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HEATING AND IONIZATION OF A GAS STREAM BY REPETITIVE, SUPPRESSED-BREAKDOWN DISCHARGES

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FOREWORD

This final technical report was prepared by the Department of Electrical Engineering, University of Michigan, Ann Arbor, Michigan, on Contract AF 33(616)-7243 for the Aerospace Research Laboratories, Office of Aerospace Research, United States Air Force. The research reported herein was accomplished on Task 7116-02,"Energy Conversion Techniques", of Project 7116, "Energy Conversion Research", under the technical cognizance of Mr. Louis Kehrt of the Thermo-Mechanics Research Laboratory of ARL.

This report records work performed subsequent to the Interim Technical Report ARL 63-54, dated March, 1963, and describes development work to increase the repetition rate of the pulse generator.

ABSTRACT

When an impulse voltage having a very fast rise time is applied to corona-type electrodes, a current of several thousand amperes may flow through the gas before appreciable spark-streamer formation takes place. If the voltage is quickly removed, several joules of energy can be delivered to an atmospheric-density gas in a single suppressed-breakdown pulse. By using pulse repetition rates of several thousand per second, many kilowatts of electrical power can be delivered to a subsonic or supersonic gas stream by a single set of electrodes. Compared to arc-heating methods, the pulsed-corona discharge is diffuse and uniform and the gas flow remains much more homogeneous.

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INTRODUCTION

When a steep-front, impulse voltage is applied to a pair of corona-type electrodes, a current of many hundreds of amperes will flow for a period of 10^{-8} to 10^{-7} second before spark streamer formation starts to take place. During this pre-breakdown period, the instantaneous power transfer to the gas may be as high as 10^{8} watts. If the impulse voltage is removed quickly enough and the duration of current flow is short enough, there is a significant amount of energy transfer to the gas without any spark breakdown. Although the pressure may be atmospheric or higher, the luminosity is low and has a diffusiveness characteristic of a low-pressure glow discharge.

In typical experiments, 1 to 3 joules of energy can be delivered to a gas in a single pulse. With high pulse-repetition rates, many kilowatts of average power can be delivered to an air stream by a single set of electrodes. The average power which can be transfered to a gas by a given set of electrodes is one to two orders of magnitude larger than in the case of a d-c corona discharge.

During the very short duration of the current pulse, the "plasma" of the suppressed discharge is in a highly non-equilibrium condition, with a high percentage of non-thermal ionization and a high value of mean electron energy. In diatomic gases at atmospheric pressure, the duration of the non-equilibrium condition is extremely short. At sufficiently low pressures and in inert gases where the recombination rate is less, the process appears to be of engineering interest for the production of a uniform stream of non-equilibrium gas.

Several possible applications are

1. Adding thermal energy uniformly and diffusely to a supersonic air

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stream in a wind tunnel. Supersonic heating offers the promise of achieving very high stagnation temperatures without excessive reservoir temperatures.

2. Producing non-thermal ionization and electrical conductivity in the gas of MHD devices. The process offers the possibility of operating an MHD generator at a low gas temperature. Also, the conductivity of the gas stream might be modulated at a suitable frequency to generate alternating-current, a-c power without the use of inverters.
3. Producing chemical dissociations and reactions in a gas which ordinarily requires much higher temperatures.
4. Producing non-equilibrium ionization in a stream of gas. Heat transfer studies involving non-equilibrium gases are of substantial engineering importance.

The experimental program has been concerned with methods of adding a maximum amount of power to a given mass flow of gas. As will be explained later, there are fewer experimental difficulties in transfering a given amount of power to the stream if the mass flow is large. Operation with reduced mass flow and a correspondingly larger increase in enthalpy is more difficult, but substantial progress has been made. This program has been primarily concerned with the factors which limit the maximum energy per pulse and the maximum pulse repetition rate. The maximum energy per pulse, as well as maximum repetition rate, tends to be limited by the formation of spark channels which have a greatly reduced electrical resistance. To minimize spark formation, the electrical circuitry is designed to deliver a high peak current in the shortest possible time. This has required a high-voltage system (150,000 volts) with low stray inductance (0.25 μhenry) in the discharge circuit.

Much of the work on this contract has been recorded in an Interim Technical Report ARL 63-54, "Energy Addition to a Flowing Gas by High-Repetition-Rate, Arrested-Breakdown Discharges", by H. C. Early and F. J. Martin, March, 1963. This present report records the results of the work since the interim report was written. Although there is some repetition, it is assumed that this final report is a continuation of the interim report.

APPARATUS

The most successful high-power-level experiments have been made with the arrangement sketched in Figure 1. The gas to be heated flows through the 3-inch-diameter glass tube. A wire screen on the outside of this glass tube serves as the grounded outer electrode. The inner "hot" electrode consists of a 1/2-inch brass rod which is threaded with sharp-edged threads. The pressurized capacitor is electrically connected to a 150,000-volt d-c power supply through a water-cooled charging resistance. When the rising voltage on the capacitor reaches the breakdown voltage of the spark-gap switch, a pulse of current is delivered to the arrested-breakdown (corona) electrodes. The spark-gap switch is quickly deionized by a high-velocity air jet and the capacitor then starts to recharge. Figure 2 shows a cross section of the capacitor and the air-blast, spark-gap switch.

The inductance shunting the electrodes provides a d-c path to ground, since there is no net d-c component of current through the glass tube. The inductance also provides an oscillatory discharge, typically of two or three half cycles duration. The rate of damping of the oscillation varies greatly depending on the electrode geometry, the temperature of the gas, and the energy

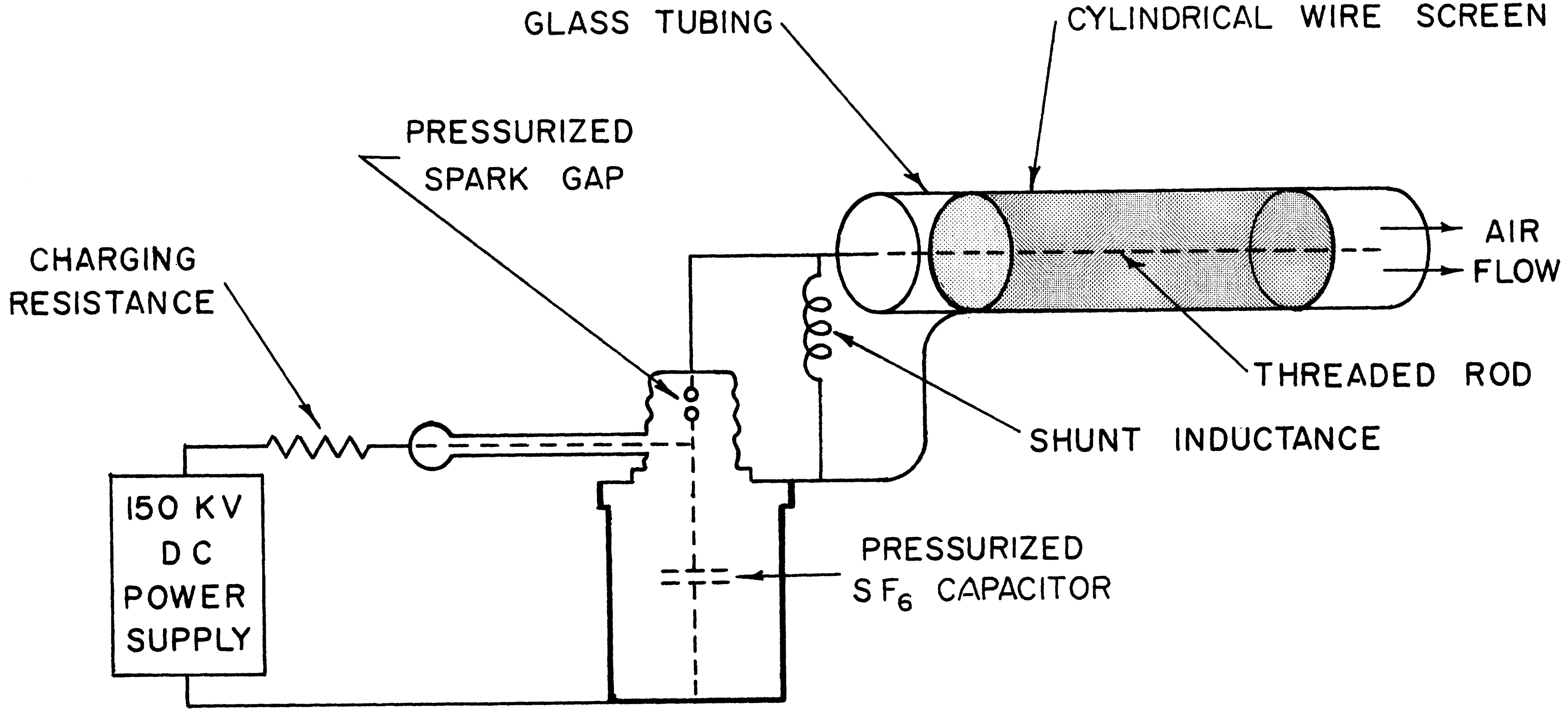

FIGURE I PULSE GENERATOR OPERATING FROM A D-C POWER SUPPLY

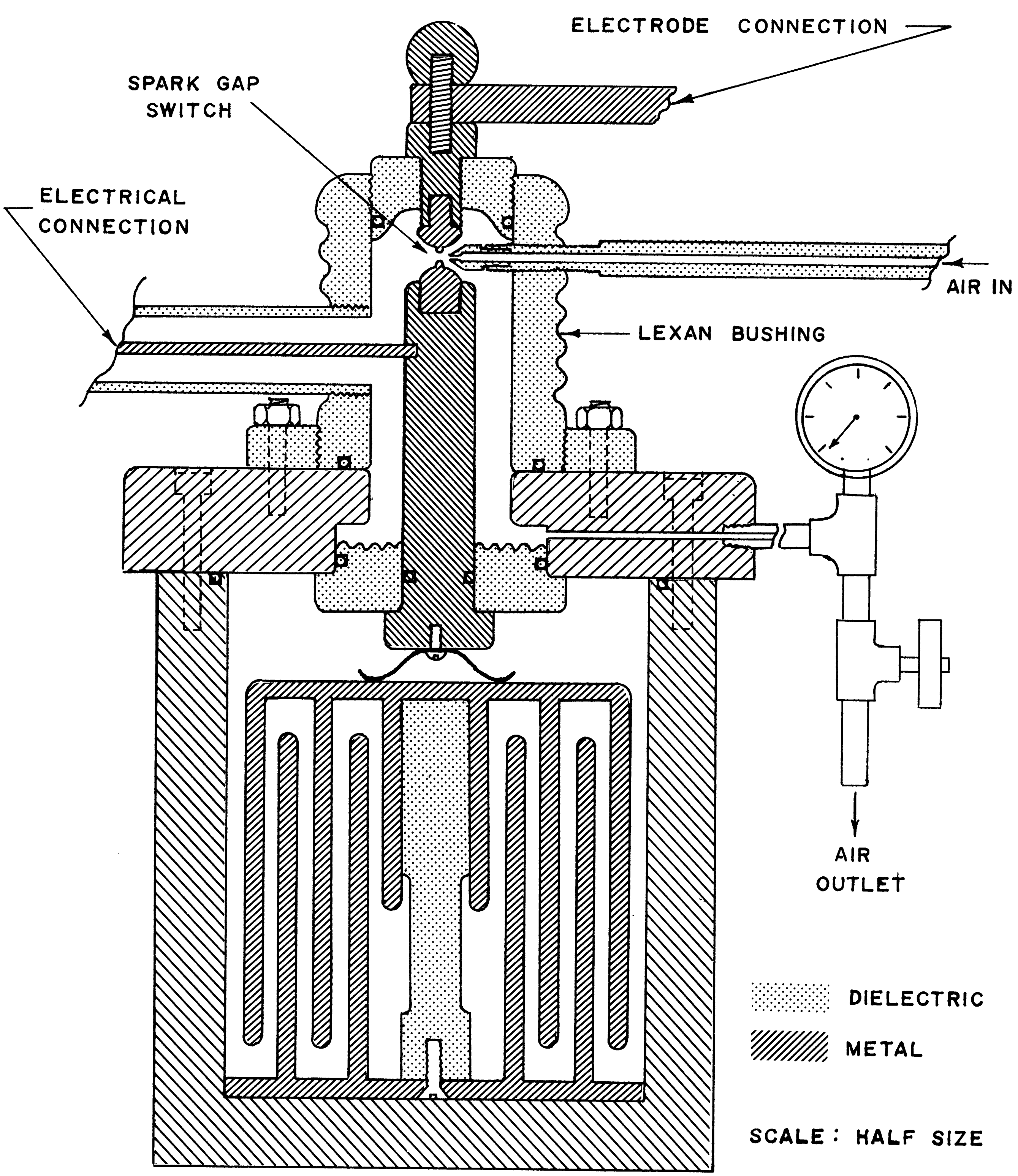

FIGURE 2 SULPHUR HEXAFLUORIDE CAPACITOR AND AIR-BLAST SPARK GAP

storage in the capacitor. Discussion on the electrical circuit behavior is given later in this report.

EXPERIMENTAL PROGRAM

This contract has been primarily concerned with finding methods of increasing the average power that can be delivered to a gas stream by a single set of electrodes.

During the first part of the research program, the principal power limitation was caused by the formation of solid sparks between the electrodes whenever the pulse repetition rate was increased beyond a few hundred pulses per second. This spark formation did not take place when there was sufficient turbulence in the air stream, but a highly turbulent air flow is probably incompatible with most foreseeable applications of the process.

The only successful way that could be found for preventing spark formation was to cover one or both electrodes with a layer of dielectric material such as glass or quartz, and this led to the adoption of the glass pipe geometry shown in Figure 1. This use of glass or quartz involves a limitation in running time so as not to overheat the dielectric. This limitation may not be objectionable for some applications, and the problem may be much less at pressures less than atmospheric.

With the elimination of the sparking difficulty, the next steps toward increasing the power level were concerned with improving the performance of the pulse-generating system by increasing the pulse repetition rate as well as the energy delivered per pulse. This effort to improve the capability of the pulse generator consisted of four tasks which will be discussed separately.

1. Constructing a high-voltage, d-c power supply for charging the

capacitor instead of the high-frequency, resonant-tank system previously used with the alternating-polarity system.

2. Using sulphur hexafluoride in the spark-gap switch instead of compressed air.
3. Increasing the dielectric recovery rate of the spark-gap switch by decreasing the energy dissipated in the switch by oscillatory discharge currents.
4. Using more capacitance so as to provide more energy per pulse.

D-C POWER SUPPLY

The original power supply for the pulse generator was designed to continuously alternate the electrical polarity of the suppressed-breakdown discharge on succeeding pulses. This design necessitated the use of a high-voltage, high-frequency tank circuit instead of the more straightforward d-c power supply arrangement as sketched in Figure 1. The problem of obtaining a fast dielectric recovery of the initiating switch was more severe when the voltage was 100 kc than for a d-c voltage. When operating with r-f voltages, any prebreakdown corona or residual plasma between the spark-gap electrodes led to very erratic operation. In order to eliminate this pre-breakdown corona, the spark-gap switch had to use Rogowski-shaped electrodes having a large radius of curvature, and the rate at which the air stream could remove the residual ionization was unsatisfactory.

By using a d-c power supply, electrodes having a much smaller radius of curvature could be used, and a cross-blast air jet was much more effective in quickly removing all residual ionization from the spark gap.

A 150,000-volt, d-c power supply having a 1-amp current capacity was built from surplus equipment available in the Plasma Engineering Laboratory.

Changing to this d-c system enabled the pulse repetition rate to be increased to 12,000 pulses per second, with an energy of approximately 1.1 joules per pulse. This was a three-fold increase over the maximum power level attained with the previous r-f supply.

SULPHUR-HEXAFLUORIDE SPARK GAP

Electronegative gases have the property of attaching or absorbing free electrons and hence are very effective for arc-quenching purposes. The dielectric recovery rate of circuit breakers is significantly higher in SF_6 gas than in air. To determine whether or not the use of SF_6 gas might permit a significant increase in pulse repetition rate, preliminary tests were made in which the spark-gap chamber was operated with SF_6 gas at a pressure of 150 psi. The flow rate through the gap was much lower than with the usual air-blown gap, since a comparable flow rate would result in an exorbitant cost for the SF_6 gas. When operating at a 60-kv level, pulse rates as high as 30,000 per second could be obtained even at a flow rate which was approximately 1 % of the air flow rate. This flow rate, however, did not permit operation at a voltage level much above 60 to 70 kv.

The use of SF_6 gas looked encouraging, but in order to explore it further, a system for recirculating the SF_6 gas was necessary. A refrigerator compressor operating from a 3-horsepower motor was used to deliver 320 psi of SF_6 to a 0.03-inch-diameter nozzle which blew the gas across the spark gap. The pressure inside the spark-gap chamber was regulated to 150 psi. The recirculating SF_6 gas was passed through activated alumina in order to remove the corrosive fluoride compounds resulting from the sparking.

After considerable effort in rigging up the recirculating system, it was found that the flow rate of the SF_6 available from the pump and compressor was not adequate to provide a repetition rate at 120 kv any higher than could be obtained with the air jet. The mass flow of the SF_6 was much lower than the tests with air, since the SF_6 nozzle pressure was lower by a factor of three, and the nozzle cross-sectional area was less by a factor of 10. In order to pursue the SF_6 tests further, a much higher capacity compressor was necessary and the project time schedule and budget did not permit such a purchase.

There is reason to believe that if SF_6 were used at the same flow rate as air, satisfactory operation with 130-kv pulses at rates of the order of 30,000 pps could be achieved.

The use of a high-flow-rate SF_6 system would have to be compared with the possible use of a pumped high-vacuum spark gap. Recent experiments at the General Electric Company have shown that vacuum spark gaps can have voltage recovery rates of approximately 10,000 volts per microsecond. This seems to exceed the most optimistic performance which could be expected from a high-flow SF_6 system.

EFFECT OF OSCILLATING DISCHARGE CURRENTS ON DIELECTRIC RECOVERY OF SWITCH

The time required for the switch to recover dielectric strength is a function of many variables such as the type of gas; the gas density; the electrode spacing; the electrode geometry; the velocity, temperature, and turbulence of the gas jet; and the amount of ionization produced by the spark. The amount of ionization produced in the gap is minimized when the discharge circuit is highly damped. Any excess ringing lengthens the duration of current flow and increases the energy and ionization in the gap, resulting in

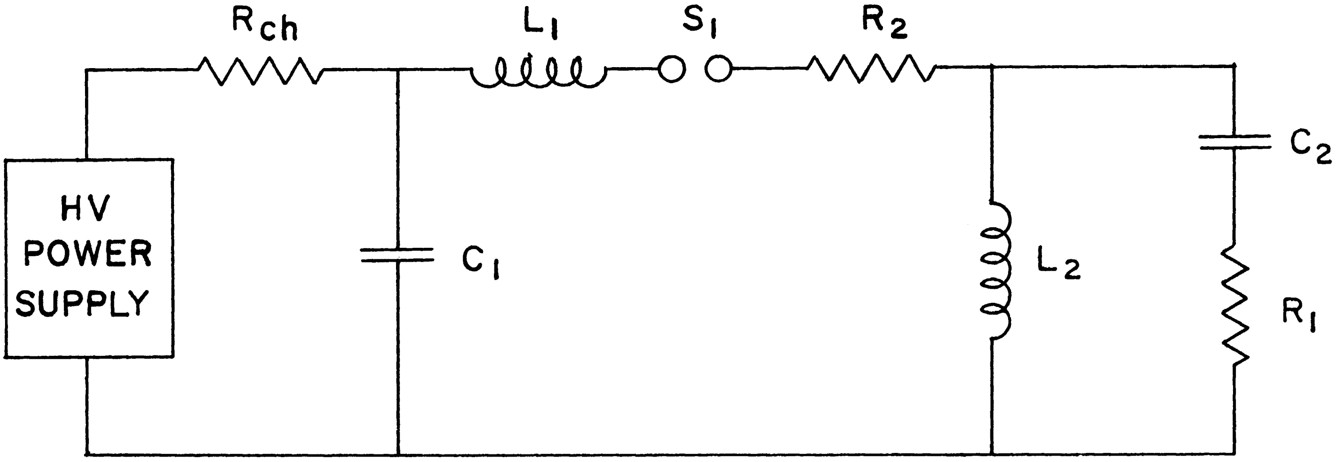

FIGURE 3 EQUIVALENT CIRCUIT OF DISCHARGE

a longer de-ionization time.

The equivalent electrical circuit of the pulse generator and load is shown in Figure 3, where

R_{ch} is the charging resistance.

C_1 is the pressurized, energy-storage capacitor (300 μμfd in typical tests).

S_1 is the spark-gap switch.

L_1 is stray inductance (approximately 0.25 μhenry).

L_2 is a shunting inductance coil.

C_2 is the capacitance of the glass tube adjacent to the outer cylinder electrode.

R_1 is the resistance associated with the energy dissipated in the suppressed breakdown discharge.

R_2 is the resistance associated with the energy lost in the spark-gap switch.

The discharge resistance R_1 is highly non-linear, since no significant current flows until the voltage reaches about 25 kv and the resistance decreases with the time of current flow. However, an assumption of a fixed resistance at R_1 leads to a useful approximation of circuit behavior. The resistance of the switch R_2 is small enough to be neglected in comparison to R_1.

The analytical solution for the transient current which flows when switch S_1 is closed with an initial charge on C_1 is a cumbersome equation and is of limited value. By means of an analogue computer, current curves for various conditions of operation were obtained which confirm oscilloscope traces. The gross behavior of the circuit is also obvious if some simplifying assumptions are made.

Consider the case where $C_1 = C_2 = 300$ μμfd, $L_1 = 5$ μh, and R_1 is very low. Then, when S_1 is closed, there will initially be a ringing current which transfers charge back and forth between C_1 and C_2. This ring frequency is $\dfrac{1}{2\,\pi\sqrt{\dfrac{C_1\,C_2}{C_1 + C_2}}}$ which in this case is approximately 26 megacycles. The damping of this ringing is determined by the loss in R_1 and is critically damped when $R_1 = 2\sqrt{\dfrac{L_1}{(1/2)C_1}} = 80$ ohms. After this ring has decayed, C_1 and C_2 are at the same potential (which is 1/2 of the initial charging voltage if the two capacitances are equal). Another oscillation also takes place but is at a lower frequency and may not get started until after the oscillation between C_1 and C_2 has dissipated. This lower frequency involves capacitances C_1 and C_2 in parallel resonating with L_2. This has a frequency of approximately 3 megacycles. Computer curves for the above approximate conditions are given in Figure 4. The "tail" on the current curves as indicated in Figure 4(a) may not exist because the discharge voltage may have fallen too low to sustain the current.

It is desirable to choose the parameters so that the duration of current flow and resultant ionization of S_1 are minimized. It is also important to deliver energy as quickly as possible to the arrested-breakdown discharge, as otherwise the discharge resistance rapidly becomes too low for effective power transfer. There is considerable advantage in choosing C_2 several times as large as C_1 because the resultant voltage on these capacitors after the oscillation between C_1 and C_2 has damped out is $V_0 \dfrac{C_1}{C_1 + C_2}$. When C_2 is large, then most of the stored energy of the system is dissipated in the initial high-frequency, highly damped oscillation between C_1 and C_2. Then, since the lower frequency oscillation involving L_2 cuts out at voltages less than about 15 to 20 kv, the latter low-frequency oscillation represents very little energy.

Choosing the variables so as to minimize the duration of the oscillatory

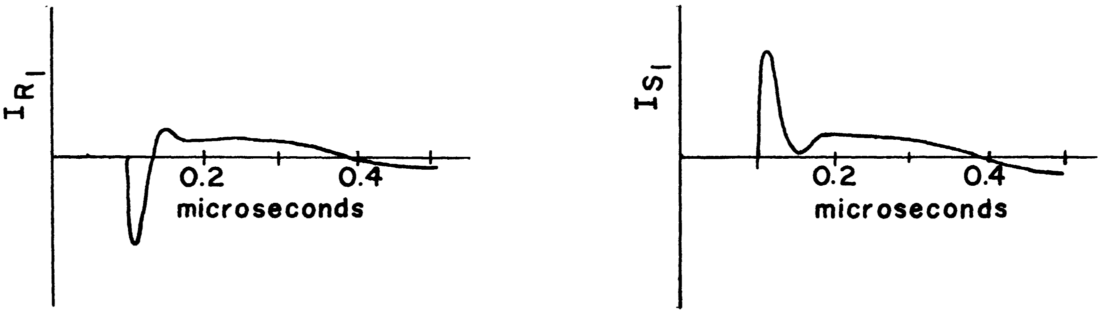

FIGURE 4 (a) CURRENT THROUGH R_1 AND S_1 FOR $L_1 = .25\ \mu h$, $L_2 = 5\ \mu h$, $R_1 = 50$ ohms, AND $C_1 = C_2 = 300\ \mu\mu fd$.

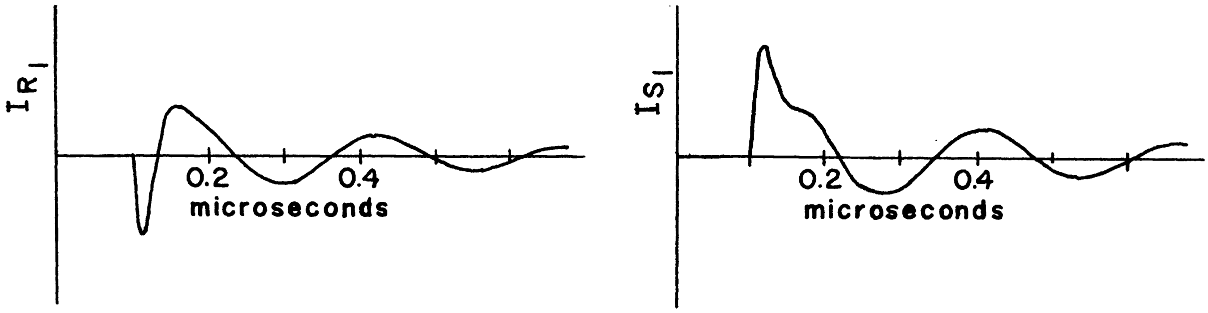

FIGURE 4 (b) CURRENT THROUGH R_1 AND S_1 FOR $L_1 = .25\ \mu h$, $L_2 = 1.0\ \mu h$, $R_1 = 50$ ohms, AND $C_1 = C_2 = 300\ \mu\mu fd$.

current flow through S_1 was found to be effective in helping to increase the voltage-recovery rate and thus permit operation at higher repetition rates and power levels.

GLASS CAPACITOR

The use of a glass-covered electrode proved so effective in reducing sparking problems that it appeared possible to increase the energy per pulse by increasing the capacitance of the 300-μμfd SF_6 capacitor. Rather than building a new and larger SF_6 capacitor, an attempt was made to use the glass tube as the energy-storage capacitor of the pulse generator as shown in Figure 5. In this arrangement, the high-voltage d-c power supply was connected to the inner electrode through the water-cooled charging resistance. A pressurized, air-jet spark gap was connected between the center electrode and ground. During operation, d-c current from the power supply flowed between the center electrode and the inner wall of the glass tube (as a corona discharge) until the glass was charged to about 80% of the potential of the d-c supply. Then, the spark gap broke down, and a high-current pulse resulted from the energy stored in the 900-μμfd glass capacitance. Then, the spark gap extinguished and the glass capacitance recharged. When this system was tested at a pulse rate of about 200 pulses per second, the operation was very satisfactory and the simplicity of the system was very attractive.

At pulse rates of several thousand per second, difficulties were encountered. The gas in the tube no longer had time to de-ionize and "homogenize" between pulses because the charging current to the glass capacitor also flowed through the gas. This charging current flowed through the gas in radial spokes, and the pulse current tended to follow these same ionized spokes. The air heating was not uniform because the current flow was

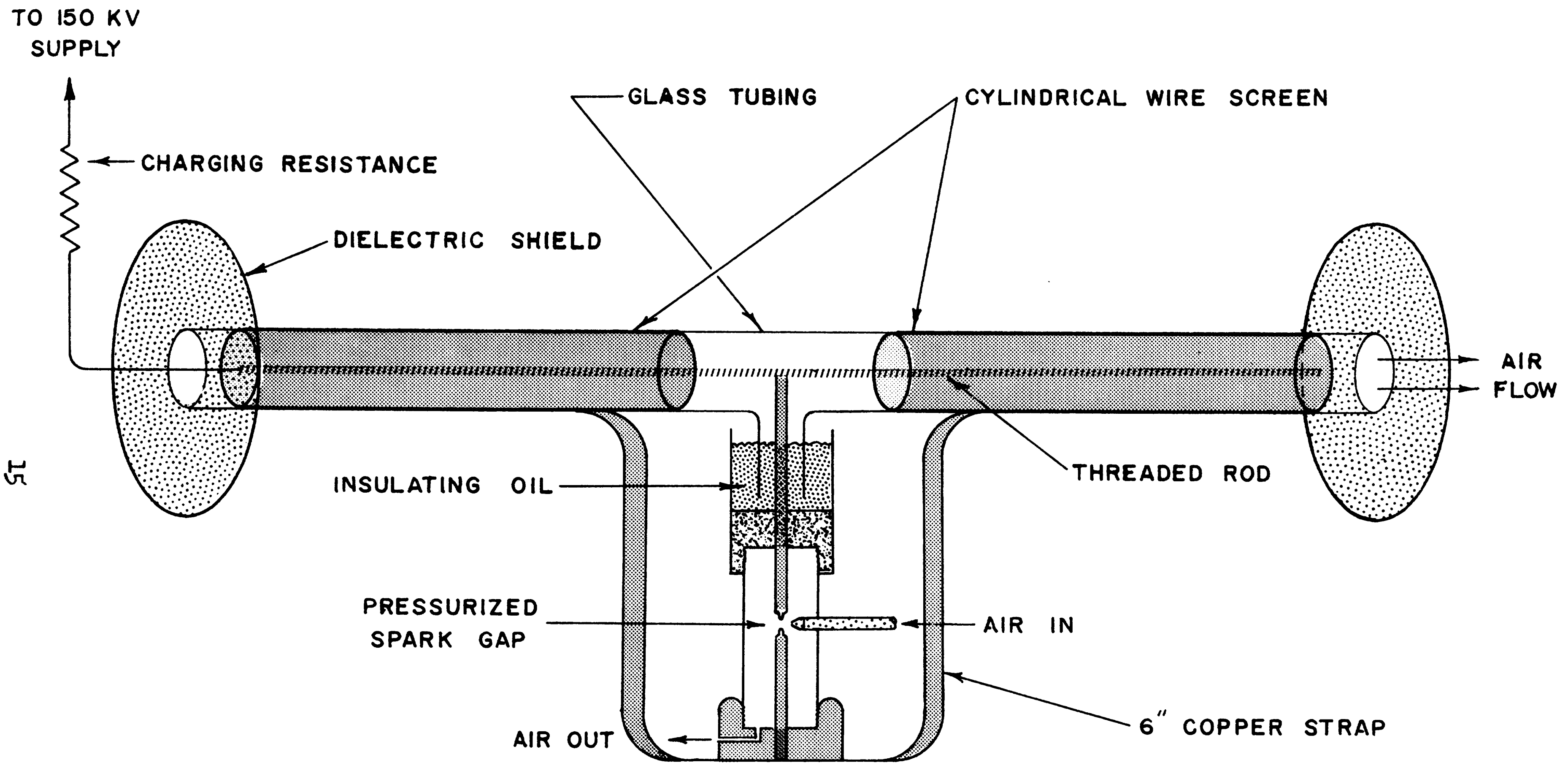

FIGURE 5 ARRANGEMENT USING GLASS TUBE AS ENERGY STORAGE CAPACITOR

mostly localized in these streamers.

With the previous system (using the SF_6 capacitor), the dielectric stress on the glass capacitance existed only very briefly during the flow of pulse current. However, with the glass serving as an energy-storage device, the voltage stress across the glass also existed during the charging period between pulses. This extra d-c component of dielectric stress necessitated many extra insulation requirements to avoid d-c arcs along the surface of the glass from the inner surface to the outer surface. This was prevented by designing high-voltage bushings, but the longer leads increased stray inductance in the system. Numerous tests were made with the "T" tube arrangement shown in Figure 6, using a 3-inch-diameter Pyrex tube with a 3/16-inch wall thickness. After two failures due to glass puncture the tests were abandoned. A quartz tube would have much superior dielectric properties, but the time schedule did not permit procuring and testing a quartz system.

HEAT ADDITION TESTS IN AN AIR STREAM

The experimental arrangement sketched in Figure 1 was used for a series of tests in which the power and temperature relationships were measured. Typical operating conditions are given in Table I.

The firing voltage of the spark gap could be accurately measured under low-repetition-rate conditions. At 5000-pulses-per-second repetition rate, the firing voltage was subject to approximately 5 % jitter and sometimes changed during the typical three-second run. Hence, the measurement of average power was not as consistent as desired.

The air which flowed through the discharge came from a 100-psi building supply line through a pressure-reducing valve. After passing through the

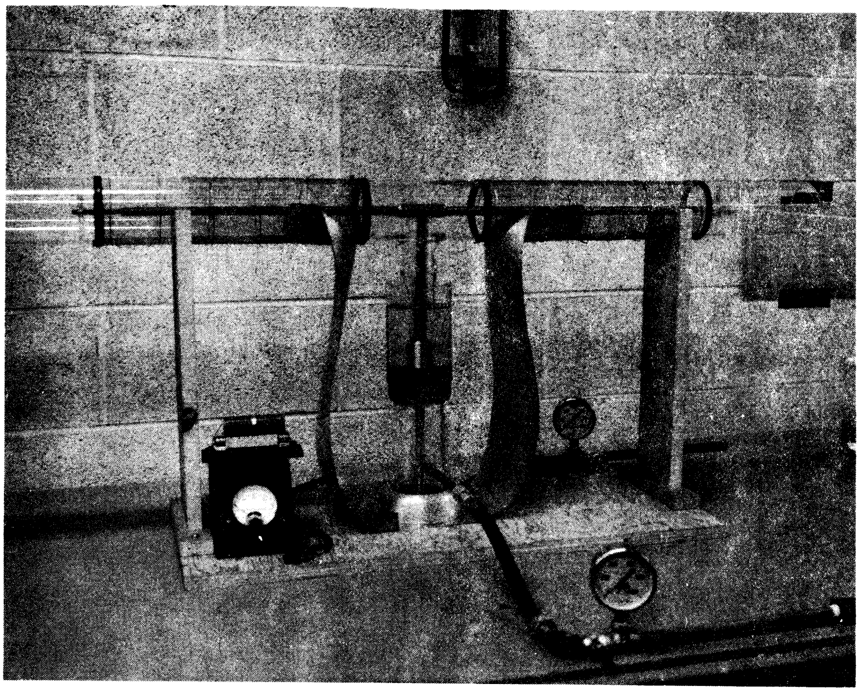

Figure 6. Photograph of Glass-Tube Energy-Storage Capacitor

Table I. Typical Operating Conditions

Power supply voltage	120 kv
Breakdown voltage of spark-gap switch	110 kv
Energy per pulse	1.8 joules
Pulse repetition rate	5000 pps
Average power from pulse generator	9000 watts
Shunting inductance	5 μhenrys
Average d-c current from power supply	0.22 ampere
Electrodes of spark-gap switch	Molybdenum rod 0.080 inch diameter, hemispherical tips
Spacing of spark-gap electrodes	.080 inch
Inner diameter of air nozzle	.070 inch
Air pressure at input to nozzle	800 psi
Air pressure in spark chamber	260 psi
Glass tube	Pyrex, 3-inch diameter, 3/16-inch wall
Length of wire screen covering glass tube	21 inches
Capacitance between inner wall and outer wall of glass tube	900 μμfd
Axial electrode inside 3-inch-diameter tube	Threaded brass rod, 1/2-inch diameter with sharp-edged threads.

valve, the air passed through a section of pipe filled with steel wool in order to obtain a smooth flow in the discharge region. The mass-flow rate remained constant, even when heat addition changed the flow velocity through the discharge region because virtually all of the pressure drop from the 100-psi supply to atmospheric pressure took place in the flow-regulating valve before the heating took place. The flow rate was measured by an oil-filled, inclined manometer. Temperature rise was measured by means of two fast-response thermocouples located in the air stream. These thermocouples were made of spot-welded junctions of copper and constantan wires 2 mils in diameter, and their output was recorded on a thoroughly shielded Tektronix 512 oscilloscope.

Figure 7 is an oscilloscope trace taken with a sweep speed of one second per centimeter. The discharge was turned on for a 3-second interval during the 10-second sweep. The irregularities on the curve during the heating interval were not due to stray electrical pick up, but are an indication of the amount of temperature homogeneity of the air stream. The time lag in the response to the temperature change is due to the fact that the thermocouples were located approximately 3 feet downstream from the discharge region. This delay varied inversely with the flow rate. The rate at which the temperature returned to normal after the power was turned off also varied inversely as the flow rate. If these time delays were due to heating of the glass walls of the tube, then one would expect the shape of the temperature curve to be different after a one- or two-second run compared with after a five-second run, but this was not the case. There was, however, substantial power expended in heating the glass walls, and this would have affected the stream temperature if the run time had been extended to sufficiently

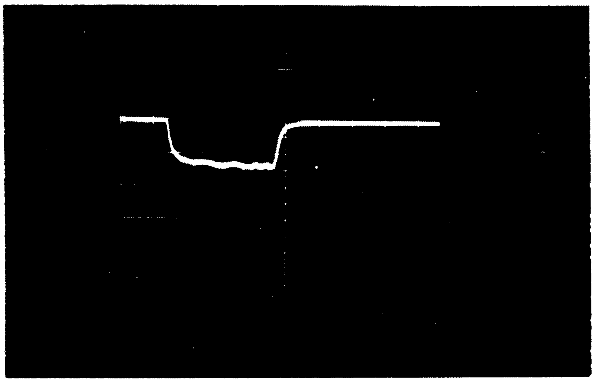

Figure 7. Oscilloscope Record of Temperature of Air Stream for a Three-Second Test. Sweep speed was one second per centimeter. Two series-connected thermocouples were located in air stream approximately 3 feet from discharge.

long periods.

Figure 8 is a curve of temperature rise vs. mass flow of the air stream. For constant power transfer to the gas, the product of mass flow and temperature rise should be constant, and the curve should have a hyperbolic shape. This is roughly the case. However, less than half of the power output of the pulse generator appeared in the air stream. For instance, at a 40 gm/sec flow rate the calculated temperature rise for 9000 watts of heat addition would be 215°C, while the measured rise was approximately 80°C. The rate of temperature rise of the glass tube was approximately 5°C per second, which would account for approximately 45% of the 9000 watts of power.

This heating of the glass was caused by dielectric loss and also by ion and electron bombardment associated with the glass surface functioning as an electrode. The measured dielectric power factor of the Pyrex glass tube was 1.1% at the frequency of interest (approximately 25 megacycles). Calculation of the dielectric loss requires information about the voltage gradient in the glass and the wave shape of the voltage under high-repetition-rate conditions which would be a rather involved measurement task. However, calculations based on assumptions which would give an upper limit to the power loss in the glass indicated that dielectric heating might account for approximately 10% of the 9000 watts from the pulse generator. Hence, the phenomena at the surface of the glass electrode are a loss factor of major importance. Substituting fused quartz for glass would greatly reduce the dielectric loss internal to the glass but presumably would not greatly affect the power dissipated at the dielectric surface.

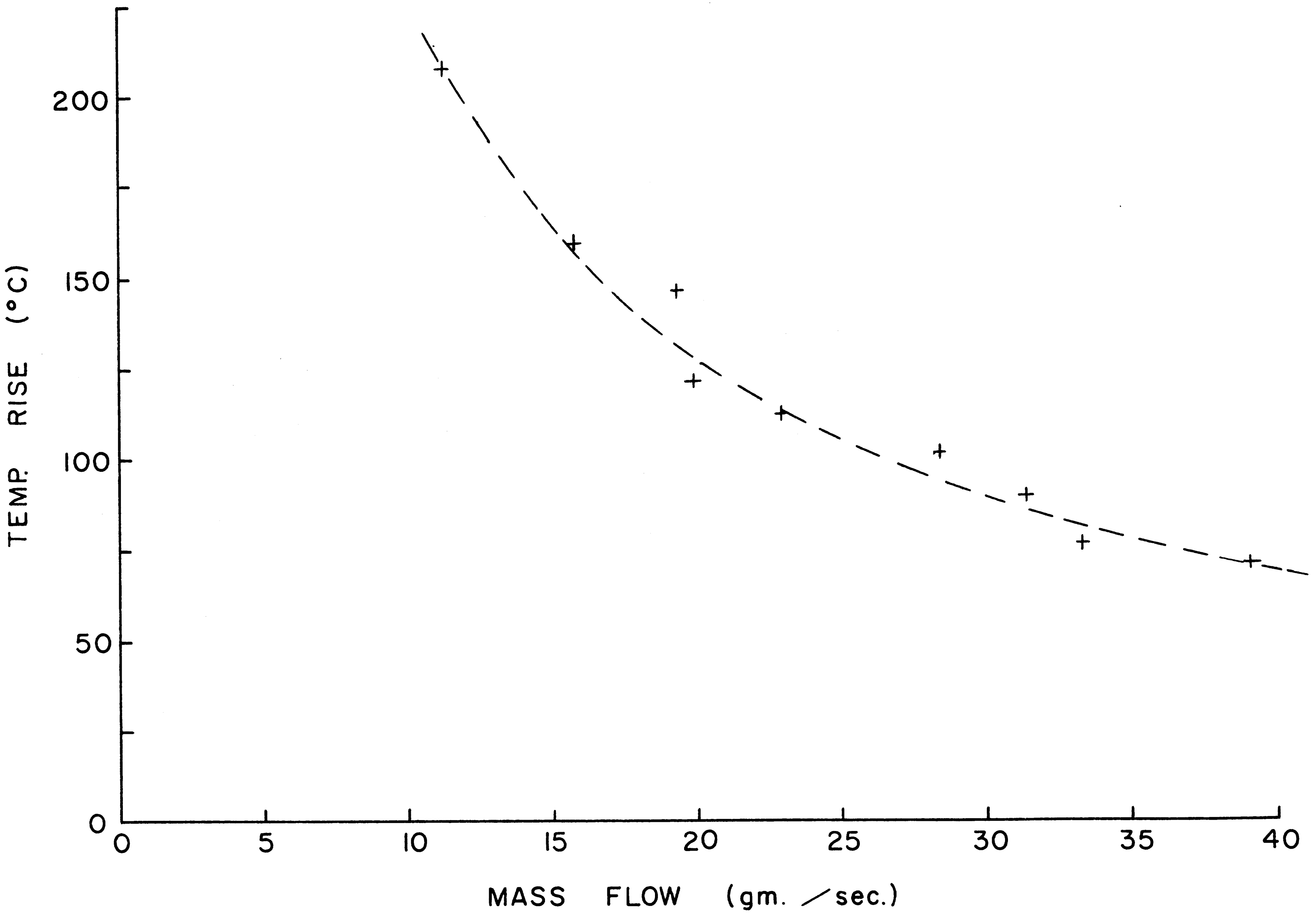

FIGURE 8 EXPERIMENTAL DATA OF TEMPERATURE RISE VS. MASS FLOW FOR OPERATING CONDITIONS GIVEN IN TABLE I

CONCLUSIONS

It is recommended that further efforts to increase the efficiency and power level of this process should proceed along the following lines:

Steps should be taken to reduce the power loss at the surface of the glass electrode. The mechanism of this loss should be studied to find out why the loss is so much higher with a glass electrode than with a metal electrode. Perhaps a dielectric electrode could be built in which hundreds of metal pellets or perhaps pins would be imbedded in the surface of the dielectric. Hopefully, this might provide the low power loss of the metal electrode with the spark-suppression properties of the glass electrode.

The use of a vacuum spark gap in place of the air-jet gap should be evaluated. Presumably, initial tests of such a gap would use a vacuum pumping system. Commercially manufactured, sealed-off gaps of a suitable voltage rating may become available, since there is at present considerable commercial interest in high-vacuum switch gear for high-voltage usage.

In the early stages of this project, the possible use of a triode oscillator for delivering short, high-repetition-rate bursts of r-f power for gas heating was rejected because the very short pulse length necessary to restrain sparking could not be obtained in this manner. Since using the glass-covered electrode, the sparking problem is reduced and the possible use of an oscillator and a radar-type modulator should be re-examined.