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HIGH VOLTAGE BREAKDOWN STUDY

W. R. Bell

Ion Physics Corporation
Burlington, Massachusetts

June 1968

TECHNICAL REPORT ECOM-00394-13

HIGH VOLTAGE BREAKDOWN STUDY

THIRTEENTH QUARTERLY PROGRESS REPORT

16 November 1967 through 15 February 1968

Prepared by:

ION PHYSICS CORPORATION
BURLINGTON, MASSACHUSETTS

JUNE 1968

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Technical Report ECOM-00394-13

OSD-1366
June 1968

HIGH VOLTAGE BREAKDOWN STUDY

Thirteenth Quarterly Progress Report
16 November 1967 through 15 February 1968

Report No. 13

Contract No. DA-28-043-AMC-00394(E)
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Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
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Prepared by

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BURLINGTON, MASSACHUSETTS

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PURPOSE

The factors influencing breakdown in high voltage vacuum devices will be studied. The information obtained will provide the basis for improvement in the design of microwave and modulator tubes that must operate at voltages greater than 100 kilovolts without breakdown.

ABSTRACT

The results of four treatments are reported from a 32-block, 5-factor, full-factorial experiment now underway to investigate the main effects and interactions of the following factors: anode and cathode material (copper and aluminum), electrode treatment (hydrogen or vacuum fired), anode size and shape (Bruce or sphere). By a process of stacking, the effect of a transverse magnetic field, exposure and energy storage will also be investigated.

LECTURES, CONFERENCES AND PUBLICATIONS

Lectures and Conferences

22 January 1968

M. J. Mulcahy visited Fort Monmouth (M. Zinn G. Taylor, M. Chrepta, J. Weinstein) to discuss progress under the contract, the bakeable bushing and the energy storage system.

Publications

There were no publications during this period.

SECTION 1

INTRODUCTION

The work reported herein describes the thirteenth three months of a study of high voltage breakdown in vacuum with particular application to problems encountered in the development of high power vacuum tubes.

The objective of this period was to prepare for and commence tests of a 32-block experiment (5-factor, full-factorial) involving aluminum and copper electrodes. By a technique of stacking, flexible factors (magnetic field, exposure and energy storage) are also investigated.

Failure of the new high voltage bushing to condition up to 300 kv was the main reason for the delay in starting the present series of tests. Four consecutive successful tests are reported here. There has been a departure from test procedures in earlier experiments in that the applied voltage is raised in 10 kv steps every minute instead of two minutes.

A theory of vacuum breakdown which explains most of the previous results is nearing completion.

SECTION 2

300 KV TEST VEHICLE

2.1 Vacuum Chamber and System

Prior to the commencement of the experimental block, the chamber was baked several times at 375°C and once at 400°C. The inside of the chamber is still wiped with Methanol before baking. Genesolv-D was used on two occasions but appeared to produce discoloration. The ion pump has been baked once. After each bake, the chamber pressure is normally less than 10^{-8} torr; a satisfactory base pressure is arbitrarily taken as less than 3×10^{-8} torr.

2.2 Feedthrough Bushing

The new bushing, installed in October after electro-polishing the chamber, unexpectedly gave voltage hold-off problems. After several bakes and conditioning runs, improvement was shown in that, for example, 250 kv was reached after several hours of conditioning. Using closed circuit television, several segments were observed to glow with intermittent bright flashes. This was accompanied by a large increase in current and chamber pressure. Similar glowing of the alumina segments was observed for the original bushing (Quarterly Progress Report No. 5) with the main difference that for this case the glowing was conditioned out with less difficulty and bushing flashover apparently eliminated at the same time. General Electric confirmed that both bushings were identical in construction material and manufacture. The following approaches were then tried in an attempt to improve the performance:

(1) improvement of contacts on the resistive grading,
(2) baking with argon inside the bushing,
(3) baking with nitrogen inside the bushing,
(4) baking with vacuum inside the bushing.

Of these, the vacuum baking was the most successful in that after some bake-outs, it enabled 300 kv to be reached and maintained without flashover for 30 minutes after about 2 hours of conditioning. At this stage, the top of the bushing was observed to have deflected approximately 3/16 of an inch when it was removed from the chamber. This was restored to its normal position after pumping down the inside of the bushing on another vacuum system, but until the cause of this mechanical failure can be ascertained, it has been replaced with the original bushing.

This bushing is now being used and can be conditioned to 300 kv in less than 1 hour. It is intended to bake and condition the new bushing during April 1968, after sand blasting the alumina. If it still proves to be unacceptable another bushing will be purchased for standby.

2.3 High Voltage Power Supply

Resistors have been replaced in the output and voltage monitoring resistance chains. The relatively short lives of these resistors is believed due to the high voltage surge at each gap breakdown. The same reason is suggested for the cable and bushing punctures which occurred on the connection between the Universal Voltronic 300 kv power supply and the T-piece.

2.4 Baking System

The heating mantle for the chamber is operating successfully. Special heaters for the electrodes have been made which should be more reliable from the vacuum point of view. Thick walled stainless steel cans were made by IPC and elements fitted by Hottwatt Ltd. These are the same size as the originals and the mounting is as shown in Figure 3 of Quarterly Progress Report No. 12. A close tolerance (0.002 inch) is maintained between the heater sides and the electrodes giving better heat transfer.

2.5 Energy Storage System

Measurements on the vacuum crowbar switch indicated a delay time of approximately 2 μsec. The delay in the trigger circuit is about 0.25 μsec, that is, a total delay time of 2.25 μsec. Analysis of the gap testing circuit shows that the fraction of capacitor energy diverted from the gap is approximately:

$$1 - \frac{2 \times \text{Total Delay}}{RC}$$

For the present system, this is 67%, leaving 33% of the energy stored to the dissipated in the gap and its series resistor. It is believed that the 33% can be substantially reduced by substituting a high pressure single stage trigatron for the triggered vacuum gap. Preliminary design and costing of the trigatron and modifications of the trigger circuit are underway.

The energy storage system and crowbar will be commissioned by substituting a high pressure gap for the vacuum test gap. In this way, the effectiveness and reliability of the crowbar can be determined without contaminating the main vacuum chamber.

2.6 Electrodes and Their Preparation

The desirability of simultaneously firing aluminum and copper meant the purchase and construction of another firing system (see Figure 1). Four retorts are used; two for copper hydrogen or vacuum firing and similarly two for aluminum. A full description of the system was given in Quarterly No. 12.

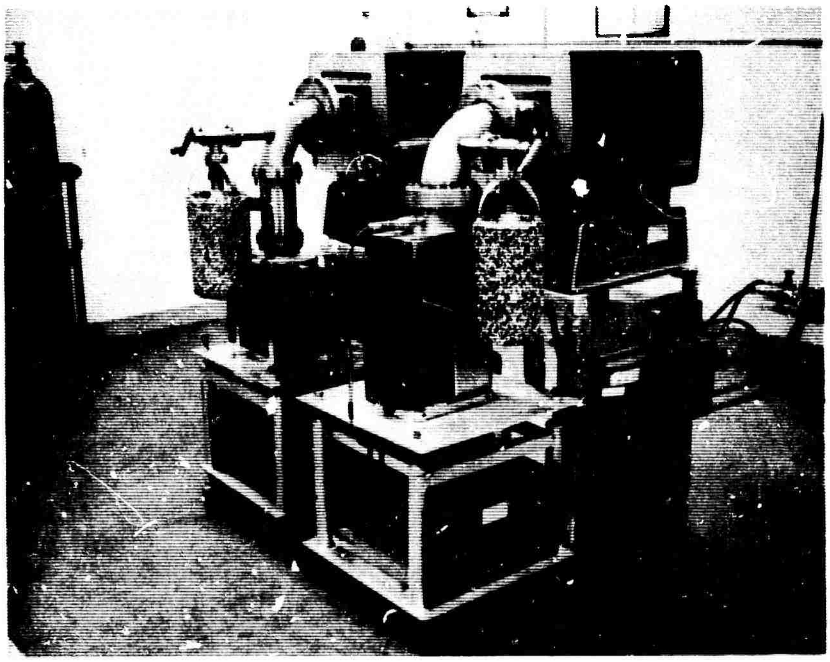

Figure 1 Double Furnace Arrangement for Vacuum or Hydrogen Firing

Two pieces of aluminum alloy 1100 were fired in hydrogen for 6 hours at 600°C in the normal manner. One piece was then baked for 8 hours at 400°C in vacuum to simulate the electrode bake in the chamber. Hydrogen analysis revealed the following information:

(1) hydrogen content after firing in hydrogen: 0.20 parts per million,

(2) hydrogen content after further baking in vacuum: 0.08 parts per million.

Similar analysis of copper in June 1967 (except that hydrogen firing took place at 900°C) gave:

(1) hydrogen content after firing in hydrogen: 0.35 parts per million,

(2) hydrogen content after further baking in vacuum: 0.14 parts per million.

Hydrogen fired aluminum electrodes are milky in appearance while vacuum fired electrodes are quite bright. The reason for this has not yet been determined.

It is planned to obtain electric field plots on a digital computer for the electrode geometries used. This will give the macroscopic field at the electrode surface.

2.7 Dielectric Envelope

The design for the dielectric envelope has been completed. The envelope support structure is shown in Figure 2. It will be possible to monitor the current flowing in the envelope since it is insulated from the cathode but is connected to ground potential by a current monitoring circuit (pico-ammeter). The envelope will need to be loaded from the top of the chamber.

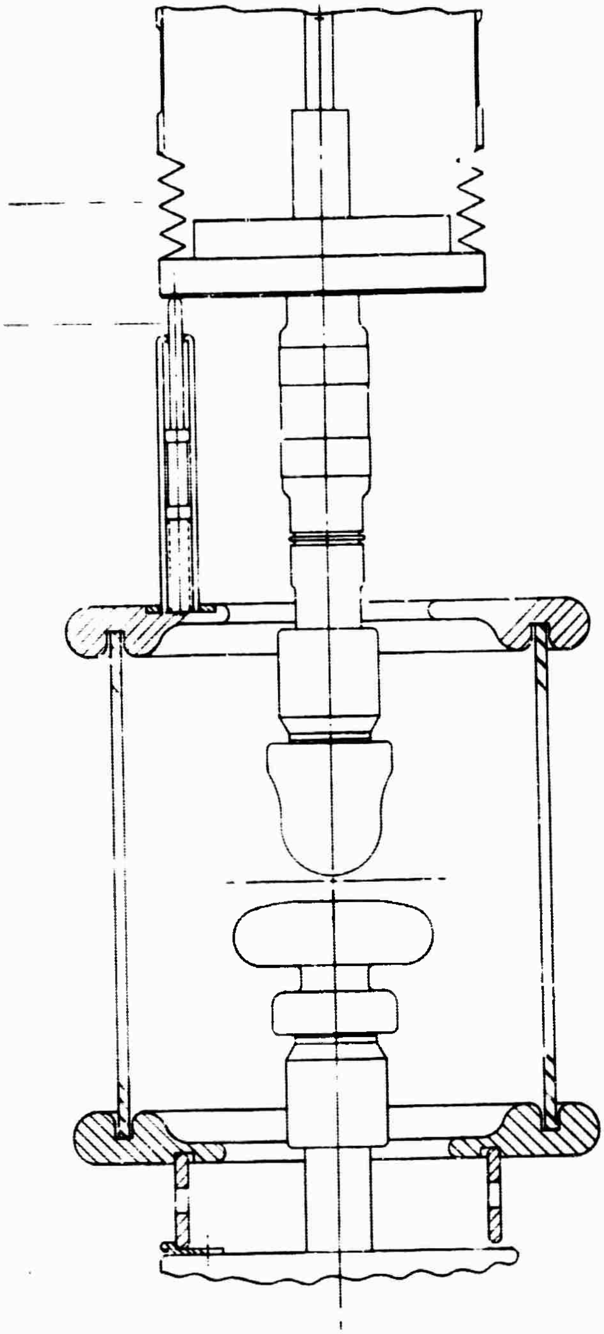

Figure 2. Dielectric Envelope Assembly

1-2545

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SECTION 3

EXPERIMENTAL DESIGN

3.1 General

The factors selected for the next experiment are given in Table 1 and are seen to consist of five inflexible factors and four flexible factors. They are as follows:

(1) Inflexible: anode material, cathode material, electrode treatment, anode size and anode shape. These are all constructional and cannot be varied without opening up the vacuum test chamber.

(2) Flexible: magnetic field, gas exposure and energy storage. Electrode spacing may also be considered a flexible factor. These can be varied continuously without disturbing the test setup.

All factors will be investigated at two levels which are designated high and low, and are represented by the lower case letter and numeral one, respectively.

It has been decided to perform a complete 2^5 factorial experiment for the inflexible factors, since third order interactions may have possible significance, and it was therefore judged imprudent at this stage in the program to neglect them by confounding with main factors in a partial factorial experiment. Once the magnitude and significance of such interactions is evaluated, they can be confounded with confidence in any future experiments introducing further factors.

The full experiment will consist of 32 individual experiments or treatments. These will be divided into two blocks typically as shown in Table 2. The selection of the treatments will be made as follows. Each block will consist of a full factorial for factors A, B, C, and D, with factor E held constant at the low level for the first block and at the high level for the second. The order of each block will be randomized. As a result of this "blocking" a statistical analysis at the half way stage will yield both main effects and higher order interactions for the 4 factors varied, with factor E at high level. Upon completion of the 32 treatments, the experiment will then be equivalent to a full factorial 2^5 block, if there is no history effect, and will be analyzed accordingly.

To incorporate the flexible factors, the technique of stacking will be employed. This has been used for the previous 2^3 block experiment and is described in the Eleventh Quarterly Progress Report. However, since additional factors are presently involved and since this marks the beginning of a major

Table 1. Factors for Stacked Block Experiment (2^5 Treatments)

Inflexible		+	-	Flexible	
A	Anode Material	Cu	Al		
B	Cathode Material	Cu	Al	F	Magnetic Field
C	Electrode Treatment (Firing)	Vac	Hyd	G	Gas Exposure
D	Anode Size (Diameter)	4 inches	1.28 inches	H	Energy Storage
E	Anode Shape	Bruce	Sphere	I	Gap

Table 2. Arrangement of Treatements in Blocks for Stacked Experiments

First 16 Treatments (Bruce Anodes)

Second 16 Treatments (Sphere Anodes)

Day 1

[1]

(1)	a	b	ab	c	ac	bc	abc	d	ad	bd	abd	cd	acd	bcd	abcd

[2]

e	ae	be	abe	ce	ace	bce	abce	de	ade	bde	abde	cde	acde	bcde	abcde

Day 2

[3]

f	af	bf	abf	cf	acf	bcf	abcf	df	adf	bdf	abdf	cdf	acdf	bcdf	abcdf

[4]

ef	aef	bef	abef	cef	acef	bcef	abcef	def	adef	bdef	abdef	cdef	acdef	bcdef	abcdef

Energy Storage

Exposure

Day 3

[5]

f	af	bf	abf	cf	acf	bcf	abcf	df	adf	bdf	abdf	cdf	acdf	bcdf	abcdf
g	g	g	g	g	g	g	g	g	g	g	g	g	g	g	g

[6]

ef	aef	bef	abef	cef	acef	bcef	abcef	def	adef	bdef	abdef	cdef	acdef	bcdef	abcdef
h	h	h	h	h	h	h	h	h	h	h	h	h	h	h	h

experiment, the parameters to be used in the analyses, the factor levels, and the complete procedures for both main and stacked experiments are now presented.

3.2 Electrode Shape and Variables to be Investigated

In addition to the breakdown voltage, V_B, the following variables will also be used in the analysis:

$V_{\Delta P}$	the threshold voltage for the appearance of pressure surges
I_{PB}	the logarithm of the ultimate prebreakdown current
T	the formative time lag for the collapse of voltage across the gap

V_B and I_{PB} will be measured for all treatments and $V_{\Delta P}$ is expected to be measurable in most. The formative time lag, T, should be measured as widely as possible over the parameters already shown to affect it, namely gap separation and magnetic field strength, as well as with the other parameters. It should be measured at two widely different gaps (e.g., 1.0 and 4.0 cm, and at 0 and 400 gauss), since these values will be used in all the treatments involving magnetic field.

The following sizes and geometries were chosen for the electrodes:

(1) Anode: 1.28 inch and 4 inch diameter spherical and Bruce profile electrodes,

(2) Cathode: 2 inch diameter spherical electrodes.

Aluminum was chosen as one of the electrode materials because of its wide differences in physical properties from copper (see Section 5.3, Quarterly Report No. 12).

3.3 Electrode and System Preparation

(i) Vacuum or hydrogen firing of electrodes for 6 hours at 900°C for copper and 600°C for aluminum, because of the lower melting point of the latter. Due to the very different sorption properties of Cu and Al to H_2, it is expected that a strong interaction of anode material with treatment should show up in the results.

(2) When cooled to ambient temperature, electrode transfer in a dry nitrogen atmosphere to the test chamber.

(3) Overnight pumping to less than 10^{-7} torr.

(4) Chamber bake at 375°C for 6 hours with concurrent electrode bake at 400°C for 8 hours.

(5) Chamber and electrodes are allowed to cool to ambient temperature.

3.4 Test Procedure

The main experiment will cover blocks [1] and [2] of Table 2, viz the full factorial of the five inflexible factors. It will be split as indicated in Section 3.1 into two separate four factor full factorial experiments thus permitting separate analyses after 16 treatments and upon completion of all 32 treatments. At the latter stage, the fifth factor, anode shape, will also be incorporated for analysis on the basis of a full factorial 2^5 experiment. This may necessitate making allowance for an experimental history effect if one is present.

At the beginning of each day of test, the bushing is conditioned up to 300 kv (and held there for 20 minutes) with the electrode gap opened up to maximum (approximately 4.5 cm). Mass spectrometer scans are taken during this period so that comparison can be made from test to test.

The breakdown voltage at each gap is determined by raising the applied voltage in steps of 10 kv every minute. The 1.0 cm gap is still considered the prime gap. Waveforms showing gap voltage collapse are taken as frequently as possible.

Day 1

Three breakdowns at 1.0 cm gap followed by single breakdowns at:

1.5, 2.0, 3.0, 0.25. 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 0.25, 0.5, 0.75, 1.0 cm.

Day 2

Two breakdowns at 1.0 cm gap with zero magnetic field. The effect of magnetic field strength on the breakdown voltage is then determined at each of the following gaps:

1.0, 2.0, 0.25, 0.5, 1.0 cm.

The levels of magnetic field (crossed with respect to the gap electric field) are:

0, 100, 200, 300, 400, 0 gauss.

Day 3

Two breakdowns at 1.0 cm gap with zero magnetic field. The effect of exposure is determined during these tests. This applies to the first 16 treatments. (For the second 16 treatments the effect of energy storage will be determined.)

The breakdown voltage is determined for the following test conditions before and after exposure for 1 minute to an 80/20 nitrogen/oxygen mixture at 10^{-5} torr. The chamber is then allowed to pump down for approximately 1 hour to restore base pressure.

Gap : 1.0, 1.5, 2.0, 0.25, 0.5 cm

Field: 0, 200, 400, 0 gauss

The field is varied at each gap in the order indicated. Finally, one breakdown at 1.0 cm gap at zero magnetic field is obtained.

SECTION 4

RESULTS OF FIRST FOUR TREATMENTS

4.1 Introduction

After several false starts at getting the experiment underway, the first successful test of treatment abe was commenced in January 1968. Previous attempts had been aborted due to one or more of the following reasons: bushing glow, heater failure, heater leak and chamber leak. The electrode preparation and test schedule is arranged so that one treatment is completed each week. This permits easy reproducibility of preparation and test conditions. Any appreciable departure from a normal schedule (time, temperature or vacuum) results in an abort of that treatment. Where appropriate the run will be used for side experiments.

The following parameters are recorded for each test: time, pressure, hydrogen partial pressure, gap current, voltage, charging current, gap spacing, magnetic field. Voltage collapse waveforms are recorded from a Tektronix 519 oscilloscope whenever possible.

4.2 Results for Treatments abe, abde, abcde, e

These are tabulated in Tables 3, 4 and 5 and plotted on Figures 3 through 10. Two inherent apparatus limitations restrict the range of test results; these are 300 kv and 2.0 ma, the maximum output of the Universal Voltronics power supply. Gap breakdown was observed visually during these tests.

4.3 Theory of Vacuum Breakdown

Theoretical analysis has been going on now for some time into a model of the breakdown process. Although not yet complete, the theory has successfully accounted for the following phenomena:

(1) At large gap separations (approximately 5 to 10 mm depending on electrode geometry and material), the breakdown voltage, V_B, is approximately proportional to the square root of gap separation, d.

(2) Below a certain gap separation, $V_B \propto d$.

(3) Curvature of the electrodes will increase the breakdown voltage in the large gap regime but will lower it in the small gap regime.

Table 3. Results for Day 1

Treatment	Gap (cm)								
	1. 0	1. 0	1. 0	1. 5	2. 0	3. 0	0. 25	0. 50	0. 75
abe	120	220	220	282	No BD*	No BD*	52	128	190
abde	127	180	170	210	290	No BD	99	156	190
abcde	174	174	170	210	238	296	44	100	147
e	180	190	209	250	286	No BD	50	120	189

Treatment	Gap (cm)							
	1. 0	1. 5	2. 0	3. 0	0. 25	0. 5	0. 75	1. 0
abe	200	280	290	No BD*	40	114	180	250
abde	209	230	280	No BD	125	160	200	220
abcde	160	200	250	295	50	97	159	210
e	209	230	290	No BD	53	119	150	210

* Greater than 300 kv breakdown voltage.

Table 4. Results for Day 2

	Gap (cm)																			
	1.0					2.0					0.25					0.5				
	Field Gauss																			
Treatment	0	100	200	300	400	0	100	200	300	400	0	100	200	300	400	0	100	200	300	400
abe	230	220	[illegible]	210	210	287	220	230	270	238	55	57	57	70	77	200	210	200	190	200
	230					290					70					228				
abde	200	230	220	230	230	280	225	284	286	287	125	128	129	133	145	180	194	190	196	200
	222					296					145					210				
abede	180	210	199	200	180	270	245	210	220	210	59	69	67	70	75	129	150	153	150	160
	199					200					75					160				
e	250	200	190	210	200	294	251	270	260	260	NB*	NB	NB	33	NB	**				
	220					297					NB					—				

* Current limited.

** No 0.5 cm gap used in this test.

Table 5. Results for Day 3

Treatment	Gap (cm)														
	1.0			1.5			2.0			0.25			0.5		
	Field Gauss														
	0	200	400	0	200	400	0	200	400	0	200	400	0	200	400
abe	236	200	210	*			255	228	236	*			160	159	150
	232						270						176		
abde	268	274	263	277	277	291	NB	290	290	80	84	96	193	200	200
	258			280			NB			104			180		
abede	250	230	220	**			NB	290	290	93	98	100	200	200	196
	250						NB			100			200		
e	200	190	190	280	260	220	297	290	260	48	49	52	125	110	107
	210			280			297			NB			121		

* No 1.5 or 0.25 cm gap in this test.

** No 1.5 cm gap in this test.

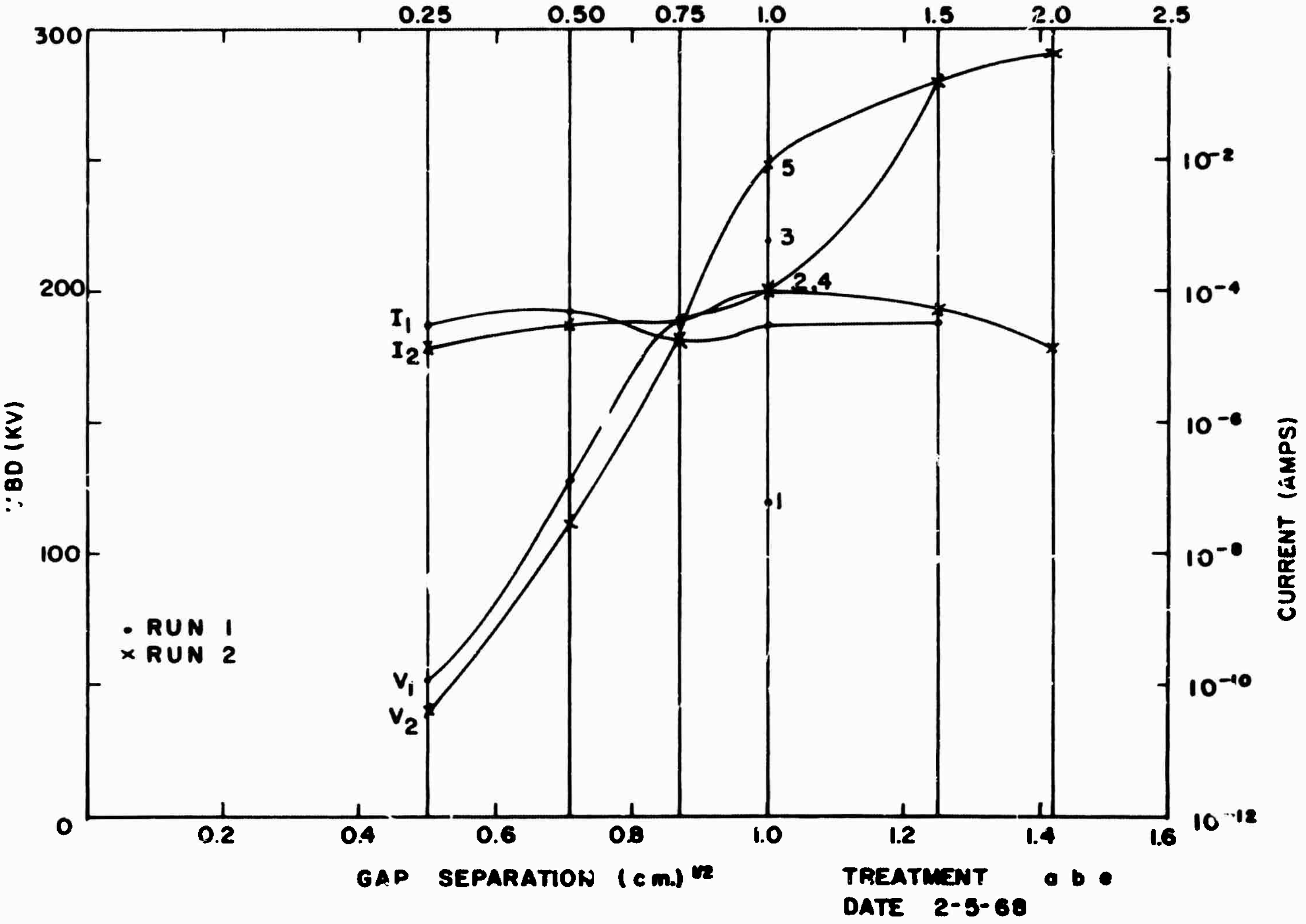

Figure 3. Breakdown Voltage and Ultimate Prebreakdown Current versus Gap Separation

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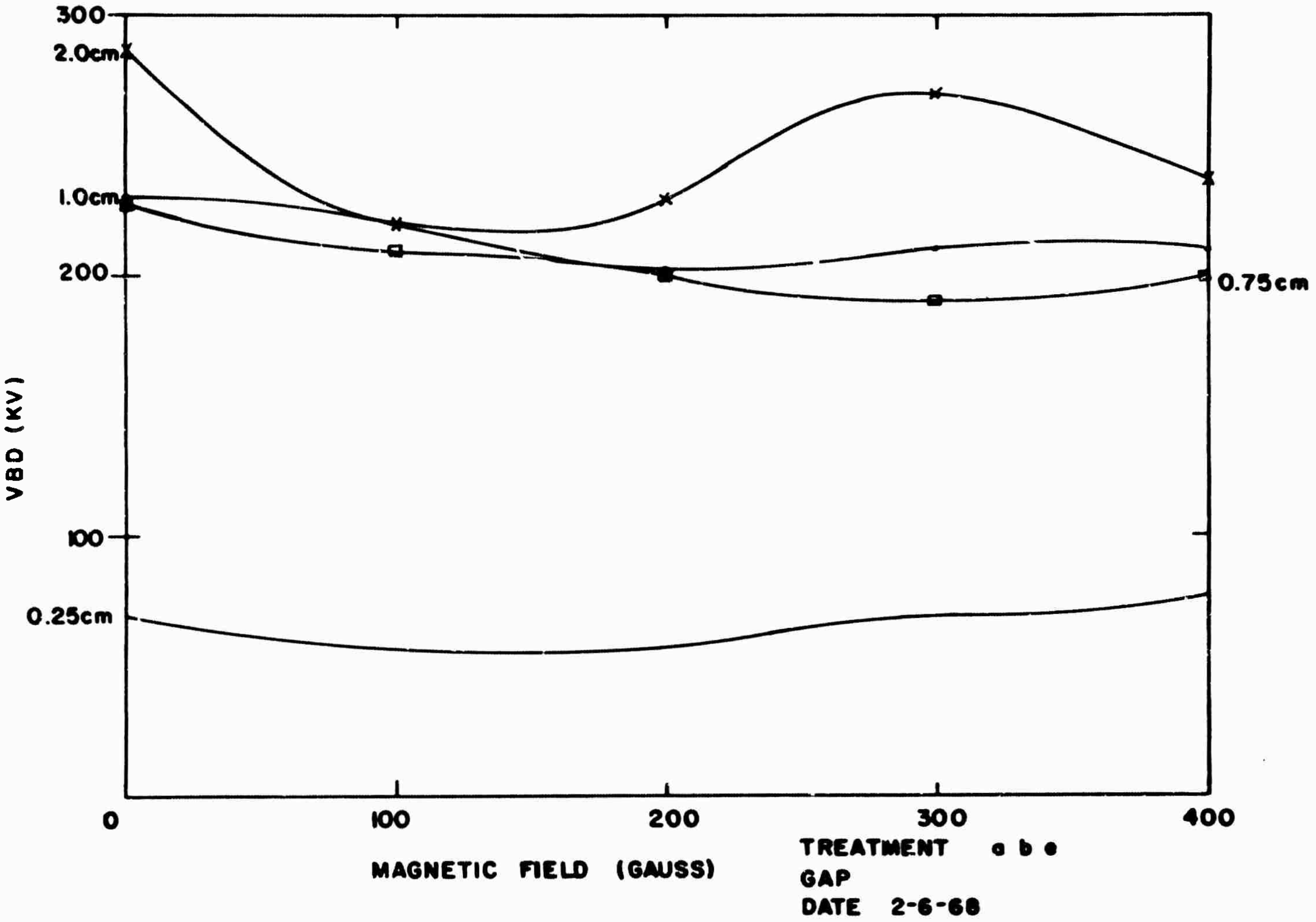

Figure 4. Breakdown Voltage versus Magnetic Field Strength

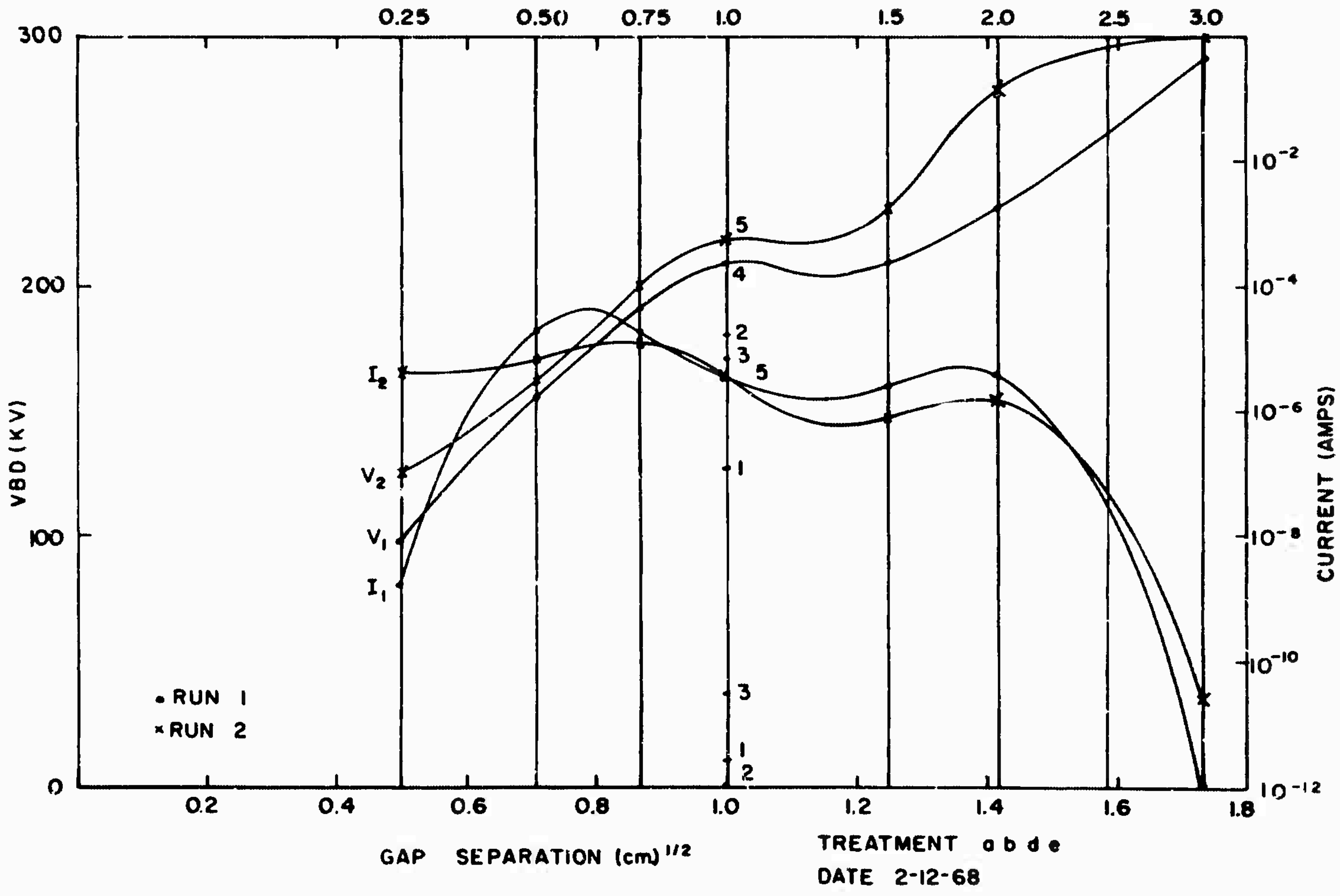

Figure 5. Breakdown Voltage and Ultimate Prebreakdown Current versus Gap Separation

1-2780

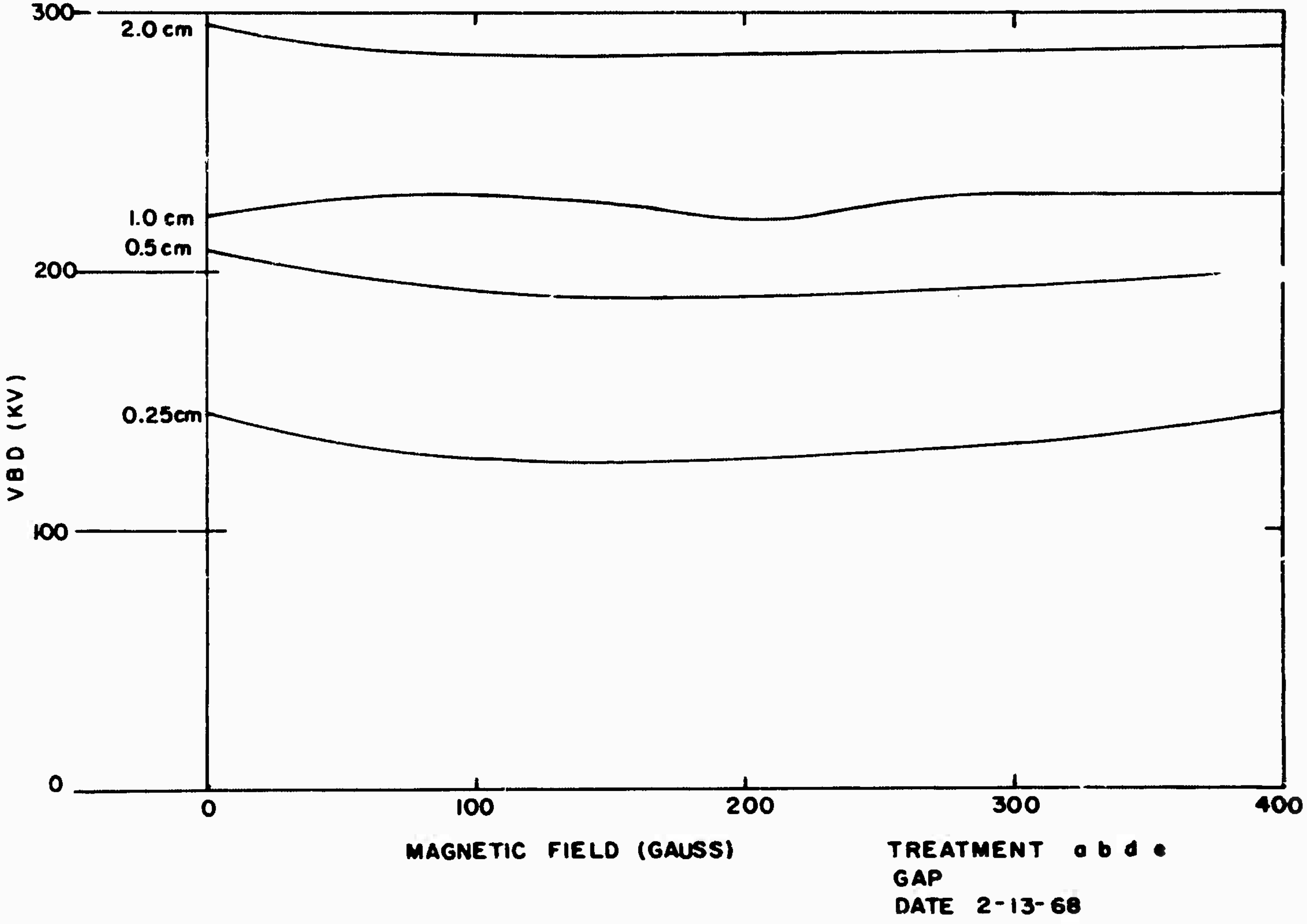

Figure 6. Breakdown Voltage versus Magnetic Field Strength

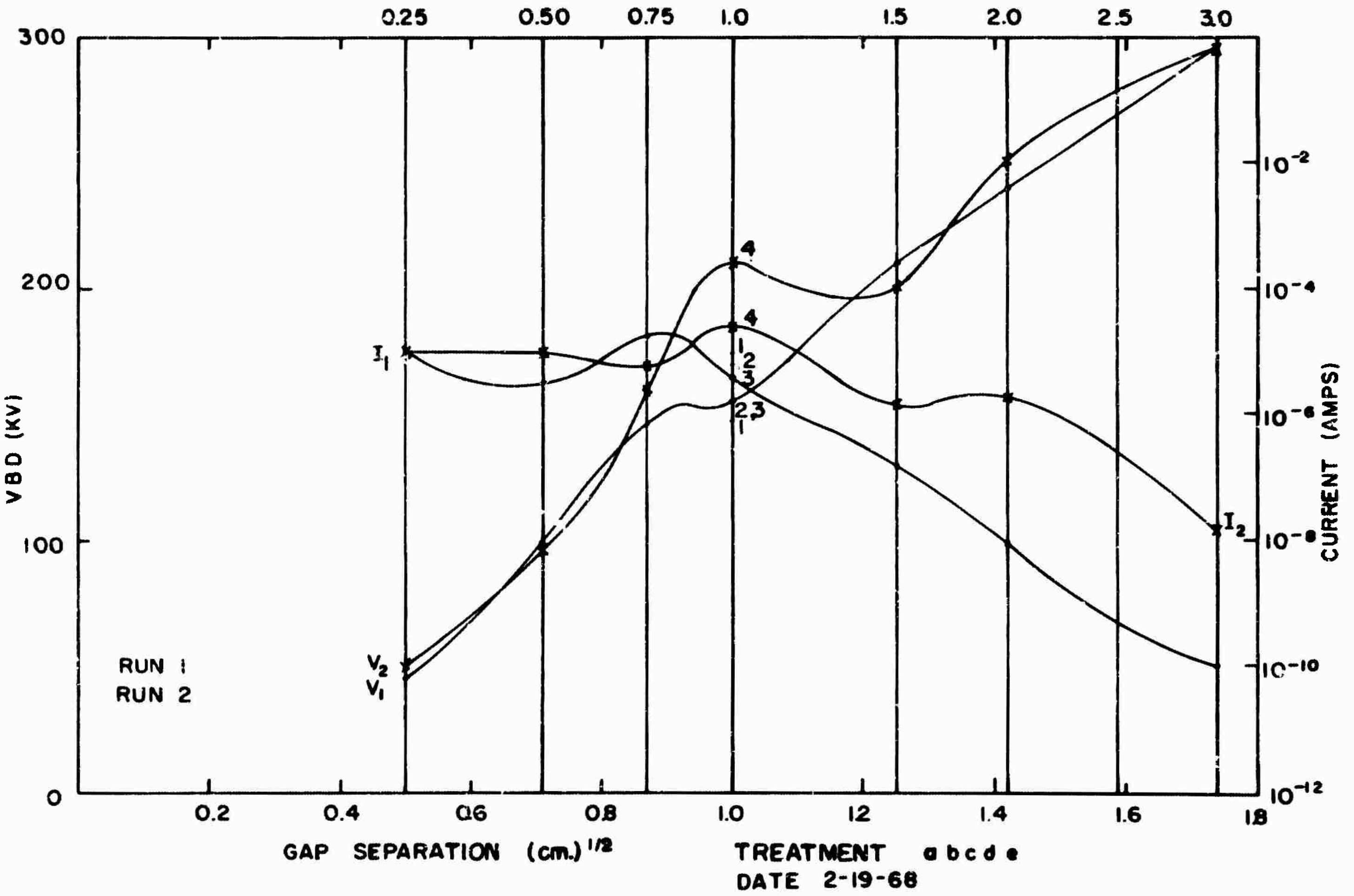

Figure 7. Breakdown Voltage and Ultimate Prebreakdown Current versus Gap Separation

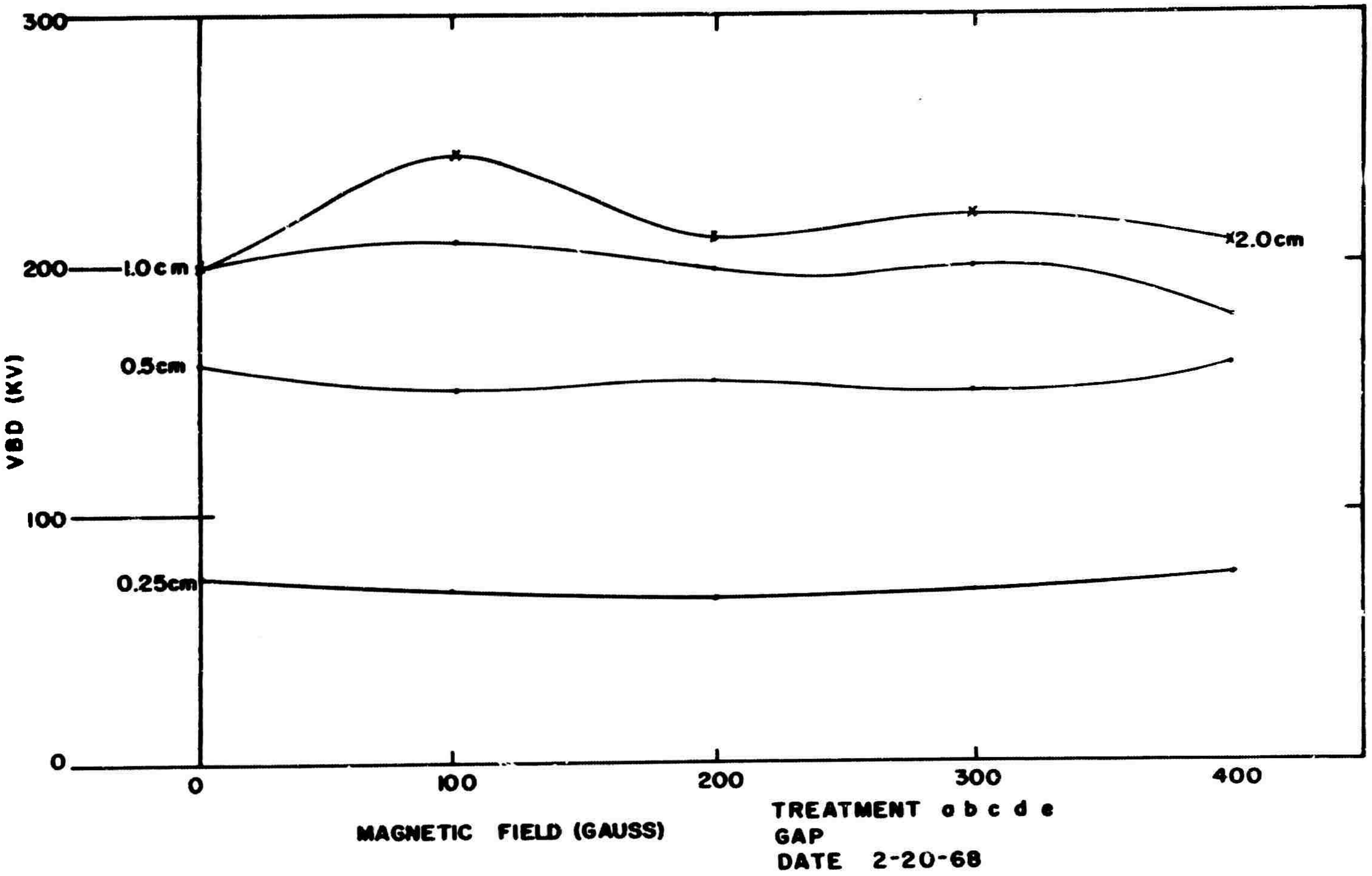

Figure 8. Breakdown Voltage versus Magnetic Field Strength

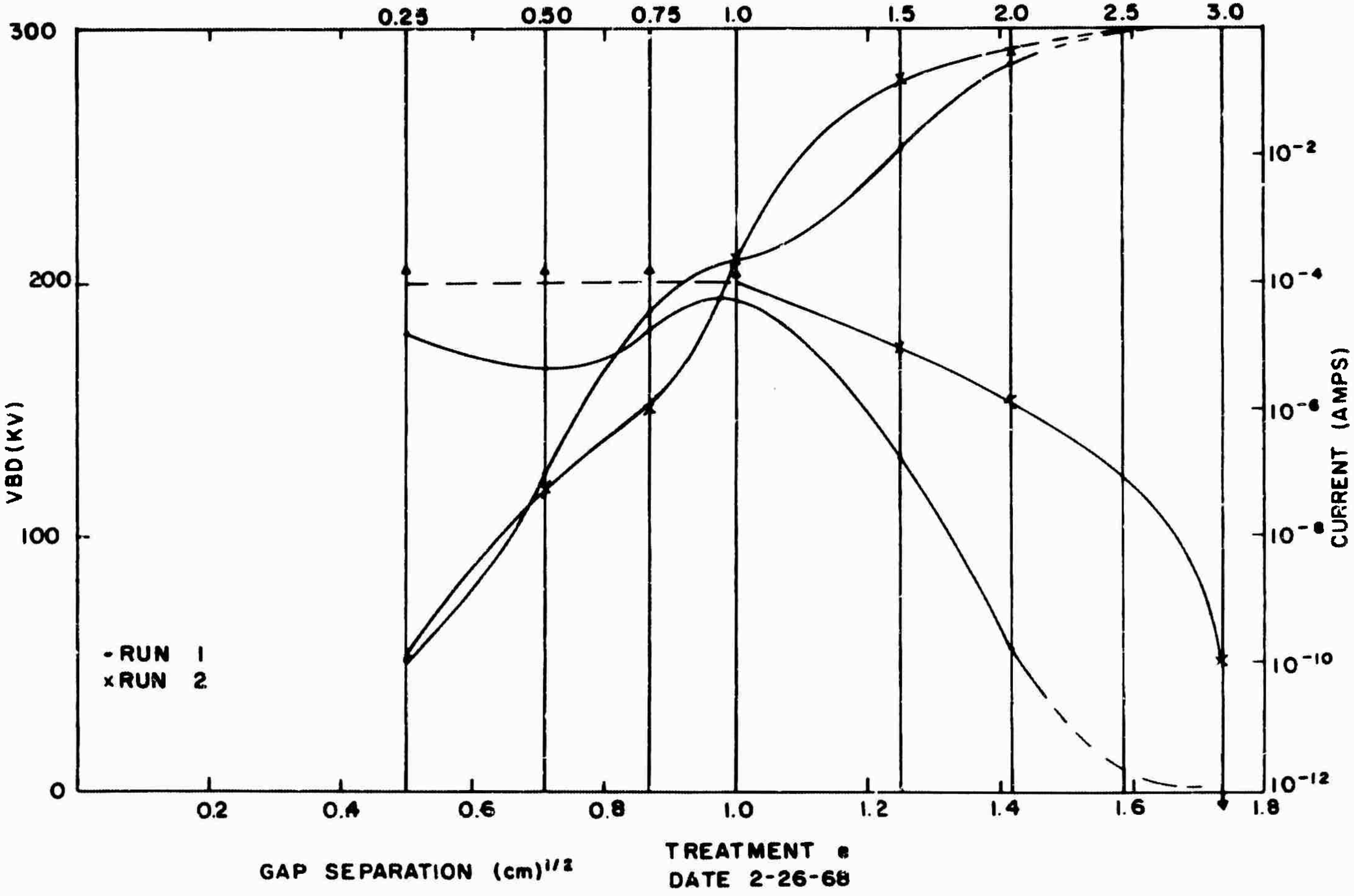

Figure 9. Breakdown Voltage and Ultimate Prebreakdown Current versus Gap Separation

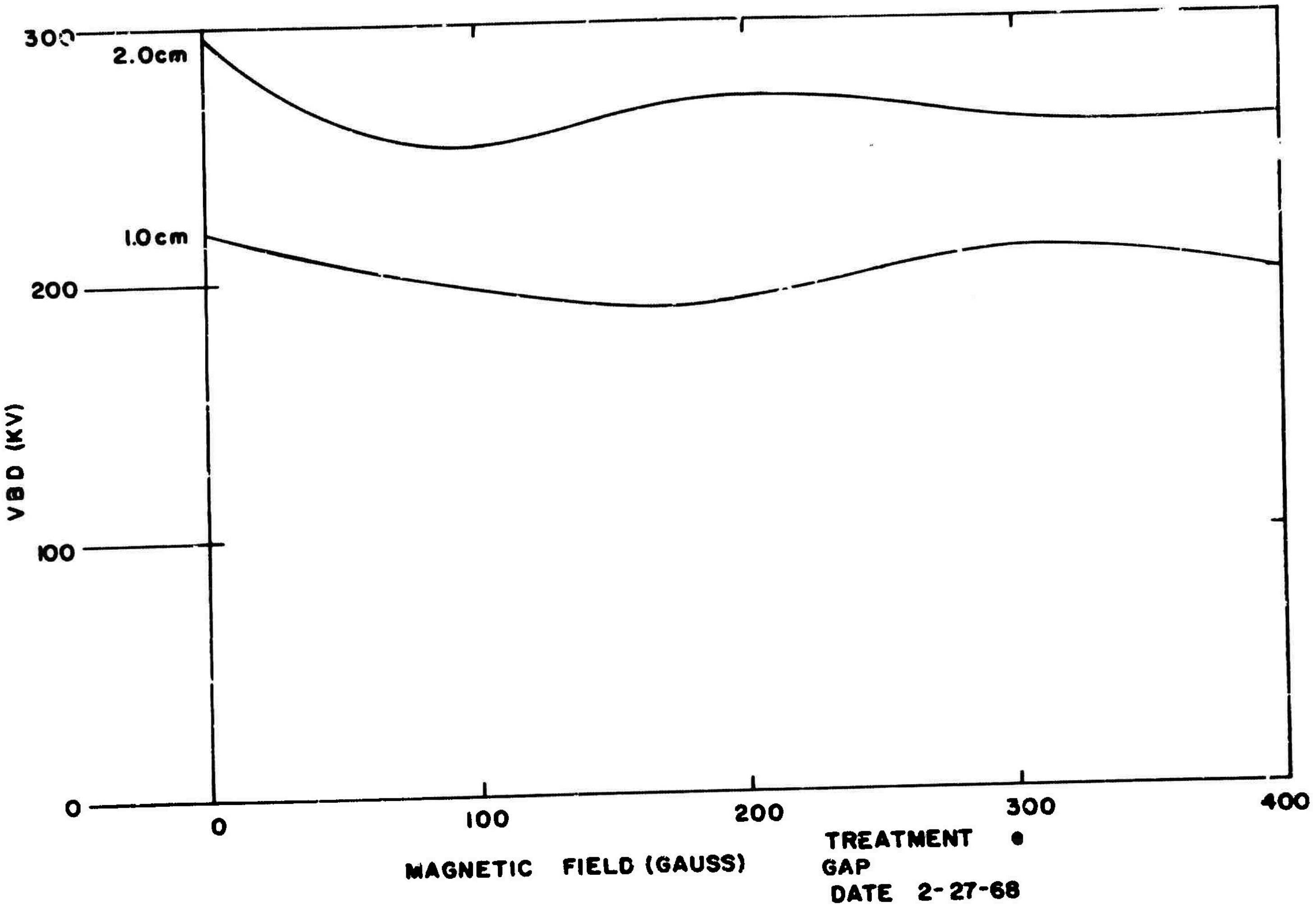

Figure 10. Breakdown Voltage versus Magnetic Field Strength

1-2784

(4) The influence of a transverse magnetic field is similarly differentiated in the two regimes, lowering V_B for large gaps and raising it for small gaps.

(5) Sorption of gas into the anode will raise V_B for large gap separations and lower it for small.

The theory thus accounts for the effects of the following factors:

- anode material physical parameters,
- cathode material physical parameters,
- anode gas content,
- ambient gas pressure,
- electrode curvature,
- transverse magnetic fields,
- gap separation.

The results of the first four treatments recorded in this report appear to be following the same pattern. Details of the above theory will be reported in a later report.

SECTION 5

FUTURE EFFORT

During the next quarter, the following will be pursued:

- Continue with 32 treatments.
- Fabricate and try dielectric envelope at the end of one or two treatments.
- Investigate crowbar efficiency.
- Check out new bushing at the end of eight treatments.
- Regular maintenance of main chamber, pumps, electrode firing system, instrumentation, high voltage power supply, magnets and their supplies.
- Continue analysis of model of breakdown process.

SECTION 6

IDENTIFICATION OF PERSONNEL

The following personnel were active in the program during the period under review:

Dr. S. V. Nablo - Vice President
Director, Particle Physics Division

Dr. M. J. Mulcahy - Project Manager

A. C. Stewart - Engineering Manager

W. R. Bell - Senior Electrical Engineer

M. M. Thayer - Senior Metallurgist

A. Watson - Senior Scientist

F. Y. Tse - Electrical Engineer

R. M. Parsons - Engineering Aide

D. Bryant - Technician

R. Benoit - Design Engineer

C. Boudreau - Engineering Aide

L. Indingaro - Metallurgical Technician

D. J. Maynard - Senior Mechanical Engineer

S. K. Wiley - Group Leader/Mechanical Engineering

Prof. H. Freeman - Consultant
Massachusetts Institute of Technology
Department of Economics and Social Science

Prof. A. Argon - Consultant
Massachusetts Institute of Technology
Department of Mechanical Engineering

Dr. N. E. Woldman - Consultant
Metallurgy

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13. ABSTRACT

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Electrical Breakdown in Vacuum						
Conditioning Procedures						
Optical and X-Radiation						
Partial Pressure and Gap Current						
Etching						

INSTRUCTIONS

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