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SUMMARY

A 5-kilojoule ignitron-switched capacitor bank was developed and experimentally investigated. The electrical characteristics of the bank are a capacitance of 12.1 microfarads, an inductance of 14 nanohenries, a voltage range of 10 to 30 kilovolts, and a resistance of 0.0038 ohm.

The bank consists of 11 identical capacitor sections, each synchronously switched with an ignitron. All components hold off voltage to 30 kilovolts for an automatic fast charging mode of operation after a laborious conditioning process. A slower 1/2-minute charging time for manual charging mode limits reliable operation to 25 kilovolts only. Synchronization to within tens of nanoseconds is obtained through the use of a fast, high-voltage trigger signal and ignitron temperature control.

Typical transient current and voltage traces, as well as the instantaneous power plots obtained from these traces, are described for each component of one section of the bank with a 150-nanohenry load. An energy inventory of these components shows that the energy consumed up to the time when the first half cycle of current oscillation has occurred is divided almost equally between the total fixed bank resistance (216 J) and the time-varying component of resistance in the 11 ignitron switches (331 J) for a 20-kilovolt (2420-J) bank charge. Instrumentation, including the adaptation of a commercial voltage probe used in an "off-ground" high-noise area, is also described.

INTRODUCTION

Experiments with the Marshall-type coaxial plasma gun (ref. 1) are being conducted at the Lewis Research Center to determine the feasability of applying it to electric space propulsion. Initial results of this investigation are reported in references 2 and 3. The

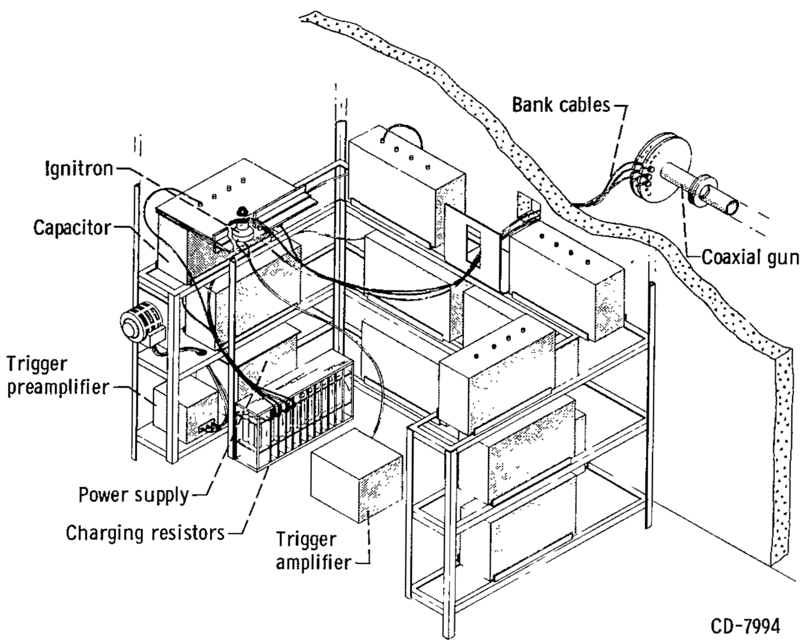

Figure 1. - Capacitor bank and gun. (Only one section shown in detail.)

coaxial plasma gun is powered by a relatively high-frequency low-inductance capacitor bank. This bank, together with the gun, is illustrated in figure 1.

Evaluation of the plasma gun required a thorough knowledge of the static and transient characteristics of the bank and the associated circuitry. This report describes these characteristics and the extension of capacitor-bank technology required to meet this application.

APPARATUS

Bank Description

The fast and efficient transfer of energy from the bank to the gun requires that the bank inductance and resistance be kept as low as possible in comparison with the gun load impedance. The maximum time rate of change of current should have a wide range for gun experiments. Therefore, a wide range in bank voltage (10 to 30 kV) and a minimum bank inductance and resistance were specified for the experiments reported in reference 2. External inductance can be added for experiments that require lower maximum time rate of change of current. General bank design has been described by Kemp (ref. 4).

The bank is of the controlled switchable type that allows a time-programed application of voltage. This feature is needed in some propulsion experiments.

Most switchable banks function dependably when working into low-impedance loads. The load produced by a plasma gun is initially a high-impedance load before the discharge forms in the gun and then becomes a low-impedance load as the discharge develops and moves down the gun barrel. This changing impedance imposes problems on the switch system and also makes it necessary to determine the transient bank and switch losses.

The one component most critical to fast, high-voltage, high-current bank operation is the switch, which can be either a gap type or an ignitron. At the time of initial bank design (1962-1963), gap-type switches had the disadvantage of more difficult maintenance for repeated usage. Ignitrons were chosen as switches for the present bank because they could be easily replaced commercially.

Thermal effects within an ignitron influence the discharge growth, as noted in reference 5. High-temperature operation provides good ignitron discharge growth and minimizes current rise time (ref. 6); however, the holdoff voltage is radically lowered, and thus there is a limitation on the potential to which the bank may be charged without premature discharge. A compromise between optimum discharge growth and high holdoff voltage has resulted in the development of a low-inductance, 20-kilovolt, 100-kiloampere ignitron, as described in reference 7. A version of this switch was chosen for the bank.

Bank Layout

The capacitor bank consists of 11 identical sections, each containing a 1.1-microfarad, 60-kilovolt capacitor, a flat-plate header and switch assembly, an ignitron (GL-7703), and three interconnecting coaxial cables to the coaxial load.[1] For convenience only one such section has been shown in detail in figure 1. The criteria for the selection of each main bank component were low inductance and resistance for the required voltage. The capacitor-bank circuit diagram is shown in figure 2. The 11 sections are in parallel and synchronously switched to the load.

The bank has been built in three tiers for easy servicing. As shown in figure 1, the power supply is on the lower left just behind the trigger preamplifier. Interconnection of the power supply with the capacitors is made through the charging resistors shown directly in front. Located in the center of the U-shaped bank is the trigger power amplifier that triggers the 11 sections of the main bank. Not shown on the header assembly are the specially designed isolation trigger transformers that isolate the main bank from its control circuitry. The control console is located in a shielded room not shown in figure 1.

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[1]Tobe Deutschmann Laboratories provided the initial design concepts and the initial equipment for the bank. The authors have since modified each component; thus the components and characteristics of the bank reported herein differ from those that were delivered.

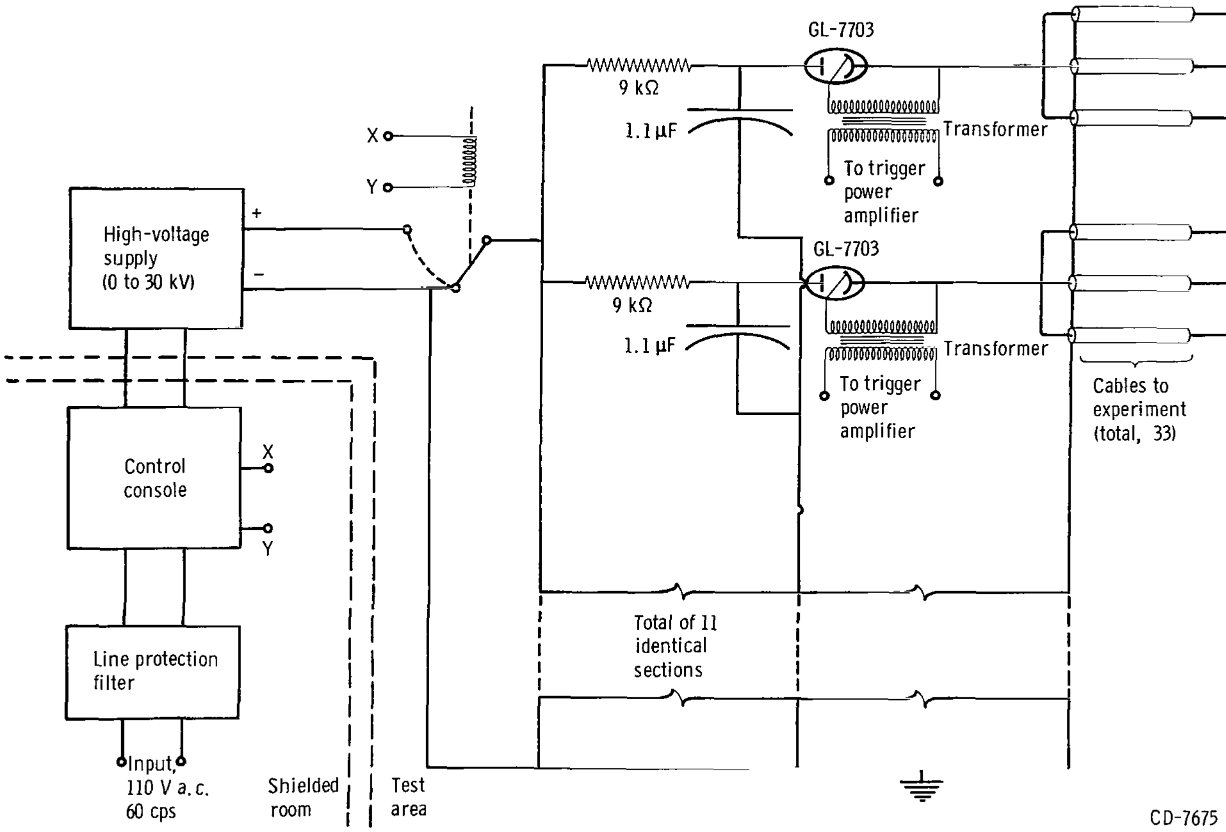


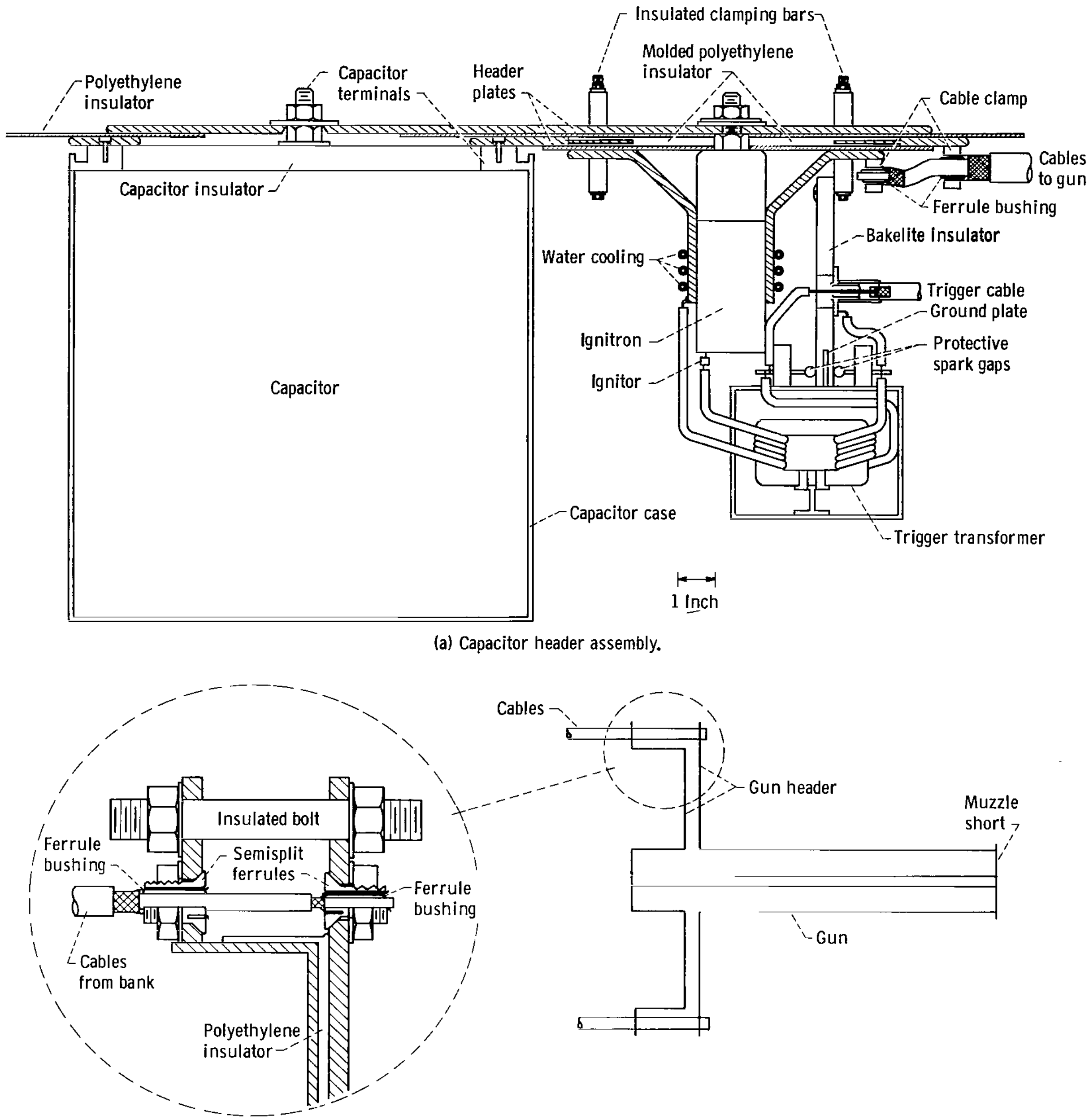
Figure 2. - Capacitor-bank circuit diagram.

During the operating cycle, each of the 11 sections was isolated. The sections were insulated from electrical ground except at the common reference point, which was maintained at the load. This was done to eliminate circulating currents.

Detailed Component Description

A cross-sectional view of the capacitor header assembly is shown in figure 3(a). Each section of the bank has such an assembly, which consists of three parallel aluminum plates (separated by polyethylene insulation) to facilitate low-inductance transmission of the energy from the capacitor to the coaxial cables through the ignitron switch. Insulating bars across the plates hold the three-plate transmission system together and alined. Three parallel coaxial cables (each having a characteristic impedance of 9.2 ohms, an inductance of 13 nH/ft, and a length of 10 ft) were used to connect each section to the gun.

A trigger-signal transformer supported from the bottom of the parallel plates is shown in figure 3(a); the transformer provides isolation of the trigger circuitry from the



(a) Capacitor header assembly.

(b) Cable connected to plasma-gun header.

Figure 3. - Single section and load.

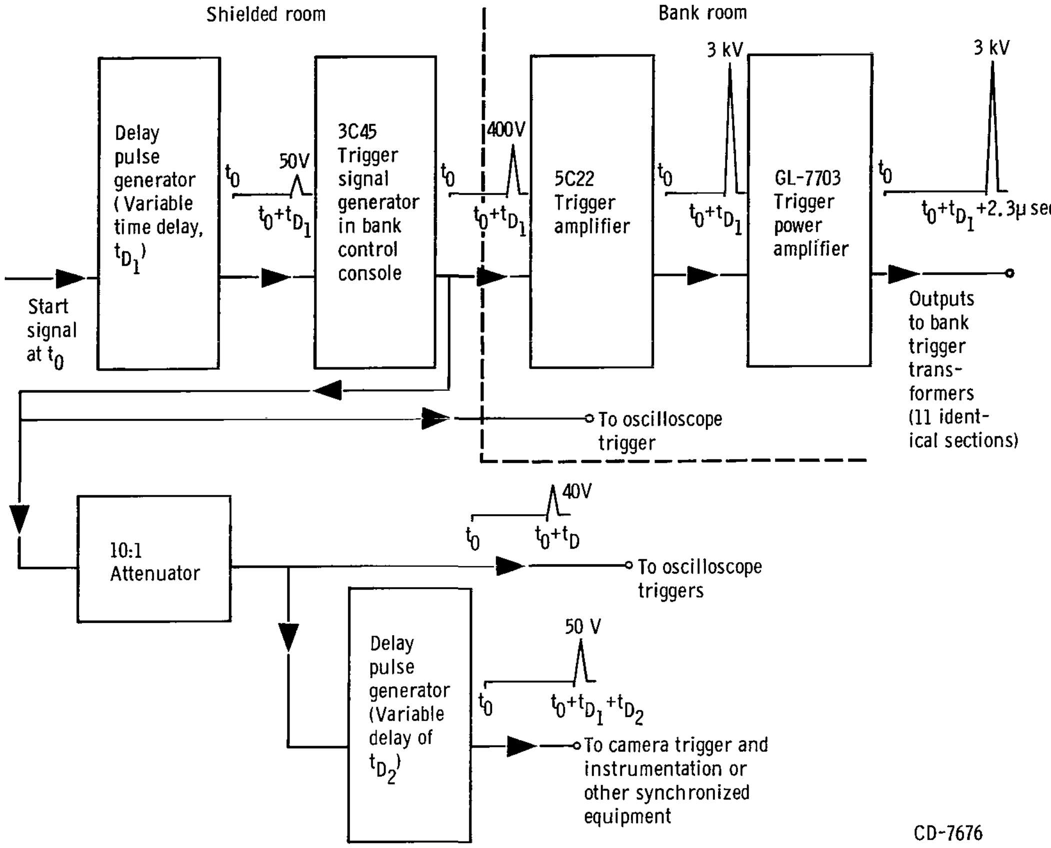


Figure 4. - Trigger system for bank and instrumentation.

main bank circuit. Protective spark gaps are installed on the primary winding to prevent any bank transients from damaging trigger circuit gear. Figure 3(b) shows the manner in which the bank cables are connected to the gun header.

Water cooling was provided for each ignitron cathode. The water temperature was maintained at $68^{\circ} \pm 1^{\circ}$ F.

The charging power supply (fig. 2) is remotely controlled from the shielded room control console. Switching at the control console allows for either 0- to 60-kilovolts manually controlled charging at a 20-milliampere maximum charging rate, or 0- to 30-kilovolts automatically controlled charging to a preset voltage. A remotely operated vacuum relay is used to connect the high-voltage power supply to the bank capacitors through 9000-ohm wire-wound charging resistors. After charging is completed, the power supply is remotely disconnected.

The trigger system and the location of trigger equipment in both the bank and the shielded rooms is shown in the block diagram in figure 4. A commercially available delay generator is used to delay the start command if the experiment powered by the bank requires a time delay. This delayed start is then sent to the trigger signal generator in the control console, which in turn provides the triggering for the recording oscilloscopes. This same pulse, after passing through the trigger preamplifier and power amplifier, is used to switch the main bank. A pulse delay generator can be incorporated if an additional delayed trigger is needed for instrumentation or other auxiliary synchronized equipment.

Operating Modes of Bank

Manual voltage charging of the bank is controlled by hand at the control console by continual adjustment of the input variable autotransformer. Adjustment of this autotransformer determines the charging rate and the final voltage of the bank (0 to 60 kV capability but never used beyond 30 kV). Depending on the experimental needs, the manual mode allows for a pushbutton "fire" command from the control console or a synchronized "fire" command from an external signal source.

In the automatic charging mode the maximum voltage to which the bank may be charged is 30 kilovolts. The bank is charged at constant current, the level of which is controlled by the position of the variable autotransformer (set in advance). The automatic charging mode allows for a pushbutton-operated "fire" command from the control console, or will automatically (after reaching a preset voltage) provide a "fire" command or a contact closure for auxiliary operations.

Bank Safety System

The voltage of the bank is monitored at the console with a meter that is provided with an adjustable mechanical trip that will safely discharge the bank if the desired voltage is mistakenly exceeded. An interlock system is provided such that any entry to the bank area would automatically discharge the bank regardless of where in the timing cycle the interruption occurred. An overcurrent protective device is also provided. A "bank-safe" switch on the console is provided so that the operator can discharge the capacitor through a shorting relay if necessary. When an unsafe condition is sensed, the control system first disconnects the power supply and then applies a discharging safety circuit.

Charging Instrumentation

The control console is equipped with a bank-voltage panel meter indicator and a charging current milliammeter. The signals that actuate these meters come from the voltage-dividing resistors or current-reading resistors in the power supply.

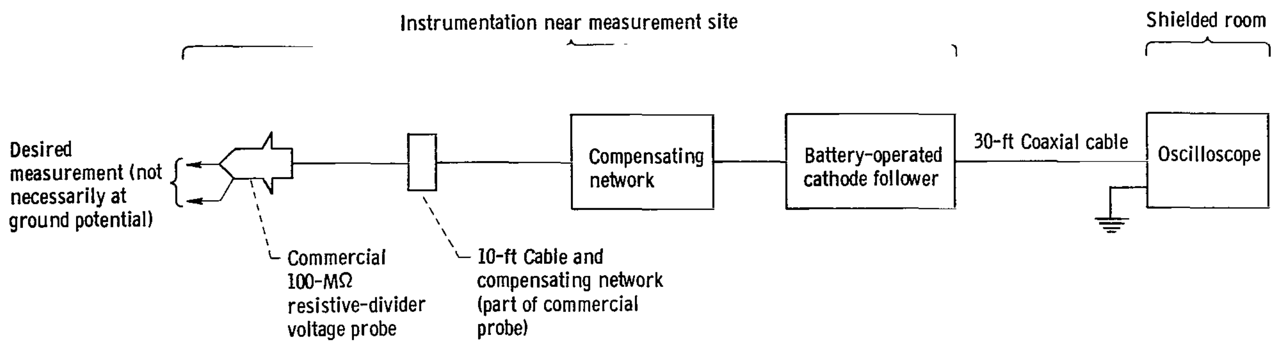


Figure 5. - Block diagram of alternate method of high-voltage measurement.

Transient Instrumentation

The voltage across the coaxial gun was monitored by means of a capacitive divider composed of vacuum capacitors. The output of the divider was fed directly to the vertical deflection plates of a high-voltage surge-type oscilloscope.

A Rogovsky coil (ref. 8) encircles the center member of the shorted coaxial-gun load. The output of the coil is proportional to the rate of change of the gun current. A passive integrator (with a time constant of 184 μsec) was used to obtain the gun current. Commercially available high-voltage resistance divider probes were used to monitor capacitor and ignitron potentials. In all cases other than the gun voltage the waveforms were recorded on dual-gun high-frequency oscilloscopes.

When a bank is operated under high-voltage, high-current conditions, it is imperative that oscilloscopes with amplifier circuitry be as far from current-carrying members as possible to minimize spurious signals.

Special Instrumentation

An alternative method of high-voltage measurements was developed and is shown in figure 5. This method allows commercially available resistive-divider probes to be applied to remote locations and in off-ground situations without disturbing dynamics. For simplicity, the specific instrumentation of each test will be described as it appears in the section PROCEDURE FOR DETERMINING BANK CHARACTERISTICS.

DESCRIPTION OF BANK DEVELOPMENT

All components in the bank, except the switch ignitrons, consist of judiciously chosen available equipment, used with known techniques. These components attained a 30-kilovolt holdoff for a practical time after some changes in the capacitor header assembly. The final version of the header assembly is shown in figure 3. Cable connection techniques determined in the development program are also shown.

Ignitron Voltage Holdoff

The required voltage holdoff performance by the 11 synchronously switched ignitrons was more difficult to achieve. Available ignitrons were used to avoid a lengthy development program. The best available ignitrons for the experiment were to be used about 10 kilovolts above the manufacturer's rated maximum voltage of 20 kilovolts. Also, no data were available for the statistical effect on voltage holdoff performance of using 11 ignitrons simultaneously.

Steps were taken to determine the factors involved in the selection of ignitrons that had a high probability of performing properly, to determine conditioning that was needed to maintain reliable performance, and to choose the proper ignitron environment (tube temperature, vibration, etc.).

As a result of numerous tests and recommendations by the author of reference 4, the following procedure was developed to select suitable ignitrons:

(1) A 2-week period of postdelivery shelf life in operating position, followed by careful handling, improved the voltage holdoff performance.

(2) Thermal conditioning with the anode temperature maintained at 150° F and the cathode temperature kept at 60° F for at least 4 hours also increased the voltage holdoff performance.

(3) An alternating-current high-pot test was performed, wherein a 60-cps, 18-kilovolt root-mean-square alternating-current voltage was applied from anode to cathode to determine the low-frequency leakage current that flowed through the tube. (Any detectable leakage was cause for rejection.)

(4) A direct-current Q-pot test was performed, wherein a direct-current high voltage from a charged capacitor is statically applied across the anode and cathode. (A maximum holdoff voltage of 30 kV was required.)

(5) Although the ignitrons are nominally rated at a maximum voltage of 20 kilovolts, after the temperature conditioning, preselection, and increasingly higher voltage Q-potting, some ignitrons were found that held off 30 kilovolts for 1/2-minute periods or more. After a set of 11 such selected ignitrons had been found, they were installed in the bank and tested for voltage holdoff as a system.

The bank was manually charged and switched through the bank ignitrons to a dummy load. The bank-switched ignitrons were operated for 100 shots at 20 kilovolts prior to attempting higher voltage shots. This switch conditioning in the bank proved necessary to obtain reliable higher voltage operation. The charging voltage for each shot was then increased at 2-kilovolt increments until excessive ignitron prefirings discharged the bank prematurely. The entire system was found to hold off 20-kilovolt voltages with no premature discharges for hundreds of operations at a time. In the manual charging mode premature discharges became increasingly prevalent beyond 25 kilovolts. At 25 kilovolts premature discharges occurred in about 4 percent of the attempts. Use of the automatic charging mode, however, permitted the operation at 28 to 30 kilovolts because the charging time above rated voltage and to "switch on" was only of the order of 5 seconds.

The method of charging and the required time of holding charge prior to switching the bank to the load affect the voltage holdoff capability of each component of the bank. If the added complication of fast charging (through a Marx charging technique, ref. 4) could be tolerated and switching accomplished within microseconds after charging, each component of the bank would have less stringent voltage holdoff requirements; and a different, higher level, and more reliable holdoff voltage could be attained. The method of charging chosen for the bank testing program was manual charging that maintained an approximately constant charging current. This was done to simplify the maintenance of the charging system and to give dependable service because of the more simple charging circuit. The high-voltage power supply is designed to supply a maximum charging current of 20 milliamperes, and this limitation requires a manual charging time for the bank of 15 to 30 seconds. This charging time requires reliable static-holdoff characteristics during this period for affected components.

Synchronization of Switch Ignitrons

To achieve synchronous switching of all 11 sections of the bank, each ignitron must simultaneously receive the proper type of trigger signal, and each must have the proper internal conditions. Since the criteria for maintaining proper conditions inside the ignitron were not known, a test program was initiated to determine the parameters that affect synchronization.

The results of this test program indicated the following:

(1) The ignitor resistance of each ignitron should be continuously monitored with the ignitron in place in the bank. The ignitor resistance should be above 25 ohms.

(2) Conditioning shots are necessary just prior to the test firing.

(3) The cathode temperature is critical, warmer temperatures providing better synchronization but poorer voltage holdoff. A compromise temperature was found (68° F), and a constant-temperature distilled-water supply was provided to keep the ignitrons at that temperature. (Note the cooling coils in fig. 3(a).)

To maintain bank jitter time less than 10^{-7} second, the electrical signal to each ignitor must be at least 1.5 kilovolts with rise time of the order of 10^{-8} second.

The trigger signal is sent to the ignitor of each ignitron through a 1-to-1 pulse transformer to provide isolation of main bank energy from the trigger amplifiers. The final version of this transformer is shown in figure 3(a) and includes spark-gap primary protection and electrostatic shielding (not shown in fig. 3(a)) that provides very low coupling capacitance from primary to secondary winding.

PROCEDURE FOR DETERMINING BANK CHARACTERISTICS

Ringing Frequency

A series of ringing frequency tests were performed:

(1) With the capacitor alone

(2) With the capacitor and ignitron assembly only

(3) With one complete section (capacitor, ignitron assembly, and three parallel transmission cables)

For each test, the load was a very-low-inductance short. The procedure was to charge the capacitor and then note the ringing frequency as the discharge proceeded. In some instances, a small magnetic probe wound like a solenoid was placed near the current-carrying member, and the fringe field changes were noted against time on an oscilloscope. At other times, where convenient, a Rogovsky coil probe encircled a current-carrying member, and this probe output against time was recorded on an oscilloscope.

When the bank was fully assembled, the output cables were connected to the load by means of a header. This header was shorted to obtain the ringing frequency of the bank system.

Capacitance

The capacitance of each capacitor was separately measured with a precision bridge. The capacitance of the remaining components was not measured because it was small when compared with the storage capacitance.

Inductance

The inductance of each component and the bank as a whole is not measured directly but is calculated from a knowledge of the ringing frequency and the applicable capacitance. Placing relatively noninductive shorts at judicious locations and noting the resulting ringing frequencies establish the inductance of each component. The theoretical expression for ringing frequency of a series resistance-inductance-capacitance circuit (ref. 9) is

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{1}$$

which reduces to

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{2}$$

when

$$\frac{1}{LC} >> \frac{R^2}{4L^2}$$

In this experiment $1/(LC)$ is about 500 times larger than $R^2/(4L^2)$. Thus, equation (2) is valid.

Fixed Resistance

The bank has a fixed alternating-current resistance dependent on frequency, type of conductors, type of connections, and switch characteristics. It can also be assumed that the bank has a time-varying resistance caused by the formation, growth, and motion of the discharge occurring in the switch ignitrons. The fixed alternating-current resistance portion of the bank resistance is determined by recording the current against time on an oscilloscope. The ratio of amplitudes of successive current peaks gives an experimentally determined decrement factor. The decrement factor, along with a knowledge of the system inductance, yields a value for the resistance.

Jitter and Synchronization

Since the bank is composed of 11 identical sections, each separately switched, each section must switch repeatedly at a predictable instant with a small tolerable random time

TABLE I. - GUN DIMENSIONS

Length, cm	48
Inside diameter of outer electrode, cm	9.5
Outside diameter of inner electrode, cm	3.2

increment. (This random time increment is called section jitter.) The switch-on time of each section must be measured for a series of triggered shots, and from the data gathered the delay time between command and switch-on can be obtained as well as the section jitter. With this knowledge, the switch-on times were made as close to coincidence as possible for each section. This coincidence was accomplished by apparatus and trigger signal adjustments. Then the individual sections were assembled together, and the whole bank system was operated into a shorted-header-type load.

The delay time between command and switch-on was recorded for all sections simultaneously by using Rogovsky coils in each section and by recording this signal against time on synchronized oscilloscopes. Trigger-signal characteristics, ignitor-resistance condition, and ignitron-cathode temperature were varied until the desired switching synchronization for the whole bank was obtained.

Energy Inventory

One method of determining energy loss is the time integration of the instantaneous power for each component and the load. This method was previously used by other authors (refs. 10 and 11) and was also used in the present study. The load chosen was a muzzle-shorted gun, the dimensions of which are shown in table I.

To determine the energy losses, the complete bank was connected to this coaxial plasma gun. The short was a very low-resistance, noninductive configuration. The equivalent circuit for this entire bank and the shorted gun load is shown in figure 6.

Measurements were made on a single bank section and on the load. Since there are 11 identical bank sections, only one was chosen as representative, and conclusions were drawn on the basis of the assumed symmetry of the bank.

Prior to the data gathering shot, the oscilloscopes were synchronized, calibrated for voltage, and checked for linearity. Measurement preamplifiers were also calibrated for gain, frequency response, and balance. The bank was charged to 10 kilovolts and discharged through the gun load. This procedure was repeated at 2-minute intervals, each shot being 2 kilovolts higher than the last, until a 20-kilovolt charge condition was attained. At least 10 similar 20-kilovolt shots were made before a 20-kilovolt data gathering shot was performed. Figure 6 shows the equivalent locations of the measurements made.

The time derivative of gun current dI_g/dt was measured with a Rogovsky coil encircling the gun center electrode at the breech end of the gun. This signal was transmitted

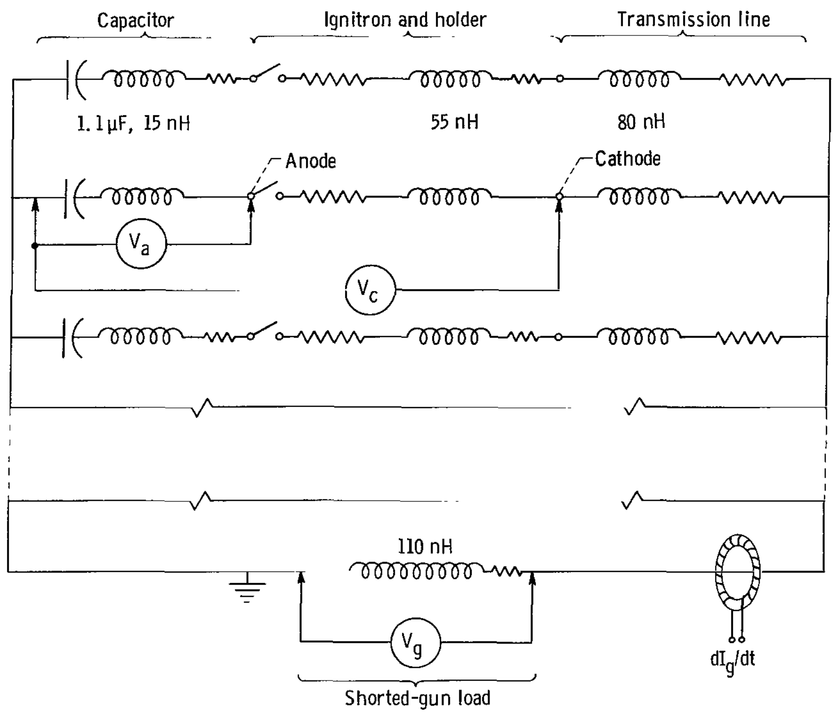


Figure 6. - Equivalent circuit of bank and load; total fixed bank resistance, 0.0038 ohm.

through coaxial cable, terminated, and recorded on an oscilloscope in the screen room. The gun current I_g was measured by passively integrating the terminated dI_g/dt signal in the screen room with a 184-microsecond time constant RC-integrator and by recording this signal against time on an oscilloscope. The gun header voltage V_g was measured with a capacitive divider directly connected to the deflection plates of a nearby high-voltage-surge oscilloscope. The signal was recorded as a function of time.

The ignitron cathode voltage V_c between the ignitron cathode and the capacitor can was measured with a compensated-resistance voltage-divider probe. The signal output of the probe was impedance-matched (through the use of a battery-operated, floating, cathode follower, see fig. 5) to a coaxial cable and recorded on an oscilloscope in the shielded room. The voltage between the ignitron anode and capacitor can V_a was measured in a similar manner. All measurements described thus far were taken simultaneously.

The ignitron potential drop $V_a - V_c$ was recorded for a separate data-gathering shot but under identical conditions. This measurement was made by using two identically adjusted and calibrated resistance-voltage divider probes, one measuring V_a and the other V_c. Two probe outputs were directly connected to a nearby floating oscilloscope with a difference preamplifier that had been balanced and voltage calibrated for the probes. The gain-bandwidth product of the oscilloscope was checked to ensure proper response. These traces were time synchronized with previously recorded traces to incorporate this measurement with the other data.

The method of operation was to charge the bank to 20 kilovolts, and then disconnect it from the charging supply. The oscilloscope sweeps were then started, and about 2 microseconds later the bank was switched to the load.

RESULTS AND DISCUSSION

Electrical Parameters

Table II summarizes the experimentally determined electrical parameters of the bank system. The experimental value of ringing frequency (bank and cables only) was determined from oscillograms, and its precision is limited by the linearity of the oscilloscope and the readability of the recorded traces.

The experimental value of capacitance was more accurately determined because a precision-bridge technique was used.

The total bank inductance was determined by using equation (2); the bank inductance accuracy is dependent on the accuracy of frequency and capacitance measurements.

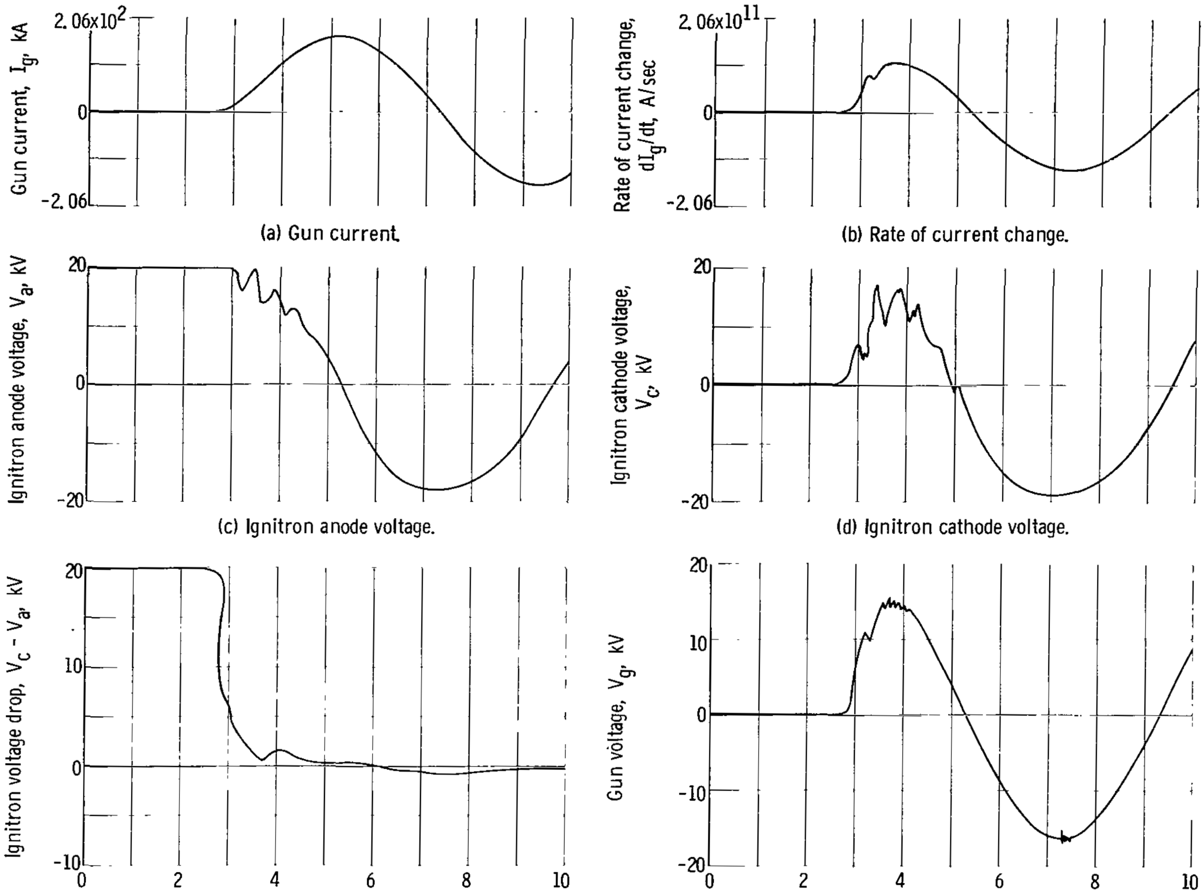
Data Traces

Typical data traces are shown in figure 7. The gun current starts at 2.9 microseconds. The ringing frequency for the bank and shorted gun load is 123 kilocycles; figure 7, however, shows a slightly lower value for the first half circle because of changing impedance. The rate of change of current also starts at 2.9 microseconds, and a dip in the trace is noted at 3.3 microseconds. This dip is caused by the relatively small negative reflected voltage due to the impedance mismatch between the cables and the load.

Ignitron anode and cathode voltages (figs. 7(c) and (d)) were measured on one ignitron only while the whole bank was in operation. The ignitron voltage drop (difference between ignitron anode and cathode voltages) in figure 7(e) was recorded in another identical shot. The voltage drop across the ignitron was measured with the ignitron anode and cathode voltage instrumentation, but these two signals were connected to a difference amplifier that provided electronic subtraction to obtain the desired voltage drop across the ignitron. This trace shows switch-on times of the order of 10^{-8} second, which are in agreement

TABLE II. - BANK CHARACTERISTICS

Voltage (variable), kV	10 to 30
Resistance, Ω	3.8×10^{-3}
Inductance, nH	14
Capacitance, μF	12.1
Mode of operation	Switched from external trigger signal
Shorted-bank ringing frequency, kc	480
Switch jitter, sec	$\sim10^{-8}$



(a) Gun current.

(b) Rate of current change.

(c) Ignitron anode voltage.

(d) Ignitron cathode voltage.

(e) Ignitron voltage drop. (This waveform was under separate but identical conditions.)

(f) Gun voltage.

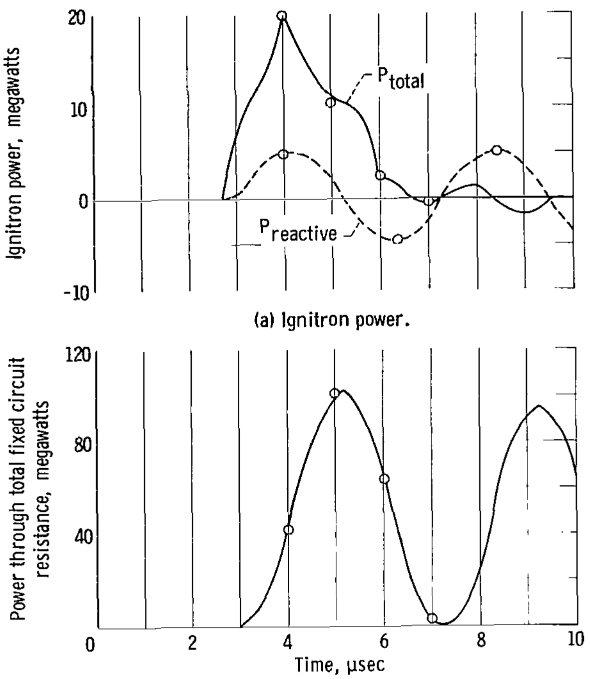
Figure 7. - Typical data traces.

with times determined by other authors for similar ignitrons (ref. 6). Ignitron voltage-drop and current measurements determine instantaneous impedance, which is composed of both time varying resistance and inductance.

The gun voltage trace (fig. 7(f)) is identical in shape and phase with the trace for the rate of current change (fig. 7(b)); thus the gun can be considered an almost purely inductive load.

Instantaneous Power Curves

The instantaneous total ignitron power (including the ignitron holder) for one section is plotted in figure 8 from measured values of ignitron voltage drop and current through an ignitron. Also shown in figure 8 is the reactive component of the power, obtained from the measured values of the current through the ignitron and the holder and their known reactance by the following equation:



(b) Power expended by measured total fixed resistance.

Figure 8. - Instantaneous power.

$$P_{IX} = \frac{I_I^2}{2} \omega L_I \sin 2\omega t$$

where

P_{IX}	reactive ignitron power, W
I_I	peak ignitron current, A
ω	angular frequency, rad/sec
L_I	ignitron and holder inductance, H
t	time, sec

Most of the ignitron power loss occurs before 5.75 microseconds. An appreciable resistive power loss is noted (P_{total} - $P_{reactive}$) in this initial period. Maximum power consumption occurs after about 1 microsecond from switch-on time. Other investigators have also observed discharge "pinches" in glass-walled and similar ignitrons after about 1 microsecond (ref. 5).

Figure 8(b) shows the power expended by the measured total fixed resistance. This is calculated from the measured fixed resistance (0.0038 ohm, determined from the decrement as described in the section Fixed Resistance (p. 12), which includes all nonchanging bank and load resistances, and the measured total current in figure 8(b).

Energy Inventory

Table III shows a typical energy inventory for the bank with shorted-gun load when the bank initial charging voltage is 20 kilovolts. For the time when first "zero" voltage occurs ($t = 5.2$ μsec) as well as for the time when the first half cycle of current oscillation occurs ($t = 7.2$ μsec). The original stored energy is 2420 joules and is shown as item (1) in table III. The energy remaining in all of the capacitors and in the total inductance is listed as items (2) and (3), respectively. Item (4) is the system energy loss obtained by calculating the difference between item (1) and the sum of items (2) and (3). Item (5) is the energy loss in the fixed resistance, calculated from the area under the fixed-resistance power-time curve of figure 8. The energy loss in all 11 ignitrons (item (6)) is calculated from the area under the resistive portion of the ignitron total-power curve of figure 8.

TABLE III. - ENERGY INVENTORY

Energy	Time, t, μsec	
	5.2	7.2
(1) Original stored energy (at t = 0), J	2420	2420
(2) Energy remaining in capacitors, J	0	1830
(3) Energy remaining in total inductance, J	1890	0
(4) System energy loss, J	530	590
(5) Energy loss in fixed resistance, J	112	216
(6) Energy loss in eleven ignitrons, J	242	331

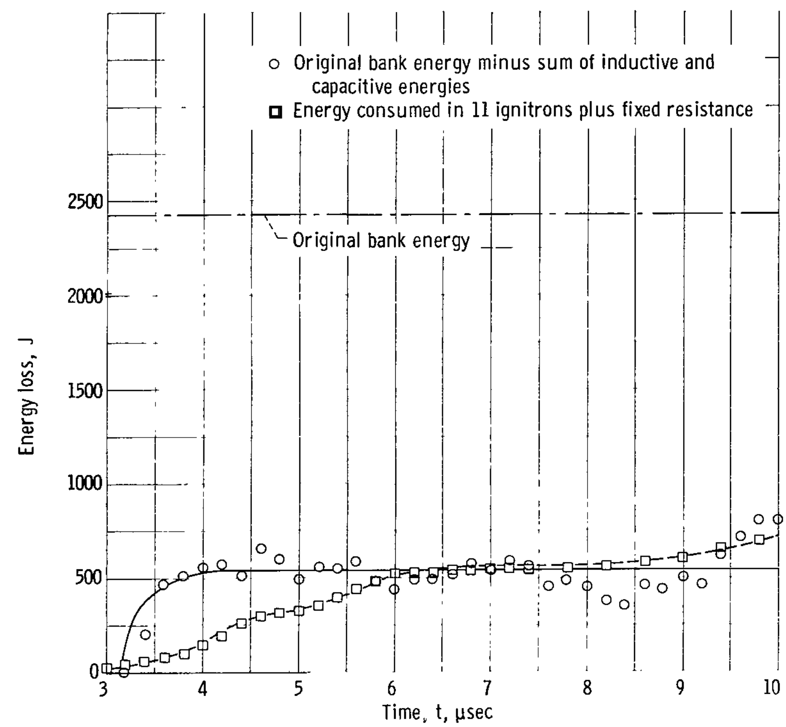


Figure 9. - System energy loss plotted against time.

The ignitrons contain a fixed resistance, which was found experimentally to be small compared with both the time-varying portion of its resistance and the fixed resistance of the system. The sum of the energy losses in items (5) and (6), the major loss terms, should equal the approximate system loss (item (4)). The agreement is good for the 7.2-microsecond case, but at 5.2 microseconds there is a difference. Presumably item (4) is in error and is too large because of the combined error in measuring items (1) and (3).

Figure 9 shows the system losses plotted as a function of time. The solid curve is obtained by subtracting the sum of the instantaneous values of total inductive and capacitive energies from the original stored energy in the bank. (A point on this curve corresponds to item (4) of table III.) The dashed curve is obtained by summing the energy consumed in 11 ignitrons with the energy expended in the total fixed resistance for each instant of time. (A point on this curve corresponds to the sum of items (5) and (6) of table III.) Figure 9 shows that two independent loss calculations agree after the first few microseconds.

SUMMARY OF RESULTS

The following results were obtained from a study of the electrical characteristics of a 5-kilojoule, ignitron-switched, fast capacitor bank:

1. The bank does not achieve reliable 30-kilovolt holdoff operation for the 1/2 minute required for manual charging, even though each individual section shows 30-kilovolt holdoff reliability. In the manual charging mode, the bank performs well and continuously for 20 kilovolts and, after conditioning, can be operated up to 25 kilovolts with some premature discharges. In the automatic charging mode, with smaller on-charge time conditions (less than 5 sec), the bank is operational to 30 kilovolts.

2. Care is required in conditioning and selecting ignitrons and, after installation, maintaining ignitron cathode temperature if the requirement of synchronization of all the sections to within 10^{-8} second is to be achieved.

3. The low inductance (14 nH) and low resistance (0.0038 ohm) of the bank meet the design criteria.

4. The voltage, current, and power were synchronously and instantaneously measured and calculated for each component of the bank when it was connected to a load simulating a coaxial plasma gun inductance. The following results were noted:

    a. The energy consumed, up to the time of the first half cycle of current oscillation is divided between the fixed resistance of the entire circuit (216 J) and the time-varying component of resistance in the ignitrons (331 J).

    b. The switch rise time ($\sim 10^{-8}$ sec) and the time of maximum power consumption in the switches agree qualitatively with the work of other authors in related studies on different ignitron switches.

The technique of adapting commercially available resistive-divider voltage probes to off-electrical-ground measurements in high-electrical-noise situations has proven useful; however, a lengthy and careful calibration process is required.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 3, 1965.

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