SOME INVESTIGATIONS INTO SPARK GAP RECOVERY IN AIR AND HYDROGEN

BY

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ABSTRACT

Studies were conducted into several aspects of the recovery of a spark gap consisting of 6 mm. diameter, flat tungsten electrodes, after an intial discharge of 32 kamp. maximum, and duration 11μsec.

The controlling effect of electrode heat transport on the intermediate recovery of the spark gap was demonstrated using air at 760 mm. Hg as a discharge medium, and gap lengths of 3,4, and 5 mm. In the intermediate stages of recovery, the increase in breakdown strength of the gap was found to be proportional to $t^{\frac{1}{2}}$, and to be nearly independent of gap length. These results are explained on the basis of uniaxular heat flow, through the electrodes.

A previously observed long-time or delayed recovery in a hydrogen spark gap between clean tungsten electrodes was investigated to establish the possible role of hydrogen-tungsten adsorption in this effect. The temperatures of the electrodes were varied by means of small heating coils,and the recovery characteristics for heated electrodes measured. By comparing these results to the normal recovery characteristic, the phenomana of delayed recovery was shown to be at least partially attributable to the adsorption of hydrogen onto the electrode surfaces.

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I am also indepted to Mr. J. Dooyeweerd, and other members of the technical staff of the plasma group for help in the construction and maintenance of the apparatus.

INTRODUCTION

Spark gaps are widely used as switching elements in high voltage circuits, and thus the study of the recovery of the breakdown strength of these devices after discharge is of importance, especially in applications where spark gaps are discharged at high repetition rates.

Immediately after a discharge, there remains between the spark gap electrodes, a column of hot ionized gas, thus for a period of time, up to several seconds after a discharge, the resistance of the gap to re-ignition will be less than its normal sparking voltage. The recovery process is physically very complex, its rapidity depending on, the rate of recombination of electrons and ions in the spark channel, the rate of cooling of the gas in the channel, the rate of cooling of the electrode surfaces, and in some cases, on other electrode effects.

It is known that electron-ion recombination will result in a neutral gas between the gap electrodes within a few hundred microseconds of the passage of a high current discharge. Because of acoustic wave propogation, the pressure in the channel will also rapidly reach equilibrium. Thermal effects in the recovering spark channel are, however, of a somewhat larger time constant. The cooling of the inter-electrode gas is somewhat difficult to treat exactly; and depends on the gap geometry. Curzon & Gautam [1] have presented a one dimensional model of heat flow, in a recovering spark channel with the same electrode geometry as that which was used here, taking into account the effect of electrode heat transport. Other electrode effects, such as adsorption of the discharge gas onto the electrode surfaces may be important, if the layer of adsorbed gas were removed during a discharge, the re-adsorption of gas would modify the electron emission characteristics

of the cathode.

In this report, the term recovery characteristic, pertaining to spark gap is to be taken to mean a plot of breakdown voltage versus the delay time after an initial discharge of the gap. Because of the random nature of spark breakdown , there are several criteria that can be used to define the breakdown voltage. The most usual is the so-called 50% breakdown voltage, that is, the amplitude of a voltage pulse which causes the gap to breakdown in more than 50% of the number of trials. As could be expected, the breakdown voltage defined in this manner depends on the shape of the restriking pulse. In this experiment a step function restriking pulse was used, and the 50% criterion adopted, with the additional requirement that breakdown occur before 100μ sec. after applying the restriking pulse to the gap. A justification of this criterion is given by M. S. Gautam [2] .

Several aspects of the recovery problem have been investigated in this experiment, for a spark gap of $\frac{1}{4}$" diameter cylindrical tungsten electrodes, through which was initially passed an arc discharge of 32 kamp. maximum, and of 11μ sec duration. In chapter one, the experimental setup is described in detail.

In chapter two results of recovery measurements at various electrode separations, in air at 760 mm. Hg, are presented, and the results compared to those expected on the basis of Curzon's model [1] of one dimensional heat flow. The main features of the recovery characteristics are found to be explained quite satisfactorily on the basis of this model.

In chapter three, results are presented of investigations into the phenomenon of long time (>100ms) recovery in hydrogen spark gaps, first noted by M. S. Gautam [2] . The dominant role in this effect, of hydrogen adsorp-

tion onto the electrode surfaces, is established by comparing the recovery characteristics of gaps in which the electrode surfaces were heated by means of auxiliary heating coils, to the recovery characteristic in the normal case.

Chapter four contains a discussion of the results and some suggestions for future research.

CHAPTER ONE APPARATUS

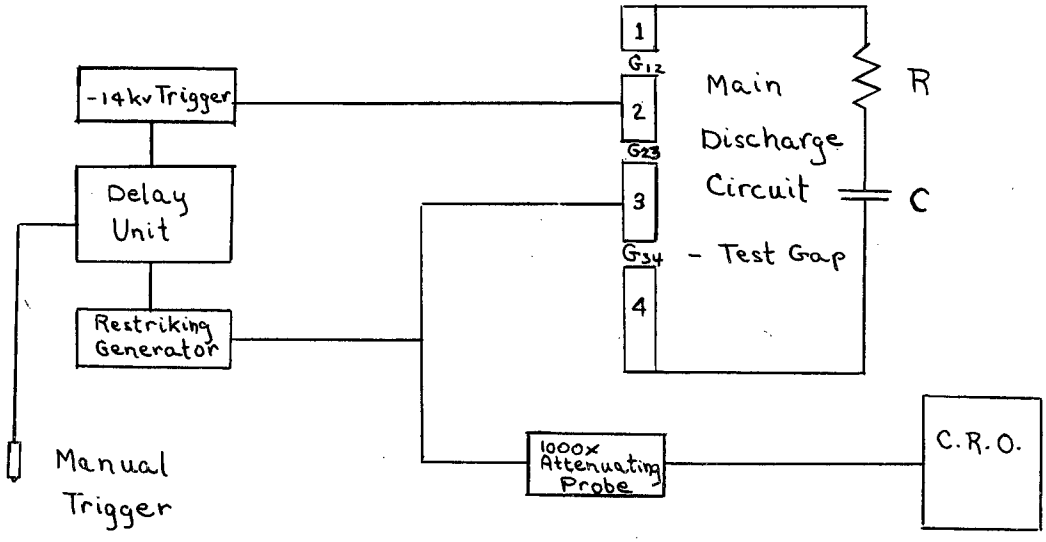
The equipment used in this experiment was very similar to that described by M. S. Gautam [2] ; and Churchill, Parker, and Craggs [3] , consequently a somewhat abridged description will be presented here.

The basic components were:

1. The main discharge circuit, which produced a unidirectional current pulse of 32 kamp maximum, and of 11μ sec duration, through the test gap.
2. A delay unit with some associated triggering circuitry.
3. A restriking generator which provided a step function voltage signal of 3-12 kv amplitude across the test gap, when triggered from the delay unit

A schematic diagram of these elements is presented below:

FIG. 1.1



BASIC COMPONENTS OF THE APPARATUS

The high current discharge was initiated by applying a -14 kv pulse to electrode 2, causing the capacitor C to discharge through the non-linear

resistor R, and the test gap G_{34}. At a variable delay time, after the initiation of the high current discharge, the restriking generator was triggered, and a step function voltage signal applied across the test gap. The amplitude of the step function was varied systematically to determine the breakdown voltage, V_R, as a function of delay time, t_D.

THE HIGH CURRENT DISCHARGE CIRCUIT:

The high current discharge circuit consisted of a capacitor bank, a non-linear damping resistor, and a discharge vessel, to which was attached the triggering spark gap assembly shown in figure 1.1.

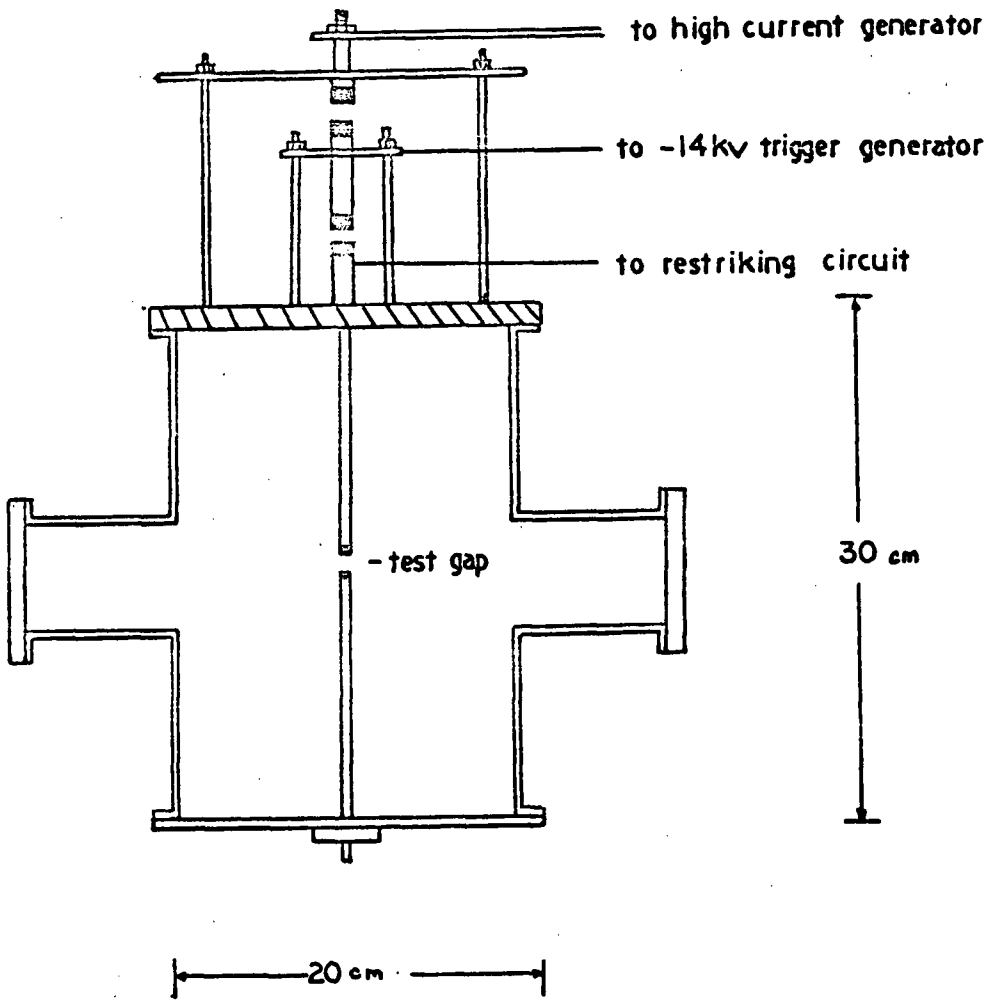
The capacitance was provided by two NRG type 201 capacitors, connected in parallel, giving a total of 10μF. These could be charged to 20kv by means of a high voltage power supply, yeilding a maximum charging current of 50 ma. The non-linear resistor was a type 801/22, Y6535333 AX, manufactured by the Morganite Company of Canada. The use of the non-linear resistor allowed a shorter, uni-directional current pulse than could have been obtained using a normal damping resistor. The device had a resistance of 17.5 Ω at 4kv; more detailed specifications can be found in [2].

The test gap, G_{34}, was mounted inside a sealed, cylindrical, brass chamber, with four protruding viewing ports, and lucite windows. The test electrodes were $\frac{1}{4}$" diameter tungsten rods, mounted in brass holders, and generally spaced 5mm apart. The switching gaps G_{12} and G_{23}, consisted of 5/8" diameter tungsten rods, mounted on top of the discharge vessel as shown in figure 1.2.

The switching gaps G_{12} and G_{23}, were so arranged that applying -14kv pulse to electrode 2 (Fig 1.1), broke down G_{12}, thus applying the full voltage of the capacitor bank to G_{23} and G_{34}, which subsequently broke

down, discharging the bank.

FIG. 1.2



THE DISCHARGE VESSEL

THE TRIGGERING CIRUITS.

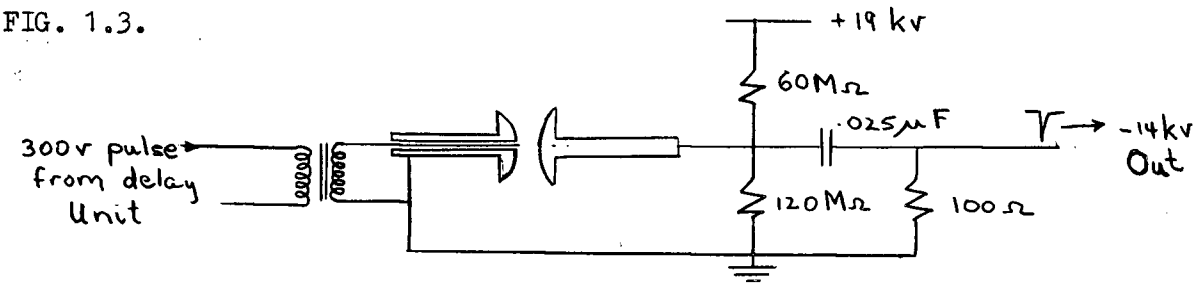
The high current discharge, and the restriking pulse were triggered from a delay unit which provided a 300v pulse when triggered manually, and another one at a delay time, variable from 100μs to 10 sec.

The first pulse was fed into a 300v-10kv pulse transformer, and then into a -14kv trigger generator to be described in the next section. The delay pulse was fed via another pulse transformer to the restriking generator.

THE -14kv TRIGGER GENERATOR:

The -14kv pulse used to initiate the high current discharge, was provided by the following circuit, constructed co-axially, in the manner described by Medley [4] , and shielded by a metal container.

FIG. 1.3.



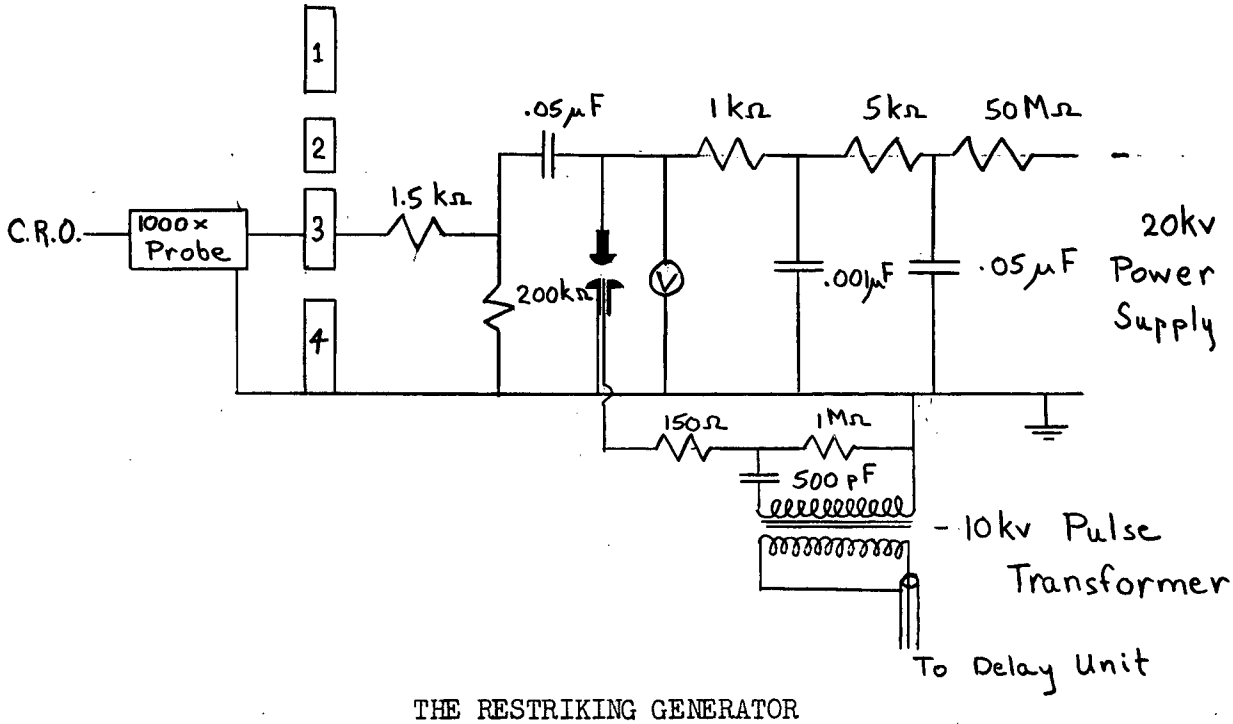
THE TRIGGER GENERATOR

The output pulse was fed into electrode 2 of figure 1.1.

THE RESTRIKING GENERATOR:

A voltage step function impulse of 0-12kv amplitude was applied across the test gap G_{34} by means of the following circuit which provided an impulse with a rise time of 0.2μs, and a droop in amplitude of the order of 1% in 100μsec.

FIG. 1.4.



THE RESTRIKING GENERATOR

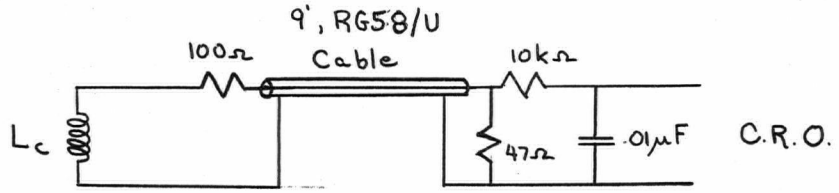
Low inductance carbon resistors were used throughout in the construction of this circuit. The voltmeter, Ⓥ , used to set the step function amplitude was a 25μamp meter, in series with a 500 MΩ, high voltage multiplier.

The output of the restriking generator was displayed on a Textronix type 551 oscilloscope, using a Textronix P6014, 1000x, high voltage attenuating probe; placed across gap G_{34}. A restriking of the test gap was seen as a collapse of the step function.

The current waveform of the main discharge could be monitored by means of a small search coil, mounted on the leads to the capacitor bank. This coil was made from 15 turns of type AWG-20 wire, 1.4 inches in diameter.

The output of the coil was integrated by a simple RC combination.

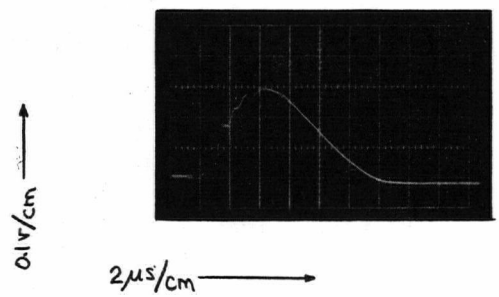
FIG. 1.5.



DISCHARGE CURRENT MONITOR

The 150Ω resistance in parallel with the coil, damped out the resonance responce of the coil, due to its stray capacitance. A 47Ω resistor terminated the RG58/U cable at the integrating circuit. The output of the coil is pictured below:

FIG. 1.6.



OUTPUT OF CURRENT MONITOR

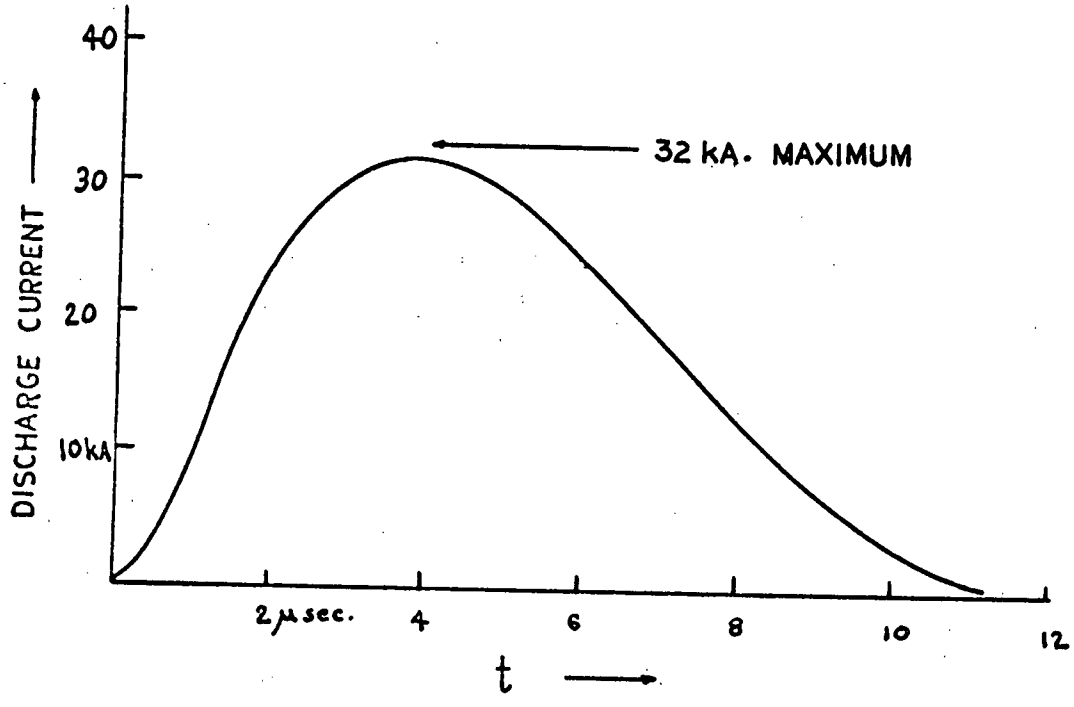
This signal can be calibrated in adsolute current units by employing the requirement that,

$$CV = \int_0^\infty I\,dt$$

where C is the capacitance of the main discharge bank (10μF), and V is the charging voltage (19kv).

Thus the calibrated current waveform became:

FIG. 1.7.



HIGH CURRENT DISCHARGE

CHAPTER 11 SPARK RECOVERY IN AIR

An analysis of the problem of uniaxular heat flow in a recovering spark channel, of the geometry used in this experiment [1] , has shown that early in the recovery period, one would expect the breakdown voltage, V_R, to increase proportionately to $t^{\frac{1}{2}}$.

Although a $t^{\frac{1}{2}}$ dependence of the recovery characteristic has been verified by Gautam [2] , for a spark in air at 760mm. Hg., between flat tungsten electrodes at 5mm separation , it was decided to examine the effect of electrode separation on the early recovery period.

Measurements were made in air at electrode separation of 3, 4, and 5mm. The experimental procedure was to increase the amplitude of the restriking pulse in steps of 0.1 kv, at a particular delay time, until the lowest voltage was found at which the gap would restrike before 100μs after the initiation of the restriking pulse, in at least 6 out of 11 trials. Before taking measurements on fresh electrodes, they were conditioned by firing 75 shots.

DISCHARGE PARAMETERS:

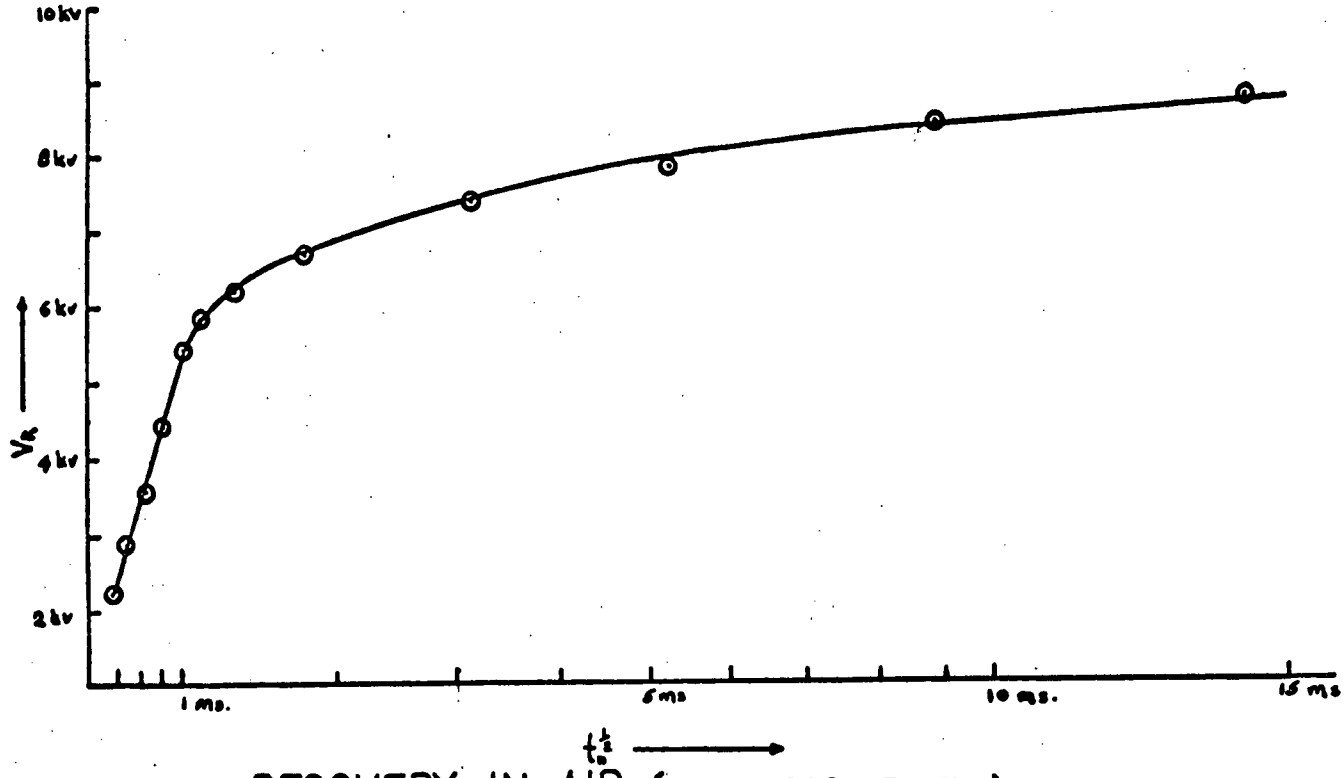
Discharge Medium:	air at 760mm. Hg
Peak Discharge Current:	32 kamp
Duration of Current Pulse:	11μsec.
Electrodes:	$\frac{1}{4}$" diameter, flat tungsten rods

Delay Time, t_D msec.	Recovery Voltage $V_R(t) \pm 0.1$kv			Percentage Recovery (V_R/V_0 x 100)		
	Gap length: 3mm	4mm	5mm	3mm	4mm	5mm
.635±.002	2.3 kv	2.2	2.1	25.6	22.0	20.7
.710±.002	2.9	2.9	2.5	32.3	29.6	24.3
.810±.002	3.6	3.7	3.0	40.0	27.8	29.1
.890±.002	4.6	4.3	3.7	51.2	43.8	35.9
1.02 ±.01	5.5	5.5	4.9	61.2	56.2	47.6
1.10 ±.01	5.9	-	5.7	65.6	-	55.3
1.31 ±.01	6.2	6.5	6.8	68.9	66.3	66.0
1.75 ±.01	6.7	7.6	7.7	74.5	76.0	74.8
3.15 ±.01	7.4	8.3	9.1	82.3	84.7	89.2
5.30 ±.01	7.8	8.8	9.6	86.7	89.8	93.2
8.95 ±.01	8.4	9.3	9.8	93.4	95.0	95.2
14.4 ±.1	8.7	9.4	10.1	96.8	96.0	98.1
40.8 ±.1	8.9	9.5	10.2	99.0	97.0	99.0
89.0 ±.1	9.0	9.7	10.3	100	99.0	100
SPARKING VOLTAGE						
$V_0(t_D = \infty)$	9.0	9.8	10.3			

The nature of the triggering in the restriking generator did not permit measurements with a restriking pulse of less than 2 kv amplitude.

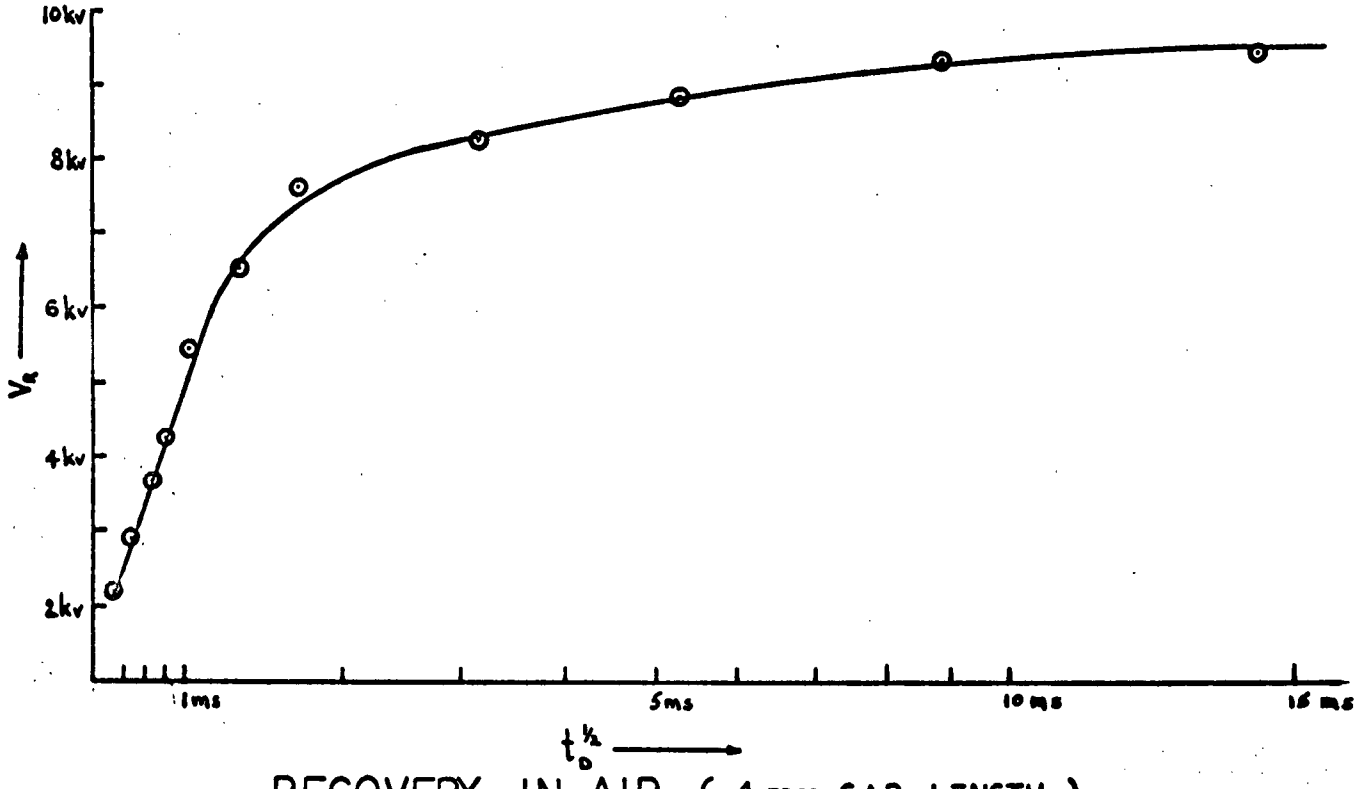
In figures 2.1 - 2.4, the recovery characteristics of the spark gap at 3,4, and 5mm electrode separation are plotted against a time scale proportional to $t_D^{\frac{1}{2}}$. It can be seen that from .5 - 1.5 msec after the initial discharge, the recovery characteristics rise very nearly as $t_D^{\frac{1}{2}}$. Furthermore, the rate of increase of the breakdown voltage is nearly the same for all three gap lengths in this period (fig. 2.4).

FIG. 2.1



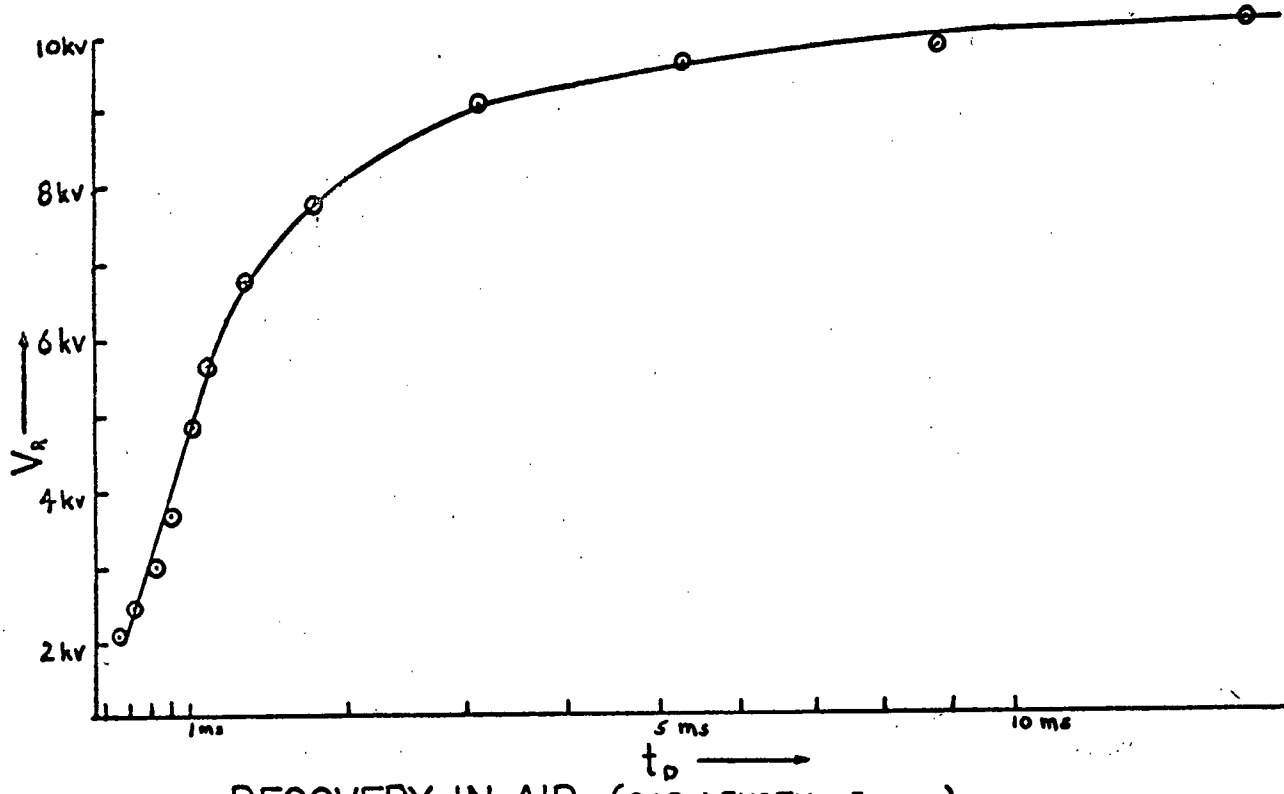
RECOVERY IN AIR (3 mm. GAP LENGTH)

FIG. 2.2



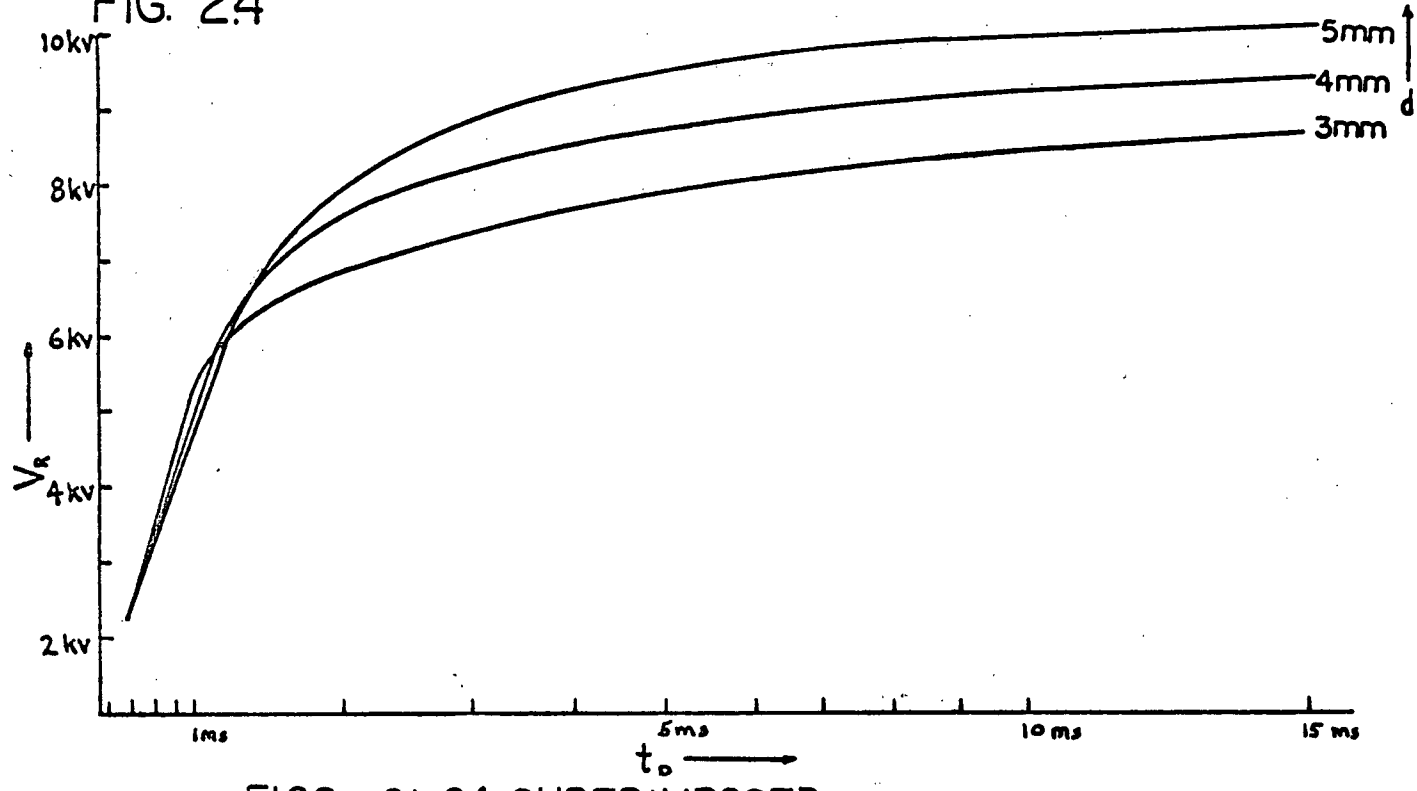
RECOVERY IN AIR (4 mm GAP LENGTH)

FIG. 2.3



RECOVERY IN AIR (GAP LENGTH 5mm)

FIG. 2.4



FIGS. 21-24 SUPERIMPOSED

FIG. 2.5

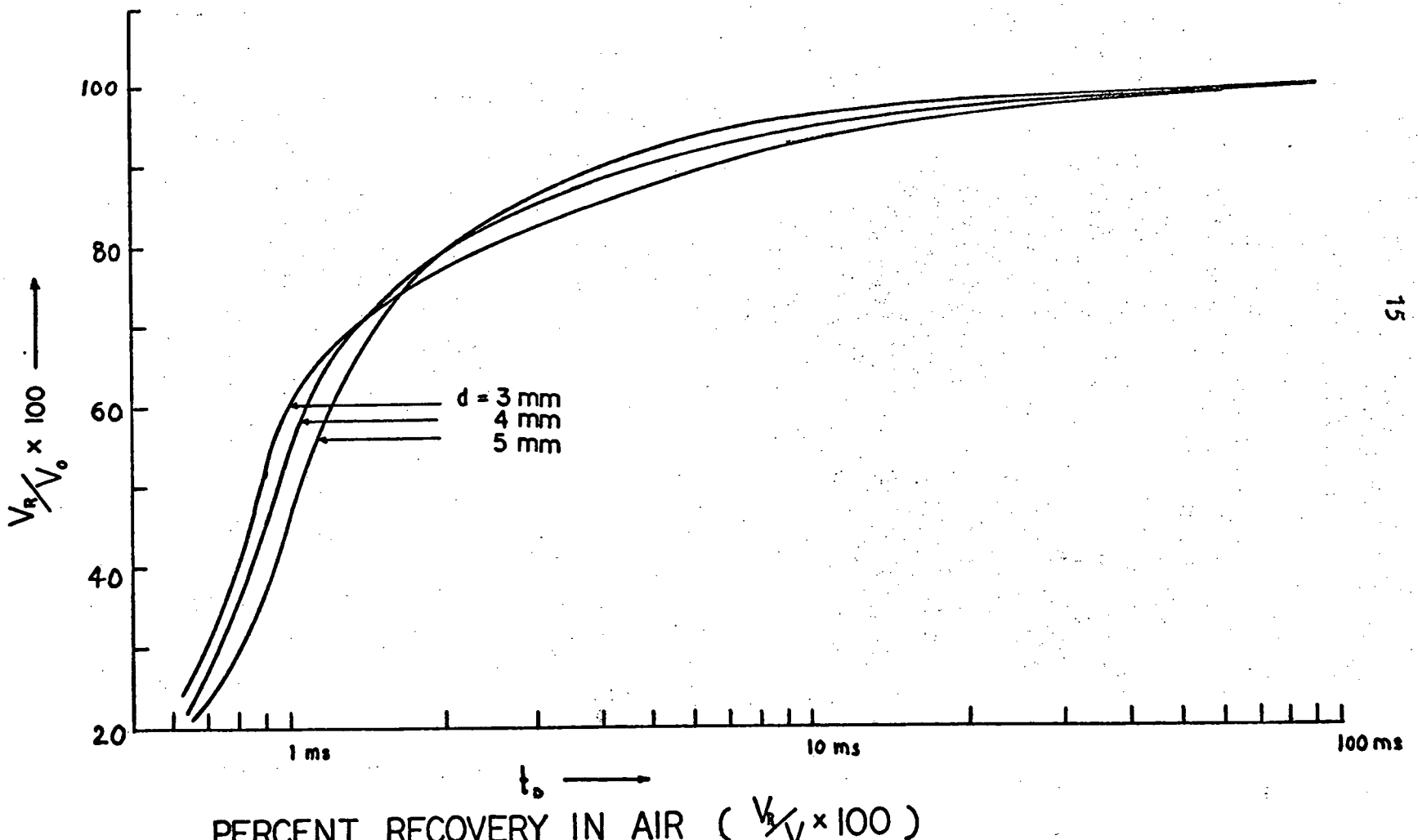

100
80
60
40
20
$V_R/V_o \times 100$
d = 3 mm
4 mm
5 mm
1 ms
10 ms
100 ms
t_D
PERCENT RECOVERY IN AIR ($V_R/V_o \times 100$)

Figure 2.5 shows the percentage recovery (V_R/V_0 x 100) of the gap as a function of delay time for the three cases. It can be seen that this quantity is only slightly affected by gap length over the range 3-5mm. The percentage recovery is seen to decrease with gap length from 0.6-1.5 msec after the discharge, and increase with gap length for times greater than this.

These results can be explained on the basis of the thermal recovery of the interelectrode gas. Curzon and Gautam [1] show that, neglecting convective cooling and lateral heat conduction, one would expect the gas temperature in the column to be given by:

(1)
$$T(z,t) = T_R + \left[\frac{t^{1/2}}{z\,(S_G/K_G)^{1/2} + l\,(S_e/K_e)^{1/2}} \right]^{-1} \frac{T_F - T_R}{\pi}$$

providing that:

(2)
$$l^2 S_e/K_e + d^2 S_G/4K_G > 4t > l^2 S_e/K_e$$

Where:

T_R is the equilibrium temperature of the electrodes and gas.

S_G, S_e, are the specific heats at constant pressure, per unit volume, of the gas and electrodes respectively.

k_G, k_e, are the thermal conductivities of the gas and electrodes respectively.

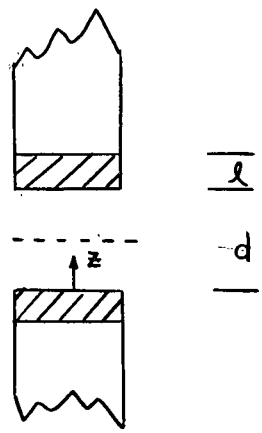
z, is the distance to the nearest electrode (fig. 2.6).

d, is the electrode separation.

l, is the depth to which the electrodes are heated by the initial discharge.

T_F, is the temperature of the electrode surfaces and the inter-electrode gas, immediately after the discharge. (assumed to be constant)

FIG. 2.6



ELECTRODE PARAMETERS

Now, if it is assumed that the breakdown voltage of the gap is related linearly to the product $\bar{\rho}\,d$, where $\bar{\rho}$ is the average density (over z) of the inter-electrode gas.

one has: (3) $$V_R(t,d) = A\,\bar{\rho}(t)\,d + B$$

(This is equivalent to assuming that the Paschen curve is linear in the region of interest [5] .)

Now, for $T_G >> T_R$, it follows from (1) that in the region where (2) is satisfied:

(4) $$V_R(t,d) \simeq \frac{A' t^{\frac{1}{2}} d}{T_F\left(\frac{d}{4}(S_G/k_G)^{\frac{1}{2}} + l\,(S_G/k_e)^{\frac{1}{2}}\right)} + B \quad ,\text{ie } \bar{\rho} \simeq \frac{A'}{A\pi T_G}$$

Assuming that only a thin surface layer of the electrodes is heated by the initial discharge, so that it is safe to neglect $l\,(S_e/k_e)^{\frac{1}{2}}$ in comparison with $d\,(S_e/k_G)^{\frac{1}{2}}$,* one obtains:

(5) $$V_R(t,d) \simeq \frac{4A' t^{\frac{1}{2}}}{T_F\,(S_G/k_G)^{\frac{1}{2}}} + B$$

that is, the recovery characteristic in the initial stage should rise proportionately to $t_D^{\frac{1}{2}}$, and be nearly independent of the electrode separation. (T_F may depend somewhat on d).

*This is equivalent to assuming that the heat flow from the gas is limited by the "thermal inertia" of the gas, rather than the rate at which heat can be removed through the electrodes.

CHAPTER 111 SPARK GAP RECOVERY IN HYDROGEN

M. S. Gautam [2] has noted a peculiary long recovery period, for a spark gap in hydrogen, between tungsten electrodes. The continued rise in breakdown strength beyond 100 msec., up to delay times of several seconds, he has attributed to the re-adsorption of hydrogen onto the tungsten electrode surfaces, which had been cleaned by the initial discharge, thus changing the work function of the cathode surface.

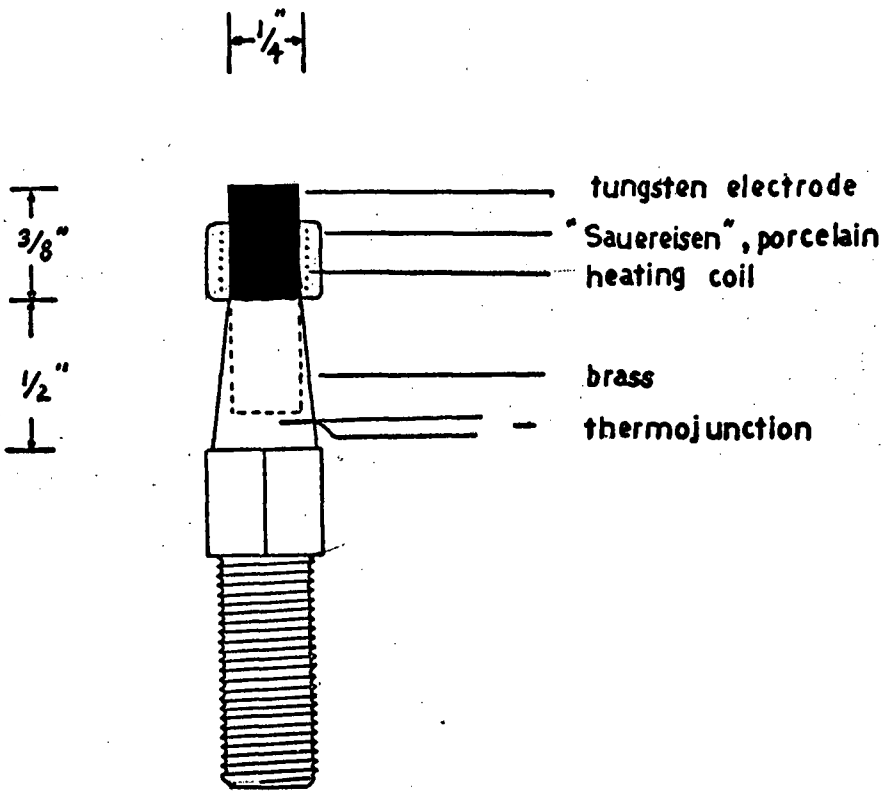
The adsorption of hydrogen onto tungsten is a well established fact, this combination was used in the early adsorption investigations, conducted by Langmuir [6] . Although several adsorbed layers may be present at high pressures, the initial layer is thought to consist of chemi-sorbed hydrogen atoms [7] . This initial layer of adsorbed hydrogen was found by J. K. Roberts [7] , to become unstable at temperatures of the order of 700°K, at a gas pressure of about 10^{-3} mm. Hg. The time required for the amount of adsorbed gas to saturate was found to be temperature dependent at temperatures below this. Although very little work has been done on adsorption at pressures above 10^{-3} mm. Hg, it seems likely that at high pressures, several layers of physically, or Van der Waals-adsorbed hydrogen molecules will also be present.

If the delayed recovery effect observed by Gautam was a consequence of adsorption, the nature of the recovery characteristic in the delayed recovery region should be altered if the electrodes were heated, since in this case, the adsorption would be delayed. The fact that the delayed recovery he observed did not begin until about 100 msec. after the initial discharge, by which time the electrodes would be quite cool, suggests that heating to a relatively low temperature would be effective.

Thus to attempt to establish the role adsorption in the recovery of this type of spark gap system, the electrodes were fitted with small heating coils capable of heating them to about 200°C.

Figure 3.1 shows an electrode with heating coil installed.

FIG. 3.1



HEATED ELECTRODE

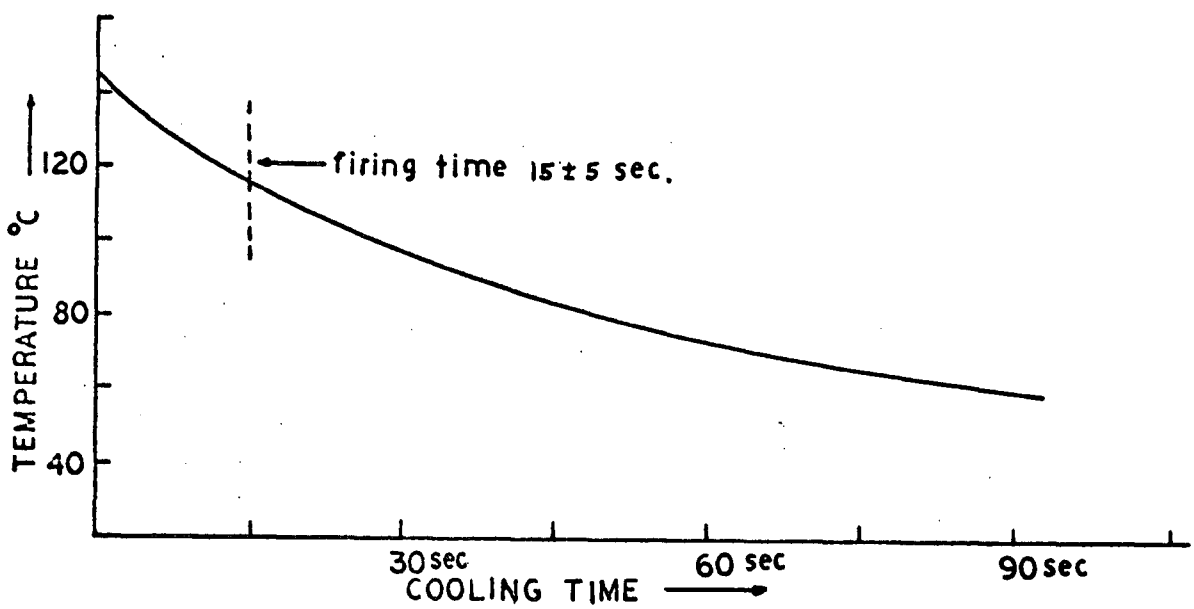
The heating coil consisted of 1.5 ft. of .0159" diameter Copper-nickel alloy wire of 1.19 Ω/ft. This would dissipate a maximum of 30 watts, when installed on the electrode. The heating coil power supply was an a.c. voltage source, variable from 0-10v. The temperature of the electrode was measured by means of a copper-constantun thermo-junction, soldered directly into the brass electrode holder. The thermocouple emf. was measured by a

potentiometer and standard cell, using the freezing point of water for a reference junction. The device was calibrated at the boiling points of water and naphthalene.

MEASUREMENTS:

To obtain recovery characteristics for heated electrodes, the procedure adopted in the first instance was to heat the electrodes at 20 watts until an equilibrium temperature of about 150°C was reached. The heating coils were then disconnected and the main bank charged. The high current discharge was then triggered 15 seconds after disconnecting the heating coil power supply. The cooling curve of the electrodes is shown in figure 3.2. It can be seen that at the time of firing, the electrode temperature was 120±10°C.

FIG. 3.2



ELECTRODE COOLING CURVE

99.8% pure, commercial hydrogen was used in these investigations, and the tank was flushed and refilled several times with the heating coil power on, before taking measurements. The electrode surfaces were polished flat using fine grain abrasive polishing paper, and it was found necessary to fire about 150 "conditioning" shots to make the breakdown voltages in the recovery period reproducible. When working with hydrogen, it was found that after about 500 shots, the main bank could not be triggered in the configuration described in chapter one. The sparking voltage of the test gap was still only about 13 kv., as could be verified by connecting a power supply, via a large resistor, directly across G_{34}, and charging. Thus, this failure to fire must have been due to an increase in the formative time lag of the gap. Therefore, a 25,000 Ω resistor was connected from electrode 2 of figure 1.1 to ground. This increased the duration of high voltage pulse applied across G_{34}, when G_{12} was triggered. This arrangement proved satisfactory and no change in the current waveform of the main discharge was detected.

Results:

Recovery characteristics were measured, heating the cathode, and anode separately, as well as with both electrodes "cold". The electrodes were conditioned as described above. Measurements were made at successive delay times:

a) with both electrodes cold

b) with the anode at 120°C

c) with the cathode at 120°C

d) with both electrodes cold

The results are tabulated below:

DISCHARGE PARAMETERS:

Discharge Gas: Hydrogen at 760mm. Hg

Peak Discharge Current: 32 kamp.

Duration of Current Pulse: 11 μsec.

Electrodes: $\frac{1}{4}$" diameter tungsten rods

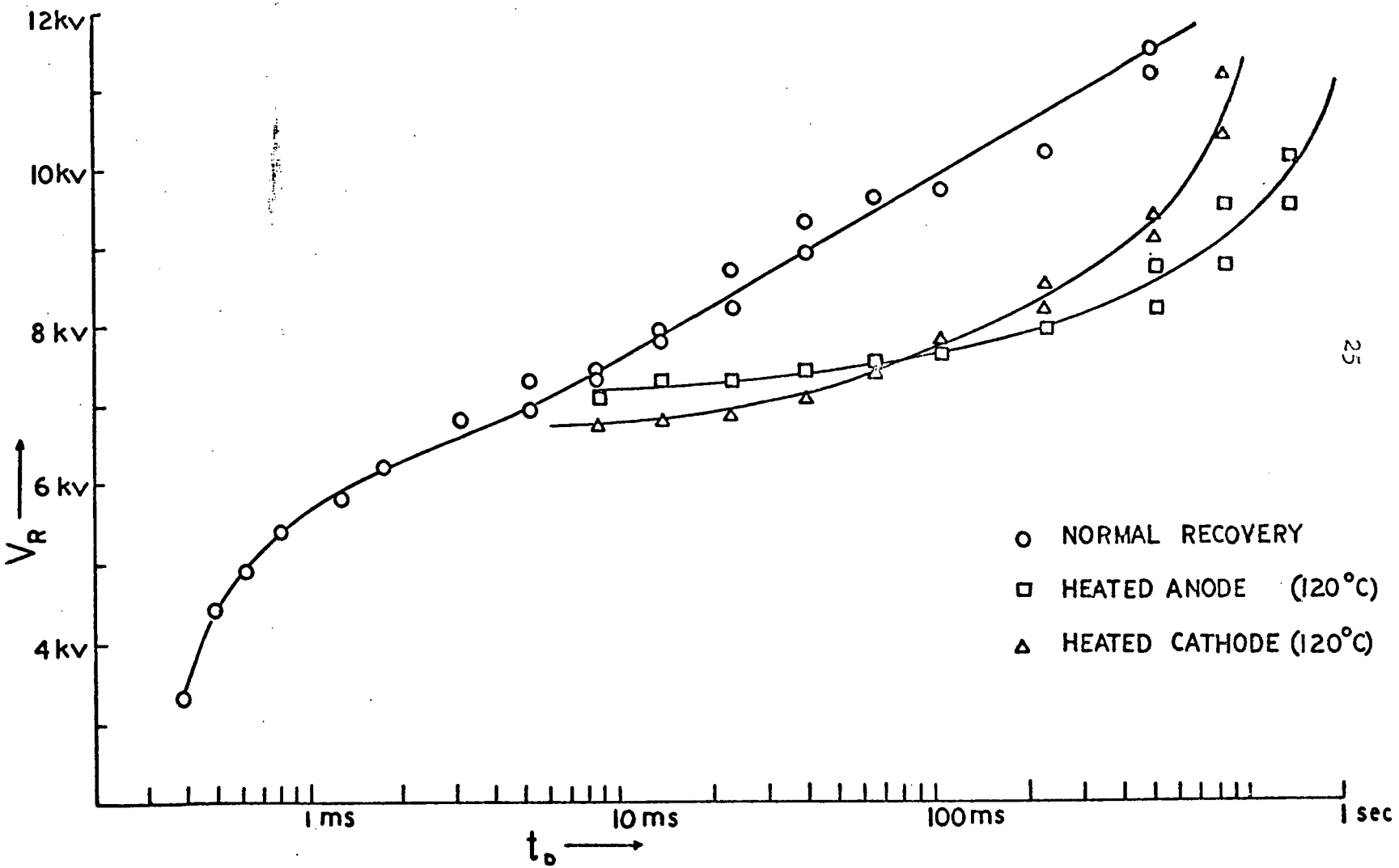
TABLE 3.1

Delay Time t_D	"Cold" Electrode $V_R \pm .1$kv	Hot Anode (120°C) $V_R \pm .1$kv	Hot Cathode (120°C) $V_R \pm .1$kv	"Cold" Electrodes $V_R \pm .1$kv
$.380 \pm .005$ms	3.3 kv	-	-	-
$.475 \pm .005$	4.4	-	-	-
$.605 \pm .005$	4.9	-	-	-
$.790 \pm .005$	5.4	-	-	-
$1.26 \pm .01$	5.8	-	-	-
$1.71 \pm .01$	6.2	-	-	-
$3.08 \pm .01$	6.8	-	-	-
$5.20 \pm .01$	7.3 (6.9)	-	-	-
$8.60 \pm .05$	7.4 (7.3)	7.1	6.7 (6.7)	7.4
$13.8 \pm .1$	7.9 (7.8)	7.3 (7.3)	6.8 (6.8)	7.9
$23.2 \pm .2$	8.2 (8.7)	7.3 (7.3)	6.8 (6.9)	8.2
$40.2 \pm .2$	8.9 (9.3)	7.5 (7.3)	7.1 (7.0)	8.9
$67.0 \pm .5$	(10.3) (9.6)	(7.4)	(7.4)	-
109 ± 1	9.7	7.6 (7.7)	7.8	9.3
235 ± 2	10.2 (10.2)	7.9	8.5 (8.2)	10.1
520 ± 5	$11.5 \pm .5$(11.2)	8.7 (8.2)	9.4 (9.1)	$11.5 \pm .5$
875 ± 5	>12 kv	9.5 (8.7)	11.2 (10.4)	>12 kv
$1.41 \pm .01$s	>12 kv	11.1 (10.5)	>12 kv	>12kv

The apparatus did not permit measurement of $V_R > 13$ kv, since at this point, the gap G_{23} (fig 1.1) broke down under the application of the step function restriking voltage to electrode 3. (fig 1.1). With cold electrodes, at recovery times greater than a second, the breakdown strength of the gap was not very well defined, and recovery measurements became quite eratic. Formative time lags $>100\ \mu$ sec were common.

Two trials were made with different sets of electrodes in which just the cathode was heated, or just the anode was heated. As the recovery characteristics seemed to change somewhat when different sets of electrodes were used (probably due to the alignment or conditioning of the electrodes), these results are included in brackets in table 3.1. The recovery points tabulated in table 3.1 are plotted in figure 3.3.

FIG. 3.3



EFFECT OF ELECTRODE HEATING ON RECOVERY IN HYDROGEN

It can be seen that heating either electrode to 120°C has a significant effect on the recovery characteristic at delay times greater than 10 msec. To investigate the possibility that the observed effect may have been due to a heating, and consequently a density reduction of the inter-electrode gas, it was decided to examine the worst possible case. Assuming that the inter-electrode gases were all at 120°C, its density would correspond to a pressure of 525 mm. Hg, at room termperature. Therefore, the recovery characteristic of the spark gap, in hydrogen, at 525 mm. Hg, was measured, and compared to the characteristics with heated electrodes. The results are presented in table 3.2, and plotted in figure 3.4.

Table 3.2:

DISCHARGE PARAMETERS:

Discharge Medium: hydrogen at 525 mm. Hg

Electrodes: $\frac{1}{4}$" diameter tungsten rods

Peak Discharge Current: 32 kamp.

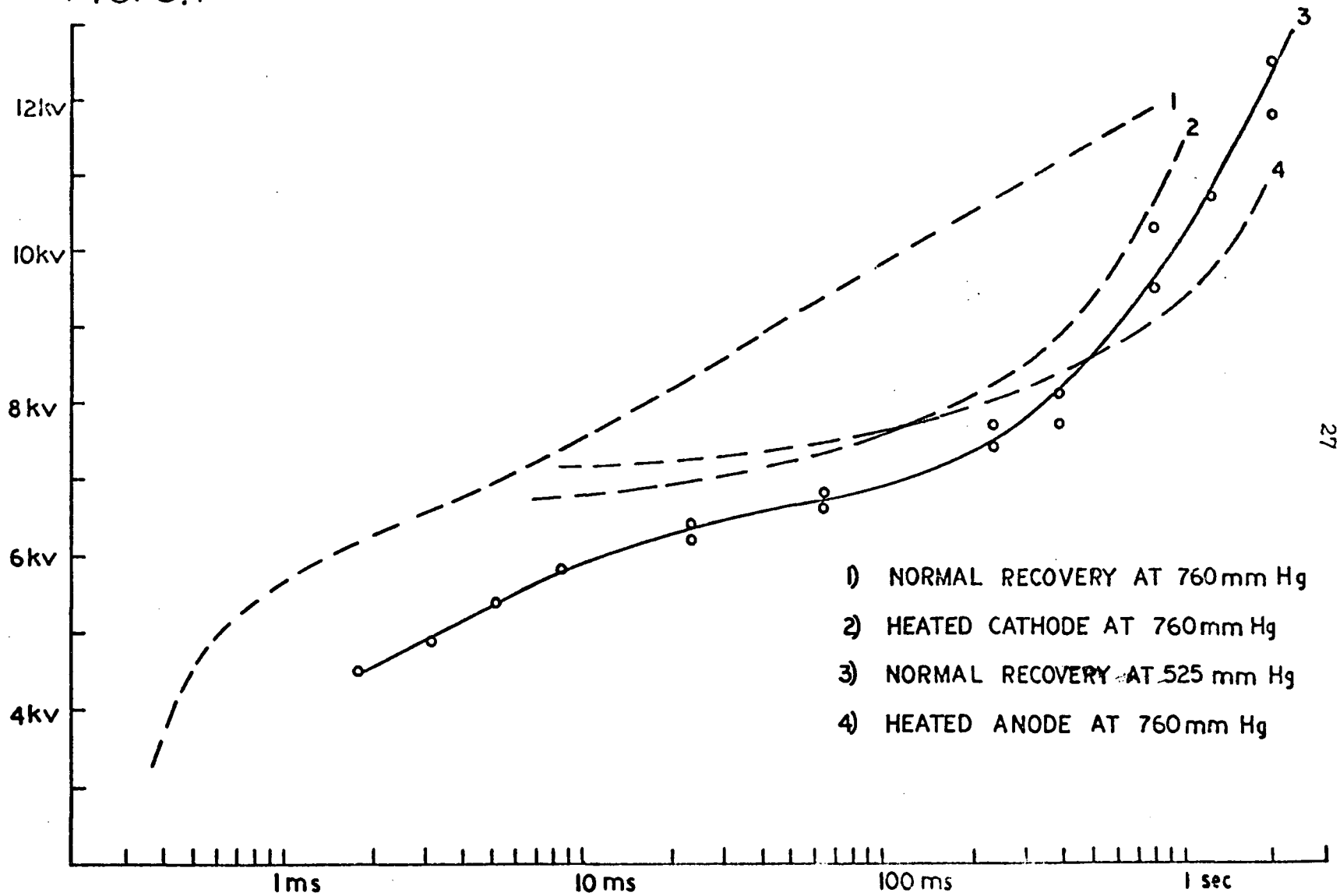
Duration of Current Pulse: 11 μ sec.

Delay Time t_D	Recovery Voltage V_R	
1.77±.02 msec.	4.5±.1 kv	
3.15±.02	4.9±.1	
5.20±.02	5.4±.1	
8.60±.05	5.8±.1	
23.5±.2	6.4±.1	6.2±.1*
65.5±.5	6.8±.1	6.6±.1*
237 ±2	7.7±.1	7.4±.1*
400 ±2	8.1±.1	7.7±.1*
825 ±5	10.3±.1	9.5±.1*
1.27±.05 sec.	10.7±.2*	
2.10±.05	11.8±.5	12.5±.5*

Sparking Voltage, $V_0(t_D = \infty)$ ~13kv

* These results were obtained using a different set of electrodes, as a check on electrode conditioning.

FIG. 34



RECOVERY IN HYDROGEN AT 525 mm. Hg

Figure 3.4 shows that reducing the inter-electrode gas density has a greater effect than heating either electrode to 120°C, except for heating the anode at delay times greater than 500 msec. However, the fact that the heated electrode characteristics join the normal characteristic at delay times below 10 msec., while the characteristic at 525 mm. Hg does not, indicates that the inter-electrode gas density was not significantly affected by electrode heating.

As a further check on this point, the effect of electrode heating, on the recovery characteristic of a similar spark gap, in air, was investigated. The recovery measurements for a spark gap, in air, in which the cathode was heated to 120°C, are presented in table 3.3, and plotted in figure 3.5.

Table 3.3:

DISCHARGE PARAMETERS:

Discharge Medium: air at 760 mm. Hg

Electrodes: $\frac{1}{4}$" diameter tungsten rods

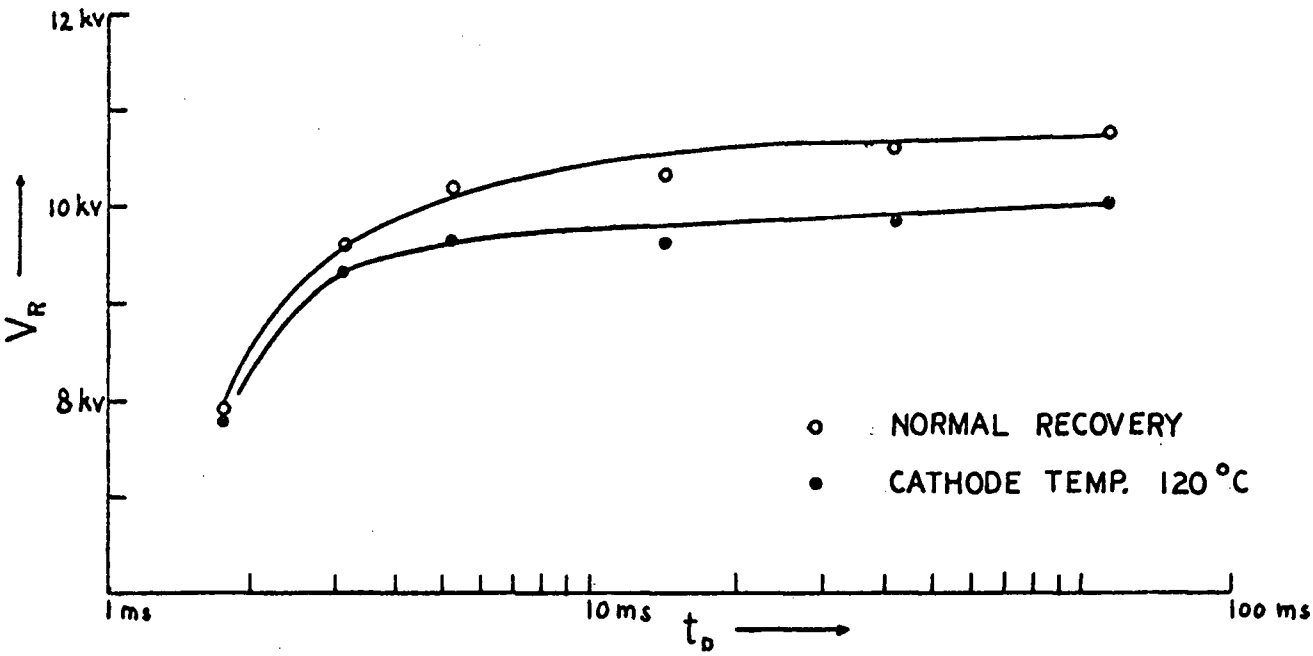
Peak Discharge Current: 32 kamp

Duration of Current Pulse: 11 μ sec.

Delay Time	"Cold" cathode	Cathode heated to 120°C
t_D	$V_R \pm .1$kv	$V_R \pm .1$kv
$1.75 \pm .01$ msec	7.9 kv	7.8 kv
$3.10 \pm .02$	9.6	9.3
$5.25 \pm .05$	10.2	9.7
$14.3 \pm .1$	10.3	9.7
$44.0 \pm .1$	10.6	9.8
111 ± 1	10.7	10.0

Sparking Voltage: V_0 ($t_D = \infty$), 10.7 kv

FIG. 3.5



EFFECT OF CATHODE HEATING ON RECOVERY IN AIR

It is apparent that although cathode heating in air does somewhat effect the breakdown strength, the result does not compare to the 3 kv difference between heated and cold cathode recovery characteristics in hydrogen. (Maximum difference in air is .7 kv at 100 msec.)

It can be seen from fig. 3.3 that heating either electrode surface in hydrogen to 120°C greatly alters the recovery characteristic at delay times greater than 10 msec. The effect of heating to this temperature decreases at recovery times greater than one second. The only possible explanation for these results is that heating to 120°C increased the time required for an effective layer of hydrogen to be adsorbed onto the electrode surfaces. It is quite surprising, however, that heating the anode to 120°C, has nearly as large an effect as heating the cathode to this temperature. It is well known, however, that certain anode processes, eg. photon emission, are import-

tant in the over-all feedback system, leading to spark formation. Space charge effects at the anode, associated with the layer of adsorbed gas, may also be of importance.

As can be seen from figure 3.3, heating the cathode to 120°C begins to lose its effect at delay times greater than 1 sec. This suggests that significant amounts of hydrogen are still adsorbed but that the time required for an effective layer to form is increased at this temperature. This is in general agreement with the observations of J. K. Roberts [7]. At a delay time of one second, the effect of cathode temperature on breakdown strength was investigated. The cathode was heated to a steady state at various coil power dissipation, and its steady state temperature measured with the thermojunction attached near the electrode.

The thermojunction leads and heating coil leads were then removed and the bank fired immediately (with 1 second of disconnecting heating coil).

The results are presented below:

DISCHARGE PARAMETERS:

Discharge Gas:	H_2 at 760 mm. Hg
Peak Discharge Current:	32 kamp
Duration of Current Pulse:	11 μ sec
Electrodes:	$\frac{1}{4}$" diameter tungsten rods

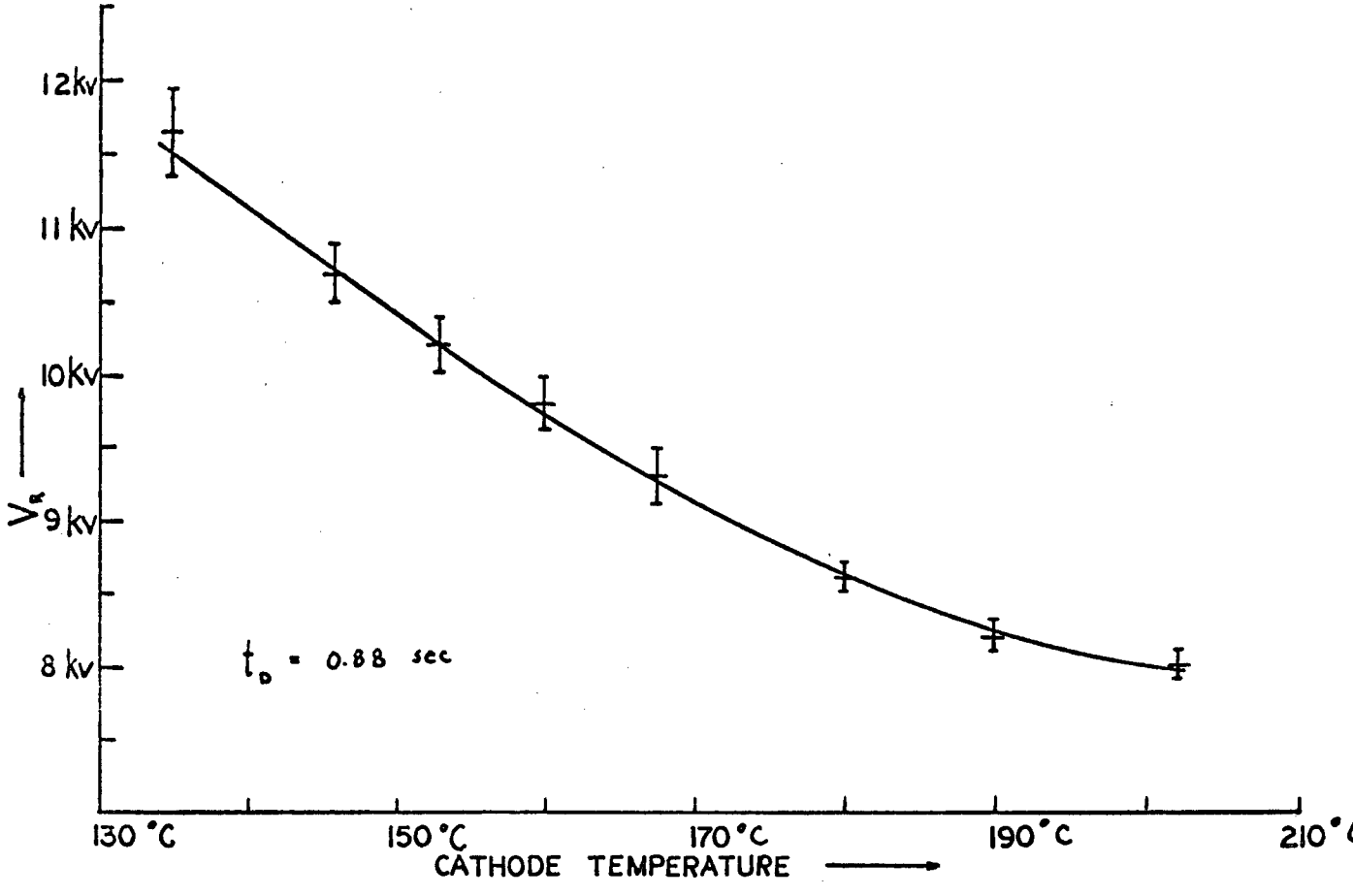
Table 3.4

Heating Coil Power	Cathode Temperature	V_R (t_D = .88 sec)
14 watts	135±2 C	11.7±.3 kv
16	146±2	10.7±.2
18	152±2	10.2±.2
19	160±2	9.8±.2
20	167±2	9.3±.2
22	180±2	8.6±.1
28	202±2	8.0±.1

These results are plotted in figure 3.6.

At temperatures below 135°C, the breakdown voltage of the gap became so erratic that further measurements were not possible. However, the breakdown strength remained less than 13 kv for temperatures from 20°-130°C. The difficulty was due to the instability of the formative time lag in this region, formative time lags much larger than 100 μsec were very common. This apparent change in the relation between t_f and overvoltage may have been due to the adsorption of hydrogen. In reference to figure 3.6 it can be seen that the effect of cathode heating begins to decrease noticeably from about 190°C. This suggests that most of the adsorbed hydrogen was removed from the cathode at this temperature.

FIG. 3.6



EFFECT OF CATHODE TEMPERATURE ON RECOVERY VOLTAGE, IN THE LATE RECOVERY PERIOD

CHAPTER 1V CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

CONCLUSIONS:

a) The results on spark gap recovery in air, at electrode separations of 3,4, and 5mm, confirm the predictions of the Curzon-Gautam theory of uniaxular heat flow, on the gap-length dependence of the initial portion of the recovery characteristic. This shows that heat flow through the electrodes is a controlling factor in the intermediate recovery of a spark gap.

b) A long-time recovery effect in hydrogen-tungsten spark gap systems has been shown to be at least partially attributable to a re-adsorption of hydrogen onto the electrode surfaces, which had been cleaned by the initial discharge.

It is felt that at least part of the observed delayed recovery in hydrogen may be due to a change in the relation between over-voltage ($V_R(t_D)$ - $V_B(t_D)$, and the formative time lag of the gap. In the early stages of the recovery ($t_D < 100$ms), formative time lags greater than 100μs were not observed, while at greater delay times, such long formative time lags were very common. Breakdown at such long formative time lags was ignored in determining V_R, according to the criterion adapted in this work. This possibility does not in any way conflict with the conclusions on the role of adsorption in the phenomona of delayed recovery. Indeed, as discussed in chapter 8 of Meeks & Craggs [8] , surface layers (eg. oxides) in other types of spark gap systems are known to affect the formative time lag.

The possibility that the effect is at least partially a consequence of a change in the relation between over-voltage and t_f may explain why other workers, using different criteria to define V_R, have failed to report a similar delayed recovery effect [9] .

SUGGESTIONS FOR FUTURE RESEARCH

a) It would be of interest to study the recovery characteristic of a similar hydrogen-tungsten spark gap system, with electrodes heated to considerably higher temperatures than those used here. At a temperature of 700°K, it is indicated by the work of J. K. Roberts [7], that at low pressures (10^{-3}mm. Hg) at least, the adsorbed layer of hydrogen on tungsten becomes unstable. Therefore, it is possible that at such temperatures, no delayed recovery would be present.

b) Theoretical curves relating t_f to percentage over-voltage, with the various secondary ionization co-efficients as parameters, have been calculated by various workers- see Llewellyn-Jones, Chapter 8, [5]. Fitting experimental curves for heated, and cold electrodes in hydrogen, to such theoretical curves, might allow changes in the secondary ionization co-efficients, due to the adsorption of hydrogen, to be studied, and thus indirectly to study adsorption at high gas pressures.

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