly over the top of the 8 in. i.d. lucite tube. The last vacuum section, which holds the target, is bolted to the table with angle brackets to prevent the vacuum system from being pulled forward while pumping. The vacuum system is approximately 100 in. long; however, the length can be increased by bolting on additional pyrex glass sections. The standard length for each straight section is 30 in.

3.4 CONTROL CONSOLE

The control console is enclosed in a 48-in. high Emcor sloped-front cabinet with standard 19-in. wide panels. It contains a high-voltage power supply for charging the capacitor bank and various indicating and control circuits for the operation of the arc plasma system (such as the trigger circuit for the spark-gap switches and an automatic sequencer for discharge of the bank). The control console was divided into three major sections (Figure 12) according to function. The top section contains the master control circuits for the operation of the bank. The middle section contains ac power controls and the voltage control for the charging circuit. The bottom section contains the high-voltage power supply and the high-voltage trigger generator for the spark-gap switches. The function of each of the panel-mounted components

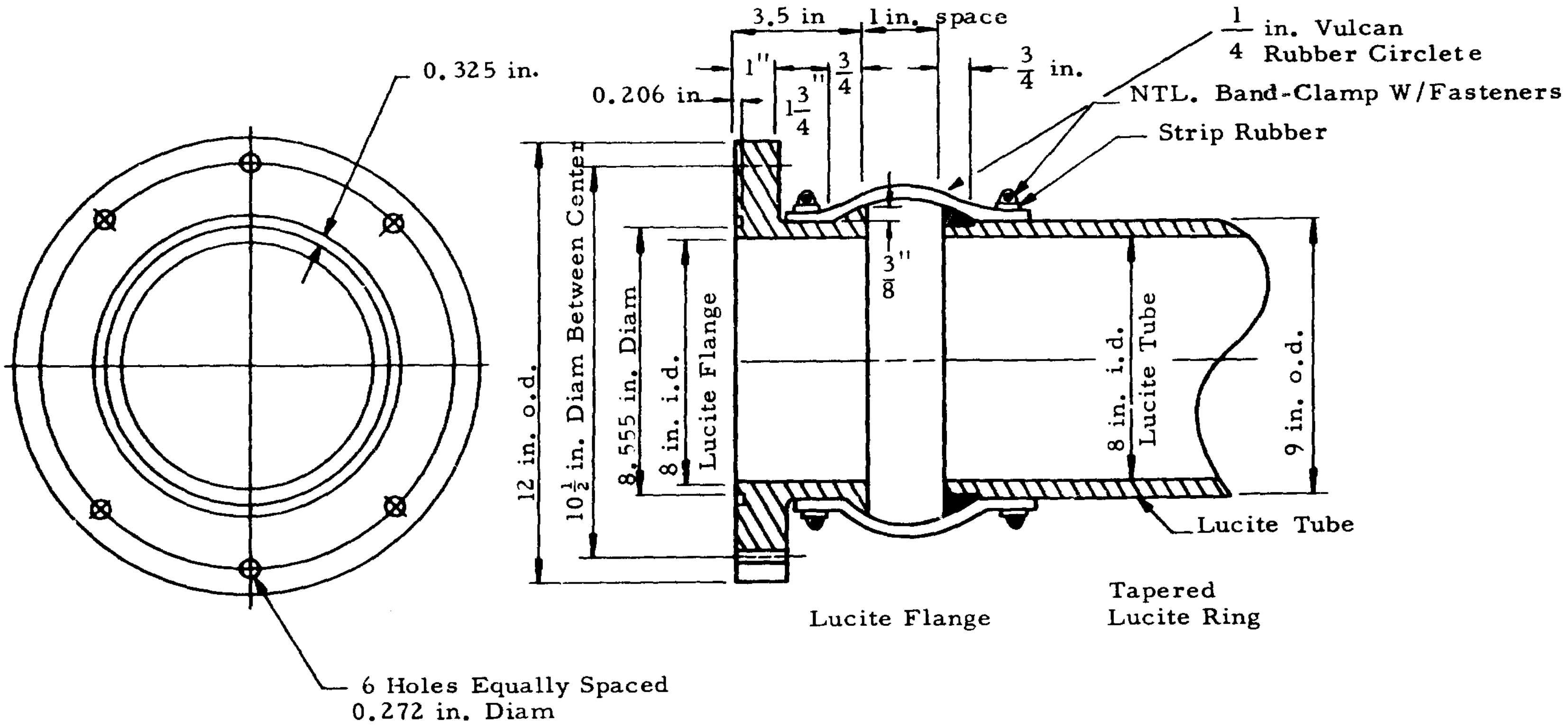

Figure 16. Shock decoupler

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of the master control section are described below.

3.4.1 INDICATOR LIGHTS

(1) Time-Delay Complete Lamp lights on the closure of the Amperite time delay switch (TD-101). The 6279 high-voltage thyratron requires a 3-min filament warmup time before high voltage can be applied to its plate. The time-delay switch begins its 3-min cycle when the 28-Vdc power supply is turned on by means of the main circuit breaker located on the ac power and Variac panel.

(2) Interlock Complete Lamp indicates that the interlock circuit through the console door switch and the safety switch (S-503) in the remote box is closed. This circuit has to be complete in order to activate the high-voltage power supply.

(3) Sequencer Normal Lamp lights when all the cams of the automatic sequencer are in their initial preset position.

(4) High-Voltage On Lamp indicates that 220 V have been applied to the Variac and that the high-voltage power supply can be increased to 22.5 kV.

(5) Charging Lamp will light if the START CHARGE switch is depressed after activating the high-voltage power supply. This indicates that the high-voltage power supply has been connected to the capacitor bank (via the charging network) and that the crowbar relay has been energized thus removing the dump circuit from across the capacitor bank. The capacitor bank may now be charged by the high-voltage power supply.

(6) Ready To Fire Lamp lights after depressing the STOP CHARGE switch which disconnects the output of the high-voltage power supply from the capacitor bank and applied it to the high-voltage trigger generator. The system is now ready to be fired either by operating the automatic sequencer or by depressing the manual ARM and FIRE switches.

(7) Sequencer Running Lamp indicates that the sequencer motor has power and is advancing the cams through one complete cycle.

(8) Vacuum Valve Closed Lamp is controlled by the automatic sequencer and is operated at t-3 sec. This indicates that ac power has been removed from the vacuum valve solenoid thus opening the vacuum line between the pump and the vacuum system.

(9) Camera Operated Lamp flashes twice indicating that the automatic sequencer has pulsed the camera shutters once at t-2 sec and again at t+1 sec. This circuit was designed to be used with an actuator similar to Tektronix Shutter Actuator Model No. 016-211.

(10) Armed Lamp indicates that the output of the low-voltage pulse generator has been connected to the input of the high-voltage pulse generator. This circuit can be activated by depressing the MANUAL ARM switch or by operating the automatic sequencer whenever the high-voltage power supply is on.

(11) Fired Lamp indicates that the low-voltage pulse generator has been triggered. This circuit is activated by either depressing the MANUAL FIRE switch or by operating the automatic sequencer. The high-voltage thyratron will also trigger if the system is armed.

3.4.2 CONTROL SWITCHES

(1) High-Voltage Switch is operated by inserting the key, turning clockwise (CW) to unlock and depressing the key. If the interlock circuit is complete and the Variac knob has been rotated fully counter clockwise (CCW), relay K-201 will energize applying ac power to the Variac and to certain control circuits. The automatic sequencer is made inoperative at this time, and the HIGH VOLTAGE ON lamp will light. Turning the Variac CW will put high-voltage dc on the high-voltage thyratron circuit only. The capacitor bank is not connected to the high-voltage power supply at this time.

(2) Start Charge Switch causes six relays to be energized. Relays K-103 and K-301 transfer the output of the high-voltage power supply from the high-voltage trigger generator circuit to the capacitor bank (via the charging network). Relays K-104 and K-601 remove the

dump circuit from across the capacitor bank. Relays K-101 and K-102 supply the necessary voltage to keep the above relays energized after releasing the start charge switch. The CHARGING lamp will light and the warning bell will begin to buzz. The capacitor bank may now be charged to the desired voltage by turning the Variac CW.

(3) Stop Charge Switch is depressed after the bank is charged to the desired voltage. Relays K-103 and K-301 drop out disconnecting the output of the high-voltage power supply from the capacitor bank and transferring it to the high-voltage trigger circuit. Relay K-101 also drops out and allows the automatic sequencer to become operative again. The READY TO FIRE lamp will light.

(4) Auto Sequencer Switch applies power to the sequencer motor. If this switch is depressed and held for one second (until the sequencer normal lamp goes out), the automatic sequencer will make one complete revolution and again stop at its normal position. The seven cam-operated microswitches will be actuated in the sequence shown in Figure 13. The SEQUENCER RUNNING lamp will be lit as long as there is power to the motor. The Auto Sequencer circuitry is located behind this panel and is mounte on the chassis. Description of this circuitry is given in Section 3.4.5.

(5) Manual Arm Switch will energize relay K-106 (if the high-voltage power supply has been activated) thus connecting the output of the low-voltage pulse generator to the input of the high-voltage trigger generator. The ARMED lamp will also light.

(6) Manual Fire Switch energizes relay K-107 thus triggering the low-voltage pulse generator. The output pulse is fed to a BNC jack on the front panel and to a BNC jack on the back of the chassis. If the system is armed when the fire button is depressed, all four spark-gap switches will receive a -15 kV trigger pulse. The FIRED lamp will light.

(7) Manual Dump Switch when depressed will shut off the high-voltage power supply and place the dump circuit across the capacitor bank. Any voltage on the capacitor bank will be discharged through the charging network within 30 sec at a peak current of 4 A. The manual

dump switch may be operated at any time, and it will de-energize relays K-101, K-102, K-103, K-104, K-201, K-301, and K-601. In order to reactivate the high-voltage power supply, the Variac must again be turned fully CCW (0 V position).

3.4.3 METERS

(1) Capacitor Bank No. 1 Meter indicates the voltage on the first quarter bank. The meter scale reads from 0 to 20 kV. The meter has a 100 μA full-scale sensitivity and is protected from overloads by a solid-state meter protector. The 200 MΩ of series resistance is mounted on the charging network board, so that only low voltage is carried to the console's metering circuits.

(2) Capacitor Bank No. 2 Meter is the same as Bank 1 but reads the voltage on the second quarter bank.

(3) Capacitor Bank No. 3 Meter is the same as Bank 1 but reads the voltage on the third quarter bank.

(4) Capacitor Bank No. 4 Meter is the same as Bank 1 but reads the voltage on the fourth quarter bank.

(5) Power Supply mA Meter monitors the current flow of the high-voltage power supply. The meter scale reads from 0 to 200 mA and has a 200-mA full-scale movement. The meter is protected by a zener diode (D-303) circuit (located in the high-voltage power supply chassis) that will shunt the meter if the current exceeds 250 mA. The metering circuit is on the ground side of the high-voltage transformer.

(6) Power Supply kV Meter indicates the voltage of the high-voltage power supply. The meter scale reads from 0 to 25 kV. The meter has a 100 μA full-scale sensitivity and is protected from overloads by a solid-state meter protector. The 250 MΩ of series resistance is located in the high-voltage power supply chassis so that only low voltage is carried through the metering circuits.

3.4.4 FRONT PANEL JACK

The output of the low-voltage pulse generator is fed to the BNC jack on the front panel. The pulse is several hundred volts in amplitude and a few microseconds in width. This pulse can be used to trigger the data recording equipment at t=0. The pulse is available by depressing the MANUAL FIRE switch or by operating the automatic sequencer.

3.4.5 ADDITIONAL MASTER CONTROL SECTION COMPONENTS

The functions of the major circuits located on the chassis but not on the front panel of the master control section are:

(1) 28 Vdc Power Supply is turned on by the main circuit breaker. The power supply is unregulated solid-state with 2 A maximum capacity used to actuate the time delay switch (TD-101), relays K-301 and K-601 and to the six lighted control switches. A large 8400 μF capacitor (C-105) is used as a filter in the output of this power supply.

(2) Time Delay Switch is needed to allow the filaments of the high-voltage thyratron time to warm up 3 min before applying high voltage to its plate. This switch (Amperite No. 26N0180) begins its 3-min timing cycle as soon as a 28-Vdc signal is applied to its heater. At the end of 3 min, the switch contacts close completing the first part of the interlock circuit.

(3) 500 Vdc Power Supply is turned on by the main circuit breaker. It is an unregulated low-current solid-state power supply used for the 2D21 pulse generator. Current flows only when the 2D21 is triggered.

(4) Low-Voltage Pulse Generator is triggered by depressing the manual fire switch or by operating the automatic sequencer. A pulse a few microseconds wide and several hundred volts in amplitude is available at the front panel BNC jack from the secondary of the output transformer (T-103) at t=0. Simultaneously, a pulse from the tertiary winding of T-103 (2:1 set-up in voltage) is fed (via ARM relay)

to the grid of the high-voltage thyratron in the four-channel trigger generator. Resistors R-103, R-104 and R-109 form a voltage divider string to supply a positive voltage on the cathode to bias the 2D21 off. Capacitor C-104 provides an RF bypass path around the cathode resistor R-109. Energizing relay K-107 applies 500 Vdc across the resistor divider string R-105, R-106, and R-107. Capacitor C-102 and resistor R-108 then differentiate the pulse and couple it to the grid of the 2D21. This triggers the thyratron into conduction causing C-103 and C-104 to discharge through the pulse transformer T-103.

(5) Control Relays are all identical and therefore interchangeable. The seven relays (K-101 through K-107) are DPDT plug-in relays with 110 Vac coils; they plug into a standard octal socket. Control relays allow the arc plasma system to be operated either manually or by the automatic sequencer. A plastic dust cover is furnished for each.

(6) Automatic Sequencer allows the operator to press one switch and the sequencer will start a 5 sec countdown which automatically closes the vacuum valve solenoid, actuates camera shutters, arms the system, fires the system, crowbars the capacitor bank and resets itself. The automatic sequencer is powered with a 110 Vac, 6 rpm synchronous motor that drives a shaft with seven adjustable cams. These cams operate microswitches in the sequence presented in Figure 14. To operate, depress and hold the automatic sequencer switch (S-104) for 1 sec (t-5 sec to t-4 sec) allowing the cam switch SS-101 to close. Switch SS-101 keeps the motor energized for one complete revolution. At t-3 sec cam switch SS-102 opens removing power from the vacuum valve solenoid, thus disconnecting the pump from the vacuum system. At t-2 and again at t+1 sec, cam switch SS-103 will momentarily close thus operating the camera shutter actuator. At t-1 sec, cam switch SS-104 closes causing relay K-106 to energize and connecting the output of the 2D21 pulse generator to the input of the high-voltage thyratron four-channel trigger generator. At t=0 sec, cam switch SS-105 closes causing relay K-107 to energize which triggers the 2D21 pulse generator.

At t+2 sec, cam switch SS-107 opens removing power from relays K-101, K-102, K-103, K-104, K-201, K-301, and K-601, which shuts off the high-voltage power supply and places the dump circuit across the capacitor bank. Any residual charge on the capacitors will be bled off through the charging network.

> NOTE: Cam switch SS-105 is a spare switch that could be used to operate an alarm bell to warn of imminent firing (within 5 sec). Each cam can be adjusted by loosening the allen screw, rotating it to the desired position, and then retightening it with the allen screw.

The middle panel (ac power and Variac panel) holds the 220-Vac 20-A circuit breaker, four indicating line fuses, a 0 to 280 V Variac and relay K-201.

The circuit breaker is the main on-off control for the entire control console. All ac power comes through this circuit breaker, a Heineman type PAM-33 two-pole common-trip breaker, with a "curve 5-trip response".

The incoming ac power is divided into four branches after the circuit breaker and protected by indicating line fuses. Fuses F-201 and F-202 are 15-A fuses supplying 220-Vac to the Variac T-201 transformer. Fuse F-203 protects the 110-Vac line feeding power to (1) the 6279 filament transformer, (2) the interlock circuits, (3) the automatic sequencer motor, and (4) the high-voltage control circuits. Fuse F-204 protects the 110-Vac line feeding power to (1) 28-Vdc power supply, (2) 500-Vdc power supply, (3) the vacuum valve solenoid, and (4) the control relays K-105 and K-107.

Turning the Variac (T-201) CW supplies voltage (0 to 20 Vac), if relay K-201 is energized, to the primary winding of the high-voltage transformer allowing the high-voltage power supply to increase to 22.5 kV. The Variac has two interlocking microswitches that are actuated by the movable arm of the Variac. These switches are closed when the knob of the Variac is in the full CCW position (zero position), and must be closed to activate the high-voltage power supply. This safety feature ensures the high-voltage power supply will always start at 0 V.

Relay K-201 is the master control relay for the high-voltage circuits. It cannot be energized unless the time delay switch is closed, the interlock circuit is complete and the Variac is turned fully CCW. When energized, it supplies 220 Vac to the Variac and 110 Vac to the high-voltage control circuits. It is now possible to turn up the high-voltage power supply and/or charge the capacitor bank. When relay K-201 is de-energized, the high-voltage power supply is shut off and a dump circuit is placed across the capacitor bank.

The high-voltage section houses the 20-kV, mA power supply and the 6279 thyratron four-channel trigger generator. The high-voltage power supply uses two Semtech No. SCH-2500 silicon rectifiers connected in series. Each rectifier is rated at 25,000 PIV and 0.5 A continuous forward current. Two 2500 Ω, 225 W power resistors (R-301 and R-302) are wired in series to limit the power supply surge current to 4 A should the output of the power supply accidentally become shorted. Resistors R-303 and R-304 are the precision current divider resistors for the high-voltage power supply's 25-kV meter. The zener diode circuit, comprised of D-303 and R-306, will shunt the 200-mA meter and will insure a ground return path for the high-voltage power supply should the 200-mA meter circuit become open. The resistance of R-307 is 1000 times greater than that of the 200-mA meter, thus it introduces less than 0.1 percent error in the meter reading. Relay K-301 is a high-voltage, oil-filled SPDT relay that transfers the output of the high-voltage power supply to either the 6279 thyratron circuit or to the capacitor bank. In its natural de-energized state, the high-voltage power supply is connected to the high-voltage generator. The peak dc output voltage is dependent upon the amplitude of the ac input power. <u>Be careful not to exceed 22.5 kV</u>.

Resistors R-308 and R-309 divide the high-voltage power supply voltage by three-fourths thus delivering the optimum 15 kV to the thyratron tube when the power supply is set at 20 kV. Capacitor C-302 controls the dV/dt of the thyratron's plate voltage to within safe limits. Resistors R-312 through R-315 supply the path through which capacitors C-303 through C-306 can charge to a maximum of 15 kV. The four capacitors are paralleled for low inductance. When the grid of the 6279 thyratron receives a trigger pulse from the 2D21 pulse generator, the tube becomes conducting, discharging the above capacitors into four equal lengths of RG-8 coaxial cable. These cables deliver a -15 kV pulse to the trigger pins of the four spark-gap switches.

3.4.6 REMOTE BOX

The Remote Box is located in the capacitor bank room and serves as a junction point for all the low-voltage circuits coming from the instrument room. These include (1) the four quarter bank voltmeter leads, (2) 28 Vdc power to the automatic crowbar relay, and (3) 110 Vac for the warning buzzer and vacuum valve solenoid. The vacuum valve solenoid can be manually controlled from the Remote Box by plugging it into the outlet provided. Pushing switch S-501 (red button) applies power to the outlet, and the lamp PC-501 will light. To remove power, either push in switch S-502 (black button) or operate the automatic sequencer on the control console. The Remote Box has the following safety features:

(1) A safety switch in series with the interlock circuit. When working in the capacitor room, this switch S-503 should be turned CCW until the yellow standby light comes on. While in this position the high-voltage power supply in the control console cannot be turned on and there is a short across the capacitor bank. In order to activate the high-voltage power supply and charge the capacitor bank, switch S-503 must be turned CW until the red danger light comes on.

(2) *A 25 kV voltmeter* is mounted on the box and will indicate any residual voltage on the capacitor bank.

(3) *A warning buzzer*, mounted on the box, will sound as soon as the START CHARGE switch is operated on the control console.

3.4.7 CHARGING NETWORK

The charging network is mounted on a large lucite sheet attached to the wall near the capacitor bank. Each quarter bank has 4000 Ω of series-charging resistance. An additional 1000 Ω is in series with the high-voltage vacuum relay K-601 used for the automatic crowbarring of the capacitor bank. Therefore, if the bank is dumped at the peak voltage (20 kV), the surge discharge current will be limited to less than 4 A. The crowbar circuit normally holds the capacitors in the discharge state. Power is applied and held on the circuit to charge the capacitor bank through a high-voltage lead from the control console attached to the common junction point of resistors R-601, R-605, R-609 and R-613. A separate high-voltage lead is connected to the end of each of these four charging resistor strings and is connected to the four spark-gap switches. Five high-voltage divider circuits for the bank voltmeters are also mounted on the sheet.

3.4.8 ELECTRICAL COMPONENTS

3.4.8.1 Schematic Diagram

A detailed electrical schematic drawing for the complete system is given in print No. 10060 (Figure 17). The number assigned to each component part on this schematic is used to identify both the function and the location of that part. Listed below is a key to the component numbering system used.

Function	
C	capacitor
CB	circuit breaker
D	solid state diode
F	fuse
K	relay
M	panel meter
PL	panel light
R	resistor
S	switch
SS	cam-operated microswitch
T	transformer
TD	time delay switch
TS	terminal strip
V	vacuum tube

Location	
100 series	master control section, console
200 series	ac control section, console
300 series	high voltage section, console
400 series	console frame
500 series	remote box
600 series	charging network

3.4.8.2 Electrical Parts List

The electrical parts used in the arc plasma system are listed on the following pages.

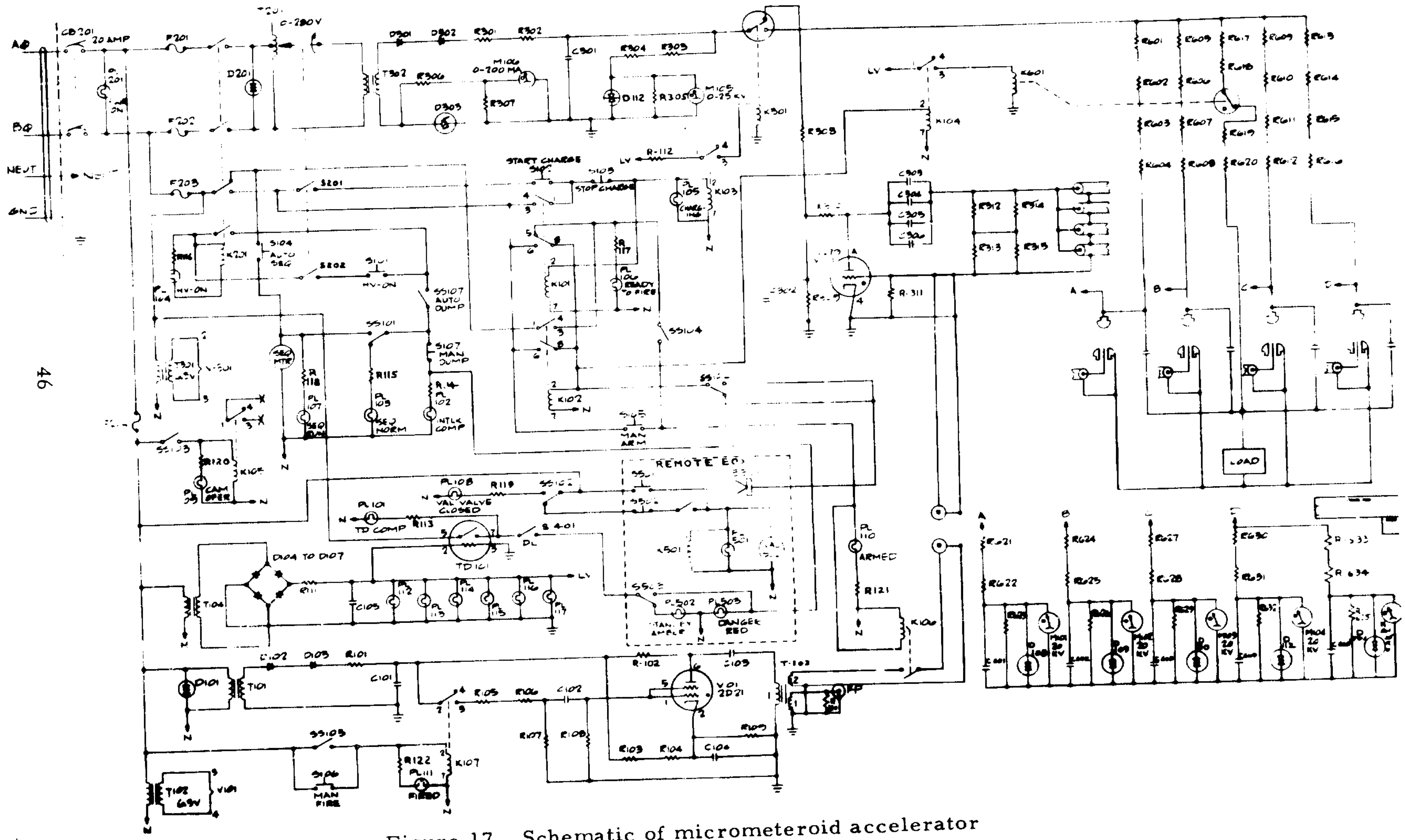


Figure 17. Schematic of micrometeroid accelerator

ITEM	DESCRIPTION	MANUFACTURING
CAPACITORS		
C-101	Electrolytic, 20 uF @ 600 V	Sprague No. TVA-1966
C-102	Mylar/paper, 0.001 uF @ 600 V	Sprague No. 6PS-D10
C-103	Mylar/paper, 0.1 uF @ 600 V	Sprague No. 6PS-P10
C-105	Electrolytic, 8400 uF @ 40 V	Sprague No. 36D84ZG040BB2A
C-301	Polyester film, 0.02 uF @ 40 kV	Film capacitors No. KM-7-400-20
C-302	Polyester film, 0.02 uF @ 40 kV	Film capacitors No. KM-7-400-20
C-303	Polyester film, 0.02 uF @ 15 kV	Film capacitors No. D6-150-20
C-304	Polyester film, 0.02 µF @ 15 kV	Film capacitors No. D6-150-20
C-305	Polyester film, 0.02 uF @ 15 kV	Film capacitors No. D6-150-20
C-306	Polyester film, 0.02 µF @ 15 kV	Film capacitors No. D6-150-20
C-601	Mylar/paper, 0.01 uF @ 400 V	Sprague No. 4PS-S10
C-602	Mylar/paper, 0.01 uF @ 400 V	Sprague No. 4PS-S10
C-603	Mylar/paper, 0.01 uF @ 400 V	Sprague No. 4PS-S10
C-604	Mylar/paper, 0.01 uF @ 400 V	Sprague No. 4PS-S10
C-605	Mylar/paper, 0.01 uF @ 400 V	Sprague No. 4PS-S10
DIODES		
D-101	Thyrector, 125 V RMS	Gen. Electric No. 6RS21SA5D5
D-102	Rectifier, 600 V @ 1 A	Texas Instrument No. IN4385
D-103	Rectifier, 600 V @ 1 A	Texas Instrument No. IN4385
D-104	Rectifier, 600 V @ 1 A	Texas Instrument No. IN4385
D-105	Rectifier, 600 V @ 1 A	Texas Instrument No. IN4385
D-106	Rectifier, 600 V @ 1 A	Texas Instrument No. IN4385
D-107	Rectifier, 600 V @ 1 A	Texas Instrument No. IN4385
D-108	Meter protector, 10,000% overload	Metergard
D-109	Meter protector, 10,000% overload	Metergard
D-110	Meter protector, 10,000% overload	Metergard
D-111	Meter protector, 10,000% overload	Metergard
D-112	Meter protector, 10,000% overload	Metergard
D-201	Thyrector, 250 V RMS	Gen. Electric No. 6RS21SA10D10
D-301	Rectifier, 25 kV @ 0.5 A	Semtech No. SCH2500
D-302	Rectifier, 25 kV @ 0.5 A	Semtech No. SCH2500
D-303	Zener 7.5 V @ 10 W	Texas Instrument No. IN2971B

ITEM	DESCRIPTION	MANUFACTURING
INDICATOR LIGHTS		
PL-101 through PL-104	Indicator housing	Licon No. 01-865000
	Lens cap, blue	Licon No. 01-951923
	Lamp, 28 V	Gen. Electric No. 327
PL-105	Indicator housing/red lens lamp, candelabra base 125 V	Dialco No. 51-0901-0111-301-1 Gen. Electric No. 6S6
PL-106 through PL-111	Indicator housing	Licon No. 01-865000
	Lens cap, blue	Licon No. 01-951923
	Lamp, 28 V	Gen. Electric No. 327
PL-501	Neon, 125 V	Leecraft No. 3200
PL-502	Indicator housing/amber lens	Dialco No. 51-9091-0113-301-2
	Lamp, candelabra base, 125 V	Gen. Electric No. 6S6
PL-503	Indicator housing/red lens	Dialco No. 51-0901-0111-301-1
	Lamp, candelabra base, 125 V	Gen. Electric No. 6S6
METERS		
M-101	3-1/2 in. panel, 0-100 μA	Allied No. 52D7202
M-102	3-1/2 in. panel, 0-100 μA	Allied No. 52D7202
M-103	3-1/2 in. panel, 0-100 μA	Allied No. 52D7202
M-104	3-1/2 in. panel, 0-100 μA	Allied No. 52D7202
M-105	4-1/2 in. panel, 0-100 μA	Allied No. 52D7238
M-106	4-1/2 in. panel, 0-200 MA	Allied No. 52D7249
M-501	4-1/2 in. panel, 0-100 μA	Allied No. 52D7238
RELAYS		
K-101	Plug-in, 115 Vac, 10A DPDT	Eagle No. 22AP2C10A115
K-102	Plug-in, 115 Vac, 10A DPDT	Eagle No. 22AP2C10A115
K-103	Plug-in, 115 Vac, 10A, DPDT	Eagle No. 22AP2C10A115
K-104	Plug-in, 115 Vac, 10A, DPDT	Eagle No. 22AP2C10A115
K-105	Plug-in, 115 Vac, 10A, DPDT	Eagle No. 22AP2C10A115
K-106	Plug-in, 115 Vac, 10A, DPDT	Eagle No. 22AP2C10A115
K-107	Plug-in, 115 Vac, 10A, DPDT	Eagle No. 22AP2C10A115
K-201	Power, 115 Vac, 25A, 4PDT	Potter Brumfield No. PM-17AY
K-301	HV oil, 24 Vdc, 20 kV, SPDT	Hipotronics
K-501	Plug-in, 115 Vac, 10A, DPDT	Eagle No. 22AP2C10A115
K-601	HV vacuum, 28 Vdc, 35 kV, SPDT	Kilovac No. H-35

ITEM	DESCRIPTION	MANUFACTURING
RESISTORS		
R-101	Carbon, 1 kΩ, 2W ±10%	Ohmite
R-102	Carbon, 1.5 MΩ, 2W ±10%	Ohmite
R-103	Carbon, 180 kΩ, 2W ±10%	Ohmite
R-104	Carbon, 220 kΩ, 2W ±10%	Ohmite
R-105	Carbon, 33 kΩ, 2W ±10%	Ohmite
R-106	Carbon, 33 kΩ, 2W ±10%	Ohmite
R-107	Carbon, 10 kΩ, 2W ±10%	Ohmite
R-108	Carbon, 100 kΩ, 1/2 W ±10%	Ohmite
R-109	Metal-oxide, 15 kΩ, 2W ±10%	Mallory No. 2MOL
R-110	Carbon, 47Ω, 2W ±10%	Ohmite
R-111	Wirewound, 3Ω, 20W ±5%	Ohmite No. 1802C
R-112	Wirewound, 10Ω, 12W, ±5%	Ohmite No. 1710
R-113 through R-122	Wirewound, 2.2 kΩ, 5W ±5%	Ohmite No. 4631
R-301	Wirewound, 2.5 kΩ, 225W ±5%	Ohmite No. 0912
R-302	Wirewound, 2.5 kΩ, 225W ±5%	Ohmite No. 0912
R-303	Carbon film, 125 MΩ, 5W ±1%	Dale No. DC-5
R-304	Carbon film, 125 MΩ, 5W ±1%	Dale No. DC-5
R-305	Carbon, 1.2 MΩ, 2W ±10%	Ohmite
R-306	Wirewound, 30Ω, 12W ±5%	Ohmite No. 1715
R-307	Metal-oxide, 270Ω, 5W ±10%	Mallory No. 5MOL
R-308	Carbon film, 10 MΩ, 50W ±5%	IRC No. MVQ-15
R-309	Carbon film, 30 MΩ, 50W ±5%	IRC No. MVQ-15
R-310	Carbon film, 1 MΩ, 5W ±1%	Dale, No. DC-5
R-311	Metal-oxide, 100Ω, 2W ±10%	Mallory No. 2MOL
R-312 through R-315	Carbon film, 1 kΩ, 5W ±1%	Dale No. DC-5
R-601 through R-616	Wirewound, 1kΩ, 225W ±5%	Ohmite No. 0909
R-617 through R-620	Wirewound, 250Ω, 225W ±5%	Ohmite No. 0906

ITEM	DESCRIPTION	MANUFACTURING
RESISTORS (cont'd)		
R-621	Carbon film, 100 MΩ, 5W ±1%	Dale No. DC-5
R-622	Carbon film, 100 MΩ, 5W ±1%	Dale No. DC-5
R-623	Carbon, 1.2 MΩ, 2W ±10%	Ohmite
R-624	Carbon film, 100 MΩ, 5W ±1%	Dale No. DC-5
R-625	Carbon film, 100 MΩ, 5W ±1%	Dale No. DC-5
R-626	Carbon, 1.2 MΩ, 2W ±10%	Ohmite
R-627	Carbon film, 100 MΩ, 5W ±1%	Dale No. DC-5
R-628	Carbon film, 100 MΩ, 5W ±1%	Dale No. DC-5
R-629	Carbon, 1.2 MΩ, 2W ±10%	Ohmite
R-630	Carbon film, 100 MΩ, 5W ±1%	Dale No. DC-5
R-631	Carbon film, 100 MΩ, 5W ±1%	Dale No. DC-5
R-633	Carbon film, 125 MΩ, 5W ±1%	Dale No. DC-5
R-634	Carbon film, 125 MΩ, 5W ±1%	Dale No. DC-5
R-635	Carbon, 1.2 MΩ, 2W ±10%	Ohmite
SWITCHES		
S-101	Operator, key lock, push button Contact block, NO	Cutler Hammer No. 10250T-434 Cutler Hammer No. 10250T-53
S-102 through S-106	Illuminated push button Lens cap, white Lamp, 28 Vdc	Licon No. 01-865530 Licon No. 01-951921 Gen. Electric No. 327
S-107	Illuminated push button Lens cap, red Lamp, 28 Vdc	Licon No. 01-865530 Licon No. 01-951922 Gen. Electric No. 327
S-201	Microswitch SPDT	Microswitch No. V3-1
S-202	Microswitch SPDT	Microswitch No. V3-1
S-401	Push button SPST NO	Hubbell No. 2167
S-501	Push button, red SPST NO	Arrow Hart No. 3391-GL
S-502	Push button, black SPST NC	Arrow Hart No. 3391-GJ
S-503	Operator, lever Contact block, NO-NC	Cutler Hammer No. 10250T-311 Cutler Hammer No. 10250T-1
SS-101 through SS-107	Microswitch SPDT	Microswitch

ITEM	DESCRIPTION	MANUFACTURING
TRANSFORMERS		
T-101	Plate, 380V @ 20 mA	Allied No. 54D2318
T-102	Filament, 6.3 V @ 1A	Allied No. 54D2030
T-103	Pulse, 1:2:1	Pulse Eng. No. PE-4034
T-104	Low voltage, 12-30 V @ 2-4 A	Allied No. 54D2332
T-201	Variac, 0-280 V, 2.8 kVA	Superior No. 236BU
T-301	Filament, 6.3 V @ 15 A	Triad No. F-17U
T-302	High voltage, 20 kV @ 100 mA	Hipotronics "custom"
VACUUM TUBES		
V-101	Thyratron, 650 V PIV @ 0.1A	RCS No. 2D21
V-101	Socket, 7 pin	Cinch Jones No. 7XM1
	Shield, tube	Cinch Jones No. 7S2
V-301	Thyratron, 16 kV PIV @ 10A	Amperex No. 6279
	Socket, 4 pin, super jumbo	E. F. Johnson No. 123-206-100
	Cap, plate	Millen No. 36011
MISCELLANEOUS		
CB-201	Circuit breaker, 220 V @ 20 A	Heinemann No. PAM 33
F-201 through F-204	Fuseholder, indicating, 125 V	Little Fuse No. 344125
SEQ MTR	Sequencer assy. with 7 switches, 115 Vac, 6 rpm motor	Western Electro-Mechanical No. 6M7
TD-101	Time delay switch, 3 minutes	Amperite No. 26NO180

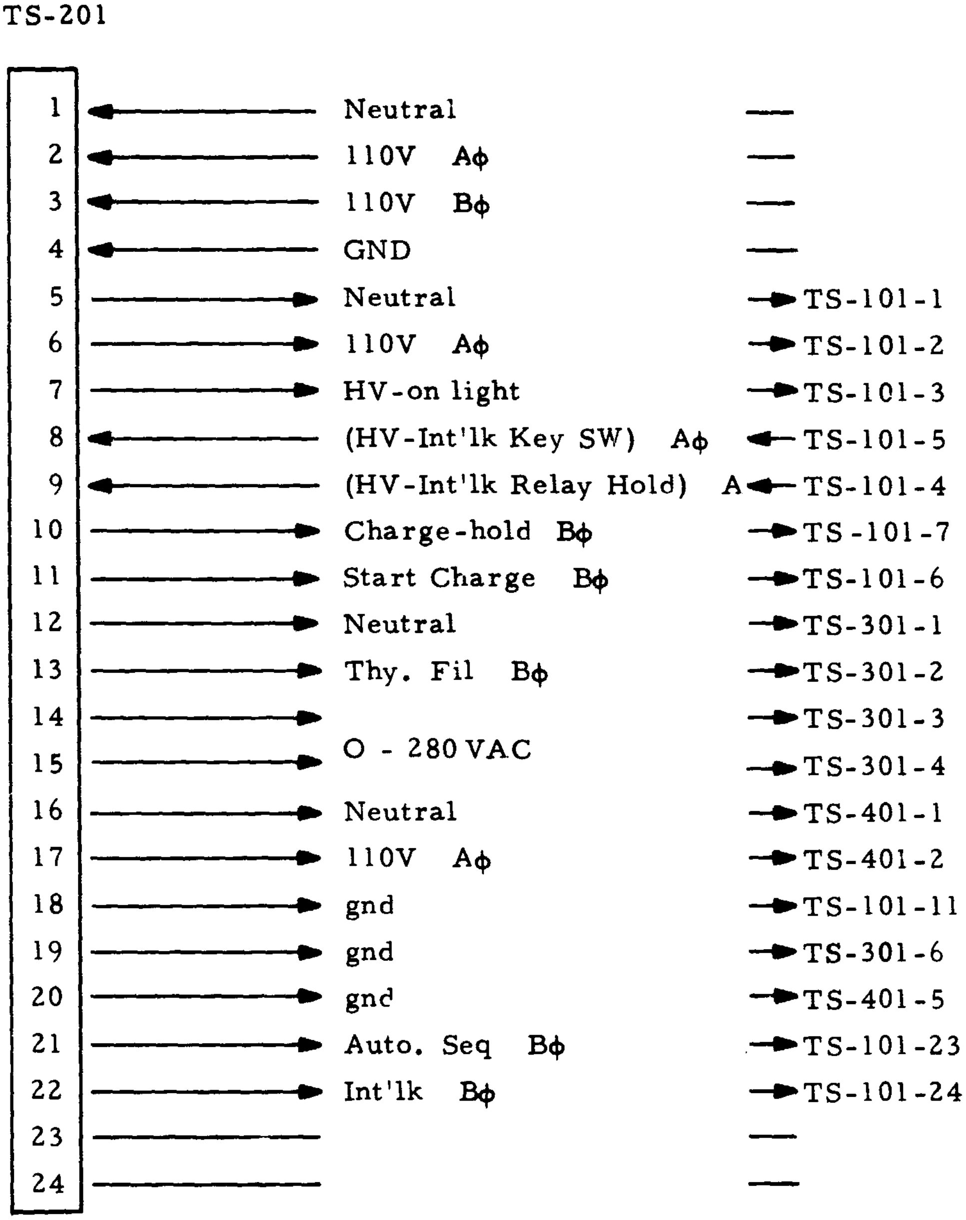
3.4.8.3 Terminal Strip Charts

Six terminal strips are used for the interconnections between major system components. Drawings showing these strips are included (Figure 18). The terminal strip (TS) number above each rectangular block identifies the location of that terminal strip while the numbers inside the block specify the individual terminal strip connection points. Each connection point is identified by major function and wiring location. The first three digits following TS signify the terminal strip number while the last two digits identify the terminal strip connection point.

TS-101

1	←	Neutral	←	TS-201-5
2	←	110V Aϕ	←	TS-201-6
3	→	HV-on light	→	TS-201-7
4	→	(HV-int'lk Relay-hold) Aϕ	→	TS-201-9
5	←	HV-int'lk Key SW) A	←	TS-201-8
6	←	Start Charge Bϕ	←	TS-201-11
7	→	Charge - Hold Bϕ	→	TS-201-10
8	←	24vdc Charge Relay	←	TS-301-5
9	←	25KV Meter	←	TS-301-7
10	←	200ma Meter	←	TS-301-8
11	←	Meter Common	←	TS-301-6 &TS-201-18 &TS-401-13
12	←	Bank 1 Meter	←	TS-401-14
13	←	Bank 2 Meter	←	TS-401-15
14	←	Bank 3 Meter	←	TS-401-16
15	←	Bank 4 Meter	←	TS-401-17
16	←	Camera SW	→	TS-401-18
17	←	No to NC	→	TS-401-19
18	→	VAC VAL. 110V Aφ	→	TS-401-3
19	→	Int'lk 110V Bϕ	→	TS-401-10
20	←	Int'lk 110V Bϕ	←	TS-401-8
21	→	Warning Buz Bϕ	→	TS-401-6
22	→	Crowbar 28vdc	→	TS-401-4
23	←	Auto Seq. Bϕ	←	TS-201-21
24	←	Int'lk 110V Bϕ	←	TS-201-22

Figure 18a. Terminal strip, control chassis



TS-201

1	◄——	Neutral	——	
2	◄——	110V Aϕ	——	
3	◄——	110V Bϕ	——	
4	◄——	GND	——	
5	——►	Neutral	—►	TS-101-1
6	——►	110V Aϕ	—►	TS-101-2
7	——►	HV-on light	—►	TS-101-3
8	◄——	(HV-Int'lk Key SW) Aϕ	◄—	TS-101-5
9	◄——	(HV-Int'lk Relay Hold) A	◄—	TS-101-4
10	——►	Charge-hold Bϕ	—►	TS-101-7
11	——►	Start Charge Bϕ	—►	TS-101-6
12	——►	Neutral	—►	TS-301-1
13	——►	Thy. Fil Bϕ	—►	TS-301-2
14	——►	O - 280 VAC	—►	TS-301-3
15	——►		—►	TS-301-4
16	——►	Neutral	—►	TS-401-1
17	——►	110V Aϕ	—►	TS-401-2
18	——►	gnd	—►	TS-101-11
19	——►	gnd	—►	TS-301-6
20	——►	gnd	—►	TS-401-5
21	——►	Auto. Seq Bϕ	—►	TS-101-23
22	——►	Int'lk Bϕ	—►	TS-101-24
23	——		——	
24	——		——	

Figure 18b. Terminal strip, ac chassis

TS-301

3	←	Neutral	←	TS-201-12
4	←	110V Bϕ Thy. Fil	←	TS-201-13
1	←	110V Bϕ O-280V	←	TS-201-14
2	←	110V Aϕ	←	TS-201-15
5	←	24vdc Charge Relay	←	TS-101-8
6	←	Gnd	←	TS-201-19 & TS-101-11
7	→	25KV Meter	→	TS-101-9
8	→	200 MA Meter	→	TS-101-10

TS-601

1	←	Crowbar 28 vdc	←	TS-501-4
2	←	Ground	←	TS-501-5
3	→	Meter Common	→	TS-501-13
4	→	25KV Meter	→	TS-501-18
5	→	Bank #4 Meter	→	TS-501-17
6	→	Bank # 3 Meter	→	TS-501-16
7	→	Bank #2 Meter	→	TS-501-15
8	→	Bank #1 Meter	→	TS-501-14

Figure 18c. Terminal strip, high-voltage chassis and charging network

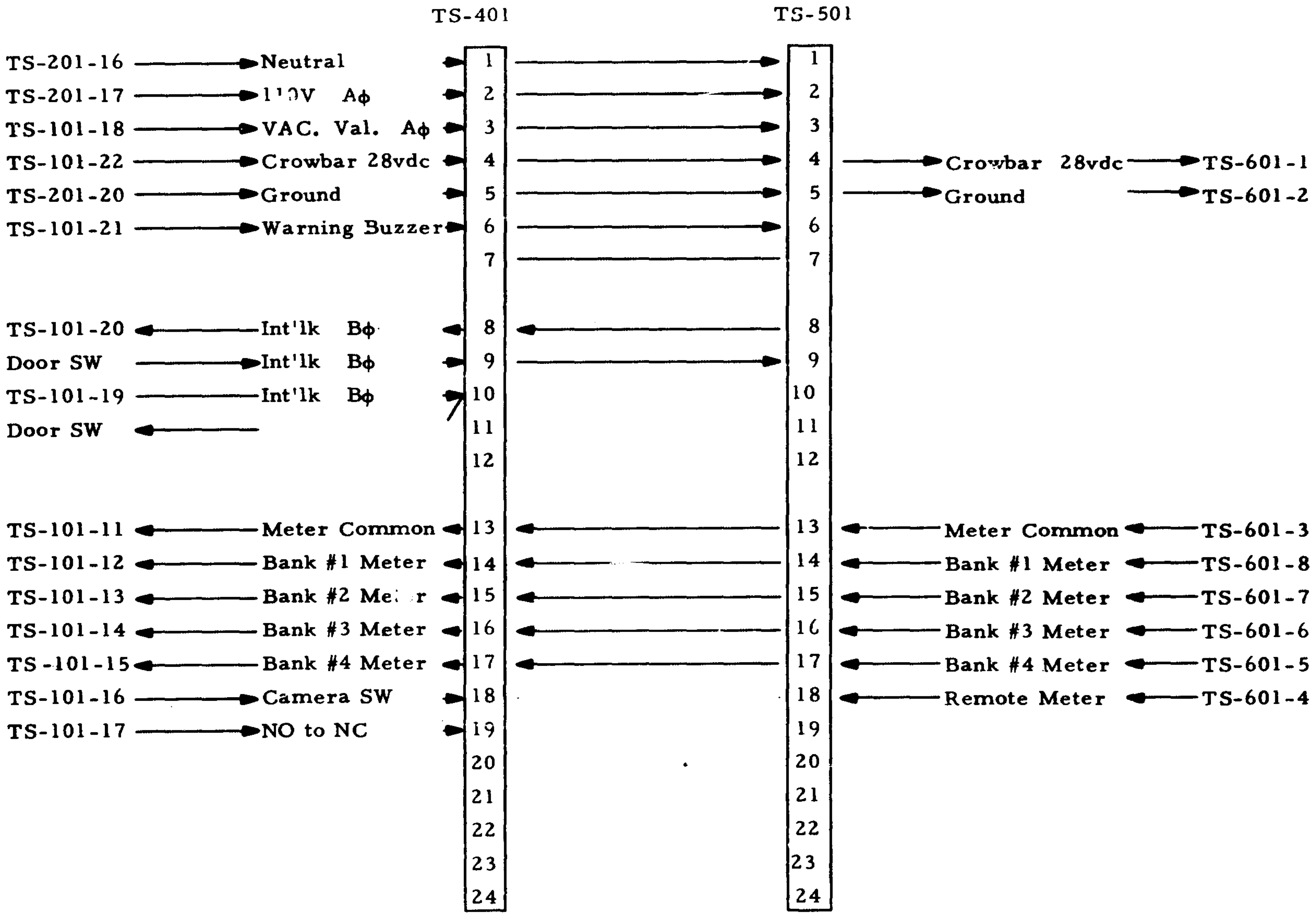


Figure 18d. Terminal strip, control console and remote box

3.5 ARC PLASMA GUN

The improved arc plasma gun is shown in Figure 15. The wall thickness of each of the two circularly wrapped retaining tubes is 1 in. The wall material is G-10 glass-epoxy (Figure 15). The inner assembly of the gun has six sections of G-10 glass-epoxy which are spring-loaded against the retaining tubes to reduce any side movement during the shot. The copper rails are held tightly against the side walls by a series of counter-sunk screws. Teflon liners 20-mil thick are placed between the copper rails and inner assembly to protect the G-10 material from the hot plasma gasses. The teflon liner should be replaced after each shot; however, the copper rails are reusable. The useful life of the copper rails is dependent upon the energy level per shot and is estimated, for a 100-kJ level, to be approximately ten shots.

Proper alignment of the two retaining tubes with the inner assembly of the gun is achieved through the use of a front flange machined from a 1/2-in. thick sheet of phenolic. The G-10 gun sections are adjusted until the tapped holes on the face of the gun assembly are mated with the alignment holes on the front flange. Button head bolts (1/4 in. 20 x 1) are then inserted through the holes in the flange into the "keen-serts" on the gun, thus locking the complete gun assembly in proper adjustment.

The procedure for assembling and mounting the arc plasma gun is as follows:

(1) Bolt a set of copper rails to the G-10 inner gun assembly.

(2) Place the teflon liners on either side of the copper rails.

(3) Add the four G-10 spacers and clamp the inner gun assembly with three hose clamps.

(4) Insert the inner gun assembly into the G-10 retaining tubes, observing the proper alignment.

(5) Bolt the phenolic flange to the front face of the arc plasma gun.

(6) Place the copper rails, which extend from the rear of the gun, onto the brass feedthrough tabs of the feedthrough assembly.

(7) Align the holes on the copper rails with the holes on the brass feedthrough tabs and bolt together.

(8) Place the 2-1/2 in. long phenolic standoffs over the six 3/8 in. diameter bolts which are inserted through the feedthrough assembly.

(9) Screw the above six bolts into the keenserts on the back end of the arc plasma gun and tighten.

All the G-10 material used in the arc plasma gun was manufactured and machined to MBA specifications by Taylor Corporation of LaVerne, California.

3.6 FABRICATION DRAWINGS

Detailed assembly and manufacturing (fabrication) drawings are provided for the following major components; spark-gap switches, electrical interface, vacuum system, and the arc plasma gun.

TITLE	NO. 003-
SPARK-GAP SWITCHES	
Spark-gap assembly	10017
Base plate, spark gap	10005
Cable clamp, outer shield, spark gap	10004
Cable termination plate, inner conductor, fixed spark gap	10015
Cable termination plate, inner conductor, adjusted spark gap	10016
Spacer bar, melamine	10020
Hold-down bar, fixed spark gap	10007
Hold-down bar, adjusted spark gap	10012
Hemisphere retainer block, fixed spark gap	10014
Hemisphere, fixed spark gap	10011
Hemisphere retainer block, adjusted spark gap	10013
Adjustable hemisphere, sub-assembly	10019
Hemisphere, adjustable spark gap	10010
Trigger electrode, adjusted spark gap	10009
Electrode spacer, adjusted spark gap	10008
Cable connector, outer shield, adjusted spark gap	10006
ELECTRICAL INTERFACE	
Spark gap and collector plate assemblies	10018
Collector plate assembly	10049
Top plate, collector	10002
Bottom plate, collector	10001
Cable clamp, outer shield, collector	10003
Hold-down clamp, collector	10048
Feedthrough flange	10043
Top and bottom feedthrough plates	10052

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TITLE	NO. 003-
VACUUM SYSTEM	
Flange, shock decoupler	10046
Lucite tube, vacuum assembly	10050
Step-down seal plate, vacuum assembly	10027
End plate carriage, vacuum support	10030
Rail, vacuum assembly	10037
Rail support, vacuum assembly	10034
ARC PLASMA GUN	
Arc plasma rail gun assembly	10054
Arc plasma rail gun, detail and assembly	10051
Arc plasma gun assembly	10044
Front flange, arc plasma gun assembly	10045

3.7 INSTRUMENTATION AND RECORDING

The residual government test equipment generated under Contract NAS8-20295 was transferred to and used in the testing phase of this contract. No new instrumentation or recording techniques were developed under this contract. A brief description of the instrumentation used is given below.

3.7.1 OSCILLOSCOPES

Six Tektronix oscilloscopes (either model C-12 or C-13, polarized) were available to record the data generated during a shot. The data recorded included: (1) the rise time and amplitude of peak current, (2) the oscillatory ring-down of the current through the gun, and (3) the plasma and particle velocities. Polaroid pictures were taken of the scope traces for later analyses. The scopes were triggered externally by either the time zero pulse from the control console, or the voltage pulse from the pickup coil, which was monitoring the capacitor bank current.

3.7.2 PICKUP COIL

Nine turns of enameled wire were wound on a 1-in. diameter lucite form. This coil was centered over the brass feedthrough tab at the entrance to the vacuum system and was oriented to interrupt the field generated by the discharge current flowing into the arc plasma gun. The signal from the pickup coil is a positive starting cosine wave coincident with the firing of the spark-gap switches. This signal is used to trigger the oscilloscopes externally and is also branched through an integrator circuit and displayed on the scope as the total bank current.

3.7.3 PLASMA MONITORS

The plasma light detector consisted of a light-tight housing around an RC 929 vacuum photodiode circuit with a 4-in. long, small diameter tube extending from the housing. When a bright light is passed directly in front of the small diameter tube opening, the photodiode conducts causing a positive pulse to appear on the scope trace. One plasma monitor is placed at the muzzle end of the gun and the other at a known distance further down range. Plasma velocity is calculated knowing the location of these two plasma monitors and the time (measured on the photograph of the oscilloscope trace) the plasma light passes these monitors.

3.7.4 PHOTOMULTIPLIER TARGET

The photomultiplier target is placed inside the last vacuum section for the purpose of measuring particle velocity. It consists of a light-tight enclosure whose front surface is the target foil. The target foils are easily replaceable and vary in thickness from 1 to 5 mil. A backing is placed behind the thin target foils to prevent collapse of the foil from the plasma gasses which arrive at the target before the particles. A photomultiplier tube outside the vacuum system looks into the light-tight enclosure via a light pipe. When a high-velocity particle penetrates the target foil, the photomultiplier detects the associated plasma light and transmits a pulse to the oscilloscope.

3.7.5 VACUUM GAUGE

An NRC vacuum thermocouple and associated meter readout are used to measure the amount of vacuum. Typical vacuum levels for the experiments ranged from 200 to 500 microns.

4.0 OPERATIONAL PROCEDURE

The following section contains the step-by-step procedure for operating the 200 kJ arc plasma system. It is important to follow these procedures carefully to insure a safe and successful test.

4.1 ARC PLASMA

Select the type and quantity of desired particles and place them inside a styrofoam container (0.260 in. x 0.260 in. x 0.180 in.). Cut a small piece of 1/2 mil aluminum foil approximately 1/2 in. wide by 1/2 in. long and fold twice in width. Place the foil and the styrofoam holder between the copper rails and teflon liner of the arc plasma gun. (The exact placement of the aluminum foil and particles is variable and is determined by the experimenter. However, the aluminum foil should be closer to the breech end of the arc plasma gun.) Assemble and mount the arc plasma gun as described in Section 3.5. After the gun is bolted to the feed-through assembly, lightly spray the exposed metal at the breech of the gun with insulating varnish (similar to Sprayon No. 600).

4.2 TARGET

Select the type and thickness of target foil based on particle size, material and expected velocities. Cut out a 4-1/2 in. diameter disk and mount it on the face of target holder. Be sure that the backing for the foil is in place. Insert the target assembly in the glass T-joint section at the end of the vacuum assembly.

4.3 VACUUM SYSTEM

Slide the vacuum system forward on the guide rails until it mates with the feedthrough assembly. Insert the six 1/4 - 20 bolts through the lucite flange of the shock decoupler and bolt it to the feedthrough assembly. Next, bolt the target end of the vacuum system to the table with the 1/2 in. diameter bolt. Finally, place the nylon strap over the 9 in. o.d. lucite section and secure it to the table. Now connect the vacuum pump and begin pumping.

4.4 SPARK-GAP SWITCHES

Set the spacing between the spark-gap hemisphere to 0.335 in. (this spacing can vary with atmospheric conditions). Check that the trigger probes are flush with the face of the adjustable hemisphere. Clean the area around the spark gap switches thoroughly.

4.5 INSTRUMENTATION

A description of the instrumentation used under this contract is given in Section 3.6. Any additional instrumentation should be set up at this time and checked out (e.g. strobe light for the photodetectors, proper scope settings, film for camera, etc.).

4.6 OPTIONAL PREFIRE TEST

If the arc plasma system has not been used for a long period of time, the three following tests should be performed.

(1) Test the performance of the high-voltage power supply by running the voltage up to 22.5 kV.

(2) Observe that all four spark-gap switches are triggered by depressing the manual ARM and FIRE switches with the arc plasma power supply at 20 kV.

(3) Check the spark-gap switches hold-off potential by disconnecting the capacitor bank from the spark-gap switches and applying high voltage across the gap. (As a safeguard a 1 MΩ current limiting resistor should be inserted in series with the high-voltage charging.) The spark-gap switches should be capable of withstanding at least 22 kV dc static.

4. 7 PREFIRE SAFETY

The arc plasma system is now ready for a charging operation. Any unnecessary personnel should be cleared from the immediate area. Remove the manual crowbar from across the capacitor bank and turn the safety switch on the remote box CW from the yellow standby position to the red danger position.

4. 8 FIRING

Described below is the sequence of operations to follow to charge and fire the arc plasma system. For a detailed description of the function for any of the various operations please refer to Section 3.4.

(1) Turn on the main circuit breaker (CB 201). Observe that the "Time Delay Complete" lamp lights after 3 min, followed by the "Interlock Complete" and "Sequencer Normal" lights.

(2) Insert key into high-voltage switch (S-101), turn CW and push. Observe that the "High Voltage ON" lamp lights.

(3) Momentarily depress the START CHARGE switch (S-102). Observe that the charging lamp lights.

(4) Turn Variac CW. Observe the six panel meters. Do not exceed 150 mA charging current. The power supply voltmeter will read slightly higher than the four capacitor bank voltmeters. As the four capacitor bank voltmeters reach 20 kV, turn the Variac CCW until there is zero charging current.

(5) Momentarily depress the STOP CHARGE switch (S-103). Observe that the READY TO FIRE lamp lights. Adjust the Variac so that the power supply voltmeter reads exactly 20 kV.

(6) The system can now be fired either manually or by the automatic sequencer (Section 3.4.5). For manual operation:

(a) Depress and hold the manual arm switch (S-105). The ARMED lamp will light.

(b) Depress the MANUAL FIRE switch (S-106). The FIRED lamp will light. All four quarter banks should discharged simultaneously into the arc plasma gun.

(c) Momentarily depress the Manual Dump Switch (S-107).

For automatic operation:

Depress and hold the automatic sequencer switch (S-104) for one second (until the sequencer normal lamp goes out). The sequencer motor will then make one revolution, actuating the seven cam operated microswitches at approximately 1 sec intervals which close the vacuum valve, operate the camera shutters, arm the trigger generator and fire the system. The last cam automatically crowbars the capacitor bank.

4. 9 SAFETY

Turn the safety switch on the remote box back to standby. Observe that the voltmeter on the Remote Box reads zero volts. Place the manual crowbar across the capacitor bank.

4. 10 POST FIRING

Disconnect the vacuum and slide it back out of the way. Unbolt arc plasma gun and begin disassembly. Remove the target foil from the target holder.

4.11 ANALYZE FIRING AND SYSTEM PERFORMANCE

Upon completion of firing the arc plasma gun and subsequent post-firing disassembly, analyses of the firing and system performance should be made. These analyses should include equipment condition (damage incurred during firing) and equipment performance (where the arc struck and duration of erosive pitting along the copper rails). These documented analyses should be used as a basis for the next tests.

4.12 SYSTEM MAINTENANCE

After each shot the following procedures should be followed:

(1) Clean the inside of the vacuum system.

(2) Remove the spark-gap hemisphere and polish.

After discharging very high current through the spark-gap switch, the brass hemispheres become pitted. It is suggested that the hemispheres be removed in order to clean and polish them. The fixed hemisphere may be removed by inserting an allen wrench through the three holes in the stainless steel bar (Item 4) and loosening the allen screws. It is then possible to remove the adjustable hemisphere by loosening the retaining bolt (Item 8), taking hold of the coaxial connector and unscrewing the adjustable hemisphere from it.

(3) Clean and inspect the brass feedthrough tabs. It is sometimes necessary to replace the outer layer of RTV.

(4) Clean the gun thoroughly. If the copper rails are to be reused, sand the surfaces smooth. Replace the teflon liners.

5.0 TEST RESULTS

Testing of the 200-kJ accelerator system began on 13 May 1968 and continued testing through the middle of August 1968. At that time, the assembled system was dismantled for delivery and checkout at National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, Alabama.

During the testing period, the system was modified for improved performance. System operation procedure and results of the tests are reported in the following section.

The primary purpose of this contract was to design and fabricate an arc plasma system which would operate successfully at a 200 kJ power. Tests of this system revealed several technical problems which have been unsolved in the final design configuration. As a secondary goal, measurements of particle and plasma velocities were made to determine system performance. Detailed test data is presented in Tables III through VII for each of the 17 firings of the arc plasma system. Table III contains the system power level, the particle size, and the spark gap setting used for each test. Distances to the photopickups (see Figure 19), the target thickness and comments about target penetration are given in Table V. In Table V, the vacuum and voltage levels are presented along with simultaneity of firing and currents achieved. Measured values of inductance, current, and delay times for the various photo pickups used are presented in Table VI. Calculated values of plasma and particle velocity are presented in Table VII. Velocities have been calculated in the same manner as Pjerrou and Farnham 1967.* It should be noted that these measurements are subject to experimental errors which can be quite significant. For example, a possible source of error is matching impedances between

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*Pjerrou, G. M. and J. F. Farnham, Jr. (1967), Development of a Micrometeoroid Accelerator, MBAssociates, San Ramon, under contract No. NAS8-20295, Final Report No. MB-R-67/14

Table III. MHD Experimental Shots

Date 1968	Shot No.	Capacity/Spark Gap No.	Power Level	Capacitance Total (μF)	Particles Size (mil)	Particles Weight (mg)	Particle Holder Dimension (in.)	Particle Holder Weight (mg)	Initiator Dimension (in.)	Spark Gap Spacing (in.)
May 13	1	1	1/18	58.8						.325
May 16	2	1	1/18	58.8						.325
May 21	3	1	1/18	58.8						.325
May 22	4	1	1/18	58.8						.325
May 24	5	9	1/2	513						.325
June 20	6	3	1/6	171	2.6	36.5	0.260 X 0.260 X 0.3	15.5	3/8 1 x 1 w x 0.005	.325
June 24	7	3	1/6	171	2.6					.325
July 1	8	6	1/3	342	2.6					.225
July 8	9	6	1/3	342	2.6					.325
July 9	10	9	1/2	513	3	18.2	0.28 X 0.28 X 0.18	9.8	3/8 1 x 1/2 w x 0.005	.335
July 22	11	9	1/2	513	3	32	0.25 x 0.26 x 0.18	8.4	3/8 1 x 1/2 w x 0.005	.335
July 30	12	12	2/3	686	2.6	33.2	0.25 x 0.26 x 0.195	9	3/8 1 x 1/2 w 0.008	.335
July 31	13	12	2/3	686	2.6	10	0.270 x 0.250 x 0.125	3.2	3/8 1 x 1/2 w x 0.005	.335
August 1	14	12	2/3	686	2.6	19.9	0.270 x 0.290 x 0.120	4.1	3/8 1 x 5/8 w x 0.005	.335
August 1	15	15	5/6	855	2.6	30	0.29 x 0.26 x 0.142	6	3/8 1 x 5/8 w x 0.005	.335
August 14	16	15	5/6	855	3.04*	20	0.260 x 0.259 x	5	3/8 1 x 5/8 w x 0.005	.335
August 19	17	9	1/2	513	2.6		1/2 mil mylar over muzzle		3/8 1 x 5/8 w x 005	

* Plus plastic particles of sizes 105μ to 177μ .

Table IV. MHD Experimental Shots

Shot No.	Distance (cm)								
	Foil to Muzzle	Particle to Muzzle	Muzzle to PU #1	Muzzle to PU #2	Muzzle to PU #3	Muzzle to PU #4	Muzzle to Target	Thickness (mil)	Penetration
1									
2									
3	40.6		0	0					
4	40.6		0	0					
5	40.6		0	0					
6	30.5	15.2	12.7	15.2			181	1	Yes
7	30.5	15.2	12.7	15.2			181	1	Yes
8	30.5	15.2	2.54	22.9	43.2		181	5	No
9	30.5	15.2	2.54	17.8	38		181	5	No
10	30.5	15.2	2.54	12.7	33		181	5	Yes
11	30.5	15.2	2.54	22.54	134.6	160	184.5	5	Yes
12	45.7	15.2	2.54	22.54	129.6	150	182.3	5	No
13	45.7	15.2	2.54	22.54	132	152.4	182.3	5	No
14	45.7	15.2	2.54	22.54	132	152.4	182.3	5	
15	45.7	15.2	2.54	50.8	139.7		184.5	5	
16	45.7	7.6	2.54	50.8	139.7		181.4	5	Yes
17	30.5	0	2.54	53.4	142.2		184.2	5	No

Table V. MHD Experimental Shots

Shot No.	Vacuum (u)	Bank Voltage (kV)	Bank Firing		Current				
			On Command	Simultaneous	Relative Amplitude (V)	T - 1/4 Cycle (usec)	T - 1/2 Cycle (usec)	T - 3/4 (usec)	T - 1 Cycle (usec)
1	ATM	20	Yes	Yes	* 7.0	40	79		
2	ATM	20	Yes	Yes	* 7.0	40	80		
3	ATM	20	Yes	Yes	0.29	6.5	13	18	25.5
4	140	20	Yes	Yes	0.32	6.0	12	17	23.0
5	140	20	Yes	Yes	1.0	10	20	28	38.5
6	500	20	Yes	Yes	0.6	6.5	12.3	19	25.0
7	700	20	Yes	Yes	0.8	6.0	12.5	18	24.5
8		16	No	No	0.81	7.3	17	22.5	31
9		18.5	No	No	0.66	6.5 - 11.5	20	27	36
10	400	20	Yes	Yes	1.25	8.5	21.2	27	36.5
11	800	20	Yes	Yes	** 1.52	8.8	19.8	27.2	36.8
12	1000	11	No	No	0.42	7.5	18	23	30
13	300	16	No	No	0.83	8.1			
14	450	20	Yes	Yes	1.70	13	26.5	34	44
15	450	20	Yes	Yes	1.95	14.5	29	38	50
16	155	20	Yes	Yes	2.2	15.5	28	38	50
17	300	20	Yes	Yes	1.60	11	22	29	38.5

** Pick-up coil support anchored more firmly.

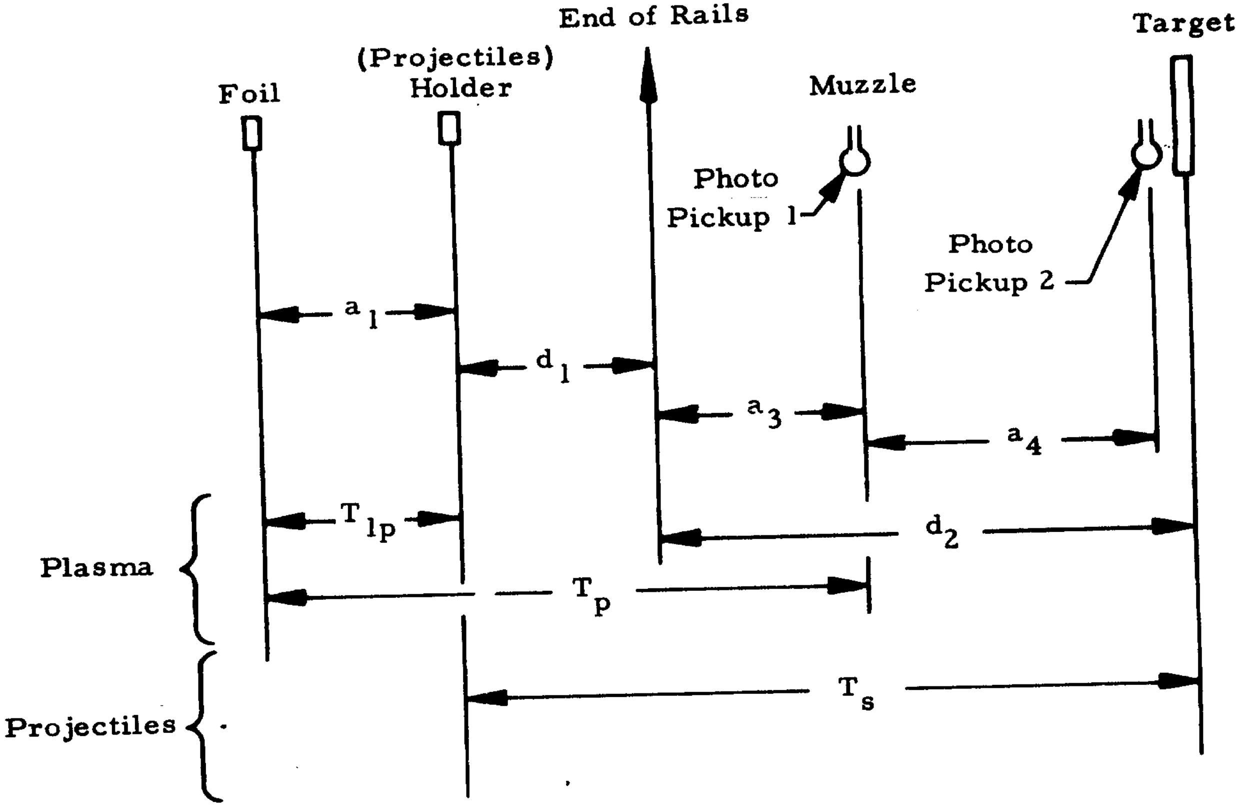
* Pick-up coil in different position than for other shots.

Table VI. MHD Experimental Shots

Shot No.	Inductance (1/4 cycle, nH)	I Peak (kA)	Flight Time To Monitors (μsec)				
			Plasma # 1	Plasma #2	Plasma #3	Plasma #4	Particles
1		46.2					
2		46.2					
3	291	284.3	84	84			
4	248	308	20				
5	80	1,597					
6	100	827					
7	85	897		20			620
8	64	1,166	28	45	72		
9			31	39	70		
10	57	1,892	27	30	38		250
11	61.5	1,829	30				260
12	132.9	395					
13	77.8	1,061			10	14	
14	99.8	1,658			48	52	270
15	99.7	1,852	34	64	150		290
16	113.9	1,733	34		140		840
17	95.5	1,466	36		164		

Table VII. MHD Experimental Shots

Shot No.	Plasma Velocity (km/sec)						Particle Velocity (km/sec)
	Foil to PU #1	Foil to PU #2	Foil to PU #3	PU #1 to PU #2	PU #1 to PU #3	PU #2 to PU #3	
1							
2							
3	9.7	9.7					
4	40.0						
5							
6							
7		38.1					3.5
8	22.7	18.6	14.5	12	9.2	7.5	
9	20.5	20.2	14.1	19.1	9.1	6.5	
10	24.0	25.0	24.7	33.9	26.5	23.9	9.1
11	21.2						9.0
12							
13							
14			46.5	46.7			10.1
15	27.6	22.2	15.4	16.1	10.9	8.9	9.5
16	27.6		16.5		12.9		2.4
17	7.6		12.4		10.9		



Measurements : T_p; T_s ; T_{1p}

Figure 19. Distance and time measurements for the projectile and plasma velocity calculations

the photo pickups, the coaxial cables, and oscilloscopes. Mismatches degrade the rise time measurement, thus making it difficult to accurately determine delay times.

Additional problems noted upon analysis of the data indicate that extreme care should be exercised in instrumentation for the arc plasma system. Radio-frequency pickup in the current loop and cables serves to degrade time measurements. Cable length should be kept to a minimum and shielded wherever possible. Also, separate ground planes should be used to minimize ground loop currents.

From the values given in Tables III and VI for the capacitance and current, respectively, and the plot of Figure 20, the inductance of the capacitor bank has been derived.

The inductance is proportional to the slope of the line in Figure 21. This is based on the assumption that the arc plasma system can be represented by an equivalent series RLC circuit. While this is not a valid assumption, it does allow for the calculation of the bank inductance.

The following relationships hold true for a simple RLC network:

$$P = 1/2\ CV^2 \qquad (1)$$

$$I = V\ C/L \qquad (2)$$

$$\tau = 2\pi\ LC \qquad (3)$$

where P is the power level, C is the capacitance, V is the voltage, I is the current, and τ is the time delay for a full cycle of the damped sinusoidal current waveform.

These expressions can be rewritten as

$$I = (2/L)P \qquad (4)$$

or

$$I = (\pi/2)\ (CV/T) \qquad (5)$$

where $T = \frac{\tau}{4}$ (measured from oscilloscope recordings of current waveform

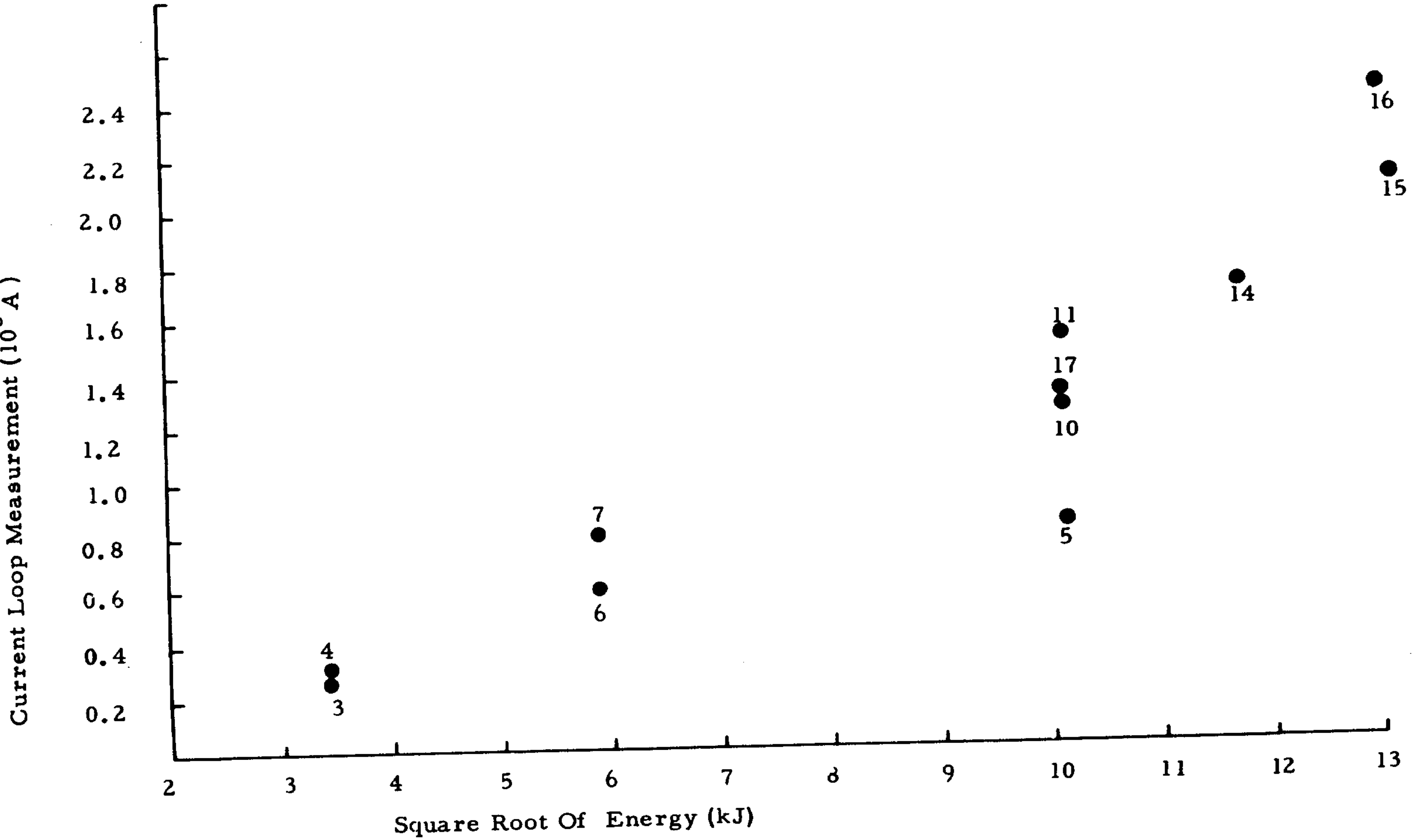


Figure 20. Peak current (loop measurement) versus square root of bank energy

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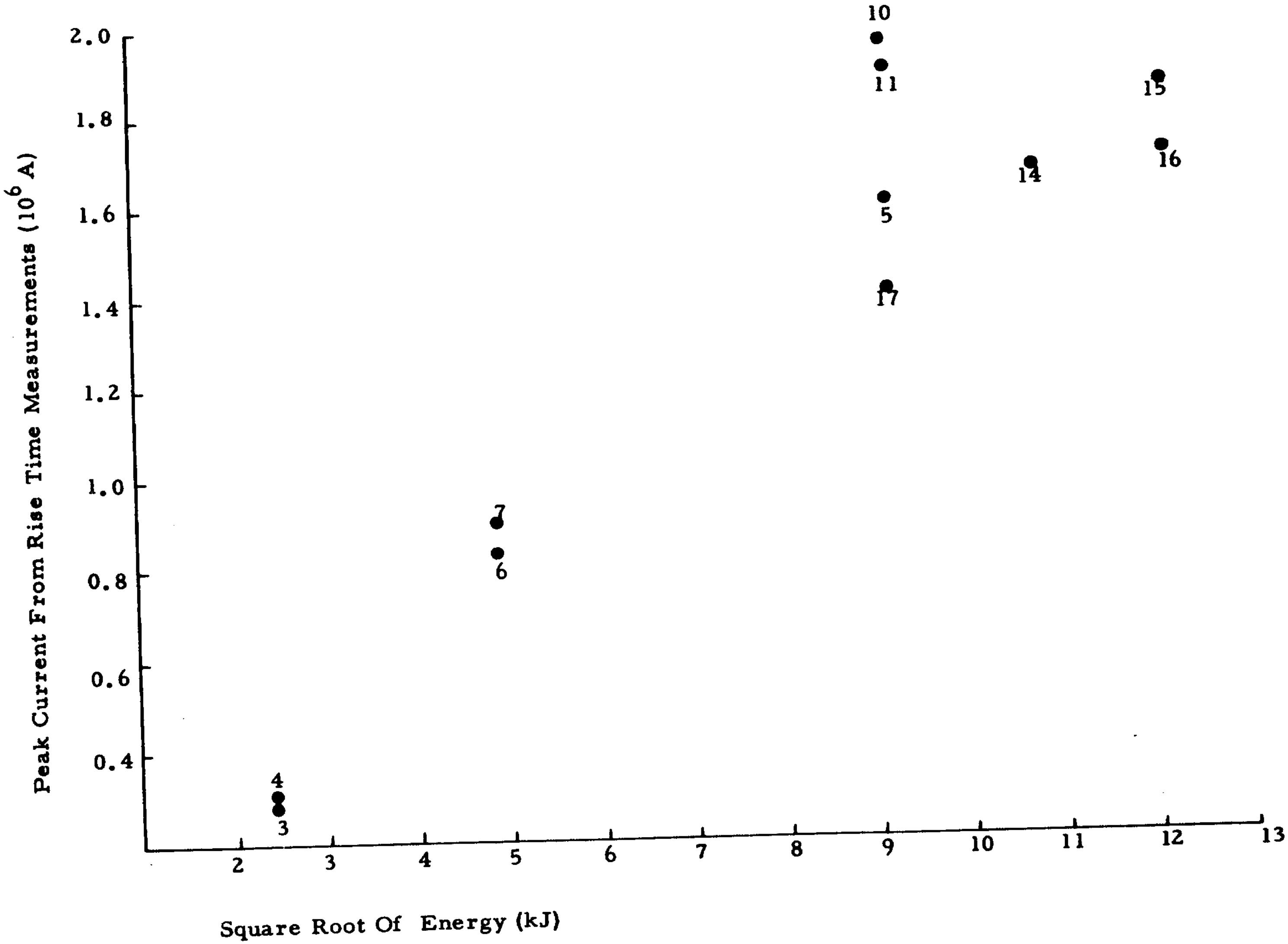

Figure 21. Peak current (rise time measurement) versus square root of bank energy

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and listed in Table V. Figure 20 is plotted using Equation 4 and Tables III and VI. From this plot the value of bank inductance, $L = 65.6$ nH was derived. Due to the nonlinearity of the arc plasma system $T \neq \tau/4$.

This is in fact apparent from the plot of current versus power from Equation 5 and Tables III and V (see Figure 21). A large spread in the values makes it difficult to find the bank inductance (i.e., several straight lines would be required to match the data and derive the inductance).

Using the value of inductance, derived from Figure 21, and the capacitance of 14.2 μF capacitance the present 200-kJ arc plasma system has a quarter cycle current waveform $t = 9.1$ μsec for half the capacitor bank, i.e. 36 capacitors. This compares well with the value of $t = 10$ μsec for the 100-kJ system developed under the previous contract, implying a slightly lower value of system inductance.

Plasma velocities on the order of 46 km/sec and corresponding particle velocities of 10 km/sec were achieved at 2/3 power level.

6.0 DELIVERY AND CHECKOUT

The complete arc plasma system was shipped by truck on 26 August 1968 to Marshall Space Flight Center, Huntsville, Alabama. Two MBAssociates' personnel arrived at MSFC on 9 September 1968. The arc plasma system was unpacked, assembled and checked out. MSFC personnel were instructed in the operation of the arc plasma system. Several demonstration shots were performed. The maximum power level of these shots was limited to 100 kJ.

7.0 RECOMMENDATIONS

In view of recent developments, a feasibility study of hypervelocity particle acceleration by focused laser beams should be carried out because of the extremely high particle velocities attainable. The interaction of an intense focused laser beam has led to demonstrated small-particle velocities in excess of 20 km/sec. Velocities of more than 40 km/sec should be attainable.

Recently, MBA acquired a laser laboratory facility, including a 4 mW helium-neon laser plus other optical equipment. This facility could be used for preliminary feasibility experiments.

7.1 200-kJ MICROMETEROID ACCELERATOR SYSTEM IMPROVEMENTS

The following recommendations are derived from operational and design experience with the system gained during this contract.

(1) The voltage hold-off reliability of the spark gap switches be improved by:

(a) A focused laser beam would provide safer, more reliable and faster switching of the bank.

(b) Controlling the atmosphere surrounding the spark-gap switches (preferably with dry air).

(2) The length and volume of the vacuum system should be increased in order to allow the gas pressure generated by the arc plasma gun a larger area to expand.

(3) The present vacuum photodiode plasma pickups should be replaced by superior solid-state photodiode with appropriate circuitry.

(4) Pick-up coils should be mounted at each spark-gap switch to monitor relative current amplitudes and time of switching.

(5) A ferro-magnetic power supply could be incorporated into the system for charging the capacitor bank. This type of supply has the ability to charge the capacitor bank to a preset voltage at a constant current level as the bank voltage varies from zero to a full charge.

(6) A front-face flash impact capability should be added to assure velocity measurements if penetration of the target is not achieved.

7.2 ATTAINMENT OF HIGH VELOCITIES WITH THE 200-kJ BANK

(1) The advantages of a gun boost effect due the gasses generated by the arc plasma gun should be investigated for additional velocity enhancement.

(2) A parametric study of the relative placement of the particle and initiating foil should be made in order to optimize velocities as functions of the capacitor bank power level with respect to capacitor bank.

(3) A numerical study with the aid of a computer should be made of the nonlinear differential equations governing the arc plasma system. Such a study would give us a quantitative picture of the dependence of plasma velocity on bank energy, rise time, mass input from the rails and other parameters such as drag. This study would enable the choice of parameters for maximum velocity.