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HEATING A SUPERSONIC AIR STREAM WITH A CORONA DISCHARGE

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SUMMARY

Thermal energy can be uniformly added to an air stream by means of a "pulsed corona" or arrested-breakdown type of electrical discharge. The rapidly pulsed discharge takes place between the inside wall of a 3-inch diameter cylindrical pipe and an axial corona wire down the center of the pipe. With an air velocity of approximately 200 feet per second, preliminary tests have demonstrated that 15 kilowatts of average power can be delivered to the air stream. The discharge region extends for approximately 3 inches along the length of the tube. With the present apparatus the power limit is caused by the tendency of the corona streamers to break down into solid sparks when the pulse repetition rate exceeds about 10,000 pulses per second. It is believed that the present power limit can be greatly increased by (1) using pulses of alternating polarity instead of the present unipolarity pulses, (2) using a higher velocity air stream, (3) extending the discharge along a greater length of the tube.

INTRODUCTION

The ultimate objective of this research is the development of a wind tunnel capable of simulating the temperature conditions encountered in hypersonic flight. A satisfactory method of adding thermal energy to a supersonic air stream would enable very high stagnation temperatures to be achieved without encountering the metallurgical problems and other limitations associated with pre-throat heating of the air supply. This report describes an investigation of the use of a "pulsed corona" type of discharge for heating a supersonic stream. The investigation is being conducted under a research contract with the Arnold Engineering Development Center. The project is administered through the Engineering Research Institute of the University of Michigan and utilizes the facilities of the Department of Electrical Engineering.

THE PROBLEM OF DIFFUSIVITY

In considering various electrical methods of heating a high-velocity air flow with an electrical discharge, one encounters several seemingly contradictory factors:

1. The heat should be added uniformly throughout the cross section of the air stream, which means that the electrical discharge should be of a diffuse character.
2. The heat should be added at high air density and low Mach number, but preferably downstream from the throat in order to avoid throat-erosion problems.
3. Familiar types of electrical discharges tend to be diffuse at sufficiently low gas pressures, but tend to constrict into small-diameter columns when the discharge column is exposed to the rapid convection heat removal encountered in an air stream.

Heating a low-density supersonic stream by means of an electric arc was investigated in a series of experiments at the University of Michigan in 1954.[1] These experiments were conducted in a Mach 4 air stream at static pressures in the range of 1 to 5 millimeters of Hg. The arc was stabilized transverse to the stream by means of a magnetic field. However, even at these low pressures, the arc tended to constrict into a narrow column and localize in the boundary layer near the wall of the tunnel. The possibility of diffuse heating by this method did not look promising.

NATURE OF THE PULSED CORONA, OR ARRESTED-BREAKDOWN, TYPE OF DISCHARGE

1. General Discussion

In order to find a more diffuse heating method, the phenomena associated with a corona type discharge was investigated. The familiar type of corona discharge takes place under conditions where one or both electrodes have sharp edges or small radii of curvature. The resultant nonuniform electric field between the electrodes permits a localized breakdown in the high field region without resulting in a spark channel across the electrode gap. For example, a high-voltage corona discharge between two parallel wires is characterized by a myriad of fine hairlike streamers in the vicinity of each wire. When viewed in a dark room, such

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[1] Haldon L. Smith, Harold C. Early, Investigation of Heating of Air Stream in a Wind Tunnel by Means of an Electrical Discharge, Contract DA-20-018-ORD-13047, University of Michigan, Engineering Research Institute, Report 2154-3-F, Ann Arbor, Michigan, October, 1954.

a discharge appears quite diffuse and the luminosity may surround each wire for a distance of several inches.

Although the diffusivity of the d-c corona discharge is very advantageous, the amount of thermal energy added to the air is quite small. A steady state d-c corona will break down into a solid spark if the corona current density exceeds a few hundred microamperes per square inch. A number of tests showed that the amount of energy which could be delivered at atmospheric pressure to a d-c corona discharge occupying a volume of one liter was limited to about 500 watts.

However, it was found that the average rate of power dissipation could be greatly increased if the corona voltage and current were pulsed. An appreciable fraction of a microsecond is required for a spark channel to bridge the gap between the electrodes, even when the pulse voltage is much greater than the normal breakdown voltage. By limiting the duration of the current pulse to a time interval of the order of 0.05 microsecond, instantaneous currents of many hundreds of amperes can be produced without forming a spark channel. Experiments have demonstrated that energies of the order of one joule can be dissipated in a one-liter volume of air in a single corona pulse. Since the corona streamers thereby produced are fine and diffuse, the removal of the pulse voltage permits the gas to be deionized at a very rapid rate. Pulse repetition rates of 5,000 or 10,000 per second have been produced, and it is expected that this rate can be increased by perhaps one order of magnitude.

2. Quantitative Characteristics

A detailed study of the electrical discharge in air will indicate the time-voltage relations of such a process. Considering a d-c voltage applied across the gap between two electrodes, no discharge will take place in the gap unless the voltage V is greater than the corona starting voltage, V_c. If V is greater than V_c, a steady-state, low-current corona discharge of the type described in the previous section will take place unless V is also greater than the gap static breakdown voltage, V_s. When V is greater than V_s, some of the corona streamers will in a very short but finite time bridge the gap and turn into a low-voltage, high-current localized spark channel. V_c is either less than or equal to V_s depending on electrode geometry. In the case of electrodes formed by two concentric cylinders, for instance, Fig. 1 shows the magnitudes and relative values of V_c and V_s for given outer diameter electrodes as the inner electrode increases in size.

When V is greater than V_s, one of the corona streamers will in time bridge the gap, shorting the electrodes with a low-impedance path and initiating the arc or spark discharge. The time required from application of voltage to formation of the arc is statistical in nature, but its mean value may be related to the voltage V across the electrodes by an exponential equation:[2]

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[2] Meek and Craggs, Electrical Breakdown in Gases, Oxford University Press, London, 1953, p. 115-116.

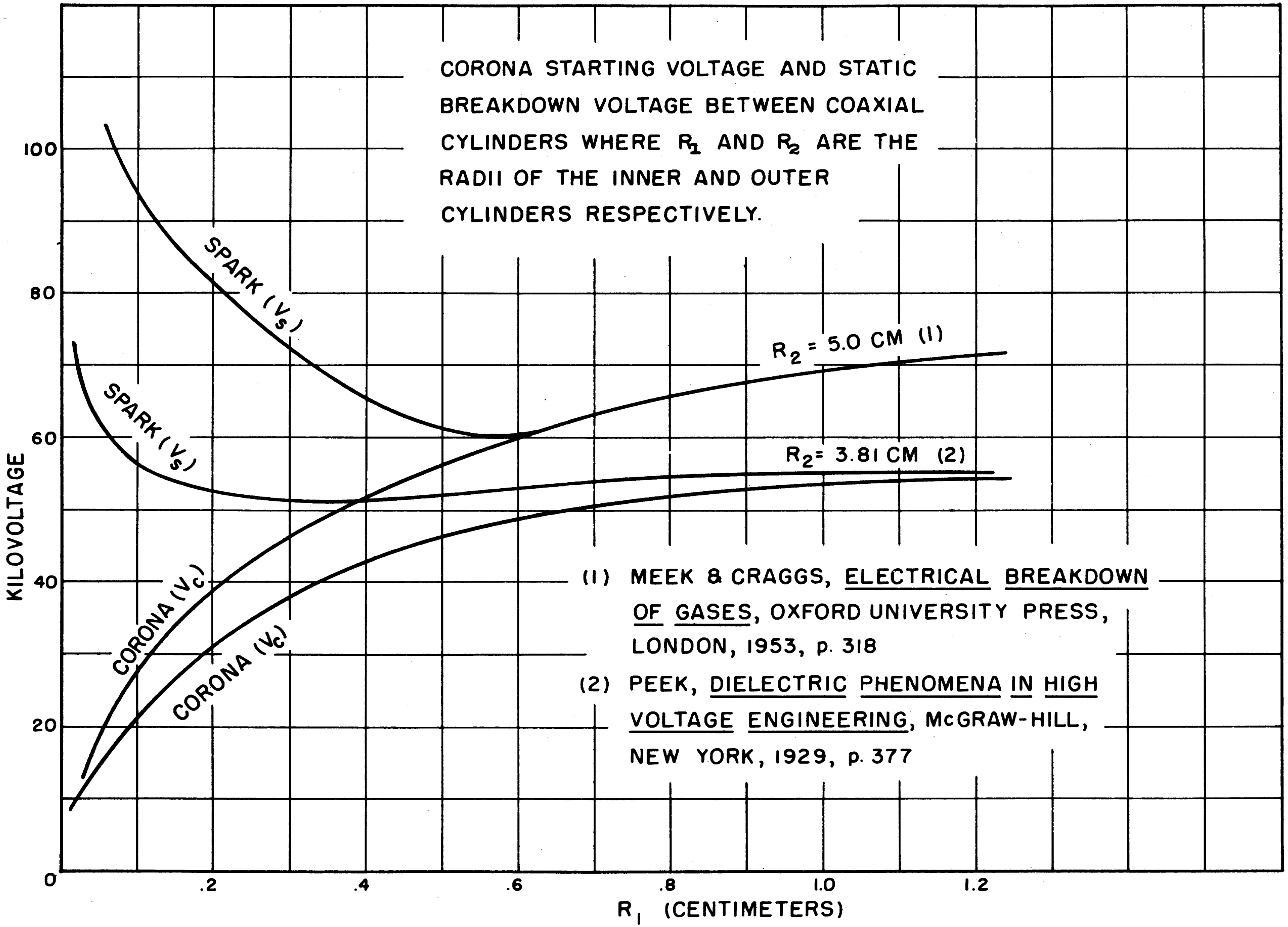
CORONA STARTING VOLTAGE AND STATIC BREAKDOWN VOLTAGE BETWEEN COAXIAL CYLINDERS WHERE R_1 AND R_2 ARE THE RADII OF THE INNER AND OUTER CYLINDERS RESPECTIVELY.
SPARK (V_s)
SPARK (V_s)
CORONA (V_c)
CORONA (V_c)
R_2 = 5.0 CM (1)
R_2= 3.81 CM (2)
(1) MEEK & CRAGGS, ELECTRICAL BREAKDOWN OF GASES, OXFORD UNIVERSITY PRESS, LONDON, 1953, p. 318
(2) PEEK, DIELECTRIC PHENOMENA IN HIGH VOLTAGE ENGINEERING, McGRAW-HILL, NEW YORK, 1929, p. 377
KILOVOLTAGE
0
20
40
60
80
100
.2
.4
.6
.8
1.0
1.2
R_1 (CENTIMETERS)

FIGURE I

$$t_f = \frac{a}{V-V_s} e^{-bV}$$

where t_f = formation time

V = electrode voltage

V_s = static breakdown voltage

a,b are constants depending on geometry, dielectric, external sources of ionization, etc.

In the case where the voltage across a gap rises at a finite rate rather than instantaneously, no references have been found in the literature which give a mathematical relation for spark formation time. Qualitative published data[3] as well as data taken in connection with the work on this project do indicate, however, that an exponential or hyperbolic type relation does exist between voltage at breakdown and time for spark formation. This is demonstrated in Fig. 2 where voltage is shown rising at several uniform rates. Breakdown occurs where each voltage-time line crosses the dashed curve. However, if the voltage is abruptly removed just before the dashed curve is crossed, spark breakdown will not occur. This "arrested discharge" produces a substantial amount of ionization and energy dissipation without resulting in a spark channel between the electrodes.

3. Re Pulse Shape

Although it is easy to demonstrate experimentally that a rapid sequence of arrested discharges will deliver much more average power to

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[3] Discussion by C. L. Fortescue following article by J. J. Torok, AIEE Transactions, 47, p.355, 1928.

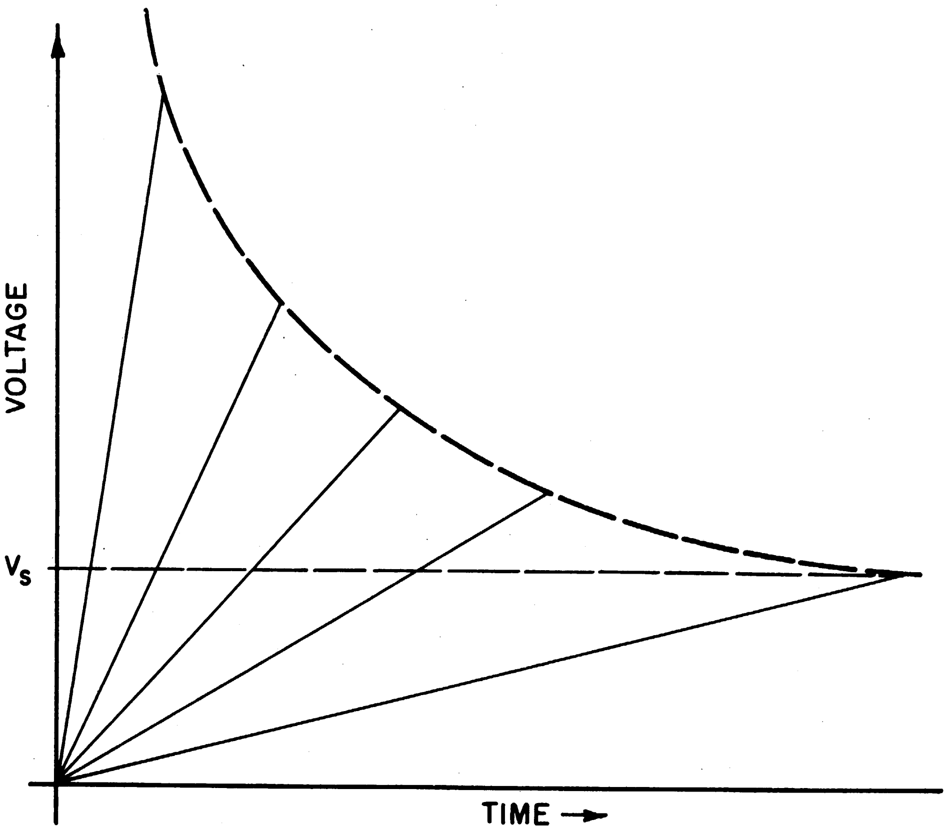
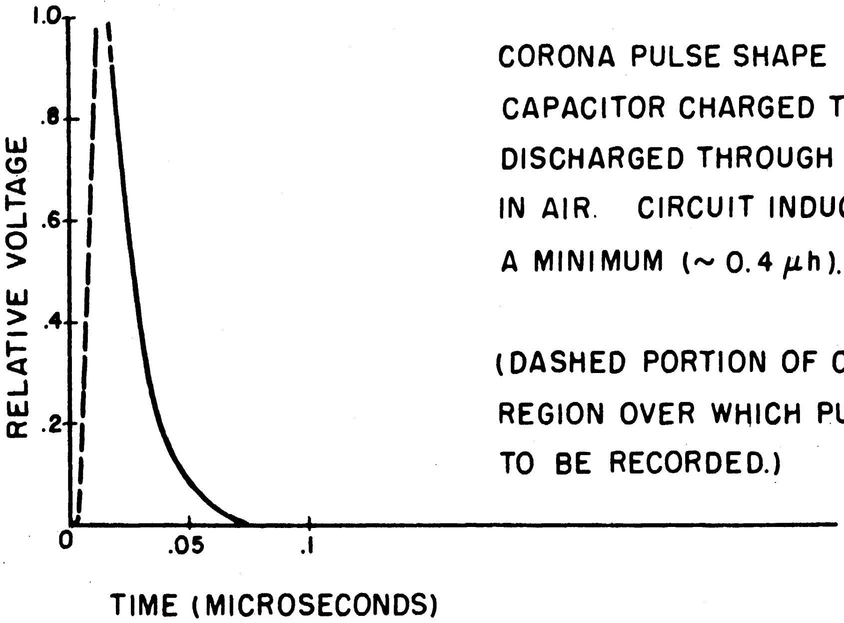


FIGURE 2

SPARK FORMATIVE TIME FOR VARIOUS RATES OF VOLTAGE RISE an air stream than will a continuous steady state corona, it is not immediately obvious which type of pulse delivers the most energy to the air stream: a pulse of maximum voltage and minimum duration, or a lower voltage pulse of longer duration. Experimentally, the pulses are produced by discharging a capacitor across the gap, and since the voltage across the gap is dependent on the stray inductance of the circuit as well as the nonlinear resistance of the corona discharge, it is difficult to vary the pulse shape, duration and voltage in any systematic manner such as in the idealized situation of Fig. 2.

Experiments were conducted using coaxial-cylinder electrodes in which the outer cylinder had a diameter of 6.4 cm and the inner electrode was a cylindrical wire of 0.1-cm diameter. The corona starting voltage was found to be about 15 kv, while static breakdown took place at 65 kv. These empirical values check the published data of Fig. 1. The pulses were produced by discharging across the electrodes a 270-$\mu\mu$f capacitor charged initially to 100 kv and then isolated from the charging supply during discharge.

All of the experiments indicated that the most energy dissipated in the corona occurred when the pulse was of maximum voltage and minimum duration. The conclusion was illustrated by a series of tests whereby the capacitor voltage was held constant and varying amounts of inductance were added to the circuit. Fig. 3 is a sketch of an oscillogram of voltage vs. time for a pulse with the minimum circuit inductance of 0.4 uh. All of the stored energy of 1.3 joules has been dissipated in the corona

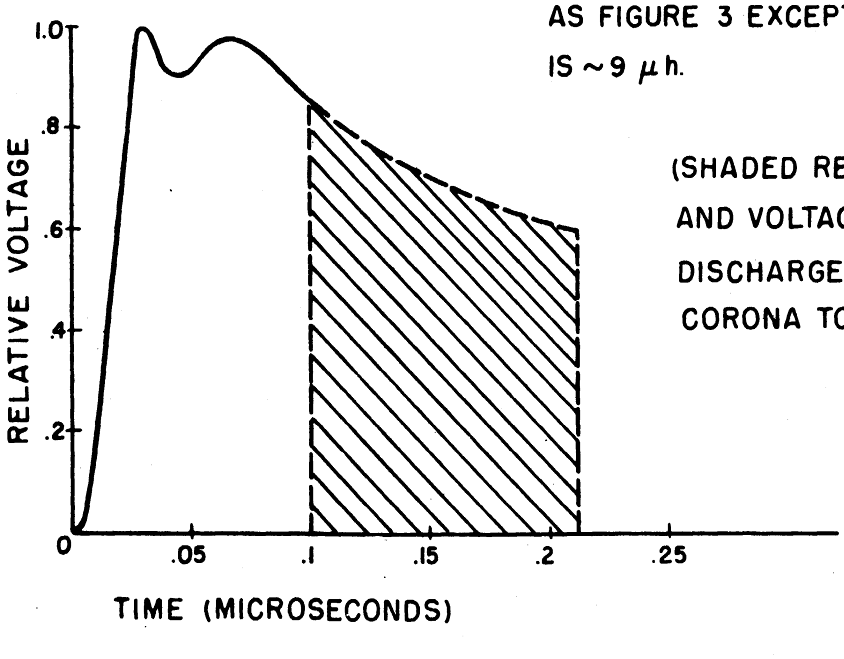


CORONA PULSE SHAPE - 270 $\mu\mu$f CAPACITOR CHARGED TO 100 KV AND DISCHARGED THROUGH COAXIAL ELECTRODES IN AIR. CIRCUIT INDUCTANCE REDUCED TO A MINIMUM (~ 0.4 μh).

(DASHED PORTION OF CURVE INDICATES REGION OVER WHICH PULSE WAS TOO FAST TO BE RECORDED.)

FIGURE 3

CORONA PULSE SHAPE - SAME CONDITIONS AS FIGURE 3 EXCEPT CIRCUIT INDUCTANCE IS ~ 9 μh.



(SHADED REGION INDICATES TIME AND VOLTAGE RANGE IN WHICH DISCHARGE WILL CHANGE FROM CORONA TO SPARK.)

FIGURE 4

without breakdown. The dotted curve indicates that the voltage peak is somewhat higher than the solid curve indicates because of limitations of the measuring equipment for such a short pulse. Fig. 4 is a slower pulse taken with 9 μh of added inductance in the circuit. When the current was limited to a lower value by this extra inductance, breakdown resulted before more than a fraction of the energy stored in the capacitor was dissipated in the corona.

In the situation of Fig. 3, where circuit inductance is minimum, no breakdown takes place, and approximately all the capacitor's stored energy is transferred to the corona, it is interesting to note the effect of reducing the capacitor charging voltage. The results of such a test are presented in the pulse shapes of Fig. 5 which show the variation with time of voltage across the corona electrodes for several charging voltages. The important points to be gained from Fig. 5 are that at lower charging voltages the corona actually extinguishes before the capacitor is completely discharged, and the efficiency with which energy is transferred from the capacitor to the corona therefore increases with capacitor charging voltage.

This study of pulsed corona is somewhat analogous to the studies which have been made of suppressed discharges in connection with power line insulators and sphere gaps. The application of a surge voltage having a rate of rise of several million volts per microsecond results in a large volume of strong luminosity and ionization previous to the

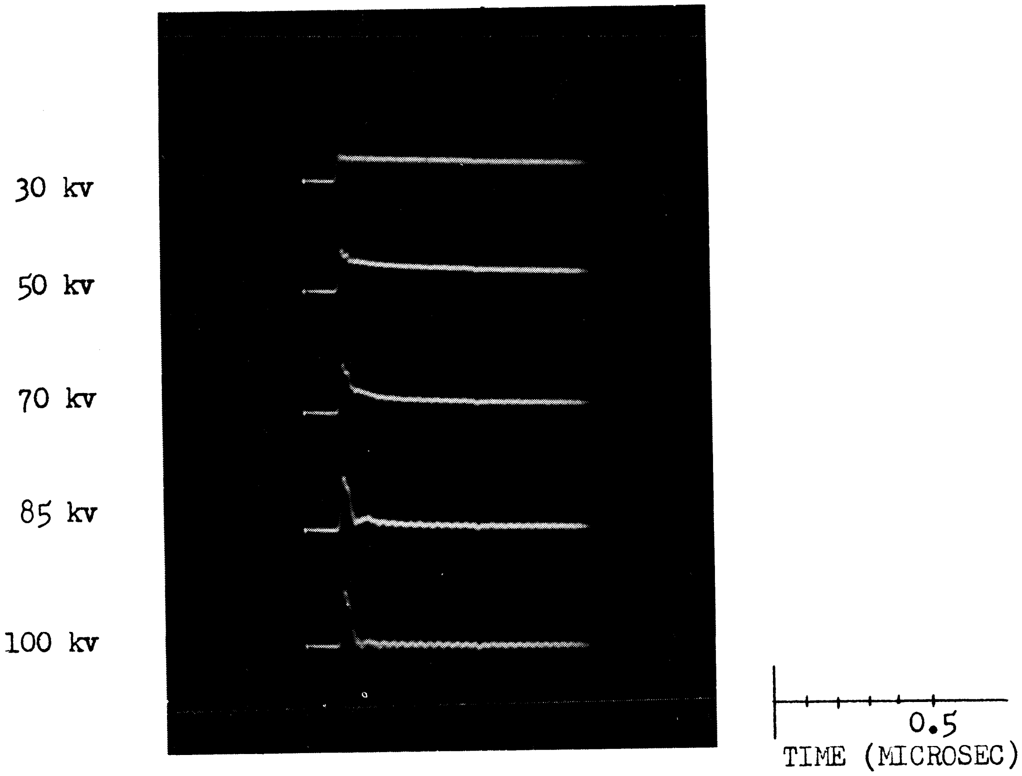


Fig. 5. Oscillogram of voltage across corona electrodes for various capacitor charging voltages.

formation of a complete spark channel.[4,5] The multitudes of luminous streamers not only grow outward from the electrodes but also originate throughout the volume of the gap. In contrast, a more slowly rising voltage wave will form a spark channel at approximately the static breakdown voltage and the pre-breakdown luminosity and ionization are very much less. Since the amount of luminosity is directly related to the amount of ionization, it appears that the maximum energy is dissipated (previous to breakdown) when the pre-breakdown voltage and current have the maximum possible rate of increase.

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[4] C. J. Miller, Jr., AIEE Transactions, "Power Apparatus and Systems", No. 26, 897, October, 1956.

[5] J. J. Torok, AIEE Transactions, 47, 349, 1928.

EXPERIMENTAL APPARATUS

Fig. 6 is a schematic diagram showing the essential components used in the laboratory tests. The pulse-generator circuit has some resemblance to a radar modulator circuit except that the much higher voltages and the much shorter pulse durations required considerable development work on the various components. The so-called "pulse-forming network" consists of a 270-$\mu\mu$f capacitor which is charged through a resistance R_1. During the interval between pulses, while the capacitor is charging, the switching device is open. At a predetermined voltage, the switch closes and initiates the pulse. The pulse energy is delivered to the corona electrodes which consist of an axial wire in the center of a metal pipe.

The charging resistance R_1 consists of a 10-foot length of rubber tubing through which water is flowing. It is electrically isolated from the water supply and drain, which are at ground potential, by means of additional lengths of rubber hose. With this present apparatus, it is experimentally convenient to waste a substantial amount of power in the charging resistance in order to avoid the complexities of resonant charging techniques which would be more efficient.

In designing the pulsing circuit, the major problem was to provide high voltage insulation and, at the same time, minimize stray inductance so that short-duration high-current pulses could be produced. The 270-$\mu\mu$f capacitance operates at voltages up to 150 kv. Since all commercial types of capacitors of this rating have excessive physical size, it was necessary to build a special compressed-gas capacitor in order to

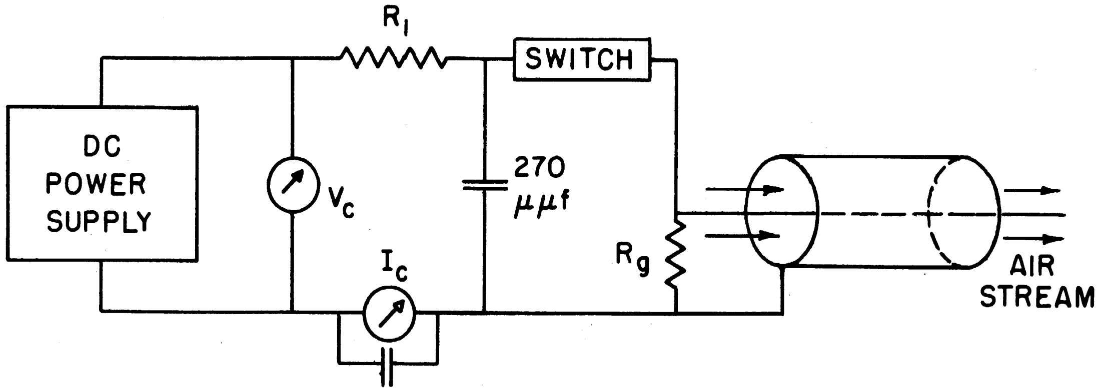
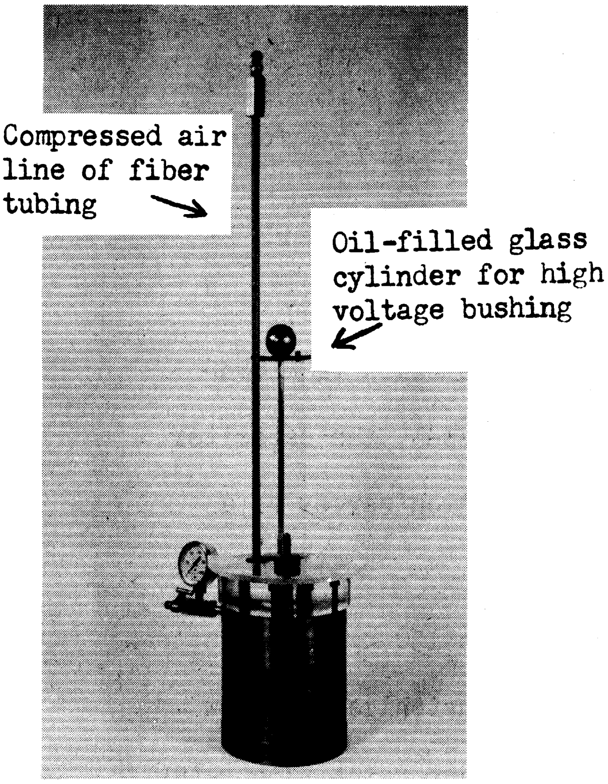


FIGURE 6
ELECTRICAL CIRCUIT

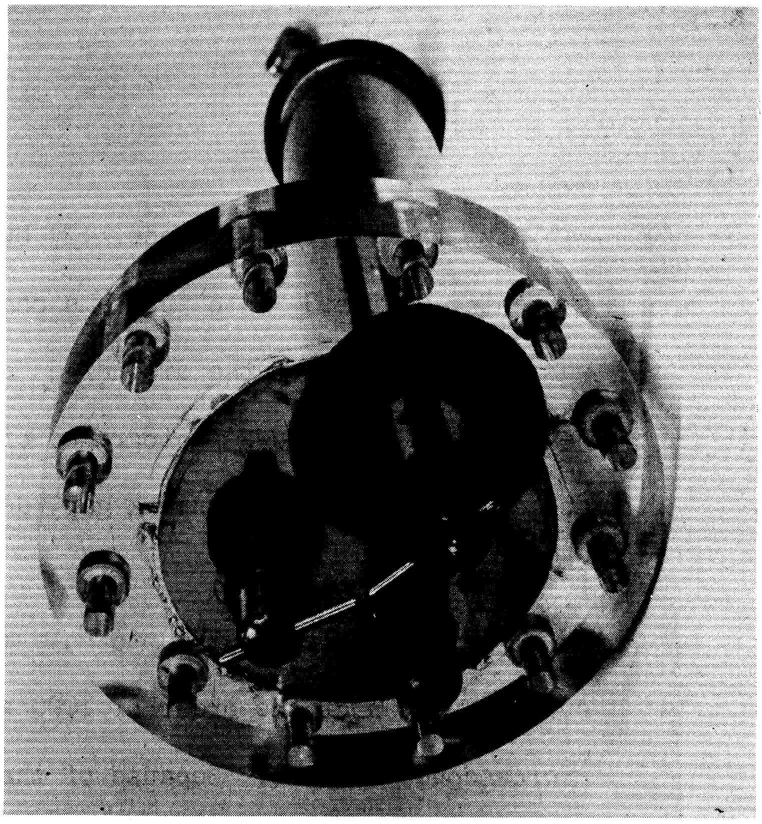
minimize the stray inductance. By building both the capacitor and the switching device S_1 into the same compressed-air pressure vessel, it was possible to keep the discharge circuit inductance below .4 microhenries. Fig. 7 shows photographs of the pressure vessel, the capacitor and also the wind-blown spark gap, described below, which serves as a switch.

The switch is required to hold off voltages up to 150 kv and pass current pulses of the order of 1000 amperes peak and deionize in a few microseconds of time. Because of the high voltage, fast repetition rate, and short deionization time, a hydrogen thyratron is not suitable for this purpose, and a wind-blown type of spark gap was developed.

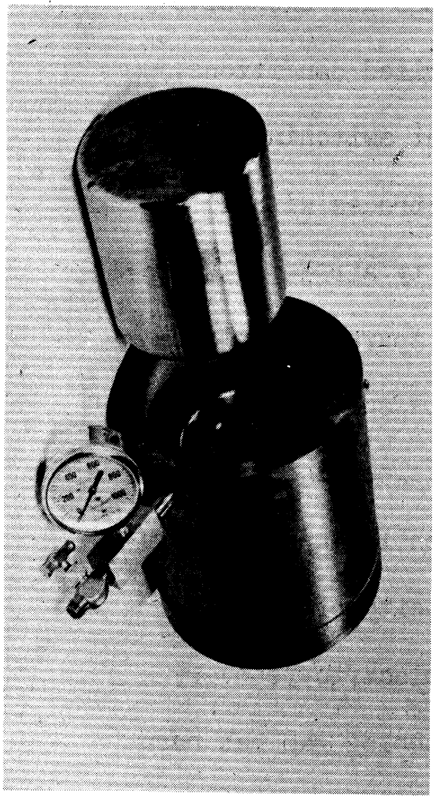
Attempts to use wind-blown spark gaps at atmospheric pressure were completely unsuccessful because of the wide gap spacings and excessive deionization time. By operating the gap under pressurized conditions, much more favorable results were obtained. The present switching gap in Fig. 7 consists of 3/16-inch diameter tungsten electrodes with a gap spacing of approximately 1/8 inch. A sonic velocity air jet flows through the space between the electrodes. After each spark a displacement of the air in this jet by 1/8 to 1/4 of an inch is sufficient to remove any ionization from the gap and restore high dielectric strength. The time required for a stream displacement of 1/4 inch is approximately 20 microseconds. Hence, with the present air jet velocity of approximately 1000 feet per second, the time required for dielectric recovery is of the order of 20 microseconds. So far, this switching gap has been used at repetition rates up to 10,000 pulses per second, and presumably much higher rates can be obtained.

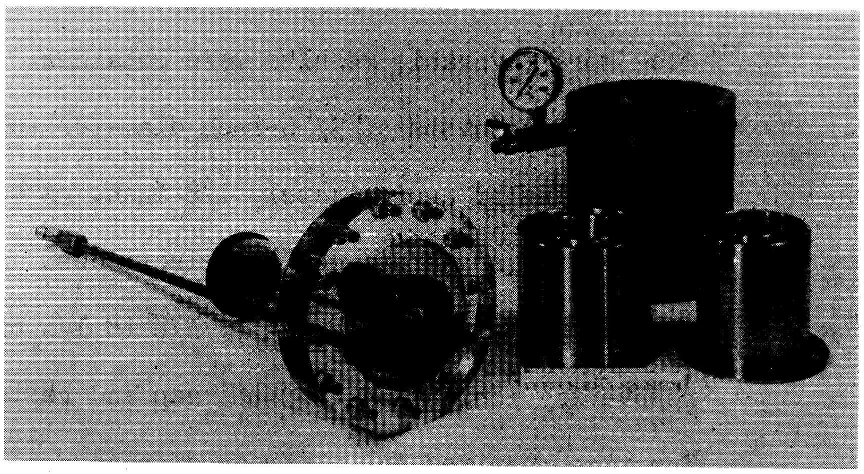


(a) Pressure vessel assembly



(b) Lucite lid of pressure vessel showing tungsten electrodes and nozzle of air jet





(c) (d) Construction of 270-$\mu\mu$f pressurized capacitor of concentric cylinders of stainless steel

Fig. 7

The air jet is supplied with air at 600 psi. Since the air from this jet is discharged inside of the pressure vessel, a bleed valve is necessary to let the air escape out of the pressure vessel. This outlet bleed valve is regulated so as to provide a pressure in the vessel of approximately 300 psi which is the approximate static pressure of the air stream as it leaves the nozzle. The 2:1 pressure ratio provides an air jet of approximately sonic velocity. Presumably, a supersonic velocity jet can be provided if it should later prove necessary in order to achieve the fastest possible pulse repetition rates.

The amount of the pulse energy lost in this switch has not been accurately measured, but tests have been made with a short-circuited load, and the ringing frequency and decrement have been observed oscilloscopically. These tests indicate that in most situations the energy lost in the switch is insignificant compared to the energy delivered to the corona discharge.

The d-c power supply is capable of delivering approximately one ampere of current at 150,000 volts. A single phase transformer delivers 60,000 volts rms to two Machlett-type ML5576/200 rectifier tubes in a voltage doubler circuit. The capacitance across the output of the rectifier consists of a bank of 12 capacitors of 7.5 μf each. The output power and voltage are controlled by means of variable resistance in the 220-volt primary circuit of the power transformer.

A variety of corona electrode geometries have been tried. Some tests have been made with wires or knife edges for electrodes. Most of the tests have used a single no. 18 wire down the center of a 3-inch diameter pipe. Slightly better results were obtained when the single wire was replaced by three parallel wires, spaced 1/2 inch apart in a triangular configuration.

INSTRUMENTATION

A good deal of effort has gone into instrumentation of the pulsed corona system, and this has been carried out with two purposes in mind, namely measurement of the power being put into the air stream, and determination of the individual pulse properties. The steady state power and the pulse measurements will of course be related, since a knowledge of pulsing rate and energy (i.e., average voltage and current) per pulse will certainly give average power delivered, but the two have actually been approached independently and with separate purposes in mind.

The average power measurement is perhaps the primary parameter in this project, since knowledge of power delivered to the air stream is immediately related to energy in the form of heat added to a given mass flow of air in the tunnel stream. It serves, therefore, both as a yardstick against which the progress of the project can be gauged with respect to a desired power goal, and as a basis of comparison with other means of air stream heating. Since the project is strictly a preliminary development program, its yardstick, power, need not be known to extreme accuracy.

The more basic information from a development point of view is knowledge of the individual pulse itself, since changes in the pulsing system will immediately affect each pulse in one or more of several ways which could only be roughly inferred from the average power measurement. The pulse itself must therefore be accurately measured both as to amplitude and duration, and a determination of the circuit's ability to recover from one pulse and to form the next is also important.

The measurement techniques employed in all phases of this program to date will be discussed in light of the previous general statements.

1. Steady State Power Measurement

Fig. 6 indicates the charge and discharge circuitry of the pulsing system and the location of meters used to measure steady state power delivered to the air stream via the corona.

The source of power is the high voltage d-c supply described in the section on experimental apparatus. The charging voltage V_c is measured with a Beta Electric Corporation Type 112 0-150 kv d-c kilovoltmeter, giving an accuracy of four percent or better. This meter reads the d-c voltage across the power input terminals. A two percent Weston d-c milliammeter is used to read average charging current, indicated as I_c in Fig. 6.

The product V_c X I_c will therefore give average power absorbed from the supply. Since only a part of this total supply power will be transferred via the corona to the air stream, all elements in the Fig. 6 circuit which absorb power must be evaluated so that corona power, V_c X I_c minus losses, can be calculated. These elements are:

a. Charging circuit

    1) Charging resistor R_1

    2) Other resistive-like losses, including lead resistance, capacitor dielectric losses, meter losses.

    3) Undesirable corona

b. Discharge circuit

    1) Wind tunnel corona

    2) Undesirable corona

    3) Switch

    4) Other resistive-like losses, including lead resistance, capacitor dielectric losses, Rg.

In designing the pulsing system, all leads have been kept short and sharp points and edges eliminated so losses due to lead resistance and undesirable corona are negligible. The shunt resistances, Rg and resistance of the voltmeter, are sufficiently large so that an insignificant amount of power is consumed in these elements.

The only significant loss in the capacitor is due to the Lucite insulation. The power factor is less than .001 in which case less than 0.1 percent of the total power is lost in the capacitor.

The spark-gap switch may be analyzed as a high-current, high-pressure air arc across the 2-mm gap between tungsten electrodes. From various sources[6,7] the voltage across such an arc can be estimated at less than

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[6] J. D. Cobine, Gaseous Conductors, McGraw-Hill Book Co., 1941, pp. 328,329.

[7] G. Busz and W. Finkelnburg, Z. F. Physik; 139, 212, 1954.

100 volts, and the power dissipated will therefore be negligibly small compared with the many thousand volts across the corona, since both are in series and carry essentially the same current.

The supply power is therefore divided between the charging resistor and the wind tunnel corona.

Power lost in the charging resistor may be calculated knowing that the charging current is given by:

$$i_C = \left(\frac{V_C}{R_1}\right) e^{-\frac{t}{R_1 C}}$$

neglecting the small fluctuations which may be present in V_c and assuming that at time $t = 0$, the capacitor charge is zero, as at the end of a discharge pulse.

$$\text{POWER}_{R_1} = R_1 \times (\text{AVERAGE } i_C^2)$$

$$= R_1 \frac{\int_0^T i_C^2 dt}{T} = \frac{R_1}{T} \int_0^T \frac{V_C^2}{R_1^2} e^{-\frac{2T}{R_1 C}} dt$$

$$= \frac{V_C^2}{TR_1} \left(-\frac{R_1 C}{2}\right) \left[e^{-\frac{2t}{R_1 C}} \right]_0^T$$

$$= + \frac{1}{2} I_C V_C$$

WHERE T = TIME BETWEEN PULSES; $T >> R_1 C$
I_C = AVERAGE SUPPLY CURRENT

The power lost in R_1 is therefore just half the total power supplied, and power delivered to the air stream must also be half the product of voltmeter and ammeter reading.

2. Fast Transient, or Discharge Pulse, Measurement

In the section discussing the nature of the pulsed corona discharge, the point was made that the most efficient pulse circuit, from the standpoint of power into the air stream, was one which gave a high peak voltage pulse of minimum duration. Thus, there are two things with which to contend in measuring this discharge pulse, namely very high voltages and extremely short times. Whatever measuring equipment is employed must withstand the voltage and reduce it to a more tenable level, and must be able to respond to the fast signal changes with negligible distortion.

High voltage transients are commonly measured by means of a cathode-ray oscilloscope and a voltage divider consisting of resistive, capacitive, or combination resistive-capacitive elements.[8,9,10]

The resistor divider, while perhaps the simplest device from the standpoint of availability of components, has the disadvantage of requiring long resistors to withstand the high voltage and therefore having large distributed capacitance to ground. Estimating this shunt capacitance to be about 30 $\mu\mu$f and using a divider with total resistance of 10,000 ohms, the measurement error at the crest of the corona pulse would be greater than 40 percent.[11] While this error could be reduced by

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[8] Craggs and Meek, High Voltage Laboratory Techniques, Butterworth Scientific Publications, London, 1954.

[9] Rohlfs, Kresge and Fisher, "The Response of Resistance Voltage Dividers to Steep-Front Impulse Waves," AIEE Conference Paper #57-353, 1957.

[10] P. R. Howard, "Errors in Recording Surge Voltages," Proc Inst. Elect. Engineers, 99, 371, 1952.

[11] P. R. Howard, ibid.

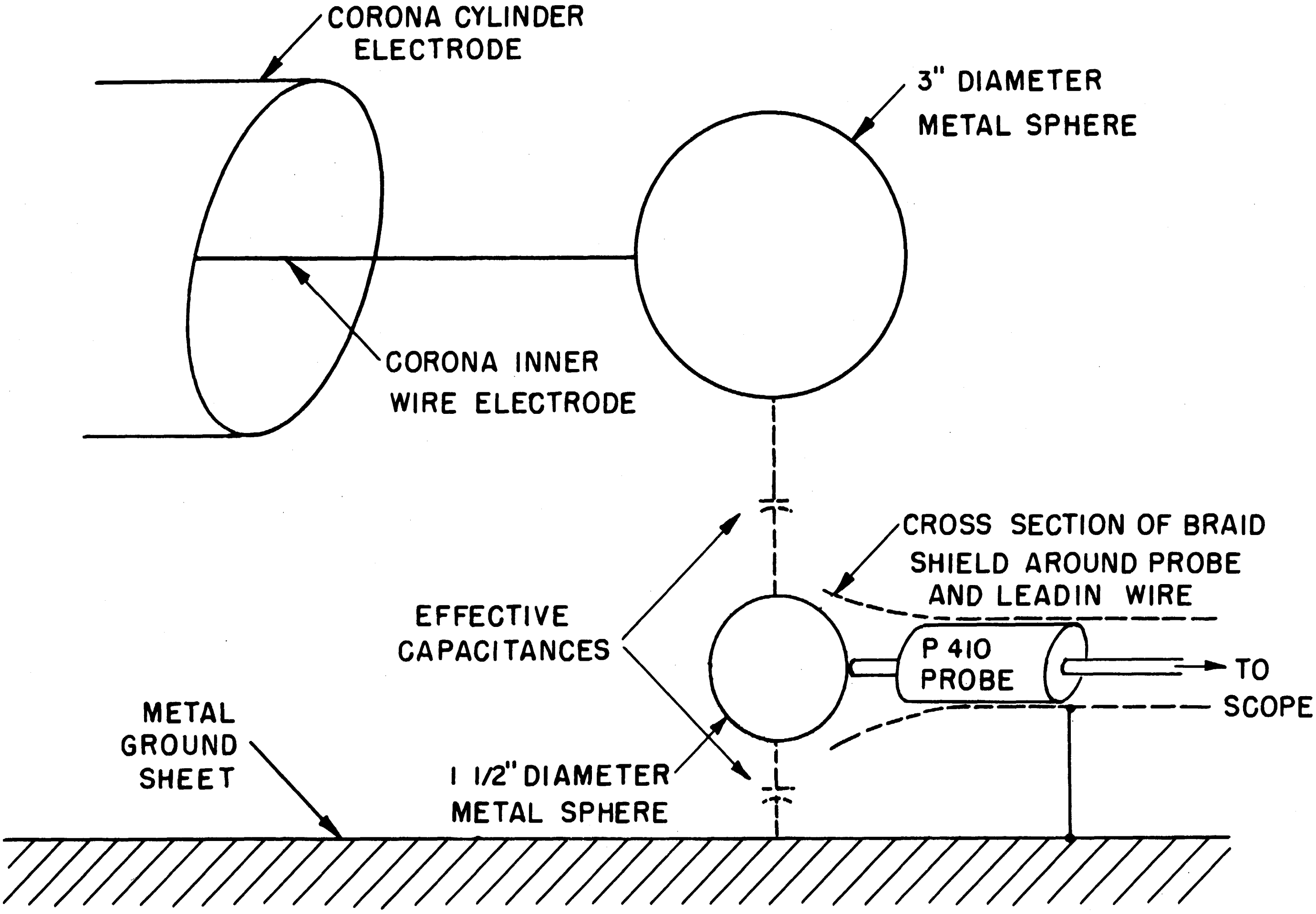


FIGURE 8

PHYSICAL ARRANGEMENT OF VOLTAGE DIVIDER FOR OBSERVING FAST TRANSIENTS lowering the total resistance, too much of a reduction would result in the divider placing an appreciable load in parallel with the corona.

Elaborate shielding techniques can be used to increase the accuracy of a resistance divider by reducing the distributed capacitance to ground, but the more simple solution is to go to a purely capacitive type divider.

From the analysis of a simple divider circuit carried out in the appendix, the sum of the capacitances need not be large, and it is advantageous, in fact, to keep these small, since internal inductance increases with the size of the capacitor. The current drawn by the divider will also increase with capacity and, since loaded and unloaded discharge pulse shapes will differ, accuracy of the measuring circuit will increase as divider capacity is diminished. However, if the capacitance of the divider is too small compared to the stray capacitances of the circuit, the desired signal may be distorted by stray pick-up from various sources.

Commercial capacitors designed for these voltages proved to be too inductive, as did a capacitance made from RG-17 U coaxial cable.

An adequate system, shown in Fig. 8, was devised in which the pulse voltage was established between a 3-inch diameter metal sphere, directly connected by a short lead to the inner corona electrode, and a ground plane of heavy copper sheet. The spacing between sphere and ground plane was on the order of 5 inches. Between the two, and about one inch above the ground plane, was a 1-1/4-inch diameter metal sphere which was connected to the probe of the oscilloscope, thereby creating a high-voltage, low-inductance minimum loading capacitive voltage divider. The division ratio could be adjusted either by repositioning the spheres or adding capacitance between the small sphere and ground. The geometry of this arrangment was such that the large sphere shielded the small one from extraneous signals such as the charging voltage on the capacitor. Spheres were employed to eliminate sharp edges, causing undesirable corona loss and possible voltage breakdown.

The signal between the small sphere and ground was fed through a 10:1 attenuating, nonringing probe and cable (Tektronix type P410) into a Tektronix type 545 oscilloscope with fast rise time amplifier. Input impedance of this probe-oscilloscope combination is 10 megohms, 8 $\mu\mu$f. The oscilloscope patterns were recorded by a DuMont type 302 oscillogram camera on Polaroid type 44 film.

No attempt has yet been made to measure pulse current, since important information (pulse length and shape) can be obtained from the voltage function, and the current can be approximately calculated. The practical difficulties of taking a signal from a current shunt in the corona loop without adding too much inductance or loss to this circuit and without picking up undesired signals are also rather imposing.

Some of the pulse data recorded with this system are presented and discussed in the section on experimental tests.

3. Slow Transient, or Pulse Repetition, Measurement

The rate at which pulses are generated is 5,000 to 10,000 per second. At this low frequency any ordinary voltage-divider circuit may be employed; in this instance, a capacitor divider was fabricated from sections of

RG-17 U coaxial cable, and this was used to observe the voltage across the storage capacitor. The wave form of Fig. 9 is a typical measurement taken while delivering about 7 kw to the air stream. The repetition rate is about 5000 cps, and 20-30 microseconds are required for the spark gap to extinguish and open the discharge circuit.

EXPERIMENTAL TESTS

A great variety of tests was conducted over a wide range of variables. The most successful operating conditions so far obtained will be summarized.

The air stream was at atmospheric pressure and was confined inside a 3-inch I.D. metal pipe. The flow velocity was approximately 200 feet per second. An axial wire down the center of this pipe served as one corona electrode, and the inside wall of the pipe served as the opposite electrode. Typically, the discharge was confined to a region extending 12 inches along the tube, but in some tests the axial extent of the active electrode area was reduced to 3 inches or less.

Fig. 10 is an oscillograph of the pulse voltage wave form across the corona gap. At the peak of the pulse, the voltage was approximately 100 kilovolts, and the total pulse duration was approximately 0.06 microseconds. At the beginning of the pulse, the energy stored in the 270-$\mu\mu$f capacitor was approximately 1.3 joules, and the charge was 2.7×10^{-5} coulombs. This amount of charge which was transferred in 0.06 microseconds represents an average current during the pulse of 450 amperes; the peak current being substantially higher.

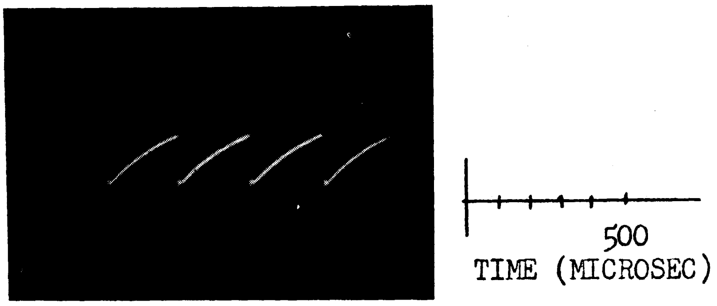


Fig. 9. Oscillogram of 270-$\mu\mu f$ capacitor voltage during corona operation.

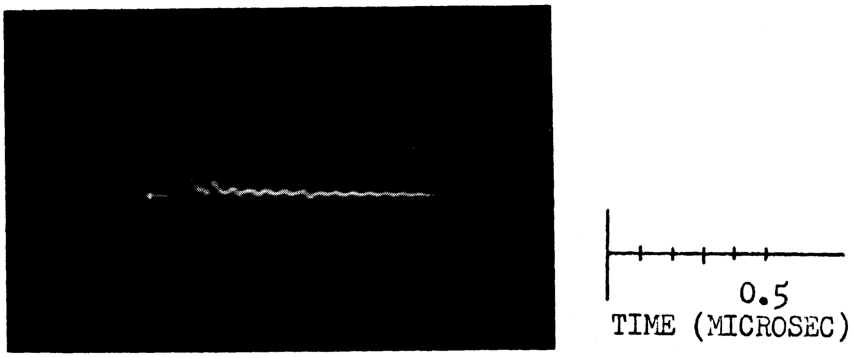
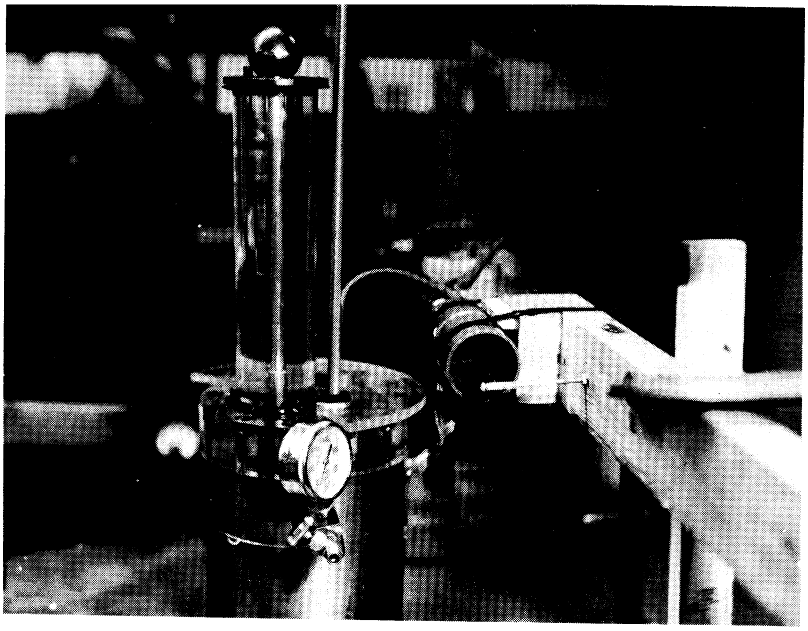


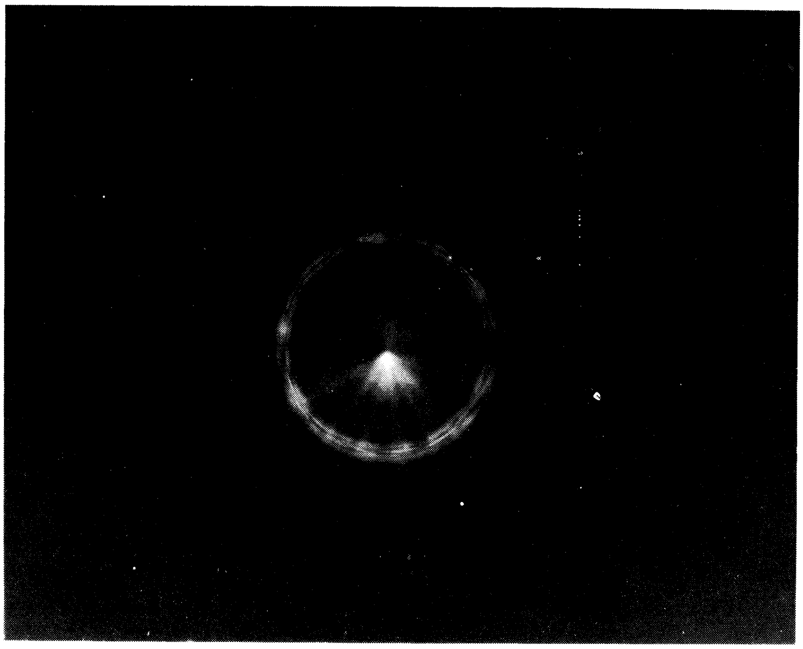
Fig. 10. Oscillogram of pulse voltage across corona electrodes with minimum circuit inductance.

Fig. 11 are photographs of the corona discharge taken from the exit end of the 3-inch pipe. Visually, the discharge appears more uniform and homogeneous than the pictures seem to indicate. This is because the photographs were taken of a single isolated pulse, while visually, when the repetition rate is fast, the streamer characteristics of individual pulses are obliterated.

Pulse repetition rates of 5000 to 10,000 per second were readily obtained. Typically, the power from the d-c supply was approximately 20 kilowatts, of which 10 kilowatts were dissipated in the charging resistance, and substantially all of the remainder was delivered to the air stream. Whenever the pulse repetition rate was increased beyond a certain threshold, there was an increasing tendency for occasional spark channels to flash across the electrode gap. This sparking tendency limited the power which could be delivered to the air stream. At input power levels of 30 to 40 kilowatts, these sparks would occur several times per second. Increasing the flow velocity of the air stream would significantly reduce this sparking tendency. However, increasing the flow velocity is an evasion of the fundamental problem, since the ultimate application requires increasing the air temperature by hundreds of degrees, and while an increase in flow velocity would increase the power dissipation from a given set of electrodes, it would not permit an increase in the temperature rise of the stream. Fifteen kilowatts of power, delivered to the 3-inch diameter 200-feet-per-second stream at constant pressure, result in a calculated temperature rise of 58 degrees Farenheit. The actual



(a) Pressure vessel and corona tube with axial wire center electrode



(b) Single pulse of corona; viewed from end of tube

Fig. 11

temperature rise has not been measured, but is presumably less than the calculated value due to the energy used in producing ozone and in fixing nitrogen compounds. It appears necessary to find methods of increasing the repetition rate and the power delivered at the present air-stream velocity by a significant amount.

The spark flashovers which occurred at fast repetition rates always occurred near the downstream end of the corona discharge. This suggested a probability that the pulses of unidirectional polarity between the asymmetrical electrodes were building up a strong space charge in the air stream which distorted the electric field and produced the flashover. This was confirmed by a test with a probe connected to a voltmeter which showed that the average d-c (negative) potential of the air stream downstream from the discharge was approximately 30 kilovolts. The pulses applied to the center (wire) electrode were of negative polarity. Also, it was observed that ungrounded objects in the exit air stream would pick up strong potentials, resulting in spark flashovers to ground.

There appeared to be two approaches to the problem of reducing this space charge accumulation. One approach was to use corona pulses of alternating polarity. The other approach was to use the same electrode geometry for both positive and negative electrodes in the hope that the space charge unbalance would be less severe. Tests were made in which the 3-inch pipe was made of dielectric, and one set of longitudinal wires in the air stream was used for the anode, and another parallel set of wires was used for the cathode. The energy which could be dissipated per pulse with this arrangement was substantially less than the highly asymmetrical situation involving the axial wire in the center of a metal pipe.

In certain tests a glass liner was placed adjacent to the inside surface of the 3-inch pipe so that the only corona current flowing to the wall of the pipe was the displacement current through the glass. This dielectric barrier has important advantages in that it prevents spark flashover between the electrodes. However, since the current through the glass is a displacement current, there can be no d-c component, and the net average d-c corona current must be zero. If the corona voltage pulses are of unidirectional polarity, the surface of the glass builds up a surface charge of many kilovolts, and the resultant pulse current characteristics for repeating pulses are much different than for an isolated pulse. If the corona pulses were of alternating polarity, then the glass liner could be used without this difficulty.

Pulses of Alternating Polarity - A method of reversing the polarity of alternate pulses seems highly desirable. A crude method of achieving this objective would be to shunt the corona electrodes with an inductance which would cause the discharge circuit to "ring". This was tried with limited success. Various values of inductance from one microhenry to 200 microhenries were tested. In general, the pulse voltage and current during the first half cycle were substantially greater than during the second half. An oscillograph of this condition is shown in Fig. 12. If the shunting inductance was as low as one or two microhenries, the "Q" of the circuit was low enough so as to ring for several cycles, but the very large circulating currents in the resonant circuit dissipated a

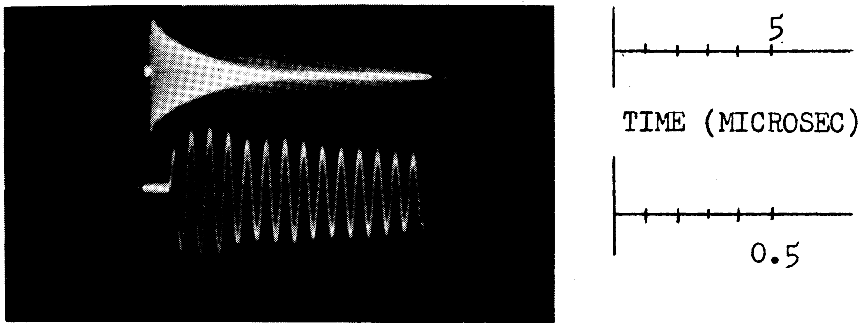


Fig. 12. Oscillogram of pulse voltage across corona electrodes with 2-μh inductance shunting corona.

substantial percentage of the energy in the switching gap. However, the results, although hard to interpret conclusively, indicate that a suitable method of producing pulses of alternating polarity is desirable.

Considerable effort has been made to find a method of using the present power supply and pulse generator to produce alternating polarity pulses. All systems so far considered using the present d-c power source involve triggered spark gaps and appear excessively complicated. The most feasible method so far considered involves constructing a vacuum-tube multivibrator of controllable frequency which would be used in connection with a step-up transformer to deliver a square-wave voltage output of approximately 100,000 volts rms. This multivibrator would be used in conjunction with the present pulse generating system. By selecting a proper value of charging resistance, the 270-$\mu\mu$f capacitance in the pulse circuit would be charged only once during any half cycle of the multivibrator voltage. Hence, alternating polarity pulses having the same characteristics as the present unidirectional pulses could be obtained.

APPENDIX

DISTORTION CAUSED BY PULSE MEASURING CIRCUITRY

The transient responses of the voltage divider and the oscilloscope amplifier may both be sources of distortion.

1. Voltage Divider

Considering the voltage-divider circuit of Fig. 13, the output voltage arising from a step function voltage E_{in} beginning at time $t = 0$ is given by:

$$e_{OUT} = \left(\frac{C_1}{C_1 + C_2}\right) E_{IN}\, \epsilon^{-\frac{t}{R(C_1 + C_2)}}$$

For e_{out} to be a true representation of a pulse input voltage, therefore, the pulse duration must be short compared with the circuit time constant $R(C_1 + C_2)$. The input impedance of the probe-oscilloscope combination, represented as R in the circuit of Fig. 13, is about 10^7 ohms, C_1 is on the order of one $\mu\mu$f, and C_2 is 100 times this, so $R(C_1 + C_2) = 10^{-3}$ seconds. Since the corona pulses have typical durations of less than 10^{-7} seconds, no voltage divider distortion will be present.

Inasmuch as the 3-inch diameter sphere has capacitance to ground, the divider will add some slight distortion to the corona pulse shape, since this shunt capacitance acts as a load delaying the rise of the pulse voltage. Although no data have been taken to measure this delay, estimates

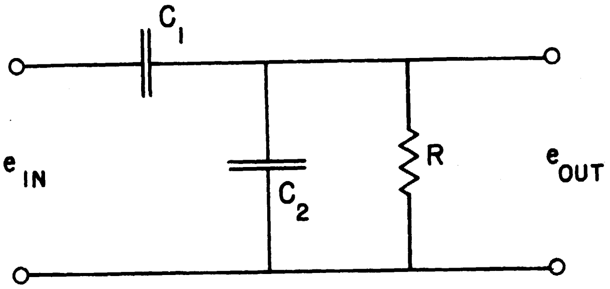


FIGURE 13

EQUIVALENT CIRCUIT OF VOLTAGE DIVIDER

Fig. 14. Oscillogram of current in discharge circuit when corona electrodes are shorted.

indicate that the presence of the divider increases the rise time of the pulse by less than 0.01 μsecond.

2. Oscilloscope Amplifier

The oscilloscope amplifier has a published rise time of 12×10^{-9} seconds. Pulses must have rise and fall durations longer than this in order to be represented faithfully. Since a very fast pulse is being employed in the corona heating apparatus, it is possible that the oscilloscope may not be able to follow it precisely, and a reasonably accurate estimate of the oscilloscope response to this signal is necessary. This will be done by evaluating the components of the pulse circuit, deriving the pulse shape from these component values and constructing the amplifier response to this somewhat idealized pulse input.

The pulse discharge circuit (see Fig. 6) will consist essentially of the following series components:

a. Capacitance - 270-μμf pulse energy storage capacitor plus negligible distributed circuit capacitance

b. Inductance - measured by discharging the 270-μμf capacitor into the pulse circuit with the corona electrodes shorted at the end away from the capacitor. This circuit will oscillate as shown in Fig. 14, and from the damping factor (R/2L) and the ringing frequency $\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$ the circuit inductance can be approximated. This turns out for 5-inch long corona cylinder electrodes to be about .4 μh.

c. Resistance - consisting essentially of the corona resistance. A typical recorded pulse shape for the same circuit and electrodes as employed in (b) above, but with electrodes unshorted is shown in Fig. 10. Since this pulse appears to be very nearly critically damped, and therefore $\frac{1}{LC} = \frac{R_c^2}{4L^2}$, the corona resistance, R_c, can be calculated at about 77-Ω. This is actually a time average resistance, since corona current will not be linear with voltage.

In Fig. 15, the normalized voltage in a 77-Ω-resistor (the idealized corona impedance) is shown as a function of time when a 270-μμf capacitor is discharged through this resistor in series with .4 uh inductance.

The output from a 12-millimicrosecond rise time amplifier with this pulse as the input may be derived by dividing the input pulse into a series of step functions and summing the amplifier step function response graphically.[12] The resultant pulse shape is shown in Fig. 6, and this is the signal which is displayed on the oscilloscope screen. Comparing this with Fig. 5 shows that the idealized and actual pulse shapes are nearly identical and that the derived values of effective circuit components are therefore valid, and comparing the two curves of Fig. 6 shows that the oscilloscope will cause a reduction in peak amplitude together with a slight time distortion in the pulse.

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[12] Arguimbau, Vacuum Tube Circuits, Wiley, 1948.

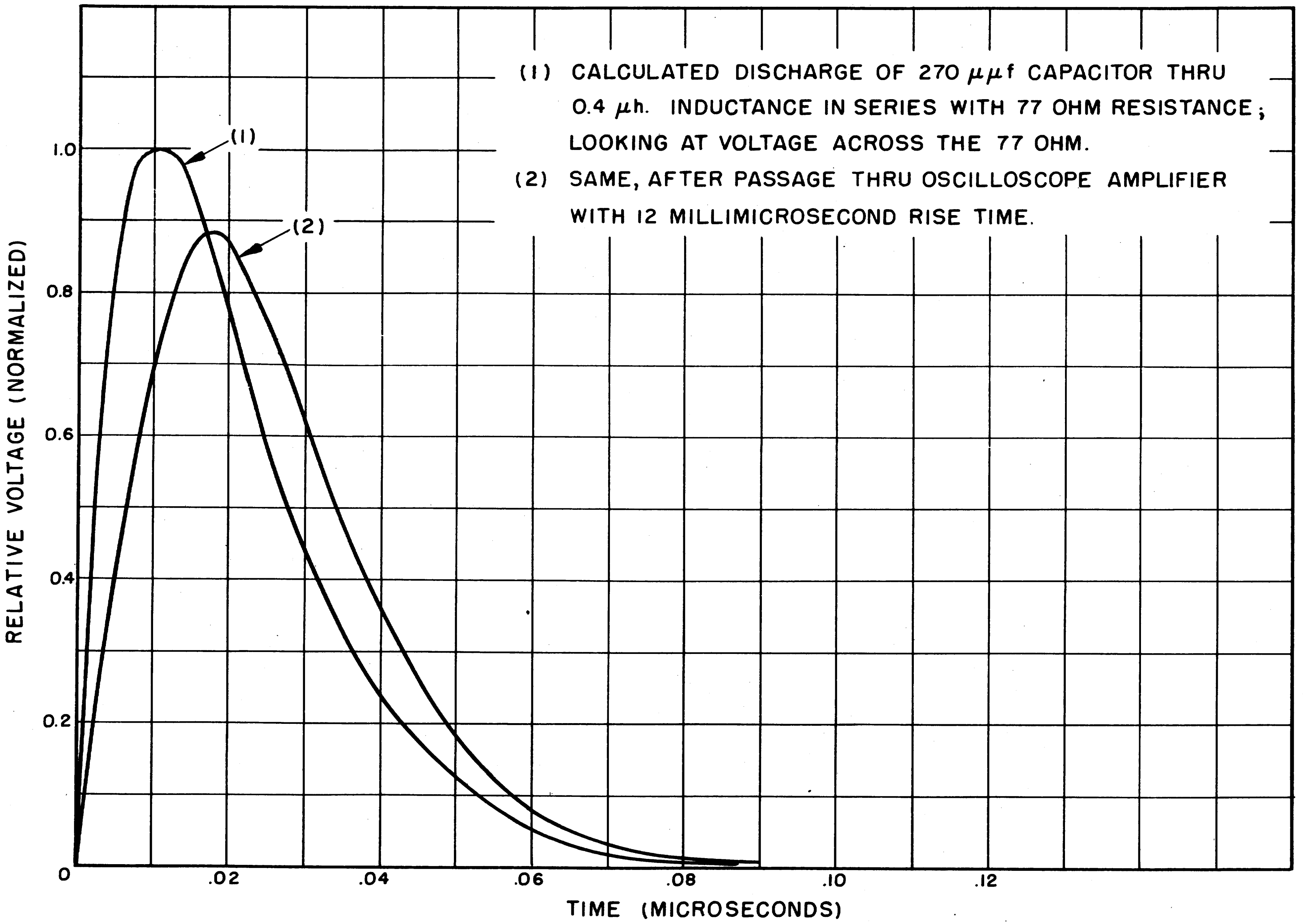
(1) CALCULATED DISCHARGE OF 270 μμf CAPACITOR THRU 0.4 μh. INDUCTANCE IN SERIES WITH 77 OHM RESISTANCE; LOOKING AT VOLTAGE ACROSS THE 77 OHM.
(2) SAME, AFTER PASSAGE THRU OSCILLOSCOPE AMPLIFIER WITH 12 MILLIMICROSECOND RISE TIME.
(1)
(2)
RELATIVE VOLTAGE (NORMALIZED)
1.0
0.8
0.6
0.4
0.2
0
.02
.04
.06
.08
.10
.12
TIME (MICROSECONDS)

FIGURE 15