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TECHNICAL REPORT ECOM-00394-15

HIGH VOLTAGE BREAKDOWN STUDY

FIFTEENTH QUARTERLY PROGRESS REPORT

16 May 1968 through 15 August 1968

Prepared by:

ION PHYSICS CORPORATION

BURLINGTON, MASSACHUSETTS

DECEMBER 1968

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198

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OSD-1366
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HIGH VOLTAGE BREAKDOWN STUDY

Fifteenth Quarterly Progress Report
16 May 1968 through 15 August 1968

Report No. 15

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BURLINGTON, MASSACHUSETTS

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

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

This report describes the fifteenth quarter of a study of high voltage breakdown in vacuum. During this period, the first half of a five-factor, full-factorial experiment investigating the effect of anode material, cathode material, electrode pretreatment, anode size and anode shape was completed. A summary of experimental conditions and procedures is given, breakdown voltage results are reported, and an analysis of the presently available data carried out. Anode and cathode material were both important influences, with copper giving significantly higher breakdown voltage than aluminum. Electrode pretreatment (vacuum or hydrogen firing) had an influence which depended on both anode and cathode material; the only simply described result being that vacuum firing is better for aluminum while hydrogen firing is better for copper. Conditioning - the change in breakdown voltage due to a series of breakdowns - was found to influence in several ways the effects reported above and makes impossible the assigning of a single unique breakdown voltage to any pair of electrodes at a given gap setting. However, the changes due to conditioning can be described, limiting values determined and the variation around this level specified. Breakdown voltage was found to vary linearly with gap below about 1.0 cm and to follow a square root law above 1.0 cm. A weak transverse magnetic field (100 to 400 gauss) was found to lower breakdown voltage for large gaps (> 1.0 cm) and to raise it for small gaps (< 1.0 cm).

LECTURES, CONFERENCES AND PUBLICATIONS

Lectures and Conferences

21 May 1968

M. J. Mulcahy visited Fort Monmouth to discuss progress under the contract, in particular the final procedures for the first Block of Sixteen.

19 June 1968

M. J. Mulcahy and W. R. Bell visited Fort Monmouth to discuss the analysis of the preliminary results an.. .rends of the Block of Sixteen.

26 June 1968

Professor H. Freeman visited Ion Physics Corporation to discuss factorial design and analysis.

11 July 1968

M. M. Chrepta visited Ion Physics Corporation to discuss progress under the contract, in particular the results of the Block of Sixteen.

13 August 1968

M. J. Mulcahy visited Fort Monmouth to discuss the results of the first Block of Sixteen, and the final design and procedure for the second Block of Sixteen.

Publications

There were no publications during this period.

SECTION 1

INTRODUCTION

This report describes the fifteenth three months of a study of high voltage breakdown in vacuum. The study has particular reference to problems encountered in the development of high power vacuum tubes.

During the present period, the first sixteen treatments and four repeat treatments of a 32-treatment experiment were completed. This five-factor, two-level, full-factorial experiment investigates the influence on vacuum breakdown of anode material, cathode material, anode size, anode shape and electrode treatment. At present, the first half of this experiment is complete; and since one factor (anode shape) was held constant during these treatments, the results can be analyzed as a four-factor, full-factorial experiment. The experimental results and a preliminary analysis are contained in this report. The effects of gas exposure and a transverse magnetic field were also studied by a technique of stacking.

Experimentation continues on the second half of the overall experiment, with three treatments completed to date. In this series, the effects of exposure to atmosphere, energy storage with crowbarring, magnetic fields, and a dielectric envelope are being investigated as flexible factors.

Regular maintenance of the test equipment has been carried out. The energy storage and crowbar system was installed and tested with satisfactory results. The dielectric envelope assembly is complete and has been used during two tests.

SECTION 2

300 KV TEST VEHICLE

2.1 Vacuum Chamber and System

The vacuum chamber and system have functioned well with only minor modifications during this period. Deteriorated electrode heaters have been replaced several times and a new heater unit is being designed. The ion pump has been cleaned as per General Electric specifications and a standby pump is being maintained under vacuum. A new ion pump control has been installed that automatically turns the pump back on if it turns off due to a temporary overload.

2.2 High Voltage Feedthrough Bushing

The original bushing has been used for all treatments during this test period and was sandblasted and cleaned during May.

2.3 Bushing Resistor

The bushing resistor used until 1 August 1968 was a deposited film carbon resistor that persistently suffered surface deterioration due to flashover. This problem has been eliminated by replacing the carbon resistor with a liquid electrolyte ($CuSO_4$) resistor of ~ 80 ohms. This appears to be working well with no flashover problem.

2.4 Dielectric Envelope

The dielectric envelope assembly as described in Quarterly Progress Reports 13 and 14, is complete and has been used twice. In these tests, envelope flashover often occurred before gap breakdown for the larger gaps. This becomes especially troublesome in the presence of a transverse magnetic field.

2.5 Energy Storage and Crowbar System

2.5.1 General Electrical Design

The energy storage and crowbar system, as discussed in previous Quarterly Progress Reports and as implemented during this test period, is designed to deliver controlled amounts of energy to the vacuum gap. The basic design is given in the schematic of Figure 1. A capacitor bank stores energy (1/2 CV^2) which is available to the vacuum gap at the other end of about 25 feet of 300 kV coaxial cable. The crowbar, when triggered, diverts energy from the capacitor bank to ground, thus limiting in a controlled fashion the energy reaching the vacuum gap. Presently, the crowbar requires a minimum of 600 ns to trigger. This system makes possible a controlled variation in the type and quantity of energy available to the vacuum arc. Further variation can be achieved by changing the capacitor and bushing resistors.

2.5.2 Energy Storage Capacitor Bank

The energy storage is supplied from four capacitors in series. These are insulated in a steel pressure vessel with 2 atmospheres of SF_6 gas. An epoxy bushing is used to lead in the 300 kV cable and the crowbar is installed directly above the capacitor stack in the same pressure vessel. The total energy available at 300 kV is 7000 joules.

2.5.3 High Pressure Gas Crowbar

The crowbar system consists of a high pressure gas insulated trigatron gap, designed to withstand up to 300 kV and its associated breakdown sensing and triggering circuitry (Figure 2). When current begins to flow through the test gap that is to be protected, a voltage is produced in an inductibe pick-up probe. The probe signal (~ 5 volts) triggers electronic circuitry which produces a 6 kV trigger voltage. This voltage in turn fires the main trigger generator, a three stage Marx circuit which will then apply a 70 kV pulse across the trigatron gap causing it to close. When crowbar gap length and pressure are adjusted properly to suit the test gap voltage, diversion can be achieved within 1 microsecond after the inductive pick-up signal occurs.

Because of the large amount of energy being diverted in this application, special electrode materials and gas mixtures have been used. Calibration curves and operating characteristics are now being obtained. Since the range of voltage over which a set vacuum gap may be expected to break down is quite large (often 25 to 30%), it may prove necessary to vary the crowbar settings as test gap voltage is raised. This could be done by varying either crowbar gap spacing or gas pressure. Changing the gas pressure is probably more practical and will be used if required.

Present tests indicate that the crowbar can be fired within 600 ns of vacuum gap breakdown.

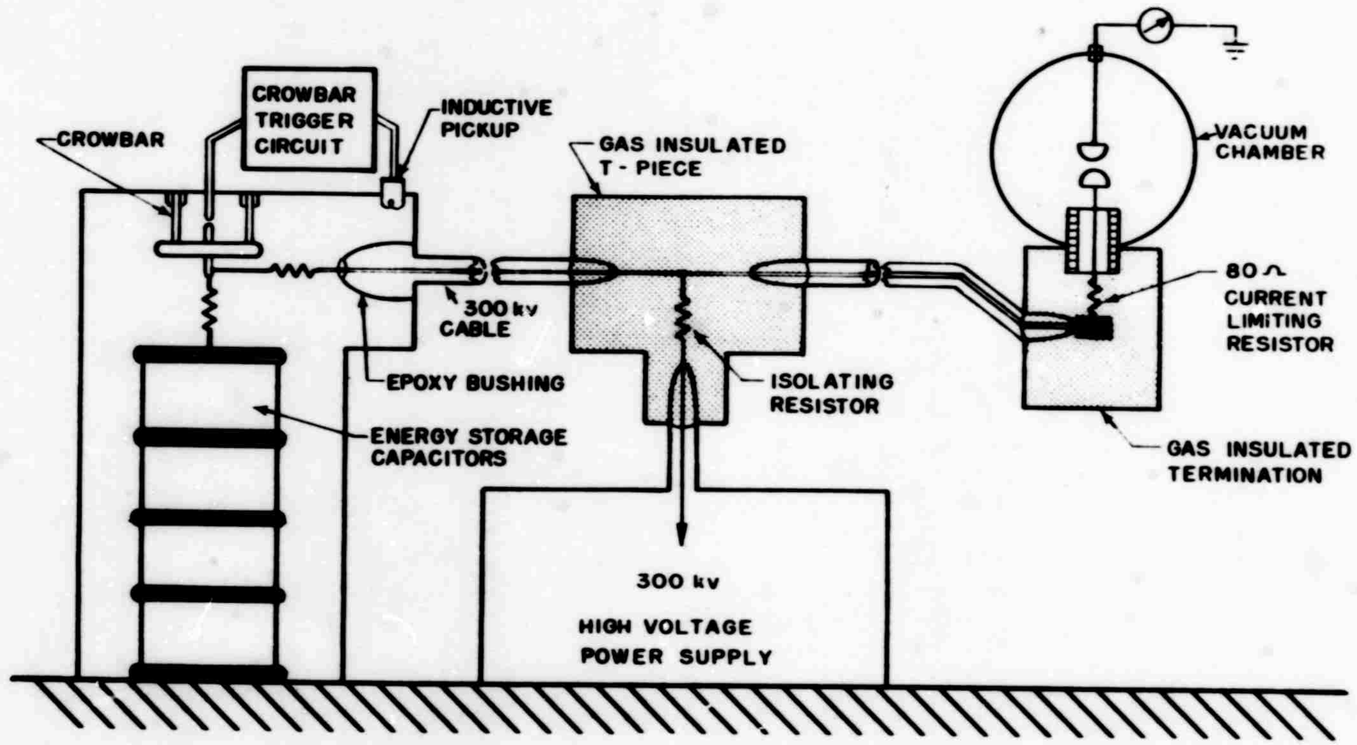

Figure 1. Outline of Energy Storage and Crowbar System

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1-2908

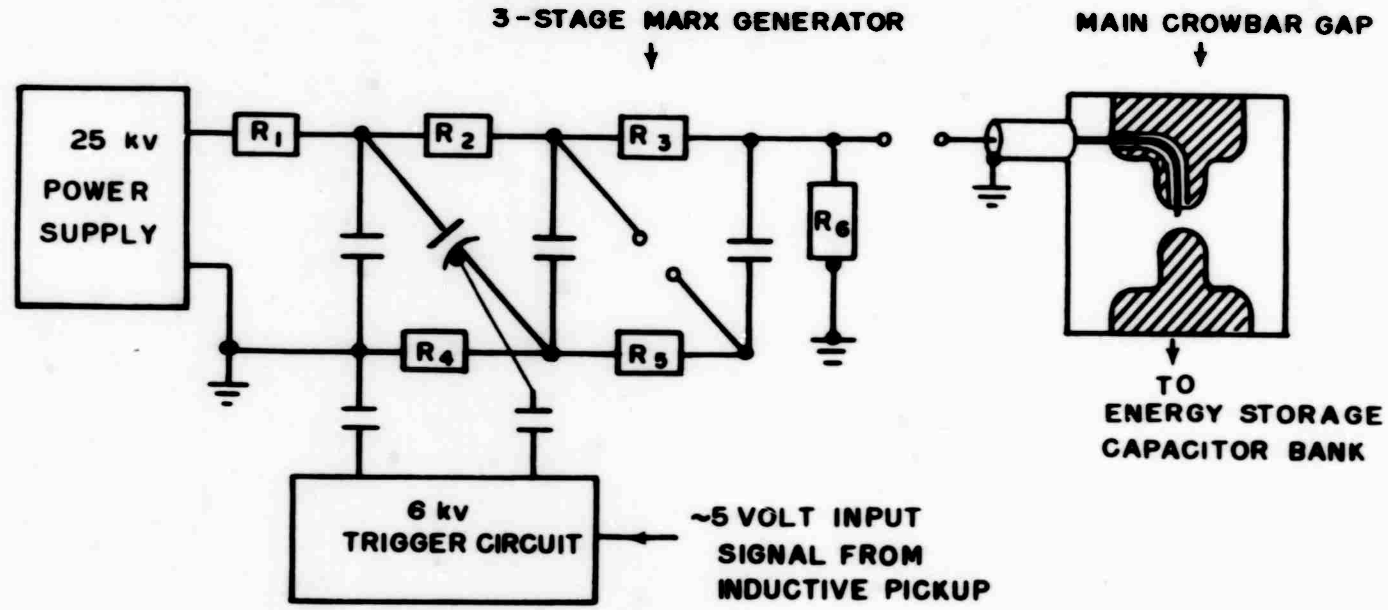

Figure 2. Crowbar Schematic

2.5.4 Resistors

In the energy storage circuit, resistances of about 4 to 100 ohms are used in series with the capacitors, cable and vacuum gap. These are constructed of lucite and filled with a liquid electrolyte ($CuSO_4$). Enough units will be used in parallel to keep the temperature rise below 3°C. These resistors limit the current and make possible wave shape variation.

To isolate the high voltage power supply from transients which might cause damage during energy storage tests, a 3 megohm spiral resistor is inserted between the high voltage terminal and test cable. This additional isolation resistor is used only during energy storage tests.

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SECTION 3

DESCRIPTION OF THE "FIRST SIXTEEN" EXPERIMENT

3.1 Introduction

The first half of a five factor, two level, full factorial experiment has been completed. This investigates the influence on vacuum breakdown of:

(1) anode material,
(2) cathode material,
(3) electrode pretreatment,
(4) anode size,
(5) anode shape.

Voltages up to 300 kV and gap separations from 0.25 cm to 3.0 cm were used. The cathode was a 2-inch diameter sphere. Table 1 outlines the factors and levels investigated.

In this first half of the experimental series, anode shape was held constant at the high level (Bruce profile). This enables the present results to be considered as a four-factor, full-factorial experiment which may be analyzed while the second half of the experiment is performed. The order of performance of the experiments making up the First Sixteen was randomized to minimize any "historical" error. Four replications have been completed. Transverse magnetic fields and gas exposure were studied as additional flexible factors. Table 2 summarizes the treatment combinations and gives the dates and order of experimentation.

3.2 Experimental Procedure

Each set of electrodes used in the First Sixteen experiment consists of a different combination of the two levels of the four factors being studied (see Tables 1 and 2). One week is required per treatment during which the electrodes and test apparatus are prepared according to strictly defined procedure and then subjected to a rigidly specified sequence of breakdowns at various gaps, magnetic field levels and gas exposure conditions. The complete preparation and testing procedures will now be summarized. Detailed description of and motivation for the procedures used can be found in previous Quarterly Progress Reports.

Table 1. Factors Investigated in Factorial Experiment

Factors		Levels	
Factorial Code	Physical Factor	High Level	Low Level
A	Anode Material	Copper	Aluminum
B	Cathode Material	Copper	Aluminum
C	Electrode Treatment	Vacuum Firing	Hydrogen Firing
D	Anode Size	4 Inch Diameter	4/3 Inch Diameter
E	Anode Shape	Bruce Profile	Sphere

Note: The designations of "high" level and "low" level are completely arbitrary and are made only for manipulative convenience.

Table 2. Treatment Combination for "First Sixteen"

Factorial Treatment Code	A Anode Material	B Cathode Material	C Electrode Treatment	D Anode Size	Date of Testing
e	Al	Al	H_2	Small	2/26/68
ae	Cu	Al	H_2	Small	4/22/68
be	Al	Cu	H_2	Small	3/26/68
abe	Cu	Cu	H_2	Small	2/5/68
ce	Al	Al	Vac	Small	4/8/68
ace	Cu	Al	Vac	Small	3/18/68
bce	Al	Cu	Vac	Small	6/3/68
abce	Cu	Cu	Vac	Small	3/4/68
de	Al	Al	H_2	Large	3/11/68
ade	Cu	Al	H_2	Large	4/29/68
bde	Al	Cu	H_2	Large	5/21/68
abde	Cu	Cu	H_2	Large	2/12/68
cde	Al	Al	Vac	Large	4/15/68
acde	Cu	Al	Vac	Large	5/6/68
bcde	Al	Cu	Vac	Large	5/27/68
abcde	Cu	Cu	Vac	Large	2/19/68
e (repeat)	Al	Al	H_2	Small	6/24/68
abe (repeat)	Cu	Cu	H_2	Small	7/22/68
ace (repeat)	Cu	Al	Vac	Small	6/10/68
de (repeat)	Al	Al	H_2	Large	7/1/68

Cathode in all cases was a 2 inch diameter sphere.

Small = 4/3 Inch
Large = 4 Inches

A treatment is designated by a code of lower case letters. The presence of the letter in the code indicates that the corresponding factor was at its "high" level, the absence of a letter indicates that the corresponding factor was at its "low" level.

3.2.1 Electrode Preparation

The electrodes are machined to the appropriate profile (Bruce or sphere) and then hand ground to a 600 grit silicon carbide finish with green soap and distilled water. Next they are cleaned by an ultrasonic process and several solvents.

The electrode treatment factor, C, consists of either vacuum or hydrogen firing. For copper the firing is carried out at 900°C for 6 hours with either a pressure below 3×10^{-7} torr (vacuum firing) or with a positive pressure flow of hydrogen. Aluminum is treated in the same way except that the firing temperature is 600°C. Ion pumps provide a clean vacuum environment and final pressure is about 5×10^{-9} torr in the vacuum firing case.

Electrodes are removed only after cooling to ambient temperature. They are handled only with lint-free cotton gloves and installed directly in the vacuum test chamber using a dry nitrogen transfer system. This procedure is usually completed on Thursday afternoon of each week.

3.2.2 Vacuum System and Bakeout

The spherical stainless steel vacuum chamber is sealed with gold and copper O-rings and pumped by a combination of a Varian "gasp" pump, two Varian sorption pumps, and a 500 liter per second General Electric ion pump. After installation of electrodes, the chamber is pumped overnight to a pressure of less than 10^{-7} torr.

The chamber is then baked at 375°C for 6 hours with concurrent electrode bake at 400°C. Then the chamber and electrodes are allowed to cool to ambient temperature over the weekend. Final pressure is less than 10^{-8} torr.

3.2.3 Power Supply and External Circuit

A Universal Voltronics 300 kV dc power supply with a maximum current capability of 2 mA serves as a high voltage power supply. Voltage is measured by a calibrated resistor in the power supply. Coaxial high voltage cable connects the power supply output to the chamber. Epoxy bushings are used for terminations.

A resistor of about 80 ohms (of deposited carbon for the First Sixteen experiment) serves to limit the current to the vacuum gap. It is located between the 300 kV cable and feedthrough bushing in a 30 psi SF_6 environment.

3.2.4 Bushing Conditioning

The bakeable ceramic-copper feedthrough bushing requires conditioning to reach 300 kV. This conditioning is accomplished by applying voltage to the bushing with the electrodes at maximum separation (about 5 cm). The voltage is progressively raised until bushing current and gas evolution limit the voltage due to current overload. Gradually this diminishes and the voltage can again be raised. Conditioning is done before each days' testing and usually takes an hour on the first day and 30 minutes thereafter. The bushing is held at a voltage of 300 kV for 20 minutes.

3.2.5 Variables Monitored

The primary variable is voltage which is measured by a calibrated high voltage resistor in the power supply. Prebreakdown current to the cathode is measured by a Keithley logarithmic electrometer ammeter (from 10^{-2} A to 10^{-4} A). A strip recorder is used to record the hydrogen partial pressure as obtained by a mass spectrometer mounted on the chamber wall.

A capacitive pickup opposite the high voltage feedthrough bushing and a Tektronix 519 oscilloscope provide a record of voltage collapse waveform due to breakdown.

Visual observation of the gap is the primary criterion for breakdown. This is done through a glass window via a mirror system.

Total pressure in the vacuum chamber, ion pump current (and hence the pumping load), radiation level, and power supply charging current are also observed.

3.3 Test Sequence

3.3.1 Voltage Application

The voltage is applied in steps of 10 kV each minute until breakdown occurs. This is done at first from zero voltage level and then, after a probable breakdown range has been established, from some voltage level 30 or 40 kV below a possible breakdown voltage. Thus, obtaining each breakdown takes up to 10 minutes. The tests done on each day will now be outlined.

3.3.2 First Day

On this day, a series of breakdowns on clean, baked, unsparked electrodes at various gap separations is obtained. The test sequence is:

(1) 3 breakdowns at 1.0 cm;
(2) 1 breakdown each at 1.5 cm, 2.0 cm, 3.0 cm, 0.25 cm, 0.50 cm, 0.75 cm and 1.0 cm;
(3) repeat cycle (2).

Cycle (2) is referred to an "unconditioned" while cycle (3) is referred to as "conditioned". Each breakdown in cycle (3) has had 6 more preceding sparks than the similar breakdown in cycle (2).

3.3.3 Second Day - Magnetic Field Tests

On this day, a transverse magnetic field (produced by coils located outside the vacuum chamber) is introduced as a flexible factor. Five levels (0, 100, 200, 300 and 400 gauss) are used. The sequence is:

(1) at 1 cm gap - 3 breakdowns at 0 field, 1 each 100, 200, 300, 400 and 0 gauss;
(2) at 2.0 cm gap - 1 breakdown each at 0, 100, 200, 300, 400 and 0 gauss;
(3) at 0.25 cm gap - 1 breakdown each at 0, 100, 200, 300, 400 and 0 gauss;
(4) at 0.50 cm gap - 1 breakdown each at 0, 100, 200, 300, 400 and 0 gauss;
(5) final breakdown at 1.0 cm gap, 0 field.

3.3.4 Third Day - Gas Exposure Tests

First, a series of breakdowns are obtained to establish comparison values which are termed "before exposure". Then the chamber is exposed for 1 minute to 20% oxygen and 80% nitrogen mixture at a pressure of 10^{-6} torr. Next, the chamber is pumped back to its base pressure of about 10^{-8} torr and the test series is repeated. The breakdown sequence in each case (before and after exposure) is:

(1) at 1.0 cm gap - 3 breakdowns at 0 field, 1 each at 200, 400 and 0 gauss;
(2) at 1.5 cm gap - 1 breakdown each at 0, 200, 400 and 0 gauss;
(3) at 0.25 cm gap - 1 breakdown each at 0, 200, 400 and 0 gauss;

(4) at 0.50 cm gap - 1 breakdown each at 0, 200, 400 and 0 gauss.

A final breakdown at 1.0 cm is taken at the end of the "after exposure" series.

3.4 Summary

The "First Sixteen" experiment varies four factors at two levels each to produce 16 sets of electrodes. These electrodes are carefully prepared and installed under identical environmental conditions. Their vacuum insulation properties are then explored in detail by a sequence of about 90 breakdowns over a three day test period. Their performance with and without a transverse magnetic field and before and after gas exposure is part of this test sequence. Gap separation is varied from 0.25 cm to 3.0 cm at voltages up to 300 kV.

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SECTION 4

RESULTS OF THE "FIRST SIXTEEN" EXPERIMENT

4.1 Breakdown Voltage

The variable of greatest interest in vacuum insulation is, naturally, the breakdown voltage. As outlined in the previous section, about 90 breakdowns were obtained with each pair of electrodes. Table 3 presents the breakdown sequence and provides a code for labeling each breakdown. A Roman numeral is used for the test series and a number gives the order of the spark within the test series.

The experimental results of the "First Sixteen" experiment are presented in standard factorial order in Tables 4, 5, 6 and 7. The results of the treatments that are considered to be replications appear in Table 8. As can be seen several breakdowns were omitted in some of these tests. When this occurs in the treatments used for factorial analysis (Tables 4 through 7) extrapolated values have been inserted.

Table 3. Test Sequence for "First Sixteen" Experiment

I

	Gap (cm)
1	1.0
2	1.0
3	1.0
4	1.5
5	2.0
6	3.0
7	0.25
8	0.50
9	0.75
10	1.0
11	1.5
12	2.0
13	3.0
14	0.25
15	0.50
16	0.75
17	1.0

II

	Gap (cm)	Field (Gauss)
1	1.0	0
2	1.0	0
3	1.0	0
4	1.0	100
5	1.0	200
6	1.0	300
7	1.0	400
8	1.0	0
9	2.0	0
10	2.0	100
11	2.0	200
12	2.0	300
13	2.0	400
14	2.0	0
15	0.25	0
16	0.25	100
17	0.25	200
18	0.25	300
19	0.25	400
20	0.25	0
21	0.50	0
22	0.50	100
23	0.50	200
24	0.50	300
25	0.50	400
26	0.50	0
27	1.0	0

III

	Gap (cm)	Field (Gauss)
1	1.0	0
2	1.0	0
3	1.0	0
4	1.0	200
5	1.0	400
6	1.0	0
7	1.5	0
8	1.5	200
9	1.5	400
10	1.5	0
11	2.0	0
12	2.0	200
13	2.0	400
14	2.0	0
15	0.25	0
16	0.25	200
17	0.25	400
18	0.25	0
19	0.50	0
20	0.50	200
21	0.50	400
22	0.50	0

IV

	Gap (cm)	Field (Gauss)
1	1.0	0
2	1.0	0
3	1.0	0
4	1.0	200
5	1.0	400
6	1.0	0
7	1.5	0
8	1.5	200
9	1.5	400
10	1.5	0
11	2.0	0
12	2.0	200
13	2.0	400
14	2.0	0
15	0.25	0
16	0.25	200
17	0.25	400
18	0.25	0
19	0.50	0
20	0.50	200
21	0.50	400
22	0.50	0
23	1.0	0

I. First Days' Tests
II. Second Days' Tests, Magnetic Field Tests
III. Third Day Before Exposure, Magnetic Field Tests
IV. Third Day After Exposure, Magnetic Field Tests

Table 4. First Days' Tests

Gap (cm)	1.0					1.5		2.0		3.0		0.25		0.50		0.75	
Gauss	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spark No.	1	2	3	10	17	4	11	5	12	6	13	7	14	8	15	9	16
e(R)	166	166	160	180	205	240	240	300	293	>300	>300	37	42	89	99	138	147
ae	145	167	180	220	220	240	269	280	290	295	>300	49	47	124	105	179	152
be	220	220	210	180	175	262	230	260	260	290	290	45	47	90	103	140	150
abe(R)	180	180	190	240	260	275	260	300	297	>300	>300	56	73	120	136	157	190
ce	130	150	170	200	230	260	270	282	294	>300	300	70	72	117	115	170	185
ace(R)	160	185	207	190	200	287	250	300	270	>300	>300	50	47	105	97	131	160
bce	82	107	117	160	200	180	250	255	300	>300	>300	29	48	87	104	128	155
abce	80	110	120	150	160	200	190	266	250	>300	300	33	37	80	100	123	146
de	100	100	120	160	180	170	220	210	280	290	300	30	56	89	90	120	135
ade	130	150	170	150	190	240	220	252	240	>300	>300	31	44	86	96	[illegible]	142
bde	130	160	180	198	199	190	250	260	270	260	260	65	67	100	129	130	174
abde	127	180	170	209	220	210	230	230	280	290	>300	99	125	156	160	190	200
cde	100	133	150	200	200	220	260	270	290	296	297	28	37	105	118	165	150
acde	170	180	190	190	210	250	230	290	260	>300	300	40	58	109	112	157	166
bcde	126	137	170	198	180	230	230	270	290	>300	>300	44	50	108	115	147	140
abcde	174	170	185	160	210	210	200	238	250	296	295	44	50	100	97	147	159

Table 5. Second Days' Tests, Magnetic Field Tests

Gap (cm)	1.0						2.0						0.25						0.50						1.0
Gauss	0	100	200	300	400	0	0	100	200	300	400	0	0	100	200	300	400	0	0	100	200	300	400	0	0
Spark No.	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
e(R)	190	147	153	160	150	175	289	250	280	230	240	295	37	39	40	40	40	42	80	89	90	95	94	90	156
ae	216	110	150	150	170	170	250	251	260	260	250	279	50	52	60	61	60	69	149	140	150	150	158	140	210
be	199	150	160	160	170	170	275	250	220	210	230	278	44	40	50	50	50	51	100	109	104	100	105	90	130
abe(R)	258	220	228	240	230	240	300	300	300	280	300	>300	(40)	(42)	(44)	(45)	(47)	(50)	96	100	118	107	115	120	(245)
ce	217	220	200	190	180	230	296	260	280	260	230	291	53	60	67	70	75	74	140	130	136	130	130	135	229
ace(R)	200	200	180	170	150	190	295	295	290	280	298	295	53	64	70	70	73	76	130	130	140	129	132	138	214
bce	200	187	200	170	200	200	295	220	240	230	210 OL	240	30	35	53	56	57	60	109	120	124	127	130	130	204
abce	166	170	180	200	180	170	280	240	270	279	279	290	57	70	77	85	83	94	170	159	170	150	160	149	230
de	188	187	200	140	169	140	250	220	210	270	260	280	38	42	45	44	48	42	90	100	90	96	97	95	179
ade	170	160	180	190	150	176	259	257	220	210	210	260	35	39	42	40	44	46	109	110	116	110	100	119	171
bde	210	210	200	220	220	230	260	240	260	250	220 OL	270	70	69	73	76	74	77	117	119	125	129	128	134	210
abde	200	230	220	230	230	222	280	285	284	286	287	296	125	128	129	133	145	145	180	194	190	196	220	210	280
cde	219	190	190	200	200	190	280	230	250	220	230	210	58	55	58	61	54	58	109	126	103	110	127	127	200
acde	190	204	220	170 OL	170 OL	209	272	230	240	230	240	260	60	69	67	79	77	78	147	150	157	150 OL	140 OL	159	210
bcde	205	150	170	160	170	140	200	180	190	230	230	240	55	59	60	66	66	67	130	130	135	116	120	120	160
abcde	180	210	199	200	180	199	270	245	210	220	210	200	59	69	67	70	75	75	129	150	153	150	160	160	210

Note: ( ) Parentheses indicate extrapolated, not experimental, values.
OL indicates overload (> 2×10^{-4} amperes), no spark.

Table 6. Third Day Before Exposure, Magnetic Field Tests

Gap (cm)	1.0						1.5				2.0				0.25				0.50			
Gauss	0	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0
Spark No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
e(R)	180	180	171	143	160	174	260	249	240	270	290	294	295	280	50	60	60	60	110	100	94	90
ae	220	220	209	210	200	220	260	260	269	270	300	294	290	300	77	80	83	80	140	180	180	120
be	197	199	190	180	160	190	230	198	160	240	280	240	220	280	50	47	50	50	97	100	109	107
abe (R)	260	260	260	250	200 OL	238	299	285	299	299	>300	300	300	>300	87	92	97 OL	95 OL	175	170	180	183
ce	250	250	246	230	210	250	280	230	279	280	290	280	290	290	95	99	104	100	170	170	140	153
ace(R)	220	220	220	220	220	190	280	280	270	280	300	299	300	300	46	65	68	80	144	134	145	150
bce	220	225	200	210	220 OL	232	280	231	230 OL	286	300	300	300	300	70	67	74	77	110	150	106	123
abce	258	258	262	239	250	250	275	268	270	290	289	280	290	300	90	97	110	116	187	179	190	190
de	110	130	150	170	177	170	248	230	220	250	270	250	240	269	49	49	47	50	96	107	100	100
ade	210	210	210	200	170	210	260	210	210	259	292	240	240	292	34	40	50	57	127	130	130	139
bde	150	226	226	220	210	240	240	250	217 OL	250	280	290	220 OL	285	86	79	80	85	117	130	141	144
abde	280	280	289	230	250	250	(295)	(265)	(275)	(280)	300	300	299	>300	(120)	(130)	(130)	(150)	157	190	200	215
cde	140	200	190	210	200	210	280	240	230	280	270	240	240	290	47	49	51	54	107	100	114	115
acde	150	200	210	170	160 OL	210	260	225	210 OL	250	284	260	230 OL	279	65	73	80	85	140	150	140 OL	160
bcde	180	210	210	180	190	220	270	220	240	260	290	230	230	250	50	58	69	72	139	147	147	107
abcde	210	215	215	190	210	220	253	260	269	275	>300	295	300	307	(80)	(120)	(130)	(115)	130	156	159	151

Note: ( ) Parentheses indicate extrapolated, not experimental, values.
OL indicates overload ($I_{gap} > 2 \times 10^{-4}$ amperes), no spark.

Table 7. Third Day After Exposure, Magnetic Field Tests

Gap (cm)	1.0						1.5				2.0				0.25				0.50				1.0
Gauss	0	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0	0
Spark No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
e(R)	154	200	200	180	180	190	248	248	160 OL	170	250	257	250	260	55	58	60	50	104	109	100	119	140
ae	224	224	225	227	220	234	249	260	260	270	290	290	290	300	62	70	80	95	160	177	170	170	230
be	170	170	188	159	140	190	227	180	180	220	231	210	200	230	48	48	50	55	94	100	105	106	169
abe(R)	250	250	255	240	220	260	280	250	260	300	>300	270	>300	>300	75	99	110	106	190	190	170 OL	190	260
ce	230	230	240	237	217	240	250	260	260	270	275	280	285	285	75	88	88	87	130	150	150	148	220
ace(R)	229	237	220	230	236	230	265	267	277	270	>300	297	300	>300	56	90	98	100	160	160	158	160	240
bce	225	227	230	230	220 OL	230	257	257	257	259	280	280	280	290	84	80	80	89	140	120	140	140	218
abce	230	262	268	260	240	230	290	283	289	297	300	290	291	>300	110	100	102	130	190	170	170	200	280
de	176	176	186	190	190	200	264	237	250	250	280	260	270	290	45	60	60	58	104	117	117	119	187
ade	220	230	239	210	200	220	250	220	240	280	290	250	235	277	49	63	66	70	140	140	150	120	220
bde	220	240	210	200	205	210	270	235	220	205	274	250	230	275	70	75	75	80	130	130	140	140	210
abde	273	260	268	274	263	258	277	277	291	280	>300	290	290	>300	80	84	96	104	193	200	200	180	240
cde	186	210	200	209	190	210	240	220	220	250	257	255	240	266	49	40	50	50	106	120	125	120	210
acde	210	210	210	190	180 OL	214	240	240	220 OL	239	270	260	230 OL	270	90	100	104	105	180	179	188	160	229
bcde	200	210	195	160	150	190	261	220	200	270	280	230	220	270	60	75	70	70	130	138	140	150	219
abcde	230	230	250	230	220	250	(280)	(250)	(260)	(285)	>300	290	290	>300	93	98	100	100	200	200	200	200	260

Note: ( ) Parentheses indicate extrapolated, not experimental, values.
OL indicates overload (> 2×10^{-4} amperes), no spark.

Table 8. Breakdown Voltages of Treatments Considered to be Replications

I. First Days' Tests

Gap (cm)	1.0			1.5	2.0	3.0	0.25	0.50	0.75	1.0	1.5	2.0	3.0	0.25	0.50	0.75	1.0
Gauss	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spark No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
e	180	190	209	250	286	>300	50	120	189	209	280	290	>300	53	119	150	210
abe	120	200	220	282	---	---	52	128	190	210	280	290	---	--	114	180	250
ace	127	150	190	268	277	290	57	127	160	200	267	280	293	67	120	190	230
de (R)	85	102	103	180	220	>300	28	70	102	136	180	240	>300	34	82	123	150

Note: The breakdown sequence was not followed exactly during treatments "e" and "abe".

II. Second Days' Test, Magnetic Field Tests

Gap (cm)	1.0								2.0						0.25						0.50						1.0
Gauss	0	0	0	100	200	300	400	0	0	100	200	300	400	0	0	100	200	300	400	0	0	100	200	300	400	0	0
Spark No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
e	224	250	---	200	190	210	200	220	294	251	270	260	260	297	--	--	--	--	--	--	---	---	---	---	---	---	---
abe	140	180	230	220	200	210	210	230	287	220	230	270	238	290	55	57	57	60	77	70	---	---	---	---	---	---	---
ace	195	210	206	200	200	200	200	200	282	278	280	260	270	260	55	57	57	65	63	66	135	147	144	150	154	150	240
de (R)	160	160	150	149	180	180	170	184	290	250	230	210	230 OL	290	40	47	49	57	59	64	124	115	117	120 OL	120	115	209

Table 8. Breakdown Voltages of Treatments Considered to be Replications (Continued)

III. Third Day, Magnetic Field Tests Before Exposure

Gap (cm)	1.0						1.5				2.0				0.25				0.50			
Gauss	0	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0
Spark No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
e	---	---	136	125	128	---	200	190	180	210	250	220	210	250	--	83	90	89	---	---	---	---
abe	240	255	220	170	200	240	---	---	---	---	270	230	240	290	--	--	--	--	88	140	160	130
ace	240	---	240	225	226	240	290	240	250	290	300	270	294	300	80	85	90	90	135	139	140	139
de (R)	150	206	206	200	190 OL	220	240	250	220 OL	230	>300	300	270	288	53	53	59	53	106	109	115	110

IV. Third Day, Magnetic Field Tests After Exposure

Gap (cm)	1.0						1.5				2.0				0.25				0.50				1.0
Gauss	0	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0	0
Spark No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
e	200	200	---	190	190	210	280	260	220	280	297	290	260	297	48	49	49	52	52	125	110	107	121
abe	222	230	236	200	210	232	---	---	---	---	255	228	236	270	--	--	--	--	160	159	150	176	238
ace	220	230	220	210	200	240	270	256	260	270	300	230	290	300	76	99	96	100	170	170	160	170	220
de (R)	190	190	203	200	220	220	280	270	240	278	250	220	200 OL	270	40	49	59	59	110	120	124	134	180

SECTION 5

ANALYSIS AND INTERPRETATION OF "FIRST SIXTEEN" EXPERIMENT

5.1 Introduction

Since this experiment is concerned with high voltage vacuum breakdown, the primary variable is breakdown voltage. The First Sixteen experiment provides about 1400 breakdown voltage values obtained under rigidly specified conditions. The physical situation contributing to the occurrence of a breakdown is described by the following measurable parameters:

Flexible Factors

(May be varied at will during experimentation)

(1) gap
(2) transverse magnetic field
(3) method of voltage application
(4) gas exposure
(5) vacuum conditions

Inflexible Factors

(Can be controlled only before experimentation begins)

(1) anode material
(2) cathode material
(3) anode size
(4) electrode firing (preparation)

Variables

(Observed but not under direct control)

(1) electrical stress history of the electrodes (conditioning)
(2) prebreakdown current
(3) pressure surges
(4) external electrical parameters

It is assumed that during the First Sixteen experiment any other factors influencing vacuum breakdown (such as cathode shape, cathode size, electrode surface finish, electrode temperature, etc) are constant. The breakdown voltage may then be related to the observed parameters, with the objective to obtain the simplest, most general and useful description of the functional dependence of breakdown voltage on the pertinent parameters. To do this, changes in one or several parameters are correlated with changes in breakdown voltage.

A fundamental difficulty arises at this point because the measurable parameters do not correspond directly or simply to the parameters that are postulated to be active in various theories of vacuum breakdown. Thus it is difficult to decide beforehand which factors merit consideration or how they should be varied and correlated. This circumstance makes the factorial design very useful, since it will, in a minimum number of experiments, point out which factors are important and which factors interact. The "inflexible" factors are the ones directly examined through the factorial design. The other parameters will be examined in a number of ways.

The first four sections that follow deal primarily with analysis, while the other section concerns interpretation. It should be noted that this analysis is preliminary in nature and complete analysis will not be possible until the second half of the overall experiment is completed.

5.2 Factorial Analysis by Yates' Algorithm

Yates' algorithm provides a standard and convenient way of computing the influence on breakdown voltage of the factors studied in this two level, full factorial experiment. Table 1 has presented the factors and levels used in the First Sixteen experiment. Tables 9, 10, 11 and 12 contain Yates' estimates of the mean, the main effects, and interactions. These results were obtained with the help of a computer and follow the form that has been used in previous reports, particularly in the Block-of-Eight Experiment.

When studying the effect of the four factors of the First Sixteen, it is possible to compute only Yates' estimates from breakdown voltages obtained with a'' other pertinent parameters constant. For completeness separate sets of Yates' estimates for each breakdown in the test sequence have been computed. Thus, the effects of factors such as magnetic field, gas exposure and gap are not explicitly contained in Tables 9 through 12.

Discussion of the validity of this approach and examination of interesting trends is reserved for Section 5.6.

5.3 Breakdown Voltage as a Function of Electrode Separation

To examine the effect of electrode separation on breakdown voltage, the latter is plotted versus the square root of gap separation. Figure 3 shows a typical plot and gives the sequence of breakdowns. The ultimate prebreakdown current has also been included. This has been done in Figures 4 through 23 for the First Day tests of each treatment and in Figures 24 through 28 for suitable averaged sets of breakdown voltage.

Table 9. Yates' Estimates for First Day's Tests

Gap (cm)	0.25		0.5		0.75		1.0					1.5		2.0	
Spark No.	7	14	8	15	9	16	1	2	3	10	17	4	11	5	12
U	46	56	104	111	147	159	133	155	168	186	202	229	237	266	275
A	6	7	11	3	10	9	14	18	16	4	12	20	- 12	6	- 17
B	10	11	2	14	- 4	9	2	4	0	0	- 3	- 18	- 14	- 13	- 2
AB	5	10	5	6	7	9	- 13	- 14	- 19	1	11	- 11	- 7	- 8	6
C	- 9	-12	- 5	- 7	- 3	- 3	- 22	- 18	- 8	- 11	- 7	1	- 4	9	0
AC	- 7	-11	- 17	- 15	- 23	- 9	22	10	6	- 21	- 20	- 5	- 22	- 1	- 18
BC	-19	-19	- 17	- 20	- 14	- 24	- 26	- 35	- 30	- 28	- 18	- 30	- 20	- 15	- 3
ABC	- 2	-12	- 7	- 6	3	- 4	0	3	5	- 8	- 8	- 2	- 2	- 5	- 15
D	1	9	5	7	3	- 2	- 13	- 9	- 2	- 6	- 7	- 28	- 14	- 27	- 11
AD	5	9	0	0	7	7	22	18	6	- 15	5	5	- 7	- 6	- 7
BD	20	12	16	7	12	10	12	16	19	15	11	8	9	7	7
ABD	0	1	5	- 3	4	- 3	0	3	- 1	- 3	- 3	- 13	2	- 22	3
CD	- 8	-11	3	0	12	- 5	42	26	22	18	10	23	4	19	5
ACD	2	5	3	0	1	10	0	- 8	- 3	8	22	- 14	12	- 4	8
BCD	- 1	- 2	- 4	- 9	- 7	- 3	27	11	19	- 3	1	25	- 4	- 4	- 6
ABCD	- 8	-10	- 10	- 3	- 11	0	3	0	3	- 3	11	2	7	10	0

Table 10. Yates' Estimates for Magnetic Field Tests

Gap (cm)	1.0						2.0						0.25						0.50						1.0
Gauss	0	100	200	300	400	0	0	100	200	300	400	0	0	100	200	300	400	0	0	100	200	300	400	0	0
Spark No.	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
U	200	184	189	184	182	190	271	247	250	246	245	268	54	58	62	65	66	69	124	128	131	127	132	132	206
A	- 6	7	9	18	0	12	7	31	18	18	28	10	11	16	13	15	17	20	29	26	35	29	31	34	45
B	3	13	9	26	30	11	- 3	- 4	- 7	3	1	- 5	12	11	13	14	15	16	9	13	17	13	20	13	20
AB	3	25	14	21	14	10	17	13	20	18	18	6	8	9	6	6	8	7	0	5	0	2	11	7	35
C	- 6	14	5	- 3	- 7	0	3	- 19	- 8	- 5	- 8	- 30	- 1	3	4	8	6	7	17	16	16	9	10	15	1
AC	- 20	1	- 5	- 13	- 17	- 10	3	- 1	- 5	0	3	5	- 3	- 1	- 3	- 2	- 3	- 4	- 7	- 5	- 5	- 5	- 10	- 10	- 28
BC	- 22	- 37	- 20	- 26	- 22	- 38	- 20	- 28	- 30	- 10	- 18	- 15	-17	-15	-14	-15	-15	-14	- 6	- 7	- 5	- 7	- 9	- 13	- 32
ABC	- 6	- 13	- 14	8	- 2	2	- 1	0	- 8	- 15	- 25	- 17	- 1	- 3	- 1	- 2	- 4	- 2	7	3	1	1	2	- 1	- 15
D	- 10	17	15	8	7	- 4	- 26	- 22	- 34	- 14	- 18	- 32	17	16	10	11	12	9	4	12	4	8	8	16	- 7
AD	- 14	8	4	- 1	- 7	13	15	5	- 7	- 24	- 26	- 6	2	3	3	3	7	4	0	6	4	8	5	8	- 15
BD	3	1	- 10	1	- 2	7	- 8	7	13	10	0	4	17	18	16	15	18	18	15	13	17	18	21	17	4
ABD	0	- 2	- 4	- 13	2	- 11	4	4	- 9	0	3	- 17	6	4	7	5	7	6	0	10	0	8	17	8	- 6
CD	13	- 22	- 10	- 8	- 4	- 8	- 9	- 10	- 13	- 23	- 8	- 18	- 7	-10	-13	-12	-16	-15	- 13	- 8	- 10	- 11	- 9	- 13	- 16
ACD	13	18	19	1	14	23	4	- 2	0	6	- 10	- 4	- 8	- 7	- 6	- 5	- 5	- 6	- 3	- 4	0	4	0	3	27
BCD	3	6	0	- 6	- 15	- 10	- 7	7	- 20	- 3	1	1	-13	-12	-14	-17	-14	-17	- 17	- 17	- 14	- 21	- 24	- 20	- 12
ABCD	5	12	4	18	5	18	18	15	12	- 13	- 11	- 16	-12	-13	-13	-16	-17	-17	- 28	- 21	- 20	- 16	- 18	- 10	5

Table 11. Yates' Estimates for Magnetic Field Tests Before Exposure

Gap (cm)	1.0						1.5				2.0				0.25				0.50			
Gauss	0	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0
Spark No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
U	202	217	216	203	199	217	266	246	243	269	289	274	267	288	68	75	80	82	134	143	142	140
A	47	30	36	20	16	12	11	19	32	10	11	18	26	16	12	23	26	28	31	35	46	46
B	34	32	30	18	24	25	1	0	4	5	5	9	4	2	21	21	24	24	9	18	23	24
AB	17	7	13	9	15	6	13	25	34	16	- 2	10	28	6	17	23	21	19	14	6	9	18
C	2	9	6	5	16	11	10	7	13	10	1	- 3	9	1	- 1	6	11	9	13	9	0	6
AC	- 35	- 28	- 21	- 23	- 11	- 23	- 22	- 3	- 22	- 13	- 6	3	- 11	- 2	- 8	- 3	- 4	- 5	- 13	- 22	- 14	- 7
BC	- 7	- 23	- 25	- 21	- 4	- 10	- 7	- 11	- 1	0	3	- 3	10	- 3	-12	- 7	- 4	- 9	- 8	0	- 7	- 25
ABC	4	9	4	13	4	13	- 14	- 2	- 10	- 3	- 4	- 9	- 13	8	2	2	4	- 1	0	0	6	- 1
D	- 46	- 17	- 7	- 14	- 6	- 1	- 7	- 18	- 18	- 13	- 7	- 22	- 35	- 9	- 4	- 1	- 1	1	- 15	- 9	- 1	1
AD	19	4	0	- 18	- 13	0	- 4	- 14	- 17	- 4	4	3	8	4	4	8	9	7	- 8	0	- 14	3
BD	18	14	14	0	14	6	0	22	28	1	8	21	20	0	14	22	20	19	8	15	17	1
ABD	- 5	- 13	- 16	- 1	10	- 13	- 2	- 2	- 5	0	0	5	11	8	- 2	1	- 2	- 1	- 23	- 7	- 6	- 10
CD	- 20	- 14	- 18	- 23	- 28	- 13	- 5	- 9	- 6	- 3	0	- 10	- 9	- 6	-10	- 5	- 5	-13	- 8	- 10	- 3	- 22
ACD	- 11	- 3	- 3	6	- 1	10	- 3	11	12	0	1	18	7	4	15	14	13	6	1	16	2	2
BCD	4	- 11	- 7	- 1	- 14	- 12	- 3	- 3	0	- 4	1	- 15	- 5	- 5	-14	- 8	- 6	-11	1	- 8	- 6	- 8
ABCD	- 6	- 1	- 9	4	0	- 5	4	7	5	9	3	15	13	10	-12	- 7	- 7	-10	- 13	- 19	- 17	- 7

Table 12. Yates' Estimates for Magnetic Field Tests After Exposure

Gap (cm)	1.0						1.5				2.0				0.25				0.50				1.0
Gauss	0	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0	0	200	400	0	0
Spark No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
U	214	222	224	214	204	222	259	244	240	257	279	266	262	282	68	76	80	84	146	149	151	151	227
A	38	30	35	37	35	29	14	23	43	40	27	26	31	22	16	22	27	33	59	52	48	42	35
B	21	16	18	10	5	10	17	0	8	14	6	- 4	0	2	17	11	9	14	22	10	13	23	10
AB	3	8	18	26	21	15	13	18	17	11	5	15	28	11	7	3	5	2	10	12	5	16	20
C	6	8	5	8	4	4	2	11	15	20	5	13	8	6	16	14	11	14	15	10	14	16	15
AC	- 23	- 14	- 15	- 18	- 11	- 16	2	- 3	- 16	- 30	- 8	- 3	- 9	- 7	4	3	1	0	- 3	- 7	- 8	- 1	0
BC	- 13	- 6	0	- 6	- 3	- 8	6	5	- 1	5	7	4	6	7	1	- 2	- 6	- 3	- 1	- 6	- 6	1	9
ABC	0	3	7	4	0	1	- 4	- 11	1	4	- 5	- 3	- 9	- 5	1	- 8	- 8	- 1	- 6	- 2	0	- 1	- 4
D	0	- 4	- 8	- 12	- 9	- 6	2	- 13	- 5	0	3	- 11	- 23	- 2	- 3	- 4	- 5	- 9	1	7	12	- 5	14
AD	0	- 6	8	0	- 3	3	- 11	- 5	- 13	- 13	- 10	- 3	- 10	- 11	5	1	0	- 3	1	0	5	- 9	- 30
BD	11	12	4	6	13	6	6	16	1	- 9	7	13	13	8	0	6	5	2	7	17	11	14	- 14
ABD	0	- 12	- 6	9	10	6	- 3	- 1	18	6	0	10	14	4	- 8	-11	- 7	- 5	- 4	0	0	- 4	9
CD	- 22	- 19	- 17	- 29	- 33	- 10	- 12	- 21	- 40	- 13	- 15	- 16	- 20	- 15	- 4	- 6	- 5	-10	- 2	2	- 3	1	- 24
ACD	12	1	3	7	9	15	4	9	16	5	7	12	18	13	10	14	13	11	14	14	15	14	24
BCD	- 2	- 12	- 4	- 14	- 15	0	0	- 17	1	21	4	- 10	0	- 1	-12	1	0	- 7	- 6	- 2	- 5	- 4	14
ABCD	0	10	3	4	8	5	4	- 1	- 7	- 9	3	4	6	2	- 4	- 2	- 1	- 7	- 1	- 9	- 7	- 5	- 14

In the plots of the First Day tests, a point on the "conditioned" breakdown curve has experienced six more previous breakdowns than a corresponding point on the "unconditioned" curve. In this and for most treatments, the 3.0 cm breakdown proved to be beyond the experimental limit of 300 kV.

The tests on subsequent days introduce a magnetic field so the effects of electrode separation are confounded with the effects of a magnetic field. For this reason, only appropriate average values of breakdown voltage have been plotted versus square root of the gap separation (Figures 26, 27 and 28) for those tests.

At smaller gap separations, the breakdown voltage appears to vary linearly with gap. To illustrate this, the average breakdown voltage for the First Day tests have been plotted versus gap separation in Figure 25.

The interpretation of these graphs is reserved for Section 5.6.

5.4 Breakdown Voltage as a Function of Prior Sparking

When a breakdown occurs, the surfaces of both electrodes experience violent damage. Subsequent breakdowns are influenced by the changed surface state and may occur at higher or lower voltages than the initial breakdowns. Exposing the electrodes to a number of breakdowns is termed "conditioning". Thus, the curves of Section 5.3 are referred to as "conditioned" or "unconditioned".

To investigate this process in more detail for the type of electrodes and external circuit parameters used in the First Sixteen experiment, breakdown voltage has been plotted as a function of "spark order" for several prime gaps for each treatment. By "spark order" is meant the chronological sequence for a certain gap. Between two sparks in a sequence for one gap, there may have been several sparks at other gap settings. Sparks with the transverse magnetic field are so designated on the graphs. Figure 29 illustrates this procedure. Figures 30 through 49 present conditioning plots for each treatment and the four replications.

The sample plot (Figure 29) uses the average breakdown voltage of the sixteen treatments as computed by Yates' algorithm.

5.5 Breakdown Voltage as a Function of Transverse Magnetic Field

The influence of a weak (100 to 400 gauss) transverse magnetic field on breakdown voltage was examined and analyzed in the Block-of-Eight experiment (see Quarterly Progress Report Nos. 11 and 12). The First

Sixteen experiment investigates this effect during the second and third days of testing. Table 3 shows how magnetic field tests are included in the test sequence. The procedure was to set a certain gap and then obtain a series of breakdowns without, with and again without a transverse magnetic field of several levels.

While the effect of a transverse magnetic field on breakdown voltage appears quite variable if a single treatment is examined (see Figures 30 through 49), the average breakdown voltages with and without a transverse magnetic field present a relatively clear pattern:

> <u>For Large Gaps</u>: presence of transverse magnetic field lowers breakdown voltage.
>
> <u>For Small Gaps</u>: presence of transverse magnetic field raises breakdown voltage very slightly.

These effects are evident in the plots of average breakdown voltage versus magnetic field strength in Figures 50 and 51. Such a pattern is in accord with the results of the Block-of-Eight experiment which investigated the magnetic effect at only 2. 0 and 3. 0 cm gaps.

5. 6 Interpretation

5. 6. 1 Introduction

The First Sixteen experiment has been presented so far as a phase in an ongoing experimental project investigating vacuum breakdown. While such an approach is appropriate to a Quarterly Progress Report, it is helpful for purposes of interpretation to regard it as an independent study. From that perspective, a more structured and complete understanding can be obtained.

To date, it has yielded a considerable amount of data. Each set of physical factors (a pair of electrodes) has been tested to establish its performance in terms of breakdown voltage. These breakdown voltages are the primary output and have been presented in Section 4. 1 of this report. Other parameters such as prebreakdown current, pressure surges and time to voltage collapse will be presented in future reports. Electrode damage due to sparking has been photographed and will also be reported.

5. 6. 2 Analysis

After the initial data was compiled in a useable form, it was subjected to various analytical manipulations in order to bring out meaningful patterns. The breakdown voltage has been presented in Sections 5.3 to 5.5 as a function of square root of gap, gap, prior sparking (conditioning), and transverse magnetic field level. Section 5.2 contains an analysis according to Yates' algorithm of the effect on breakdown voltage of the four factors under investigation. These analytical techniques will be extended to other observed variables in future reports. Other techniques will also be considered, in particular a statistical analysis of the error associated with the various measurements.

5.6.3 Conclusions

The present analysis of the First Sixteen experiment supports the following conclusions:

- Effect of Factors

  The most influential factors emerging from this factorial experiment are those related to electrode material. In particular, the effect of anode material becomes greater as conditioning proceeds, with copper giving significantly higher breakdown voltages. Cathode material has a less predominant effect but again copper is superior to aluminum. These observations are in line with the very obvious transfer of anode material to the cathode surface as breakdowns occur. In most cases, the sequence of about 90 breakdowns produced an adherent and relatively continuous coating of anode material on the cathode; this result being especially evident when dissimilar metals were being used for anode and cathode.

  As a consequence of the use of different materials for cathode and anode, the effect of pretreatment (vacuum or hydrogen firing) was complex. The results do indicate superior performance for vacuum fired aluminum electrodes with hydrogen firing preferred for copper. When two metals are involved, the interactions preclude simple conclusions.

- Breakdown Voltage as a Function of Gap Separation

  A functional relation of linear form below 0.50 to 1.0 cm and of square root form above 0.50 to 1.0 cm appears to describe the dependence of breakdown voltage on gap. The transition from linear to square root regime depends on the treatment.

- **Breakdown Voltage as a Function of Prior Sparking**

  Prior sparking (or conditioning) almost invariably results in higher average breakdown voltages. This increase is often as much as 50%. The number of breakdown events necessary to reach a plateau varies from several to a hundred or more. On the other hand, continued sparking in some cases reduced breakdown voltage. Thus, it is usually impossible to define a single unique breakdown voltage for any treatment or gap. It is possible, however, to describe the changes in breakdown voltage as a function of prior sparking and other pertinent factors (such as gas exposure). It has been found that in most cases the "conditioning curve" rises monotonically to a plateau which can be maintained throughout many breakdowns. However, the variation of breakdown voltage about this limiting level is often quite large (> 20%) and must be considered when specifying an average working level for the gap conditions.

- **Breakdown Voltage as a Function of Magnetic Field**

  A transverse magnetic field of 100 to 400 gauss on the average lowers breakdown voltage for large (> 1.0 cm) gaps and raises it slightly for small gaps (< 1.0 cm). Such results for a weak field such as employed here has previously received little attention. Sanford* has reported briefly on this effect. Watson (see Addendum to Quarterly Progress Report No. 14) has presented a theory to account for this phenomenon based upon the Hall effect.

* Sanford, J. R., Proceedings of First International Symposium on Insulation of High Voltages in Vacuum, 431 (1964).

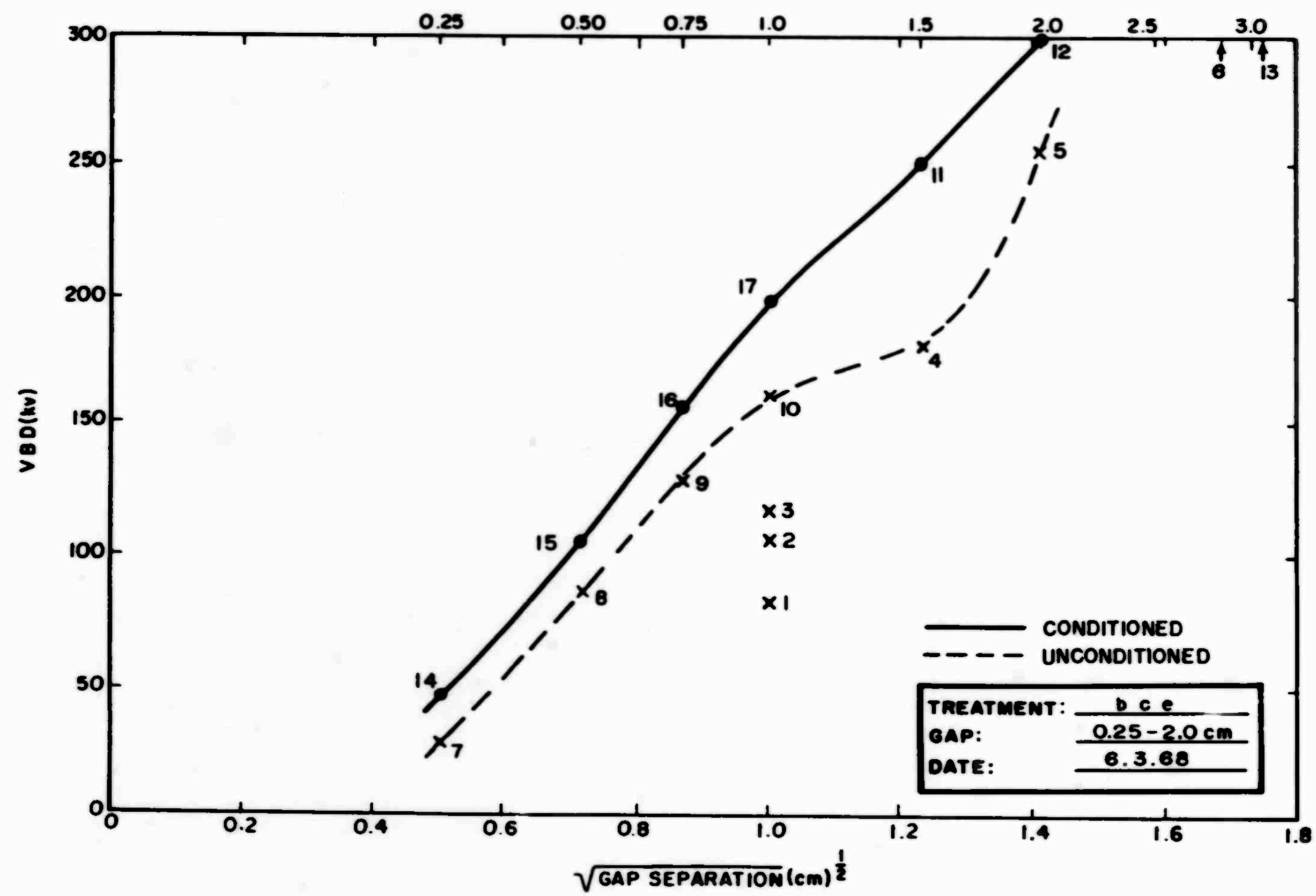

Figure 3. Sample Plot Showing Sequence of Breakdowns (Treatment bce) for First Days' Tests

1-2910

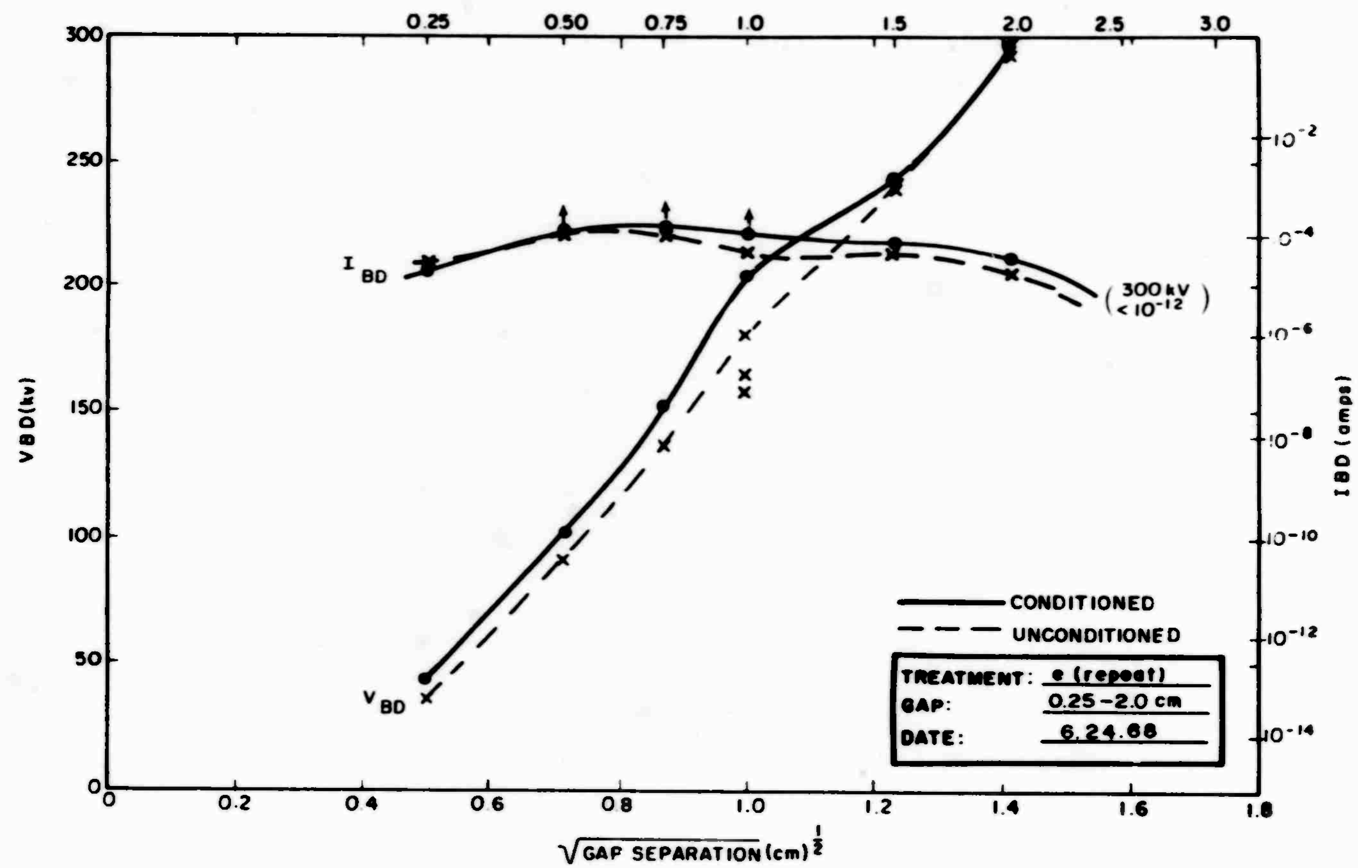

Figure 4. Breakdown Voltage vs Square Root Gap Separation for Treatment e (repeat)

1-2911

1-2912

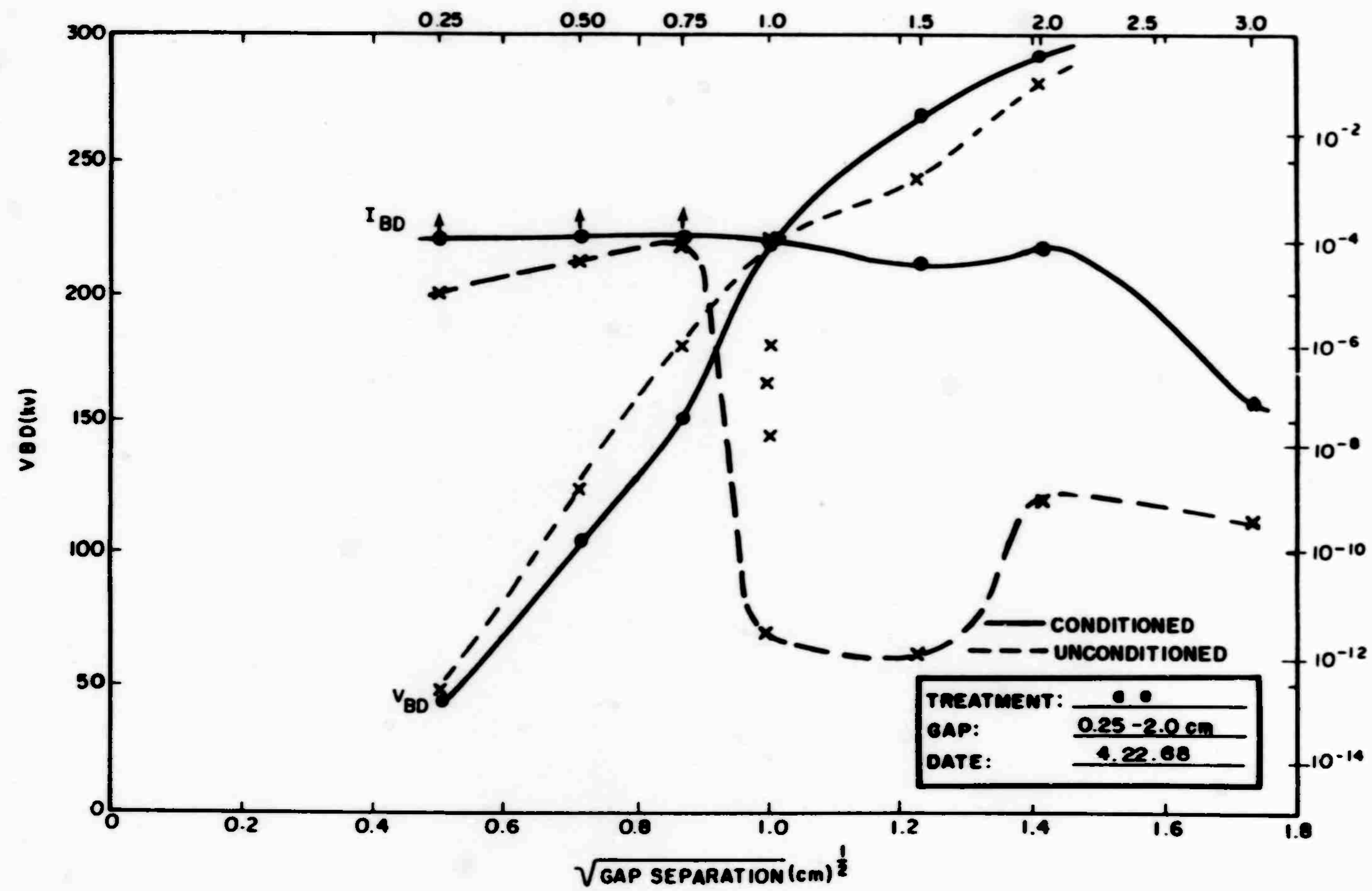

Figure 5. Breakdown Voltage vs Square Root Gap Separation for Treatment ae

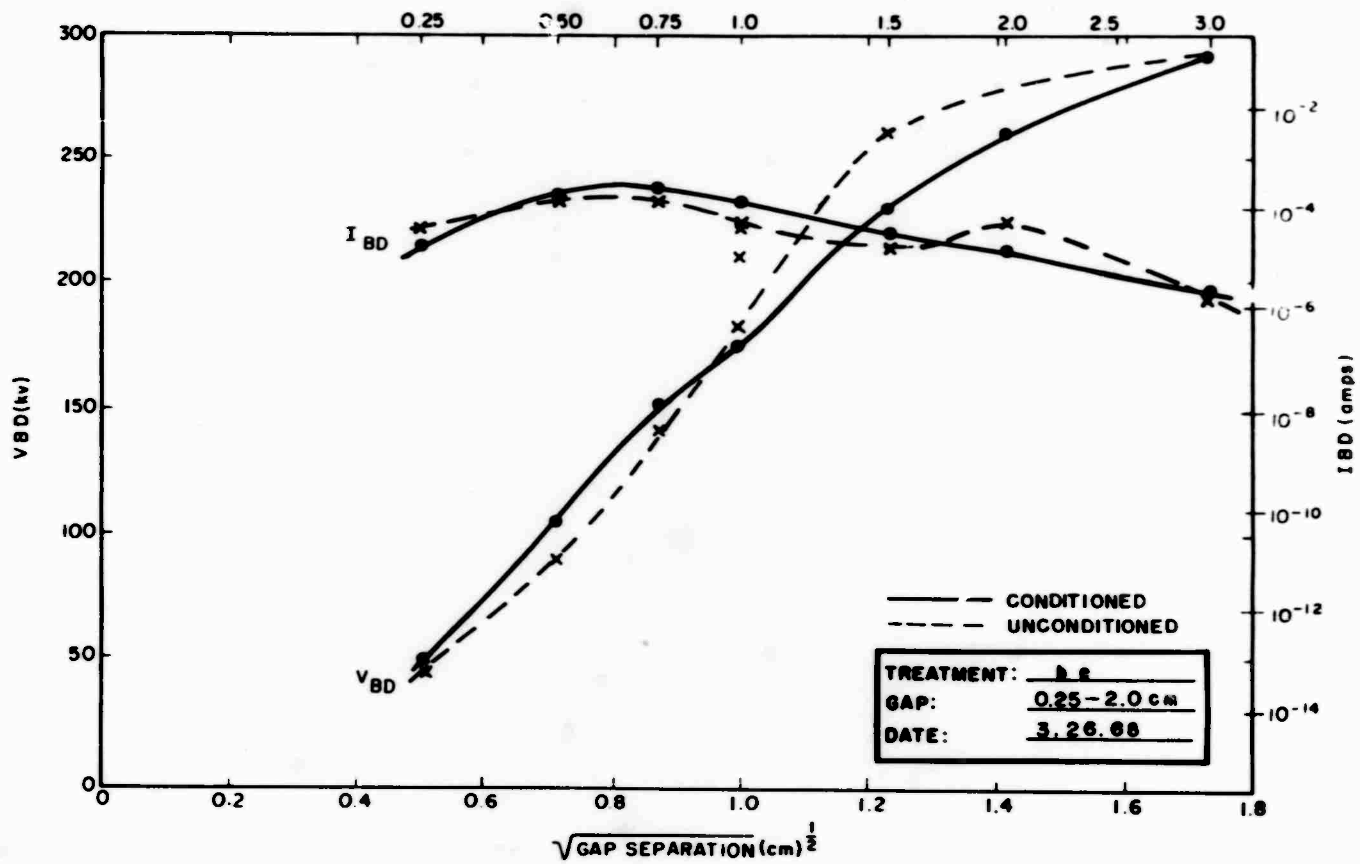

Figure 6. Breakdown Voltage vs Square Root Gap Separation for Treatment be

1-2913

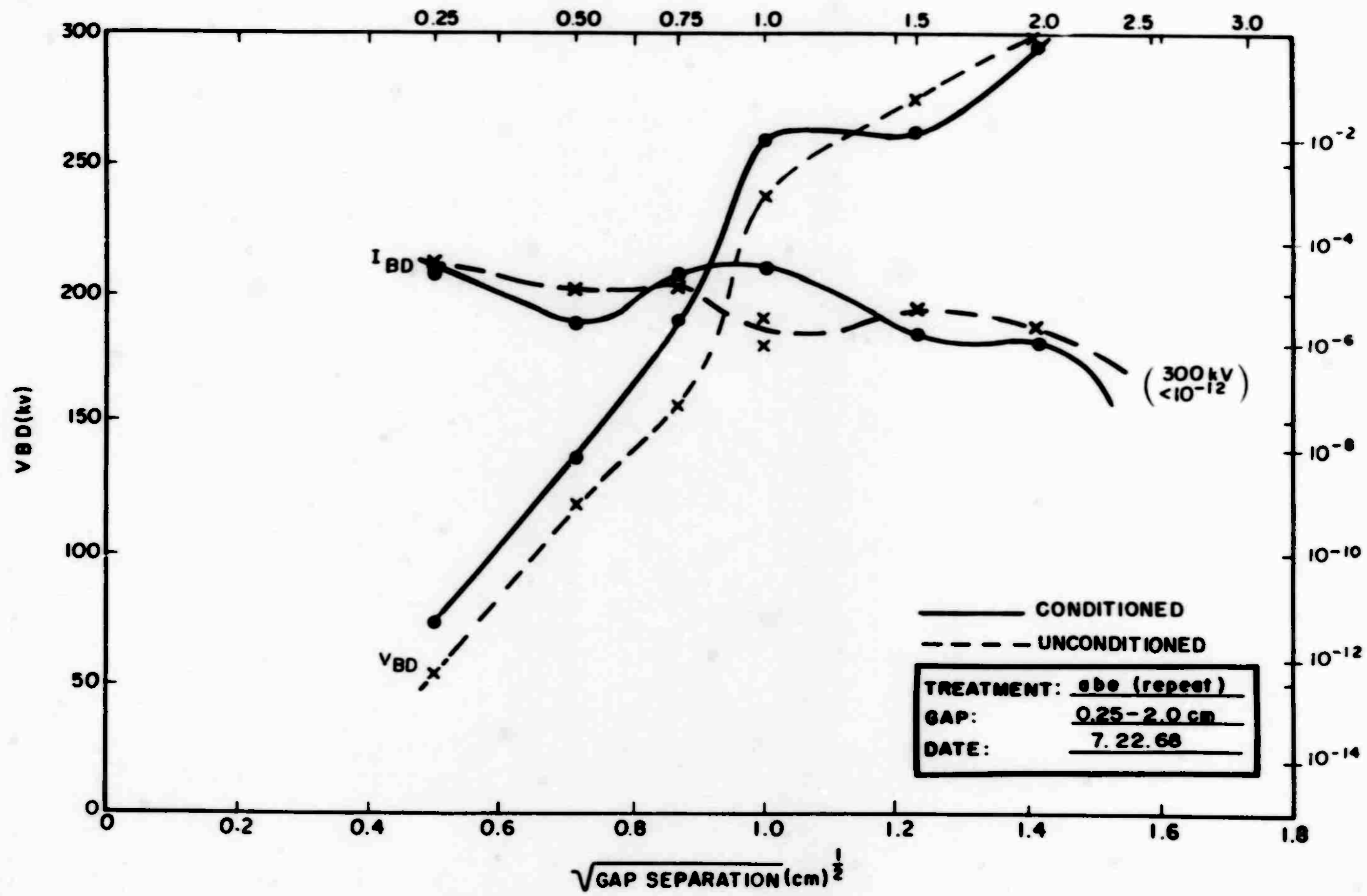

Figure 7. Breakdown Voltage vs Square Root Gap Separation for Treatment abe (repeat)

1-2914

1-2915

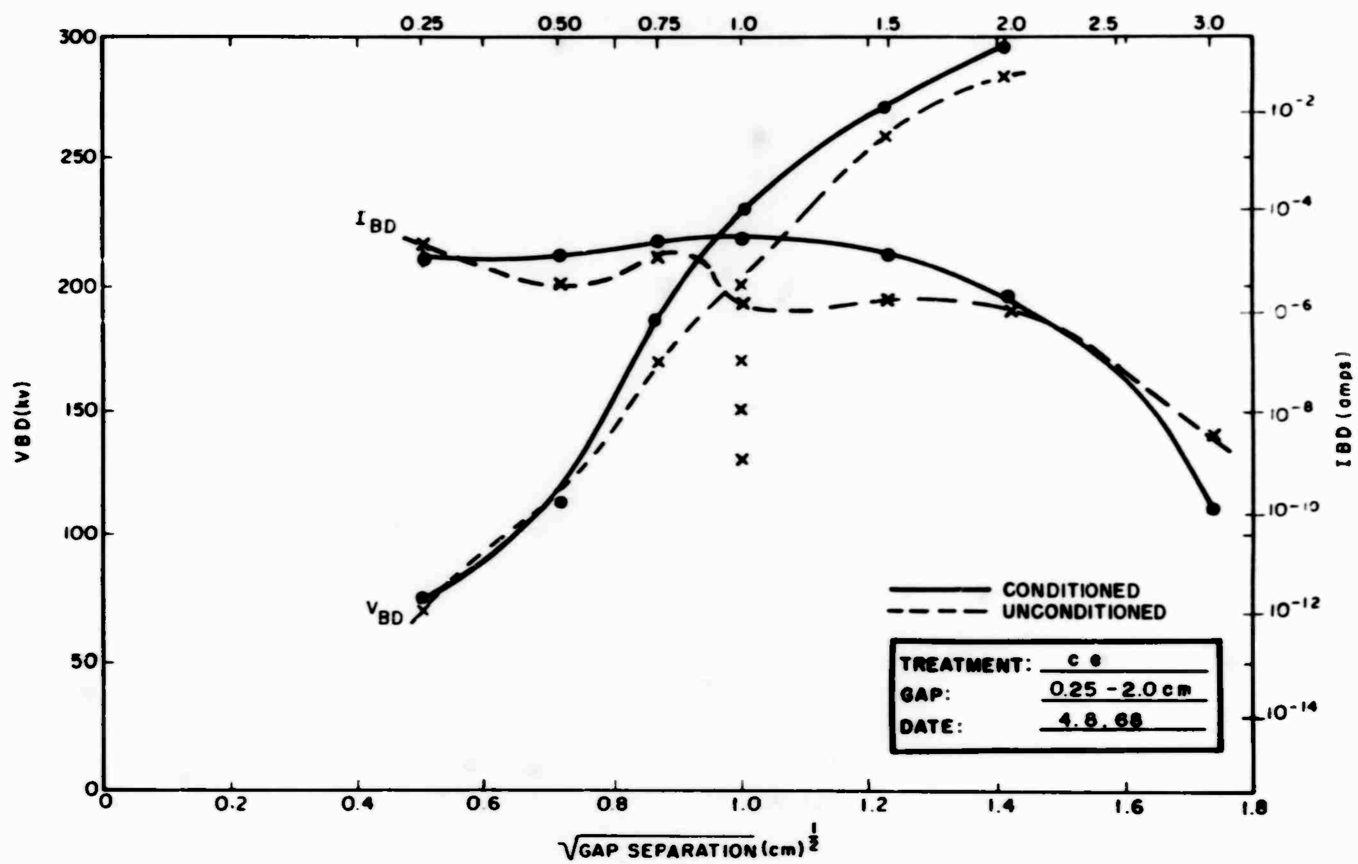

Figure 8. Breakdown Voltage vs Square Root Gap Separation for Treatment ce

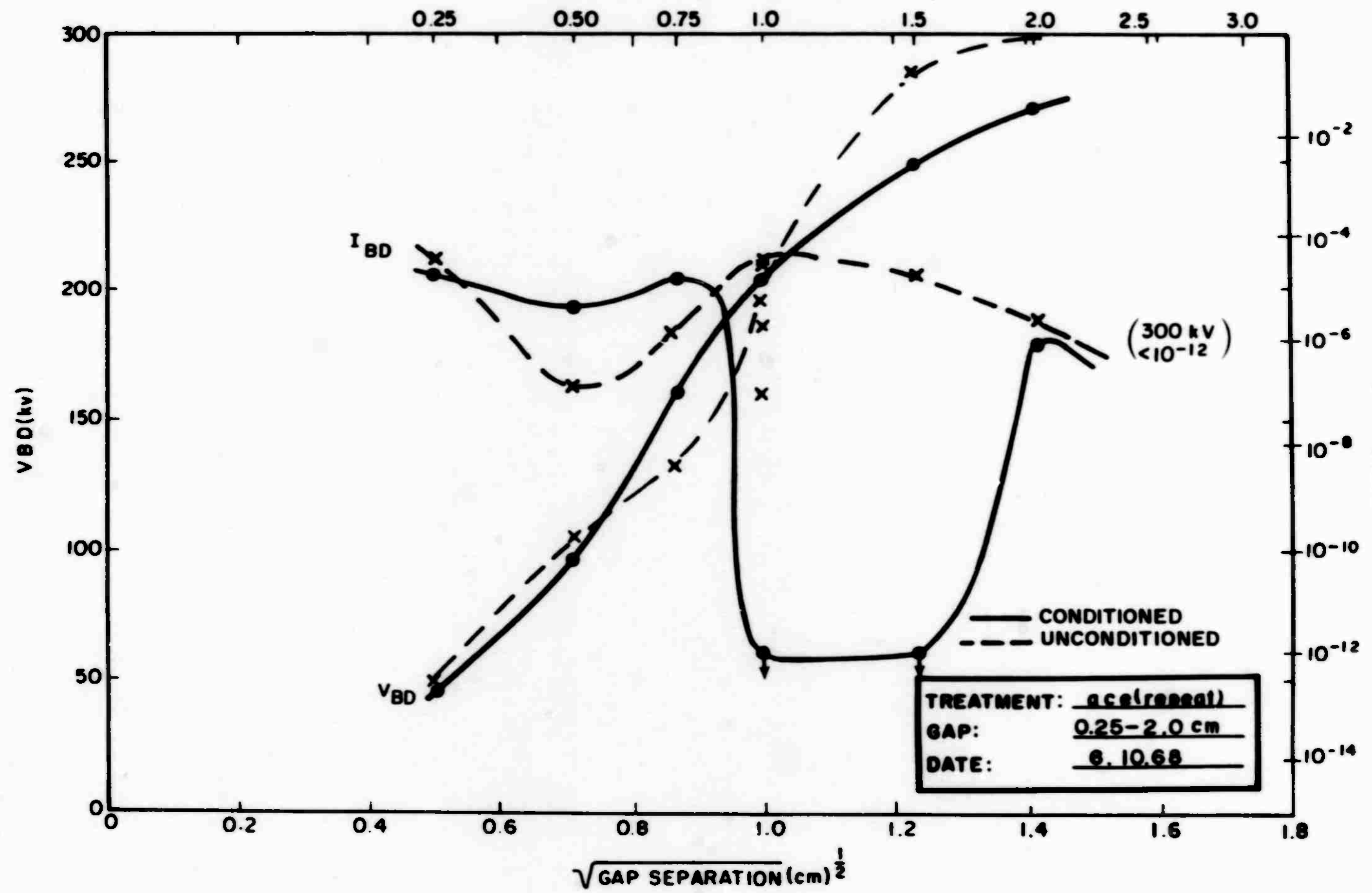

Figure 9. Breakdown Voltage vs Square Root Gap Separation for Treatment ace (repeat)

1-2916

1-2917

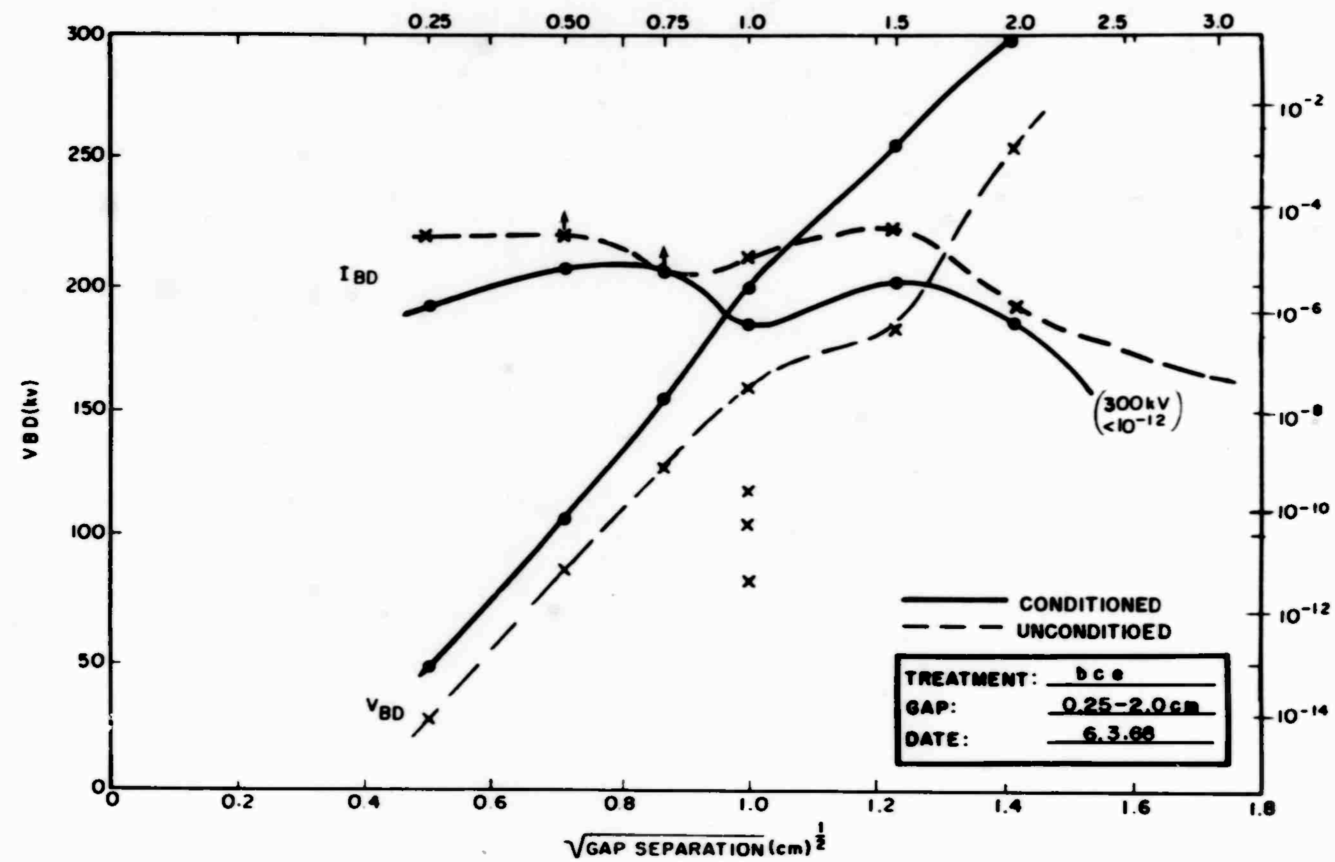

Figure 10. Breakdown Voltage vs Square Root Gap Separation for Treatment bce

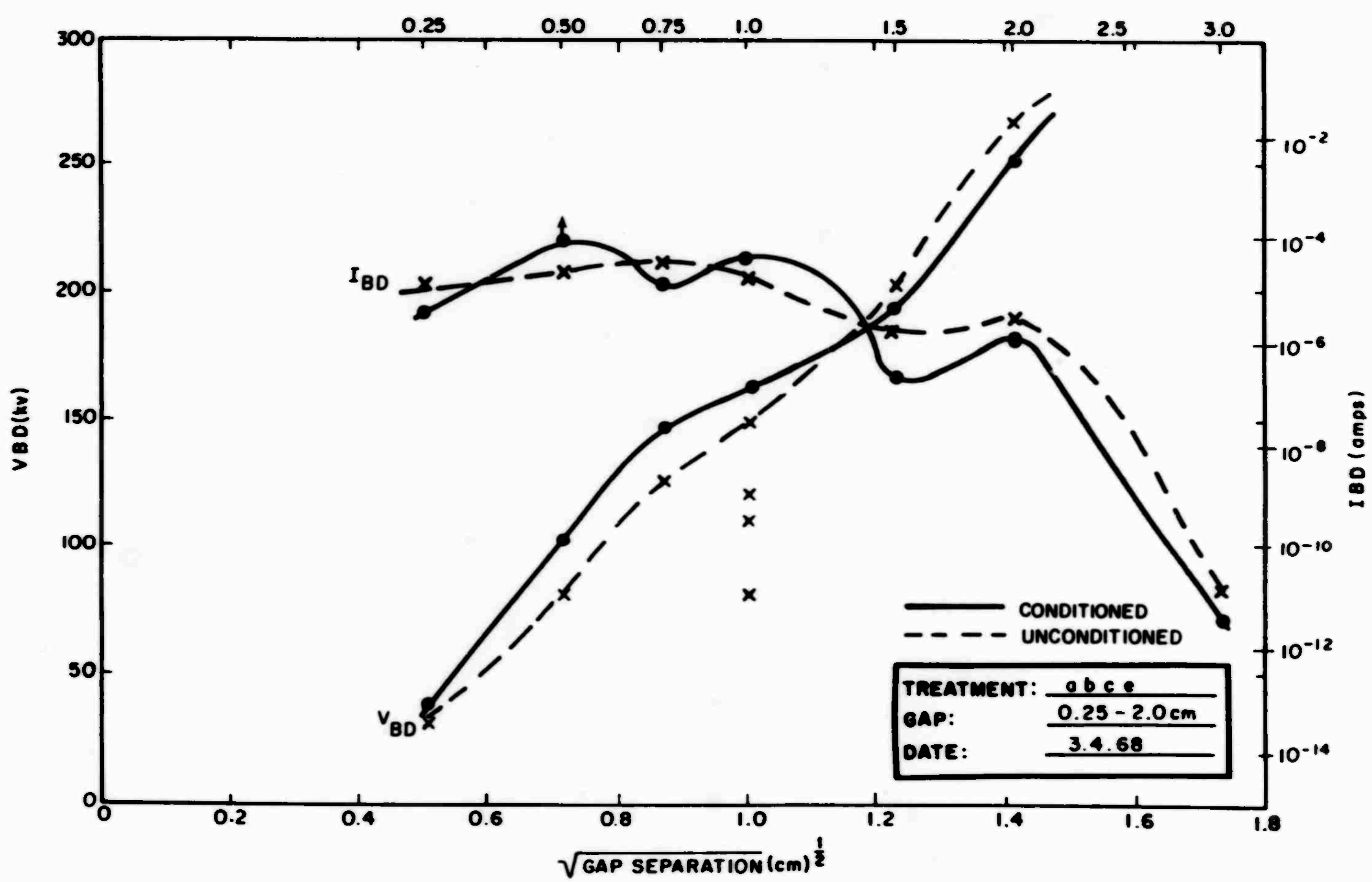

Figure 11. Breakdown Voltage vs Square Root Gap Separation for Treatment abce

1-2918

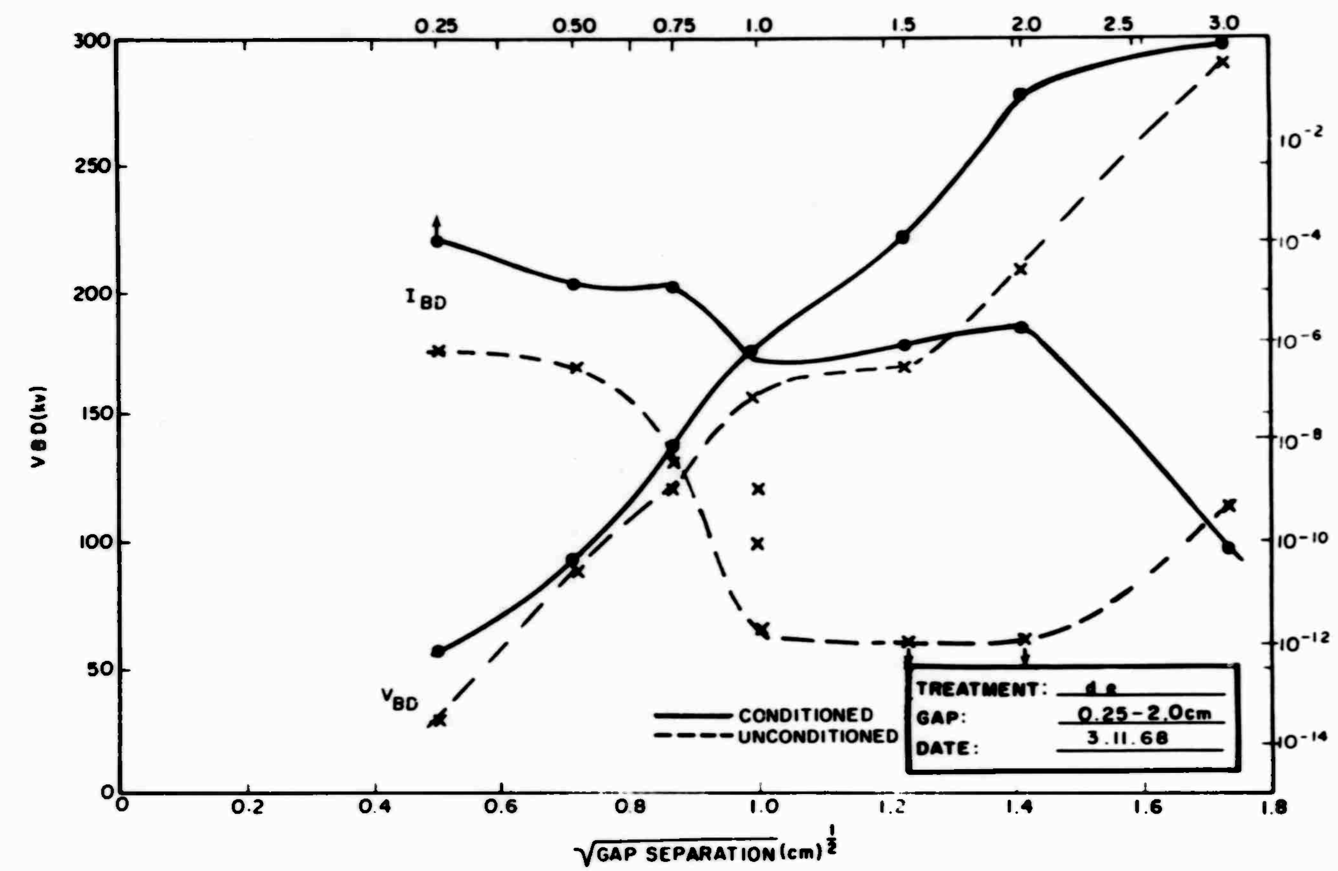

Figure 12. Breakdown Voltage vs Square Root Gap Separation for Treatment de

1-2919

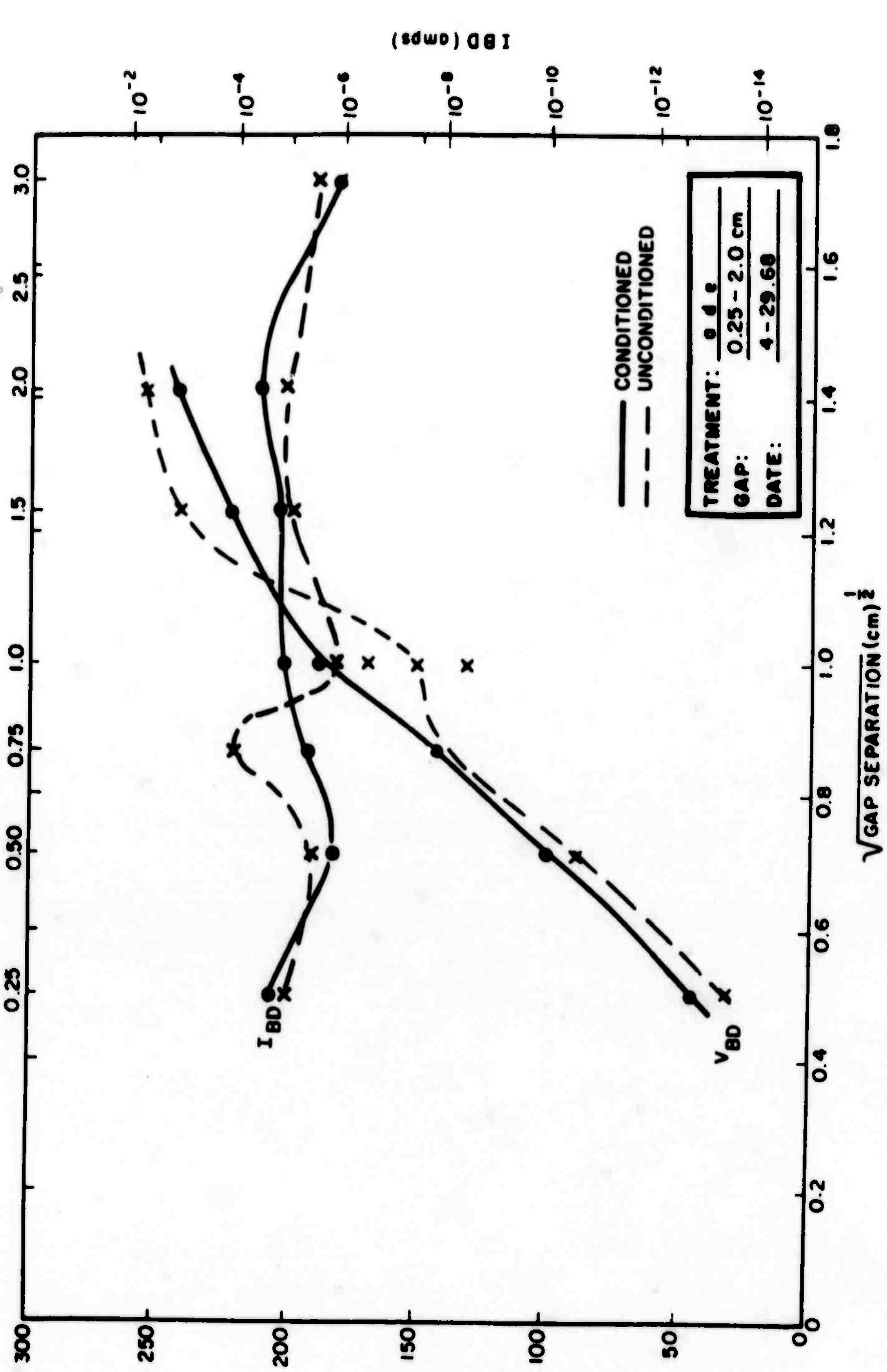

Figure 13. Breakdown Voltage vs Square Root Gap Separation for Treatment ade

1-2920

1-2921

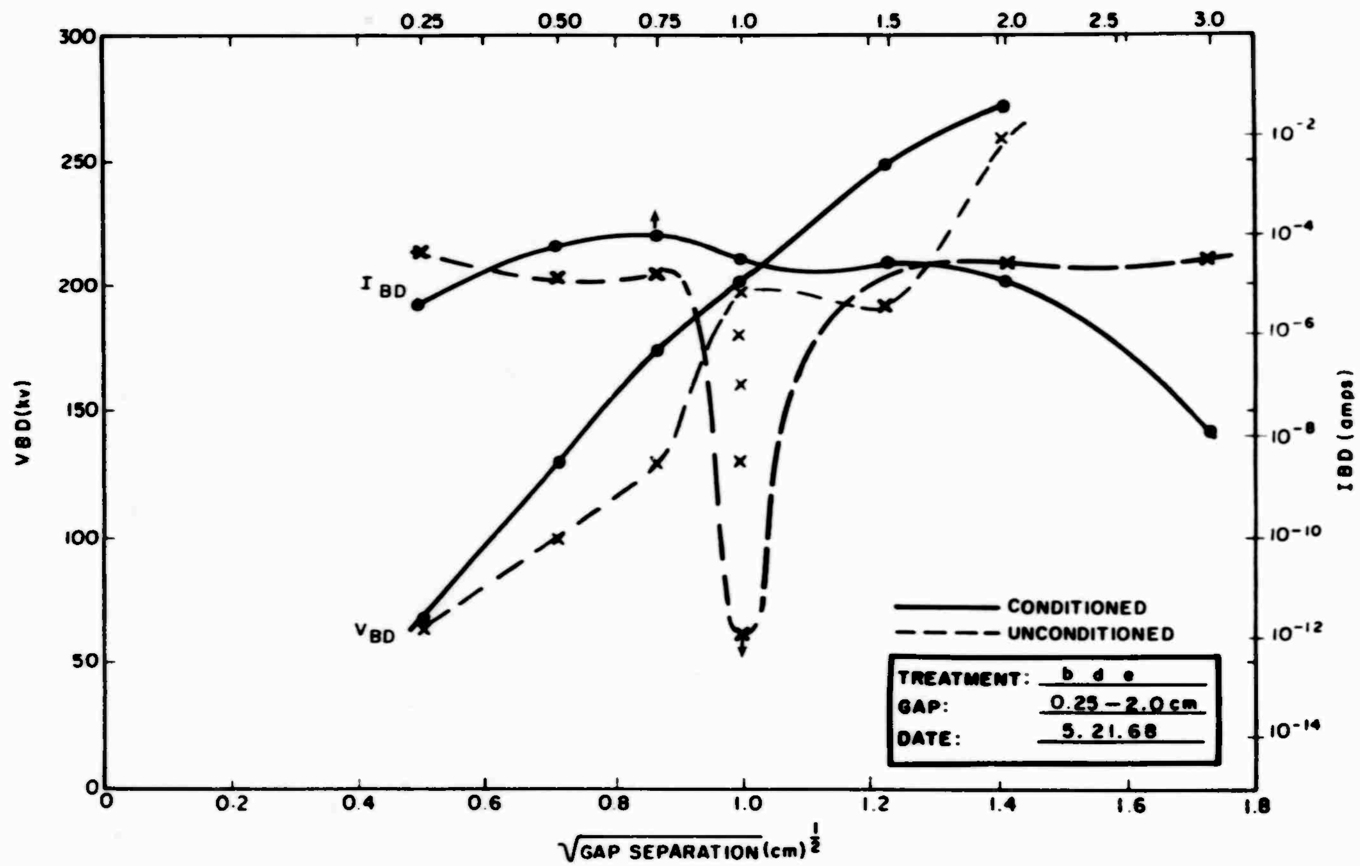

Figure 14. Breakdown Voltage vs Square Root Gap Separation for Treatment bde

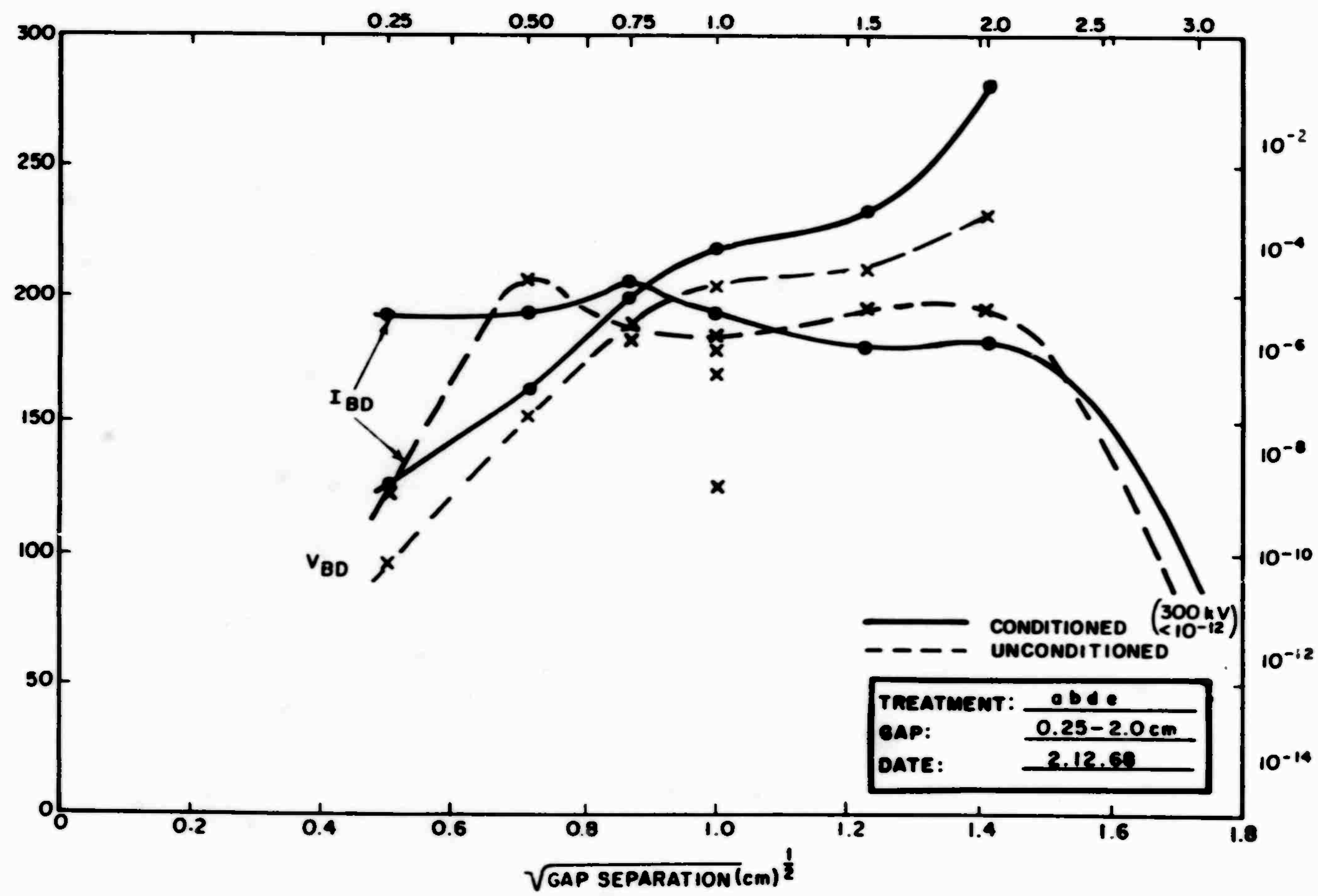

Figure 15. Breakdown Voltage vs Square Root Gap Separation for Treatment abde

1-2922

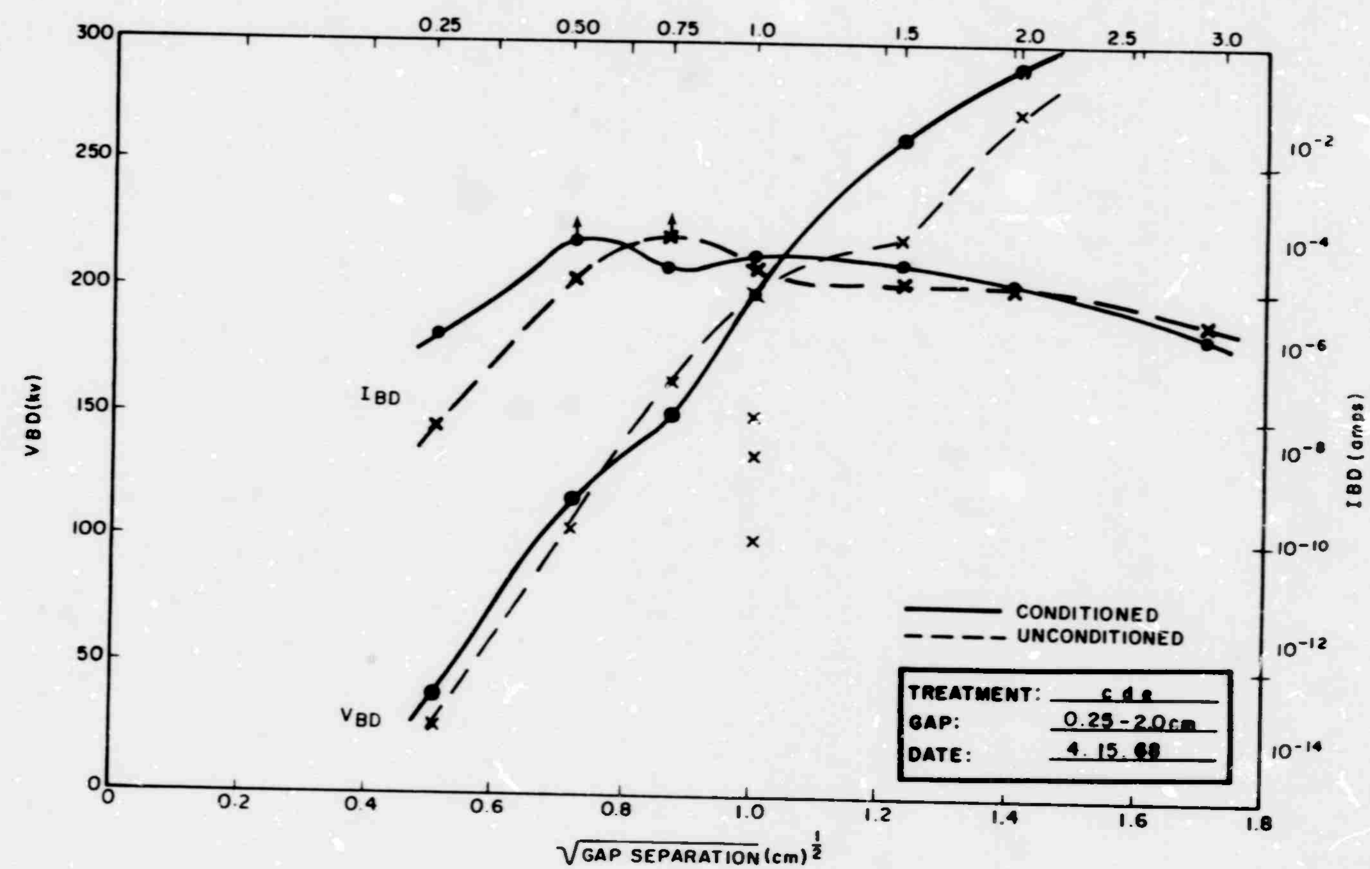

Figure 16. Breakdown Voltage vs Square Root Gap Separation for Treatment cde

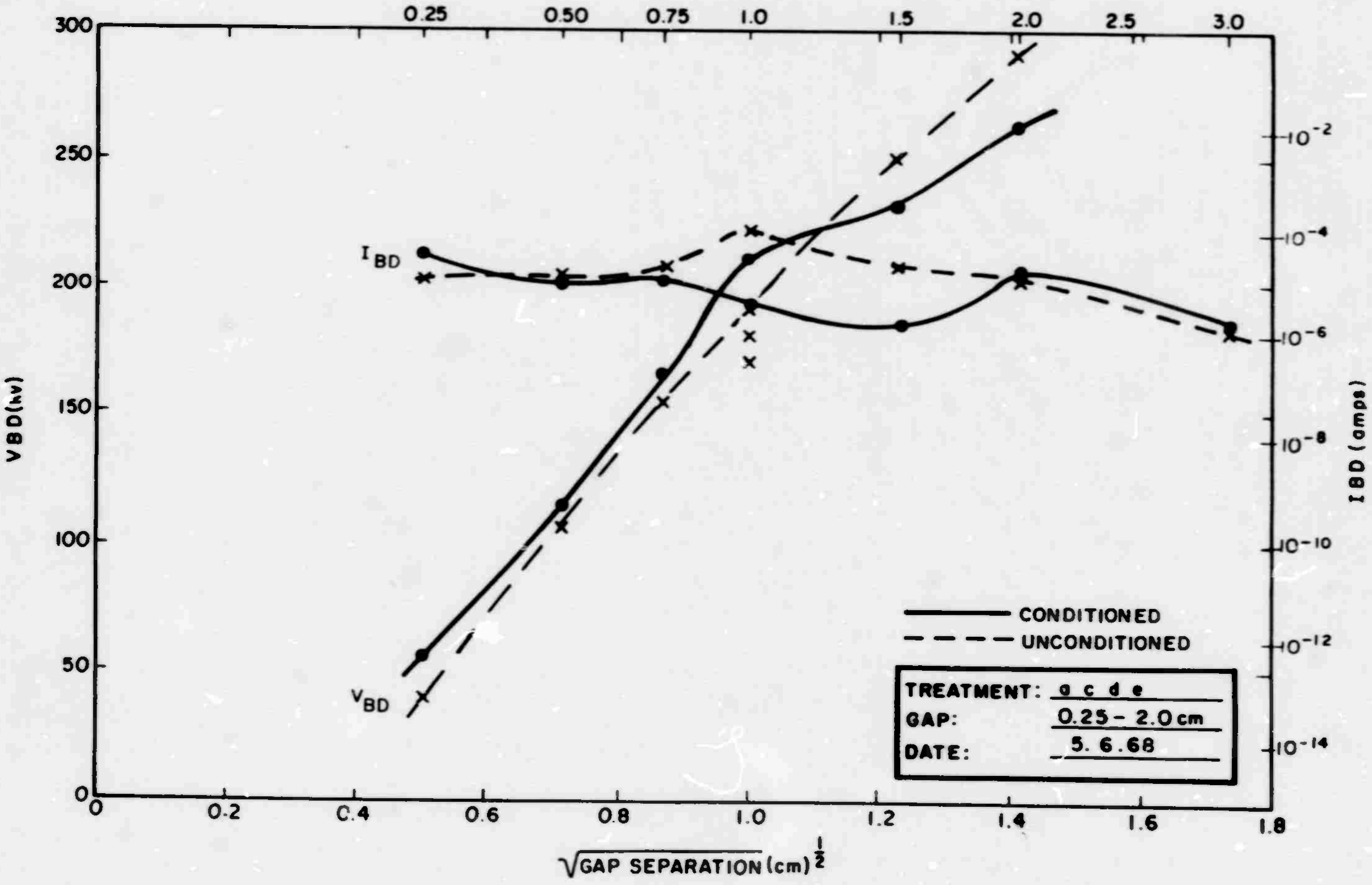

Figure 17. Breakdown Voltage vs Square Root Gap Separation for Treatment acde

1-2924

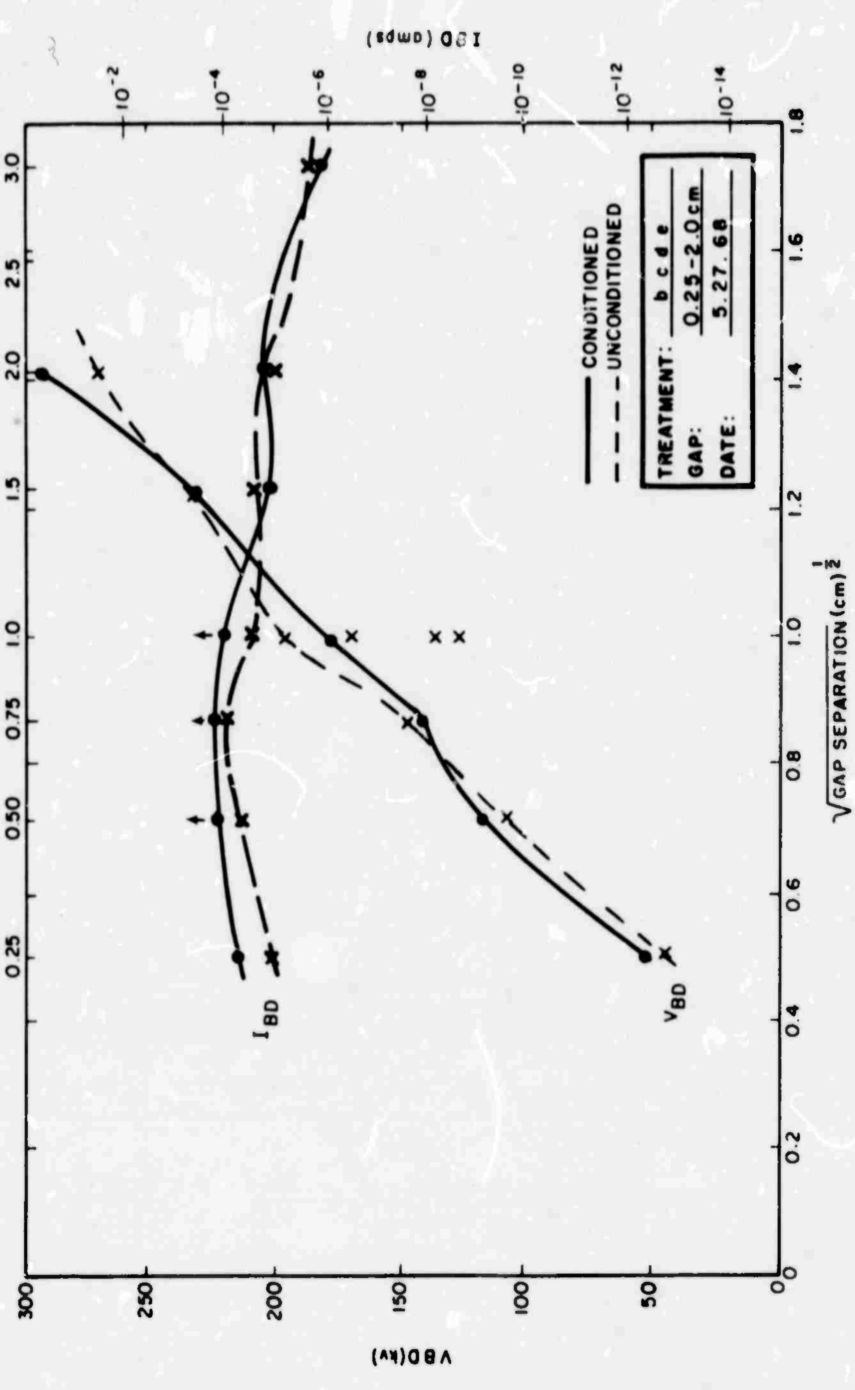

Figure 18. Breakdown Voltage vs Square Root Gap Separation for Treatment bcde

1-2925

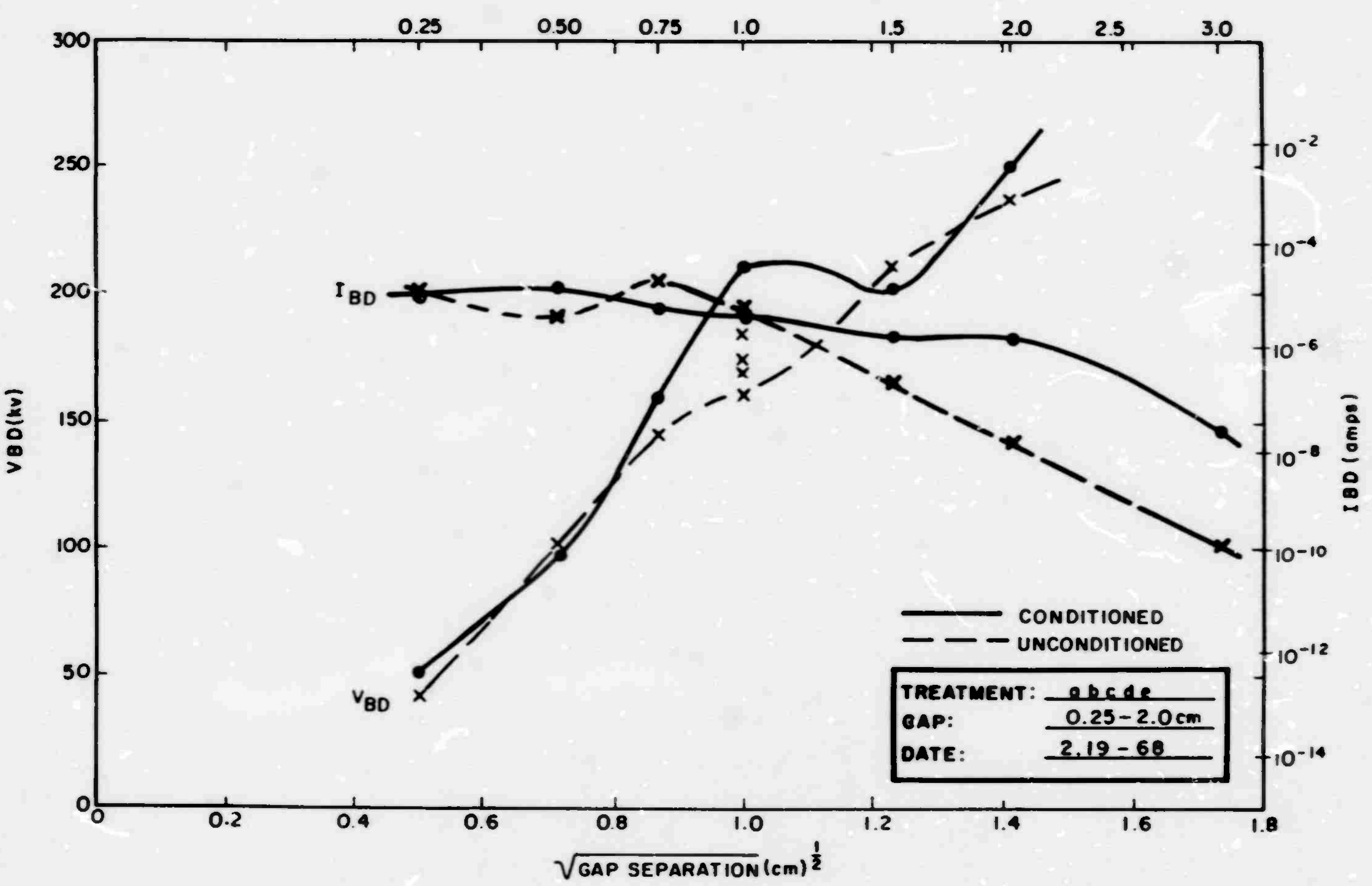

Figure 19. Breakdown Voltage vs Square Root Gap Separation for Treatment abcde

1-2926

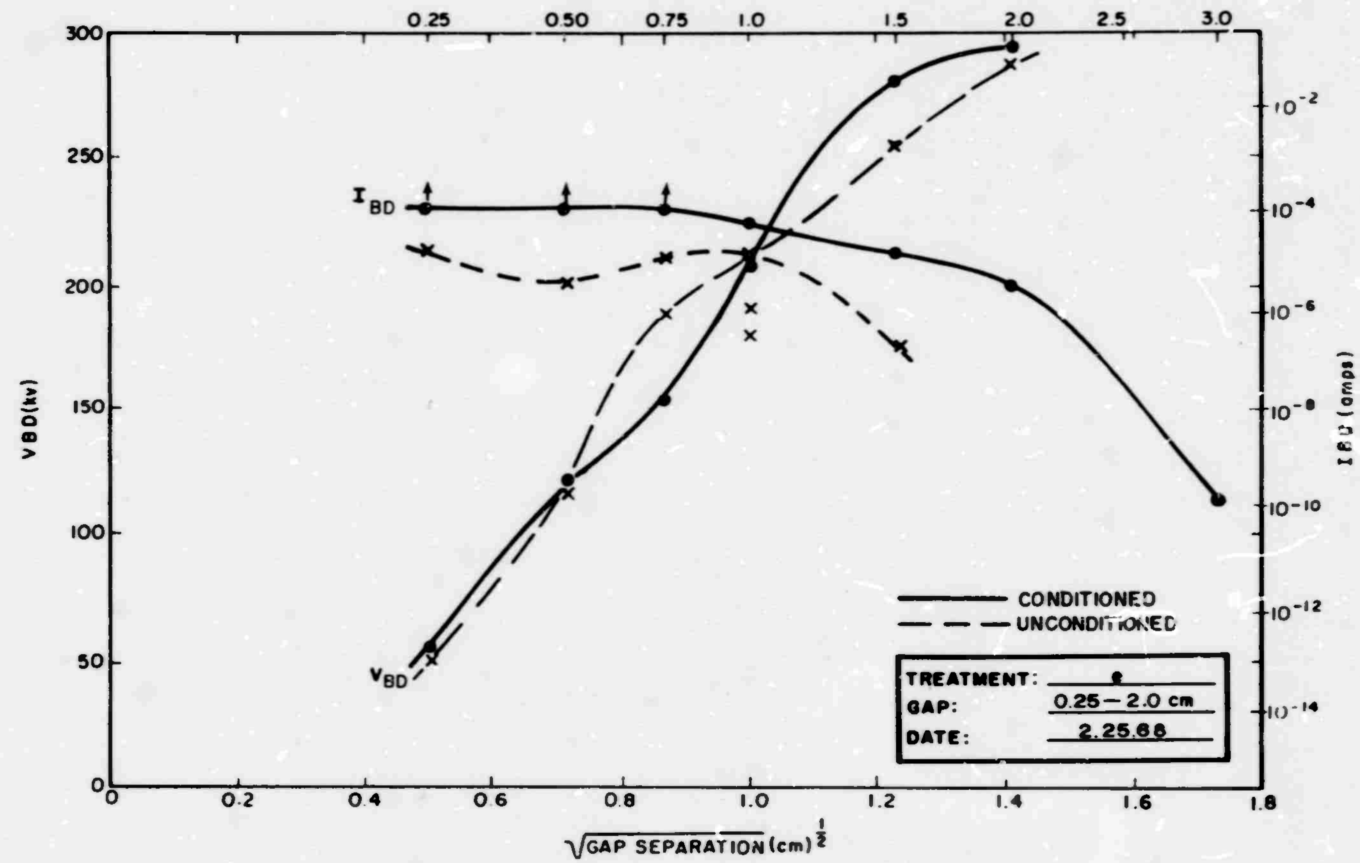

Figure 20. Breakdown Voltage vs Square Root Gap Separation for Treatment e

1-2927

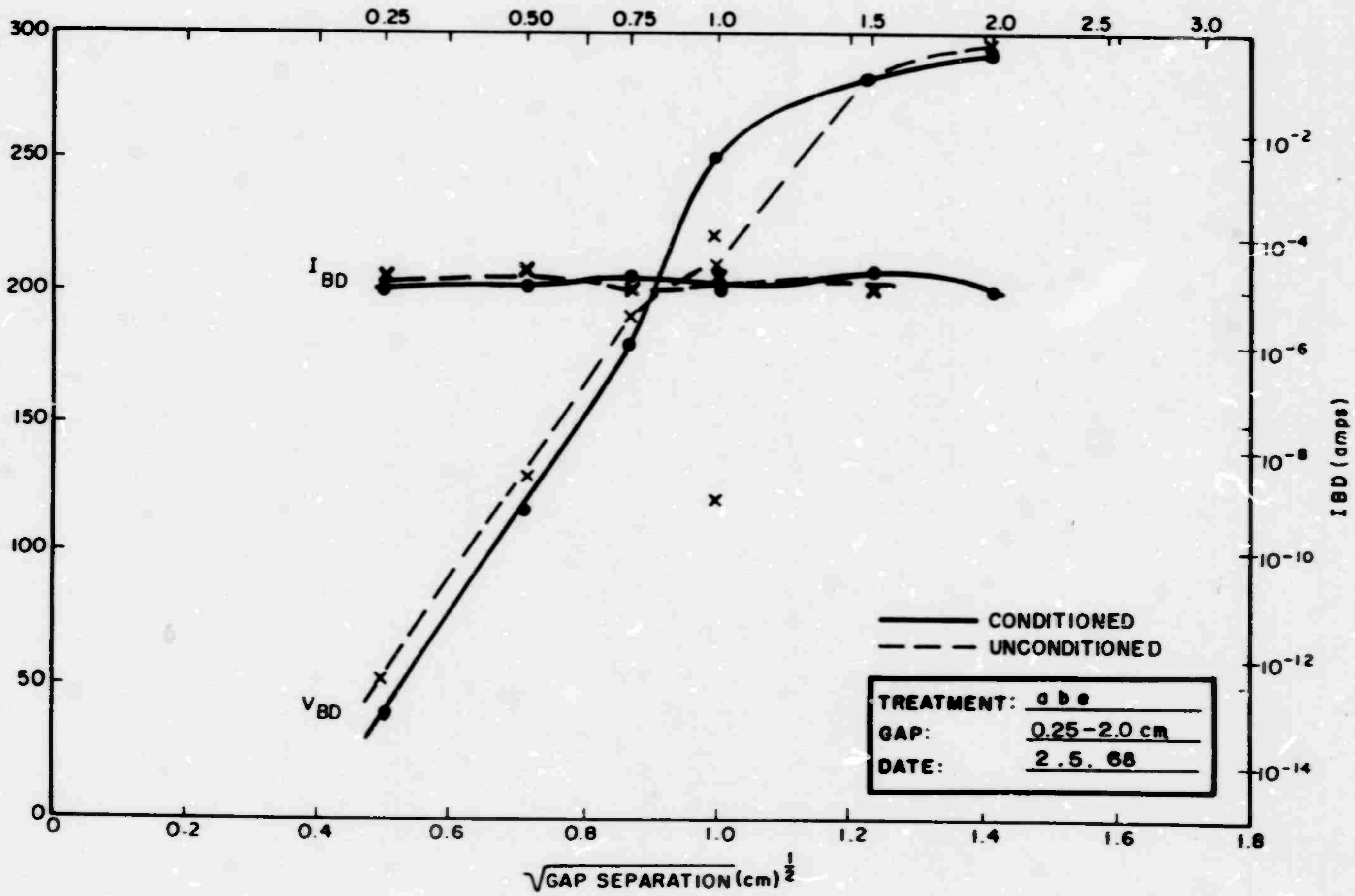

Figure 21. Breakdown Voltage vs Square Root Gap Separation for Treatment abe

1-2928

1-2929

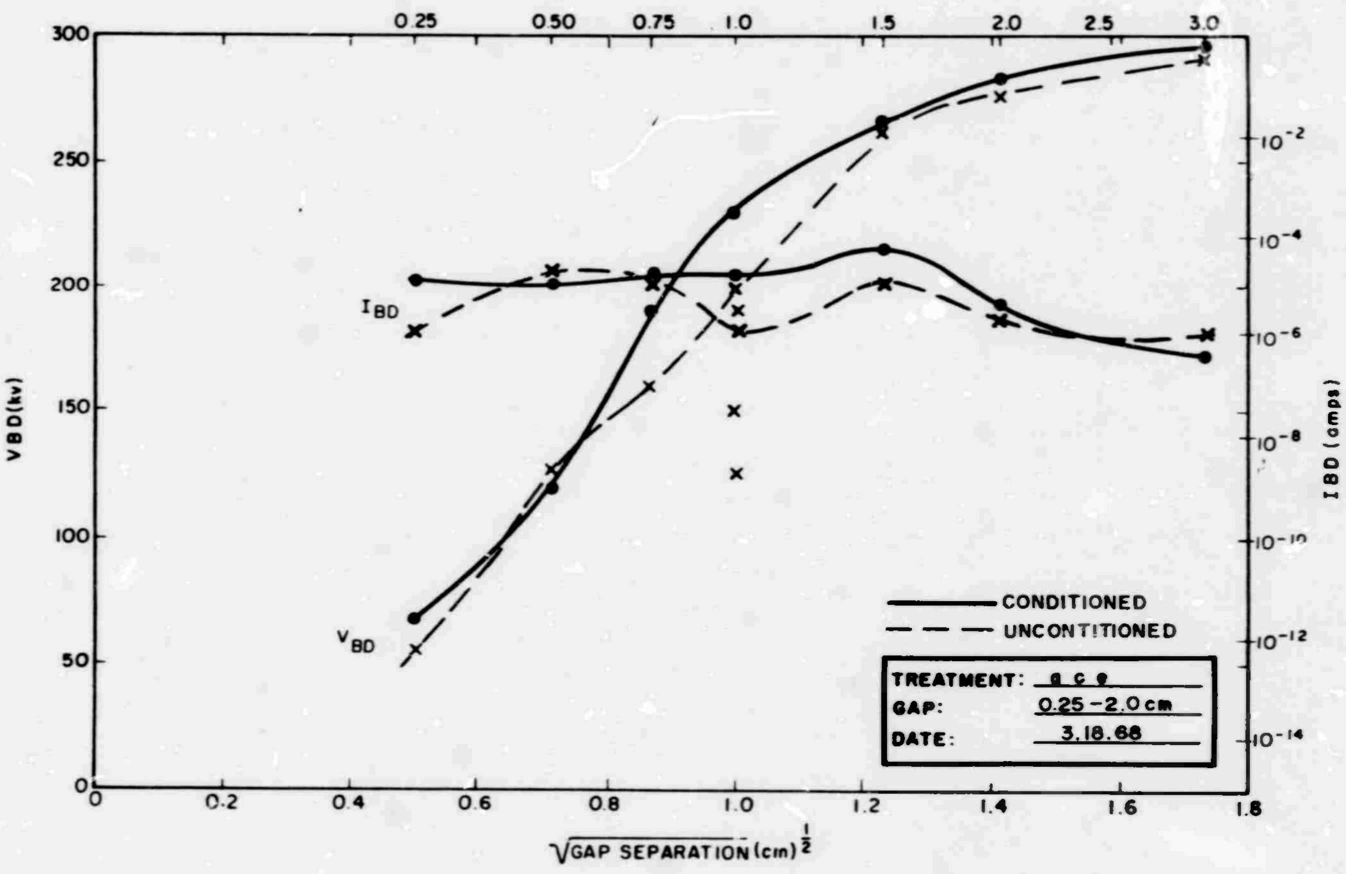

Figure 22. Breakdown Voltage vs Square Root Gap Separation for Treatment ace

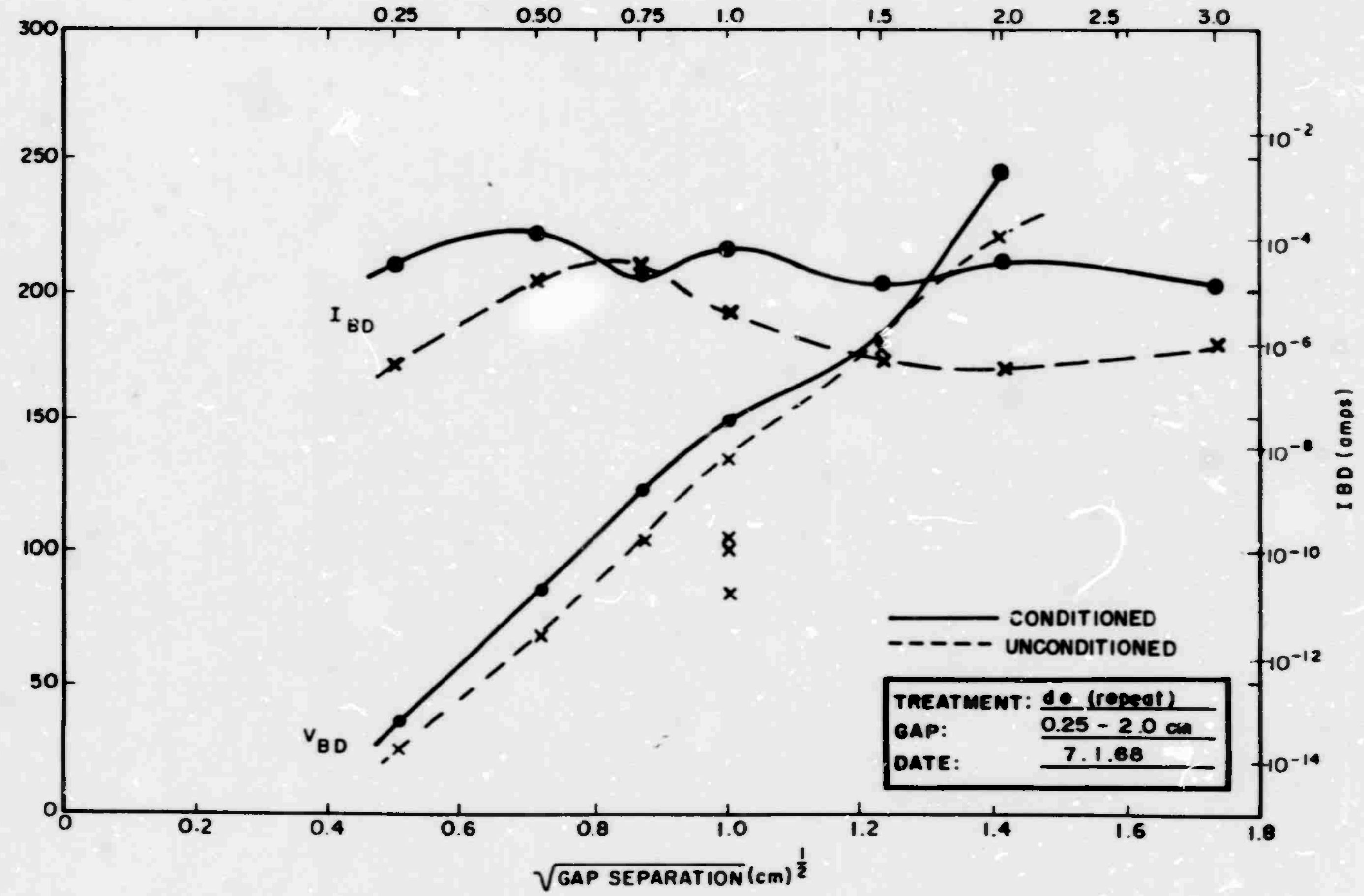

Figure 23. Breakdown Voltage vs Square Root Gap Separation for Treatment dc (repeat)

1-2930

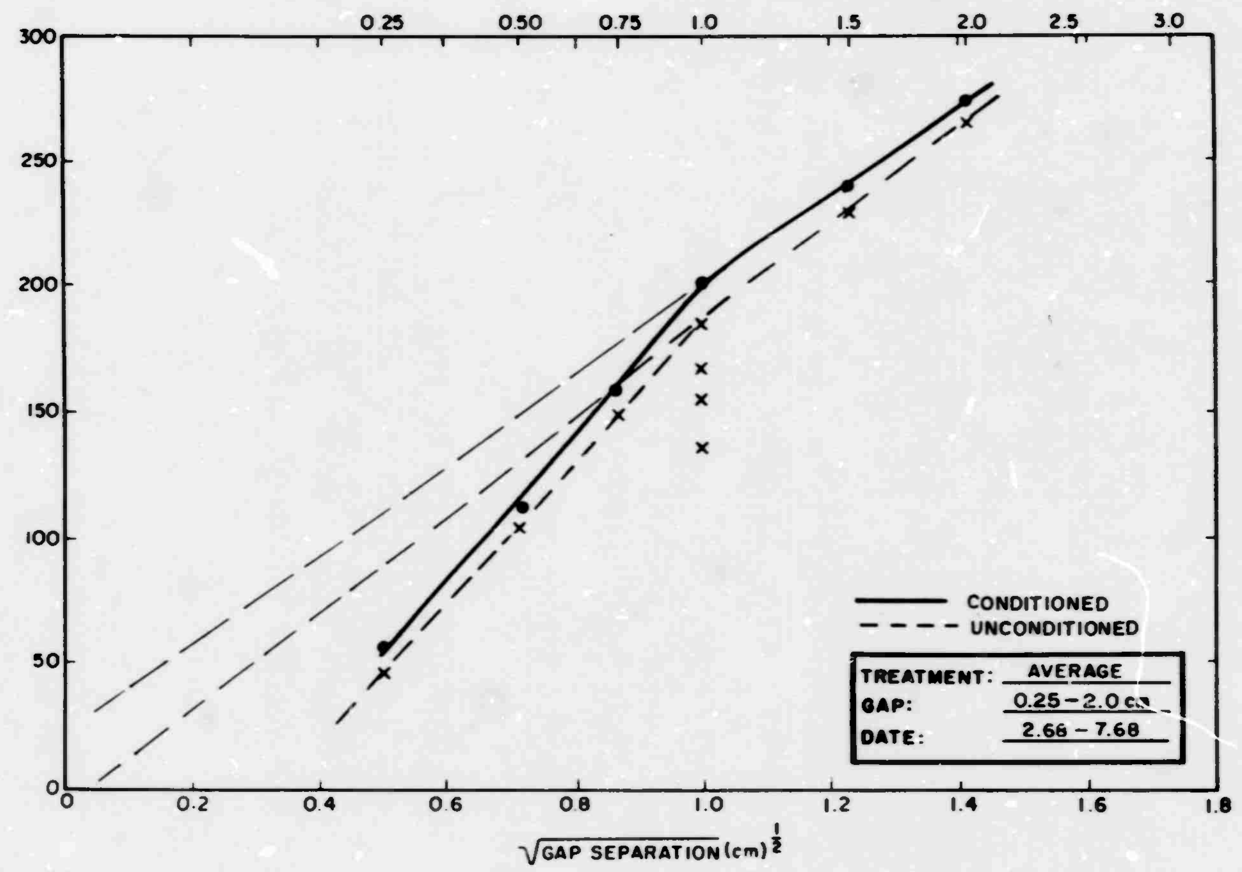

Figure 24. Breakdown Voltage vs $(Gap)^{1/2}$ for Average of All Treatments (First Days' Tests)

1-2931

1-2932

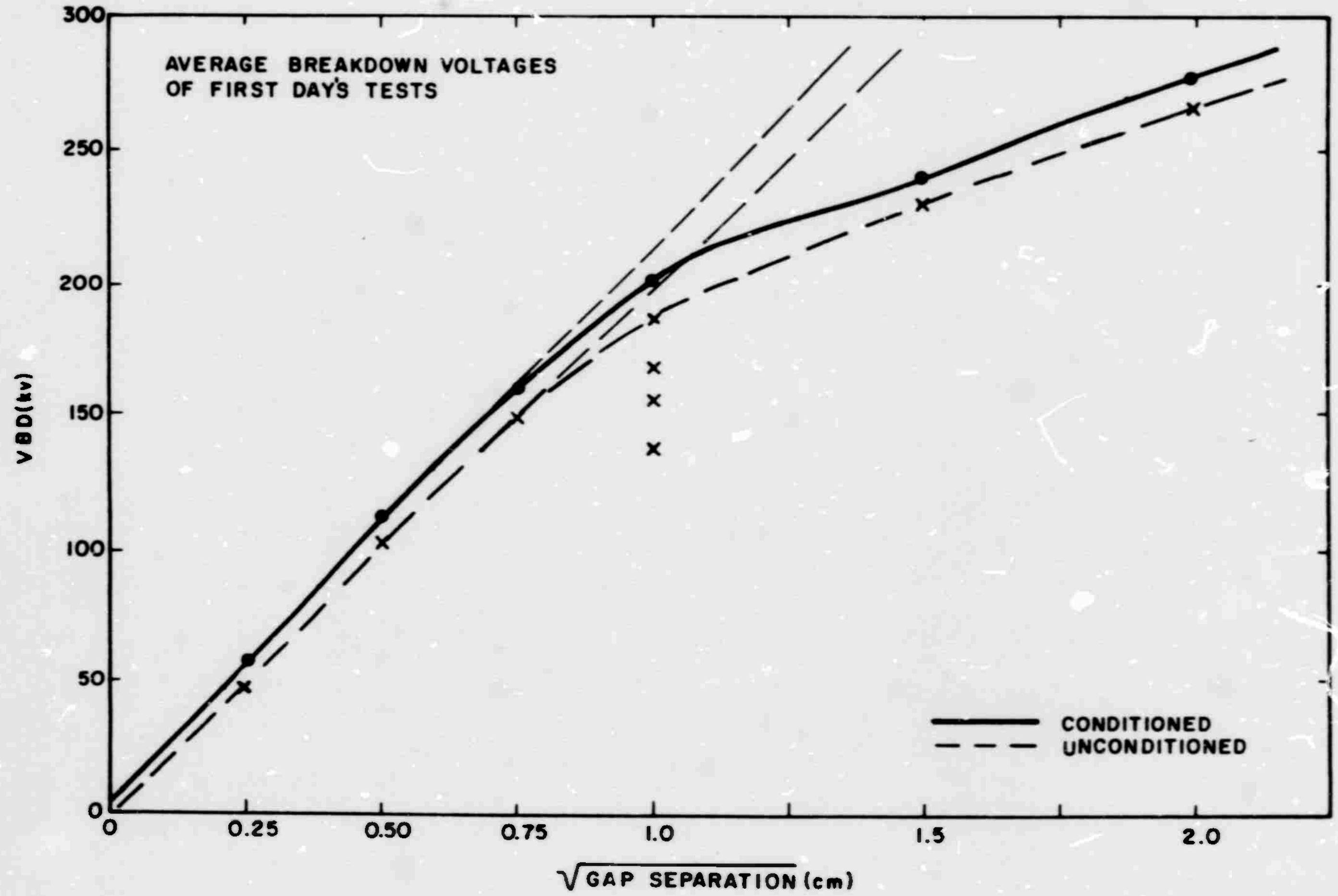

Figure 25. Linear Plot of Average Breakdown Voltage vs Gap for First Days' Tests

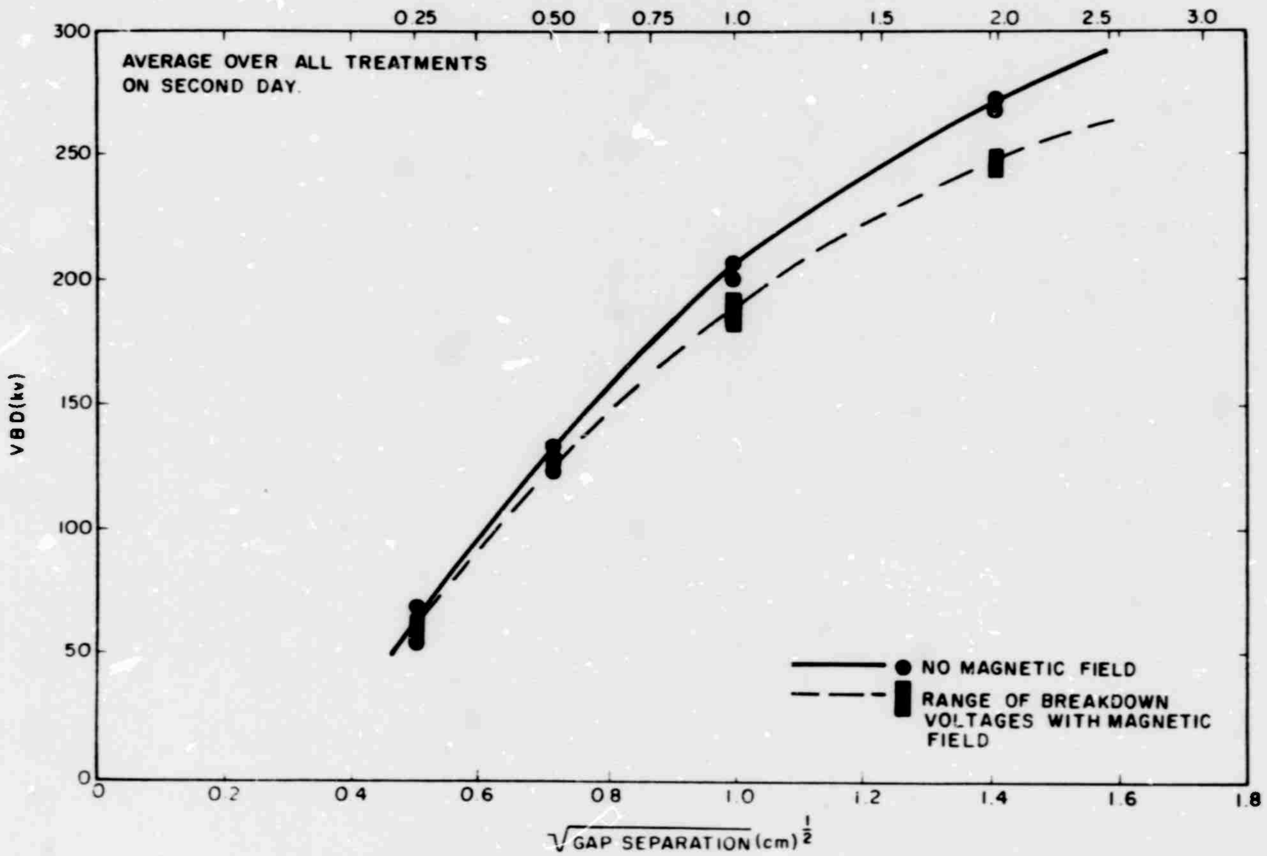

Figure 26. Breakdown Voltage vs $(\mathrm{Gap})^{1/2}$ for Second Days Tests (Magnetic Field Tests)

1-2933

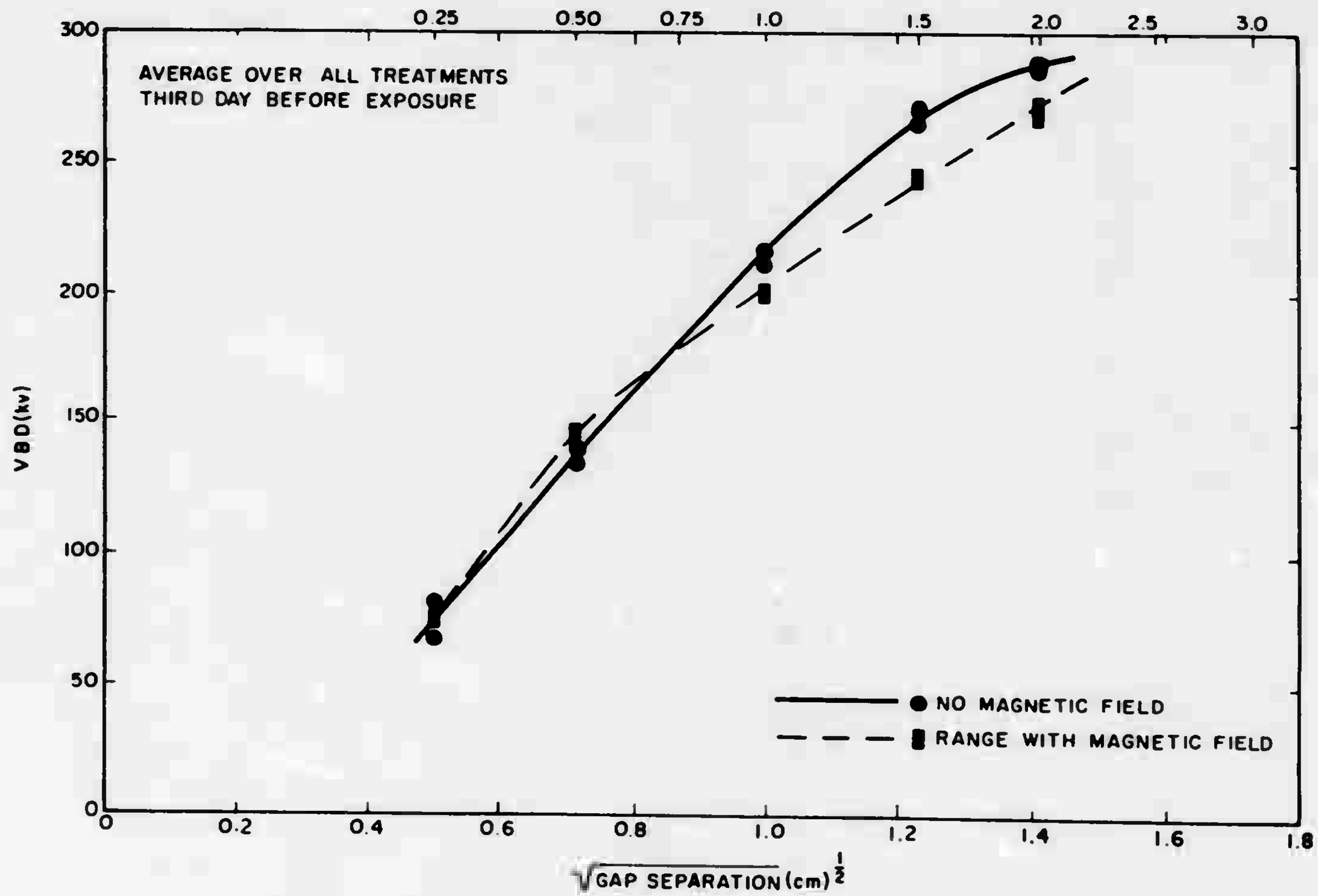

Figure 27. Breakdown Voltage vs $(Gap)^{1/2}$ for Third Days' Tests After Exposure

1-2934

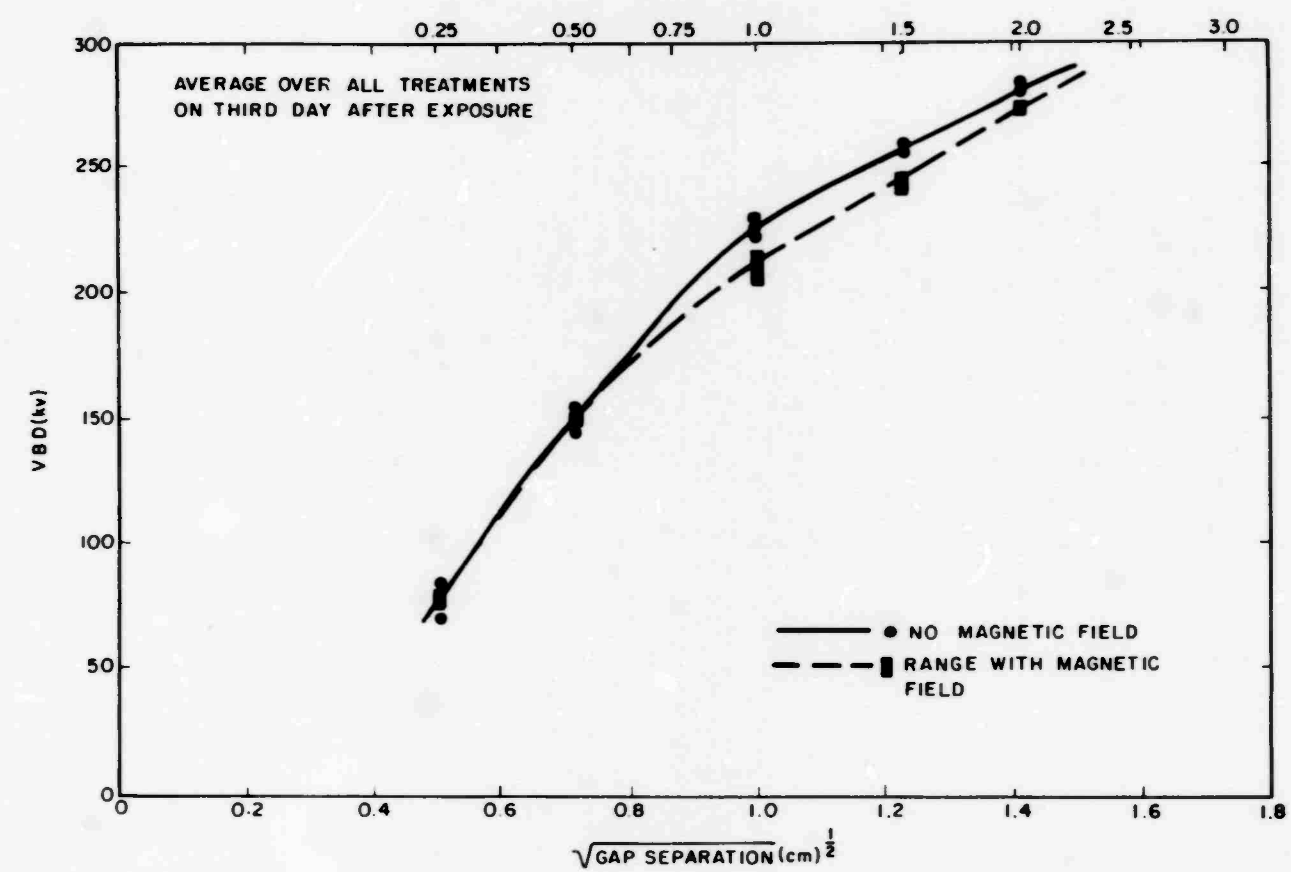

Figure 28. Breakdown Voltage vs $(Gap)^{1/2}$ for Third Days Tests Before Exposure

1-2935

1-2936

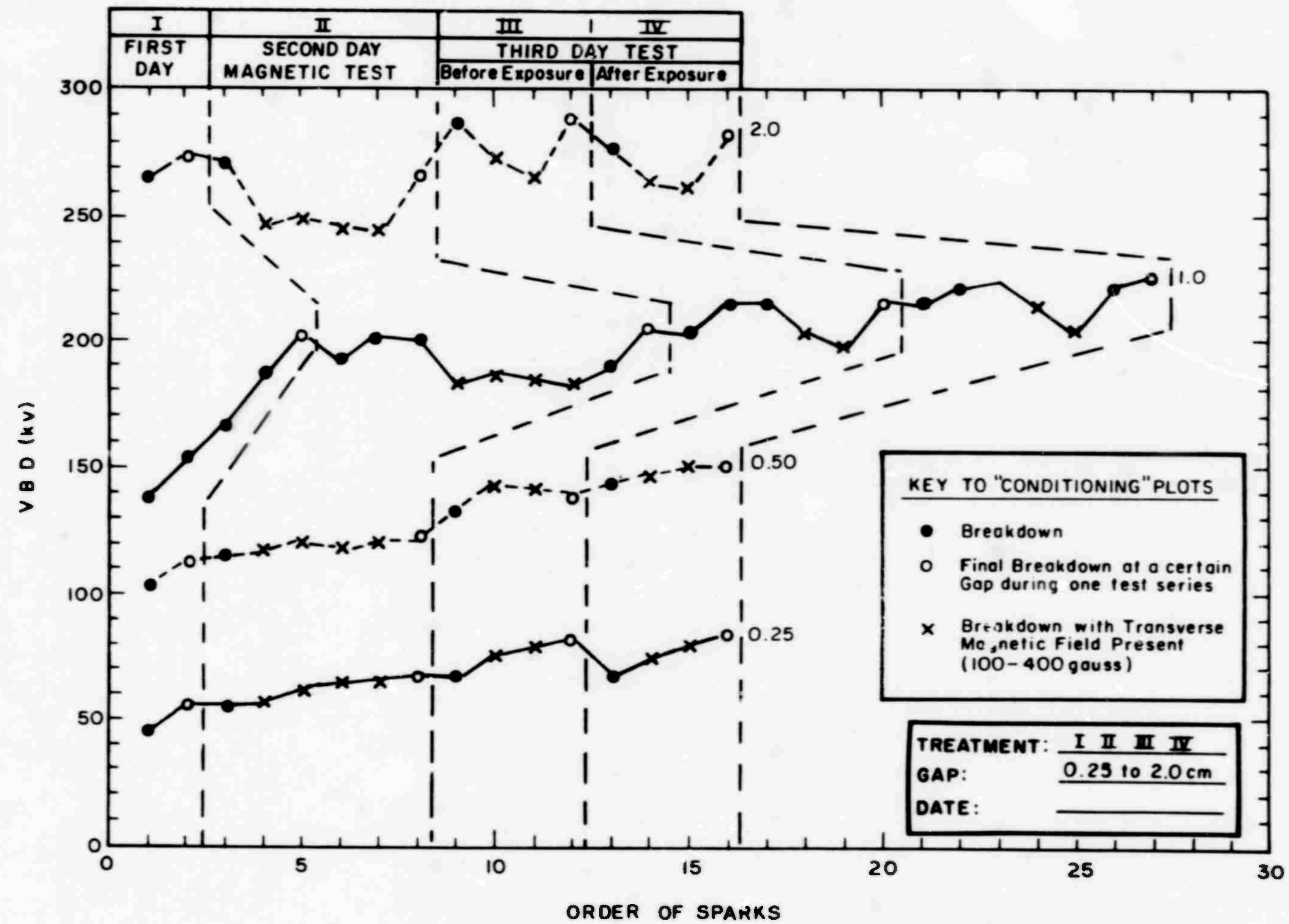

Figure 29. Sample Plot, Average Breakdown Voltage Over 16 Treatments

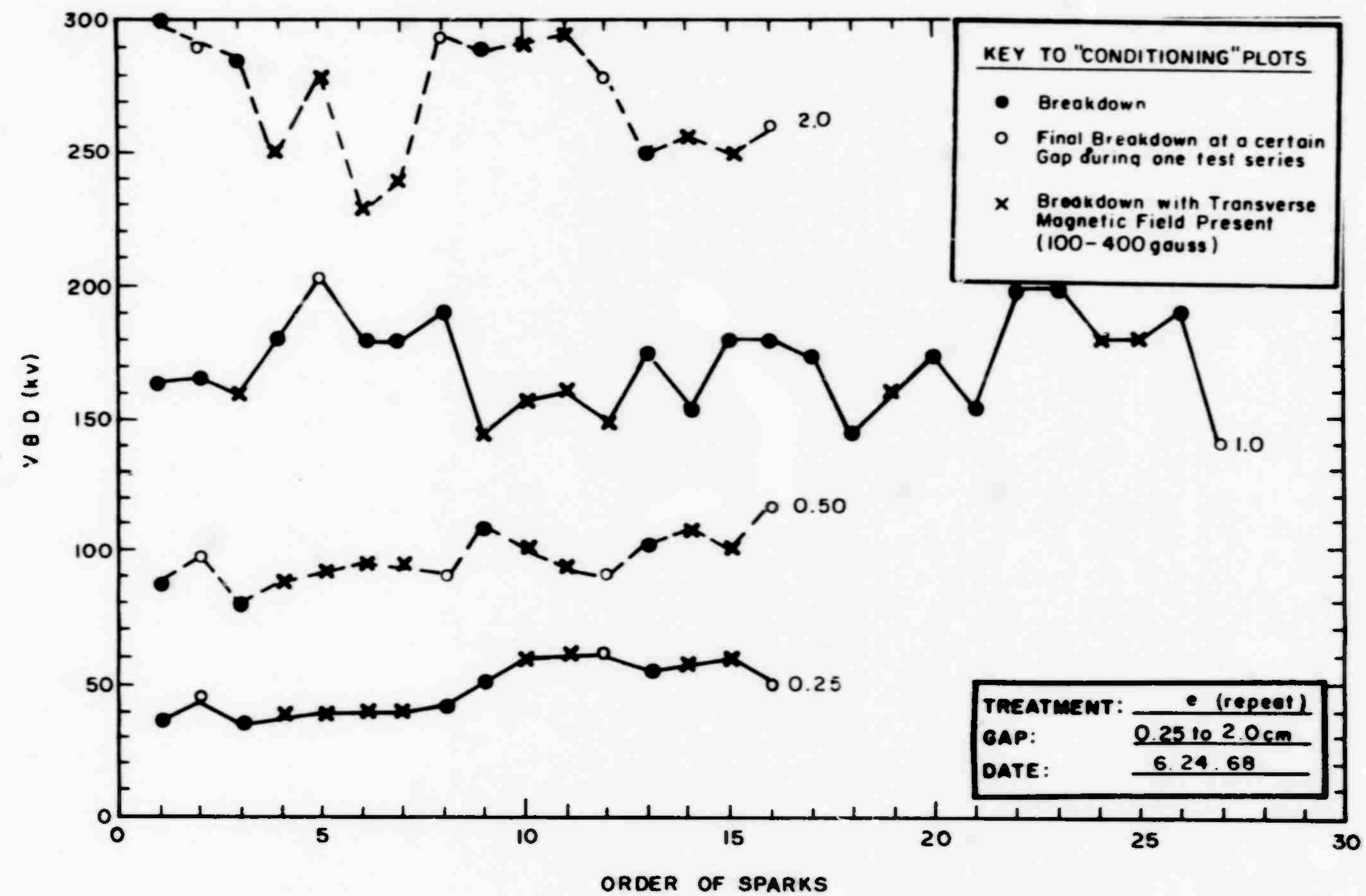

Figure 30. Breakdown Voltage Conditioning Plot for Treatment e (repeat)

1-2937

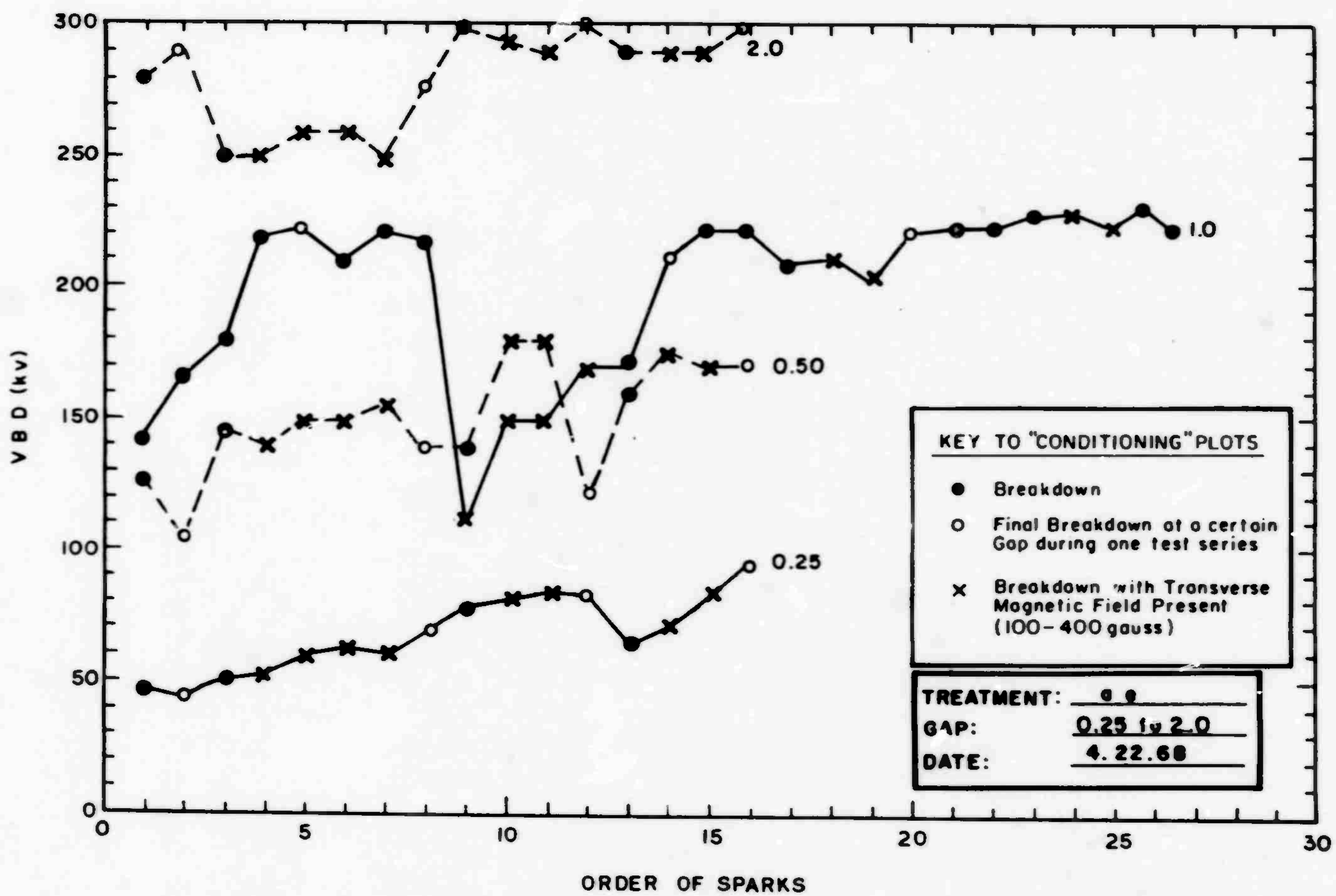

Figure 31. Breakdown Voltage Conditioning Plot for Treatment ae

1-2938

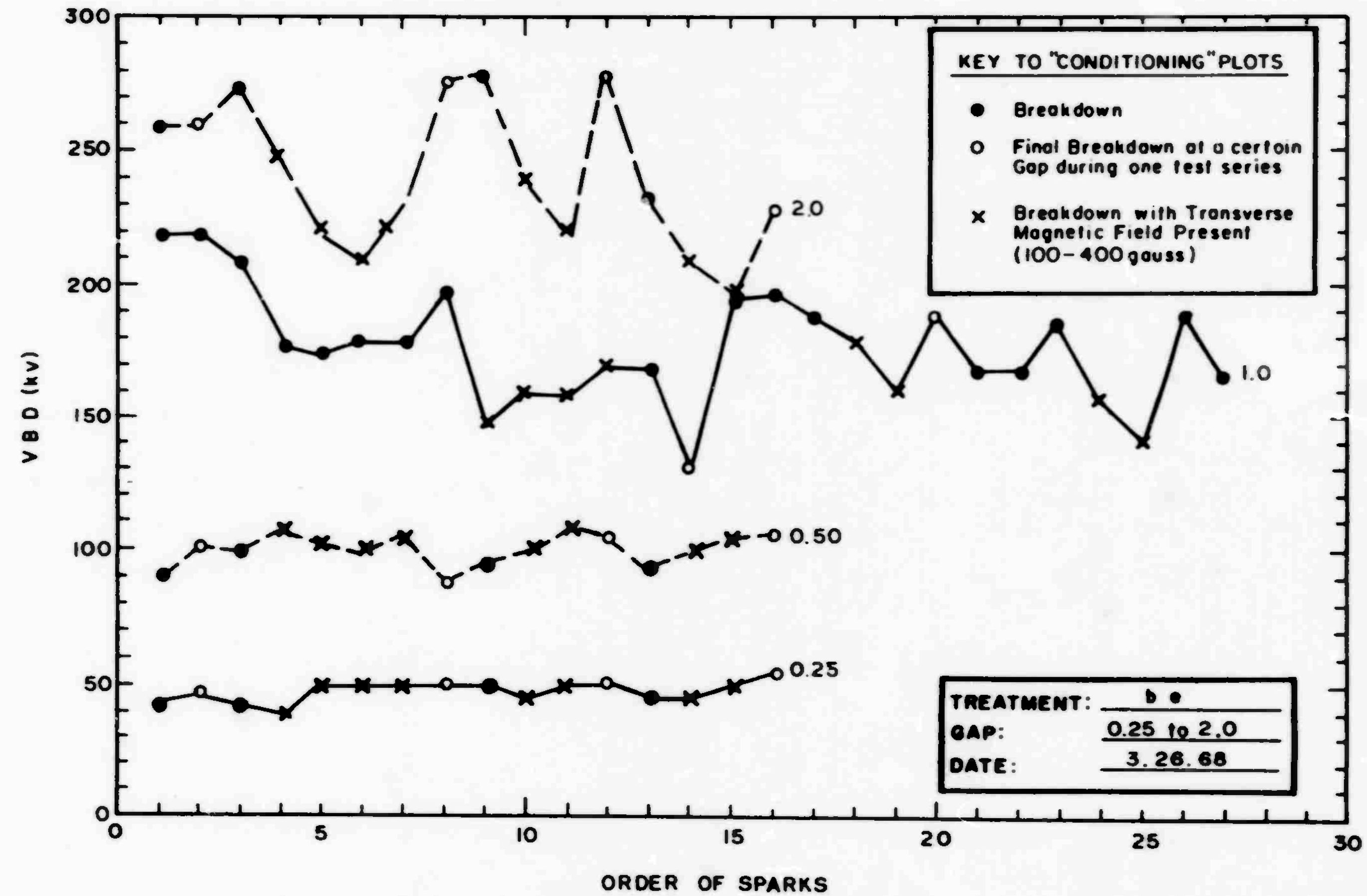

Figure 32. Breakdown Voltage Conditioning Plot for Treatment be

1-2939

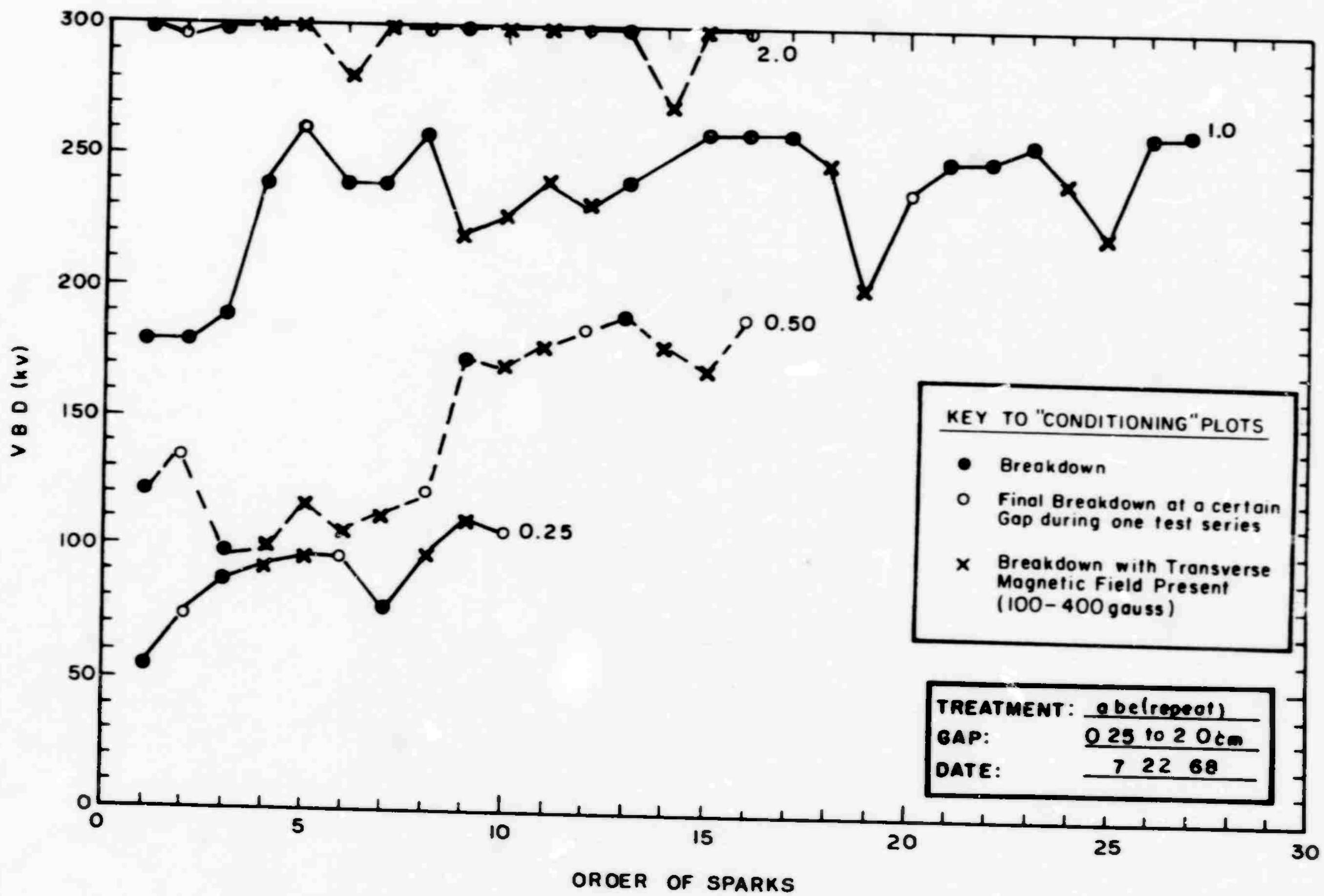

Figure 33. Breakdown Voltage Conditioning Plot for Treatment abe (repeat)

1-2940

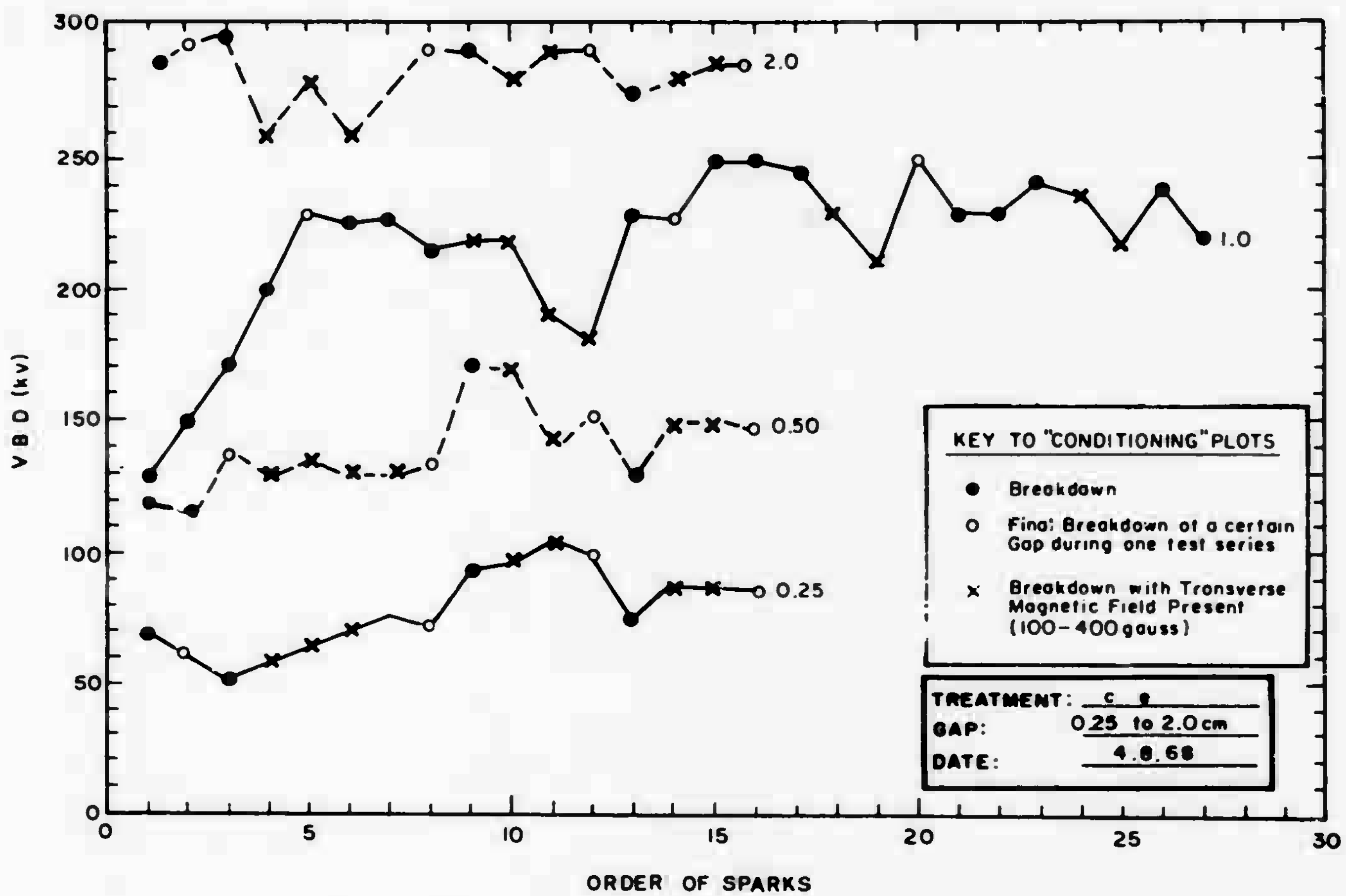

Figure 34. Breakdown Voltage Conditioning Plot for Treatment ce

1-2941

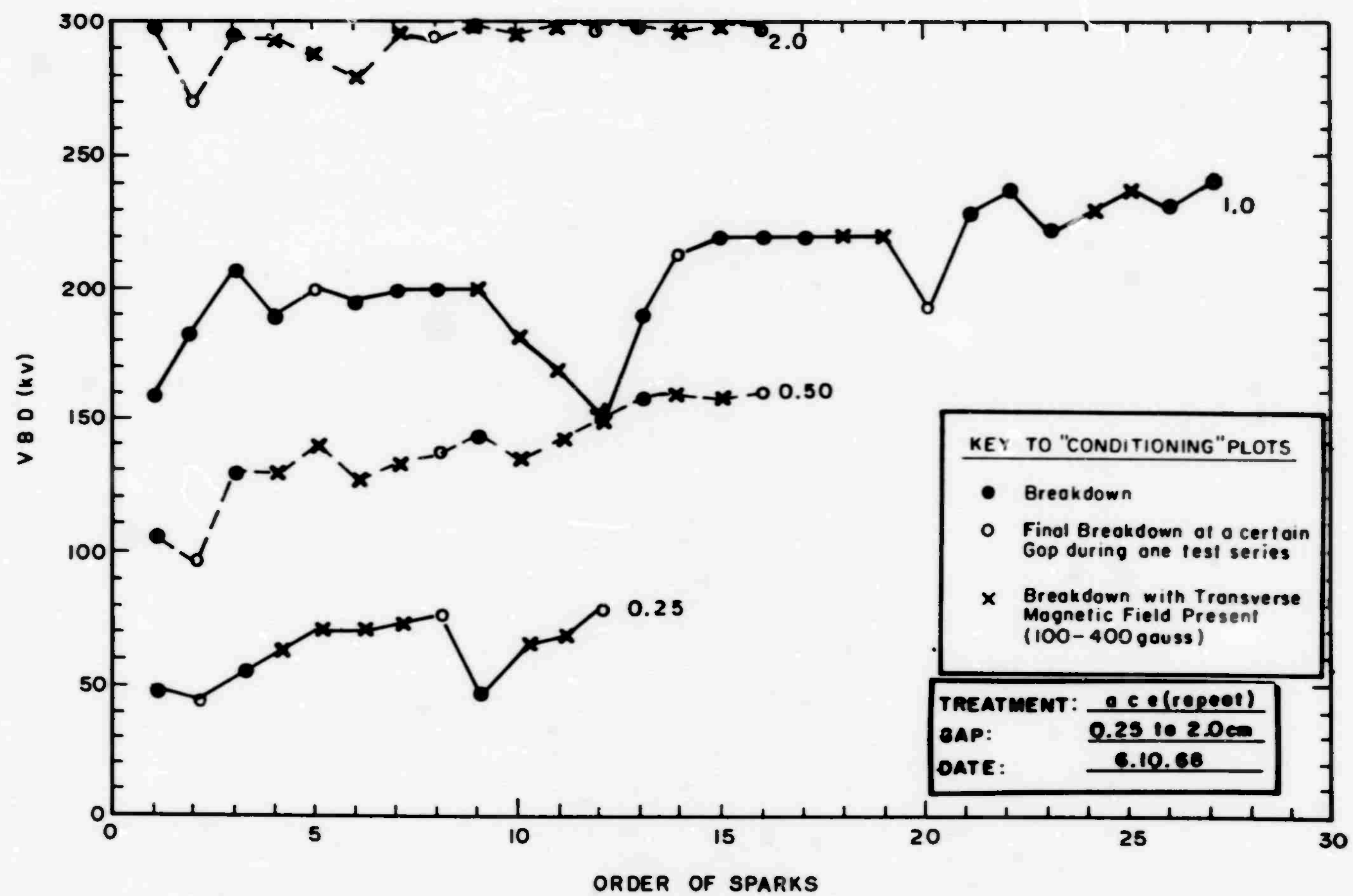

Figure 35. Breakdown Voltage Conditioning Plot for Treatment ace (repeat)

1-2942

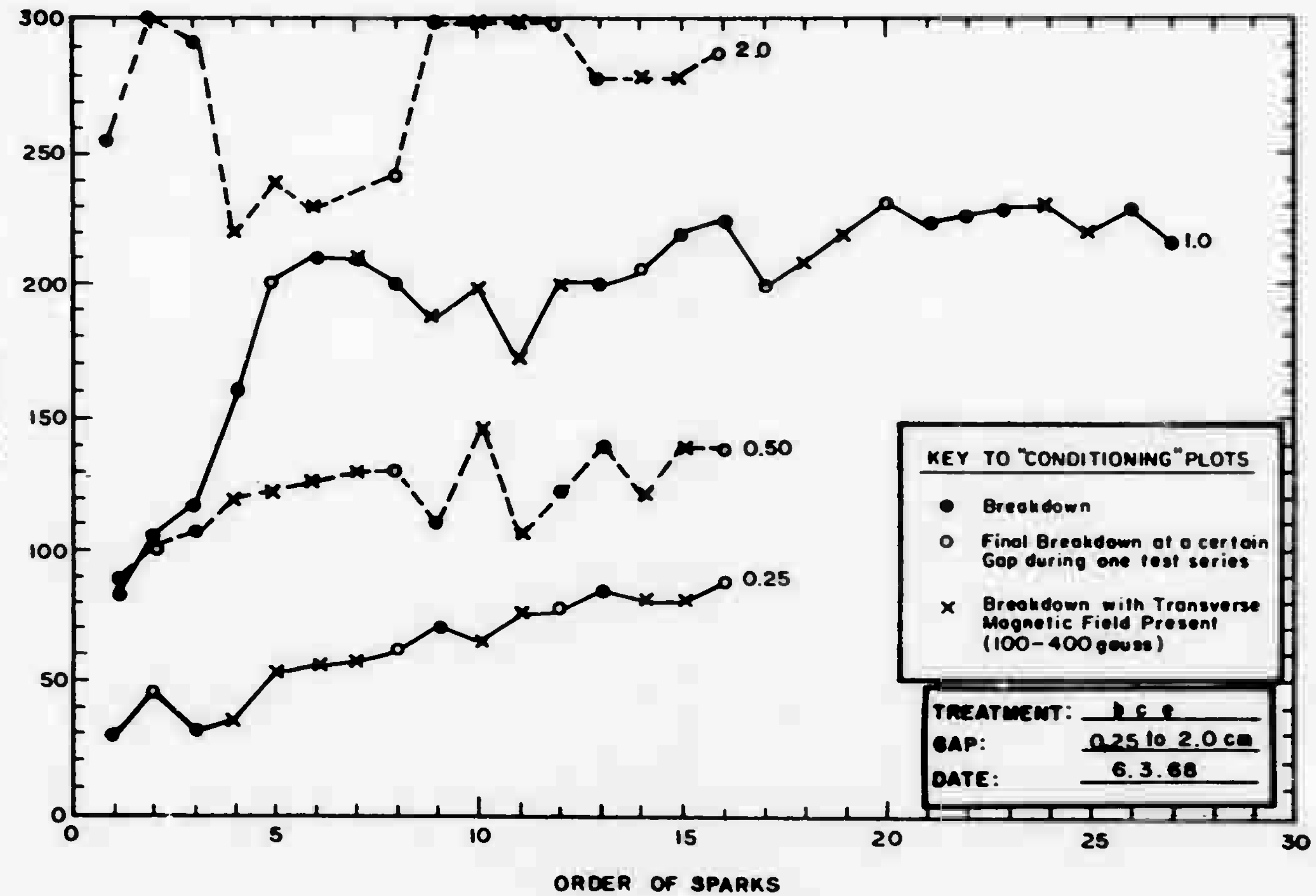

Figure 36. Breakdown Voltage Conditioning Plot for Treatment bce

1-2943

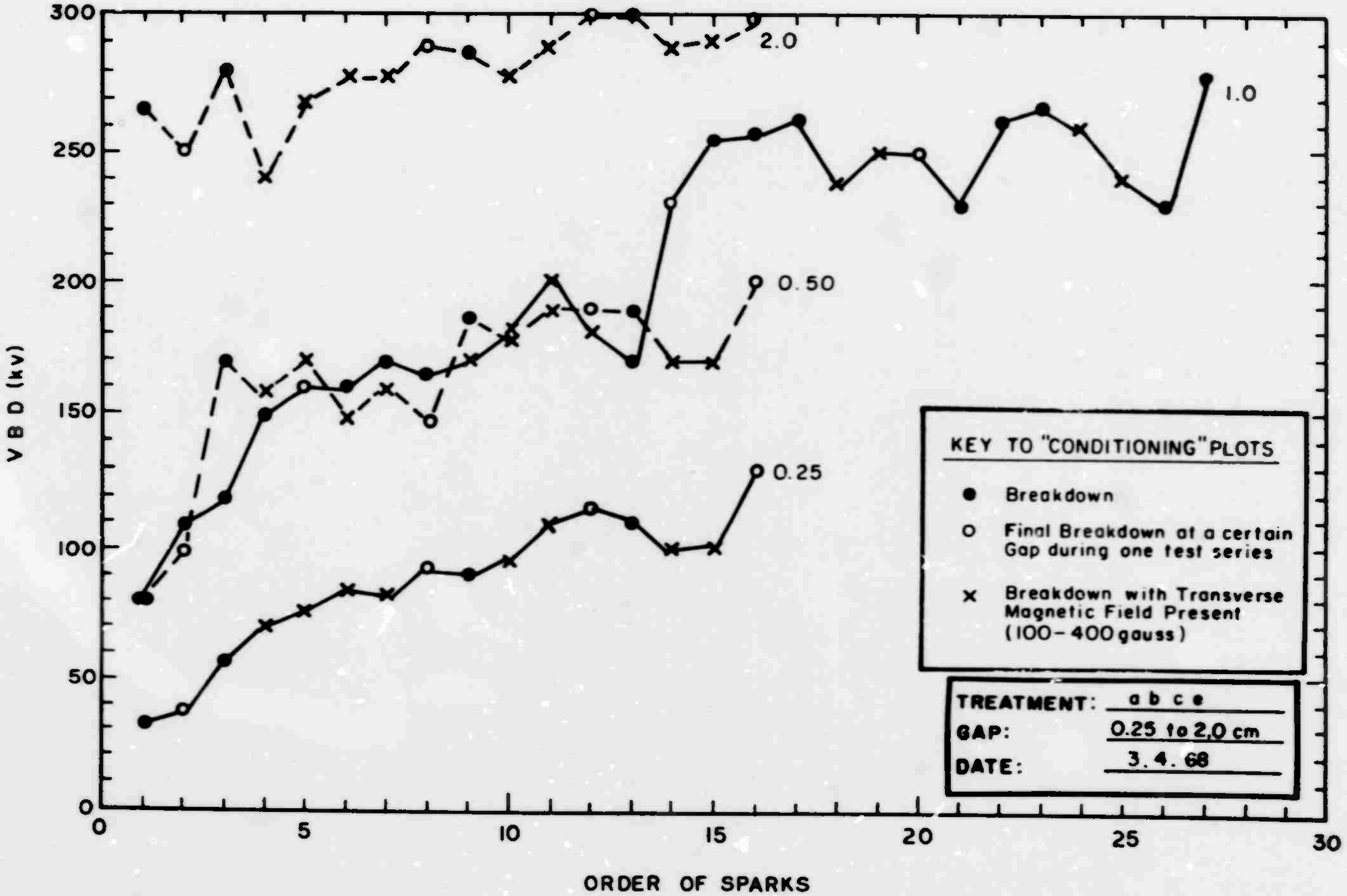

Figure 37. Breakdown Voltage Conditioning Plot for Treatment abce

1-2944

1-2945

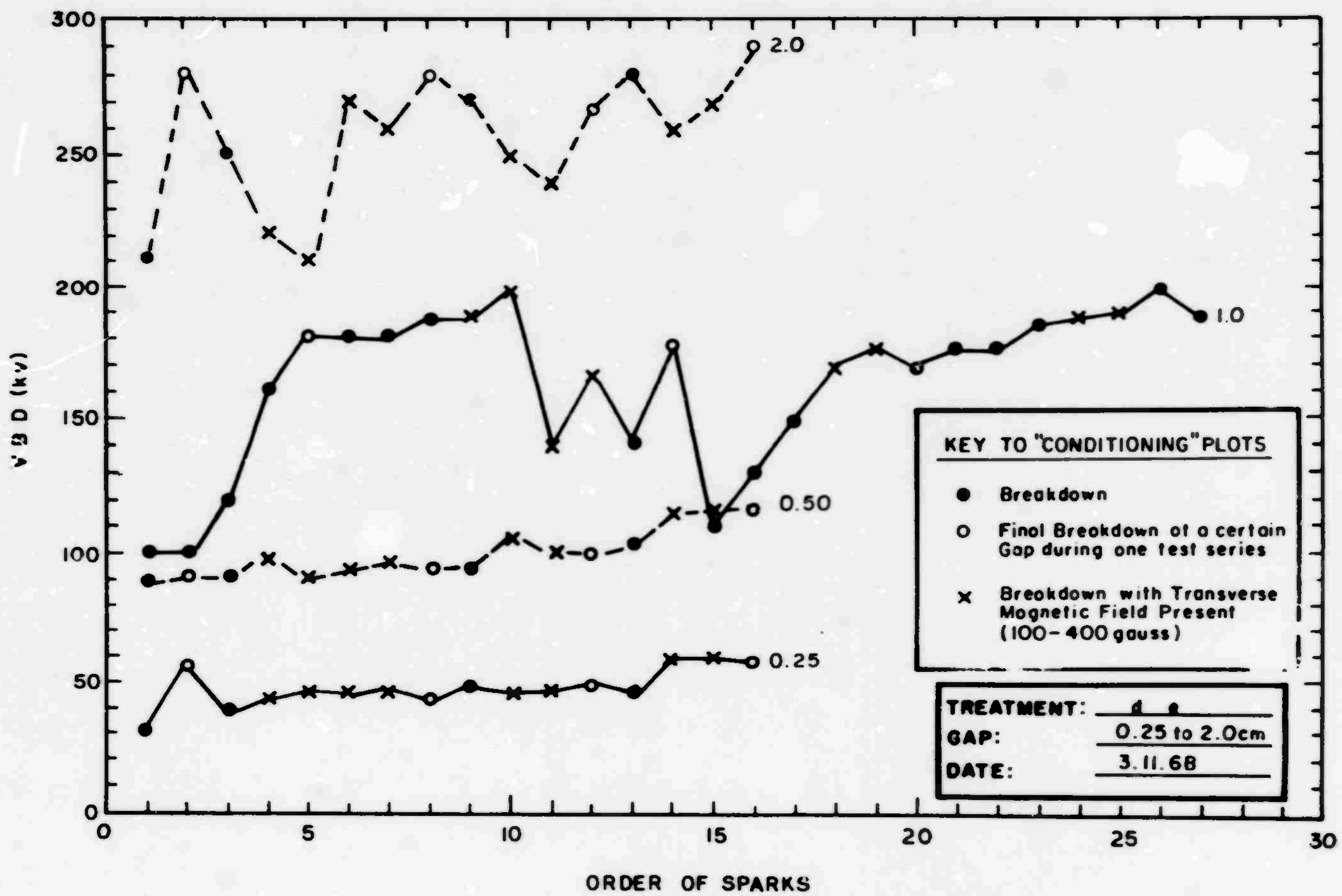

Figure 38. Breakdown Voltage Conditioning Plot for Treatment de

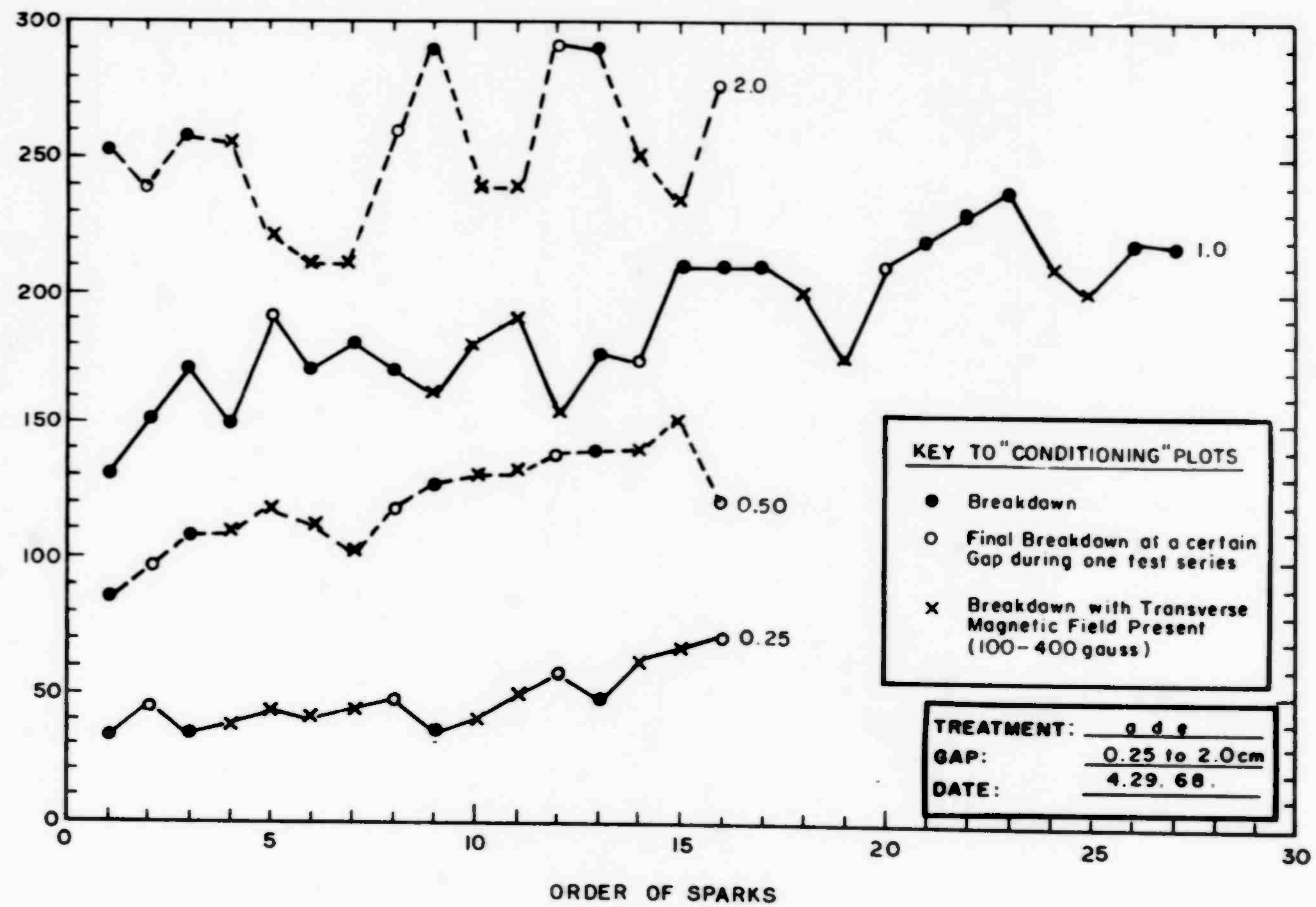

Figure 39. Breakdown Voltage Conditioning Plot for Treatment ade

1-2946

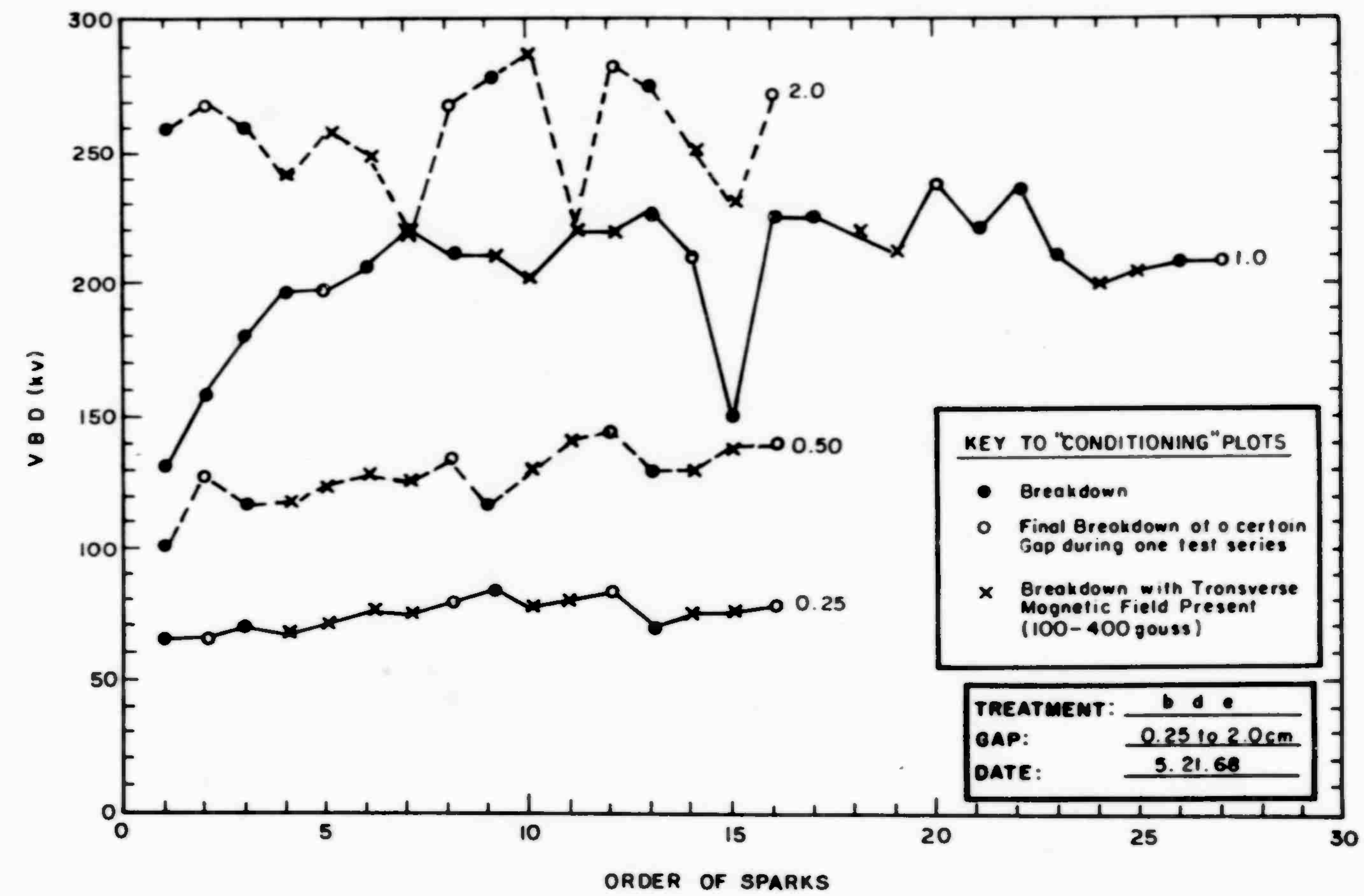

Figure 40. Breakdown Voltage Conditioning Plot for Treatment bde

1-2947

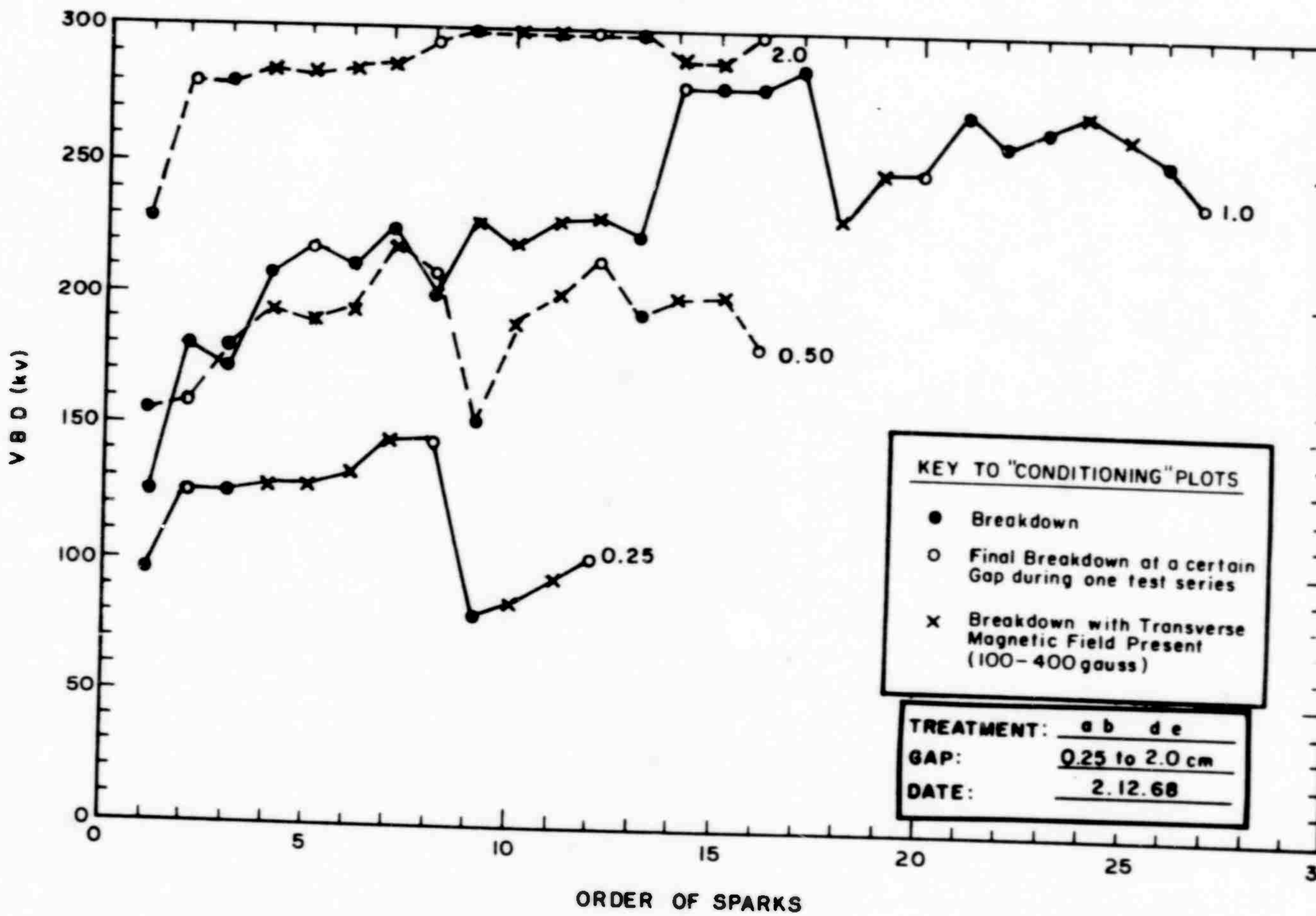

Figure 41. Breakdown Voltage Conditioning Plot for Treatment abde

1-2948

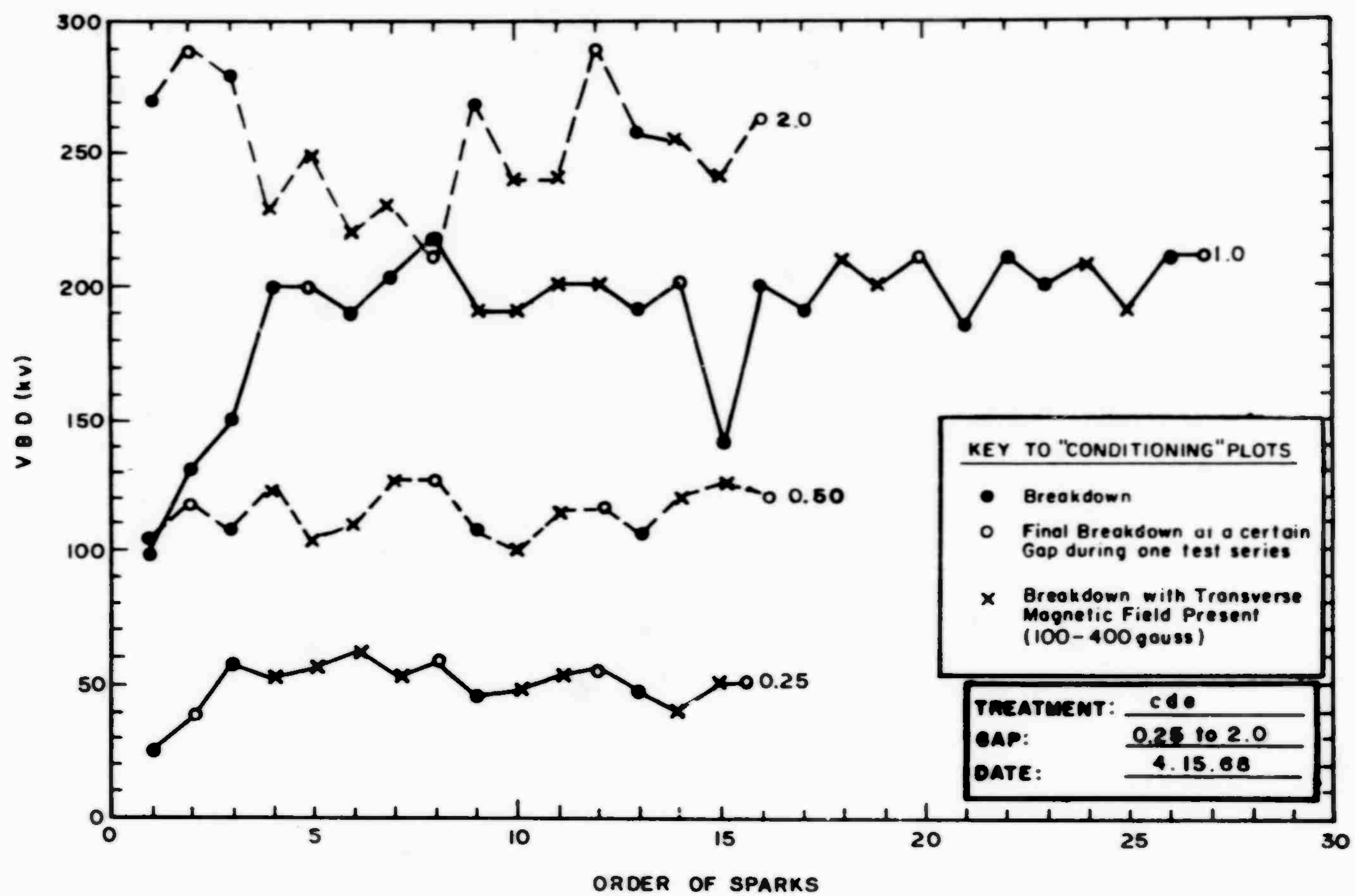

Figure 42. Breakdown Voltage Conditioning Plot for Treatment cde

1-2949

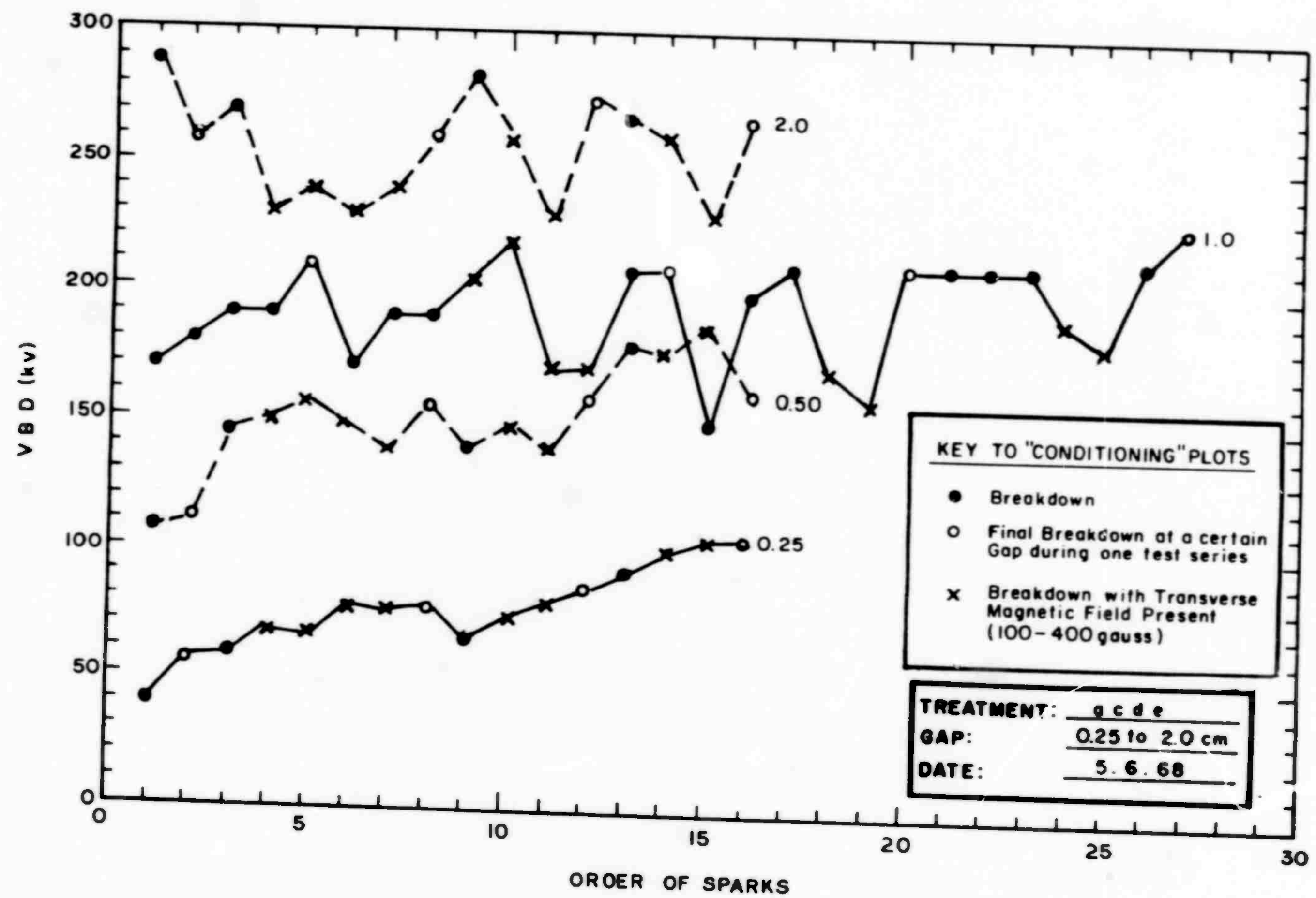

Figure 43. Breakdown Voltage Conditioning Plot for Treatment acde

1-2950

1-2951

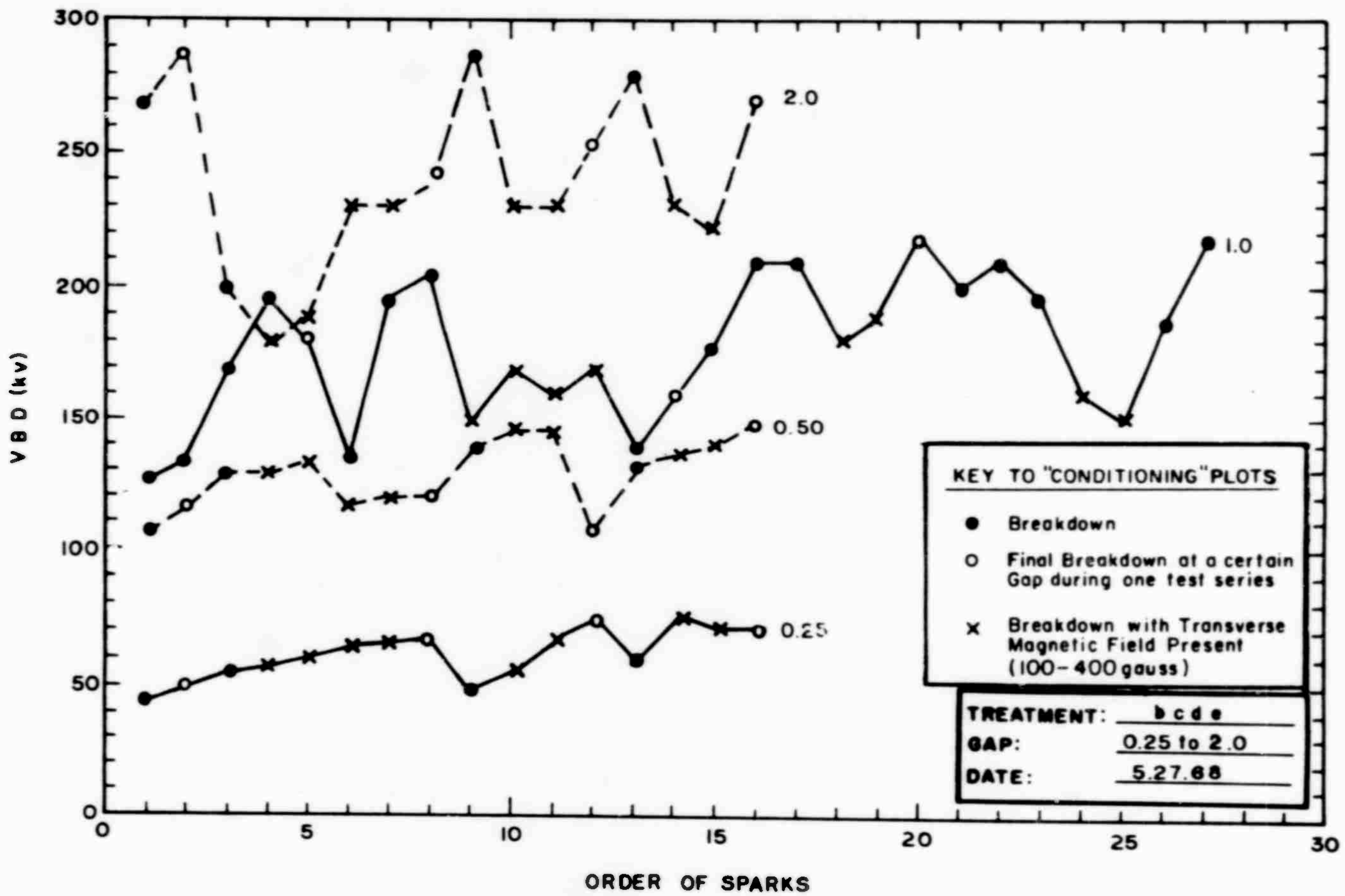

Figure 44. Breakdown Voltage Conditioning Plot for Treatment bcde

1-2952

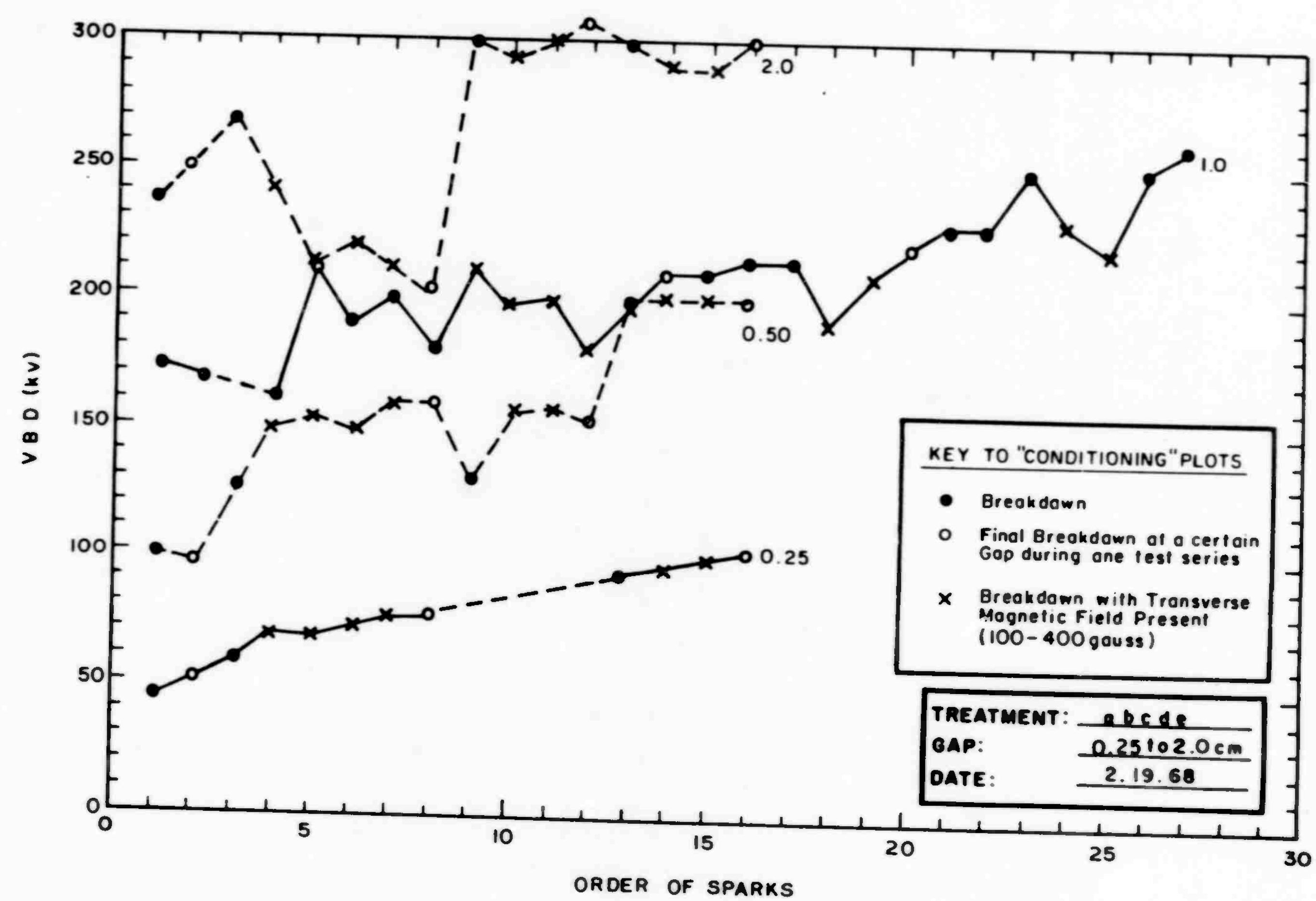

Figure 45. Breakdown Voltage Conditioning Plot for Treatment abcde

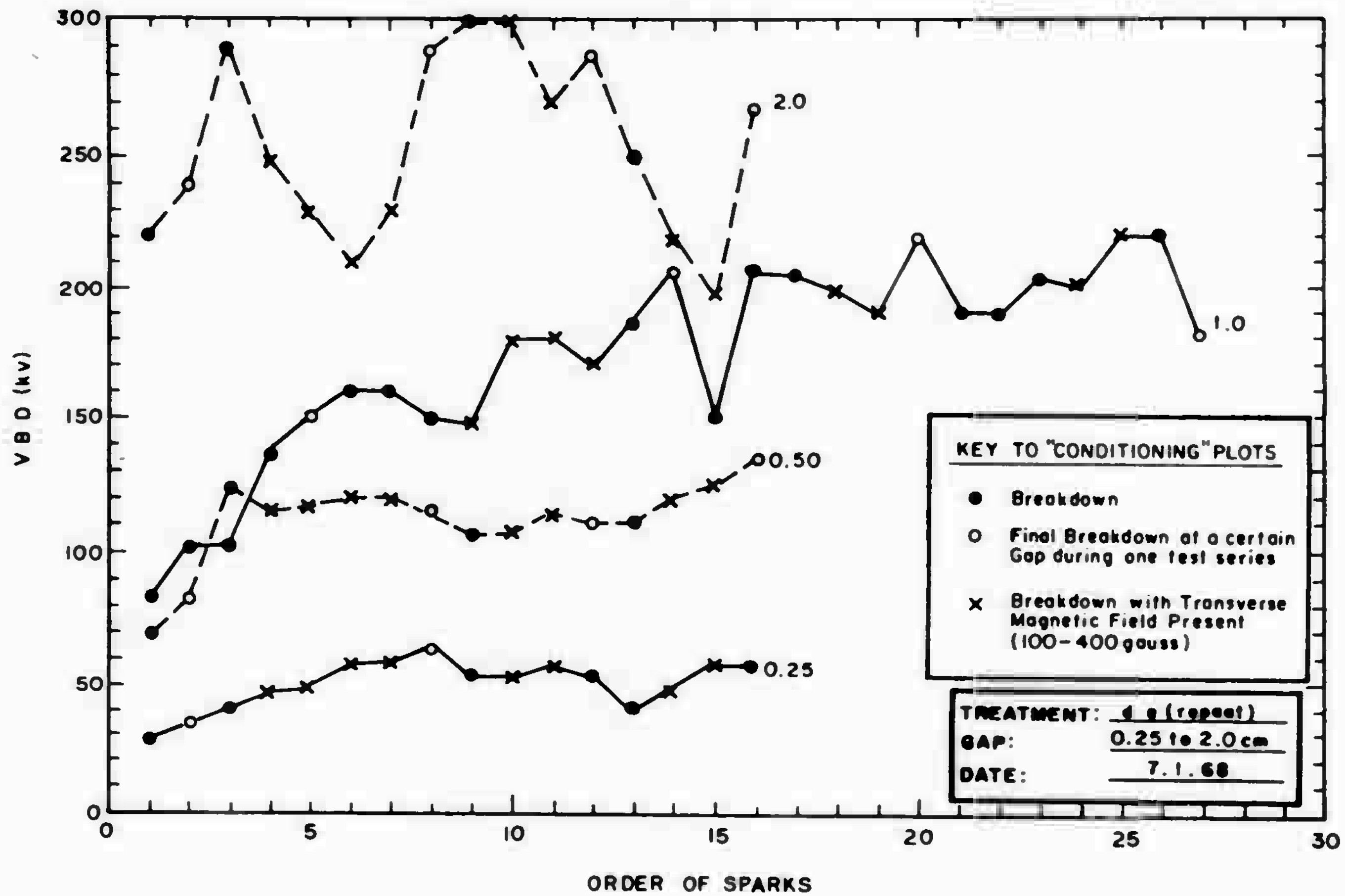

Figure 46. Breakdown Voltage Conditioning Plot for Treatment de (repeat)

1-2953

1-2954

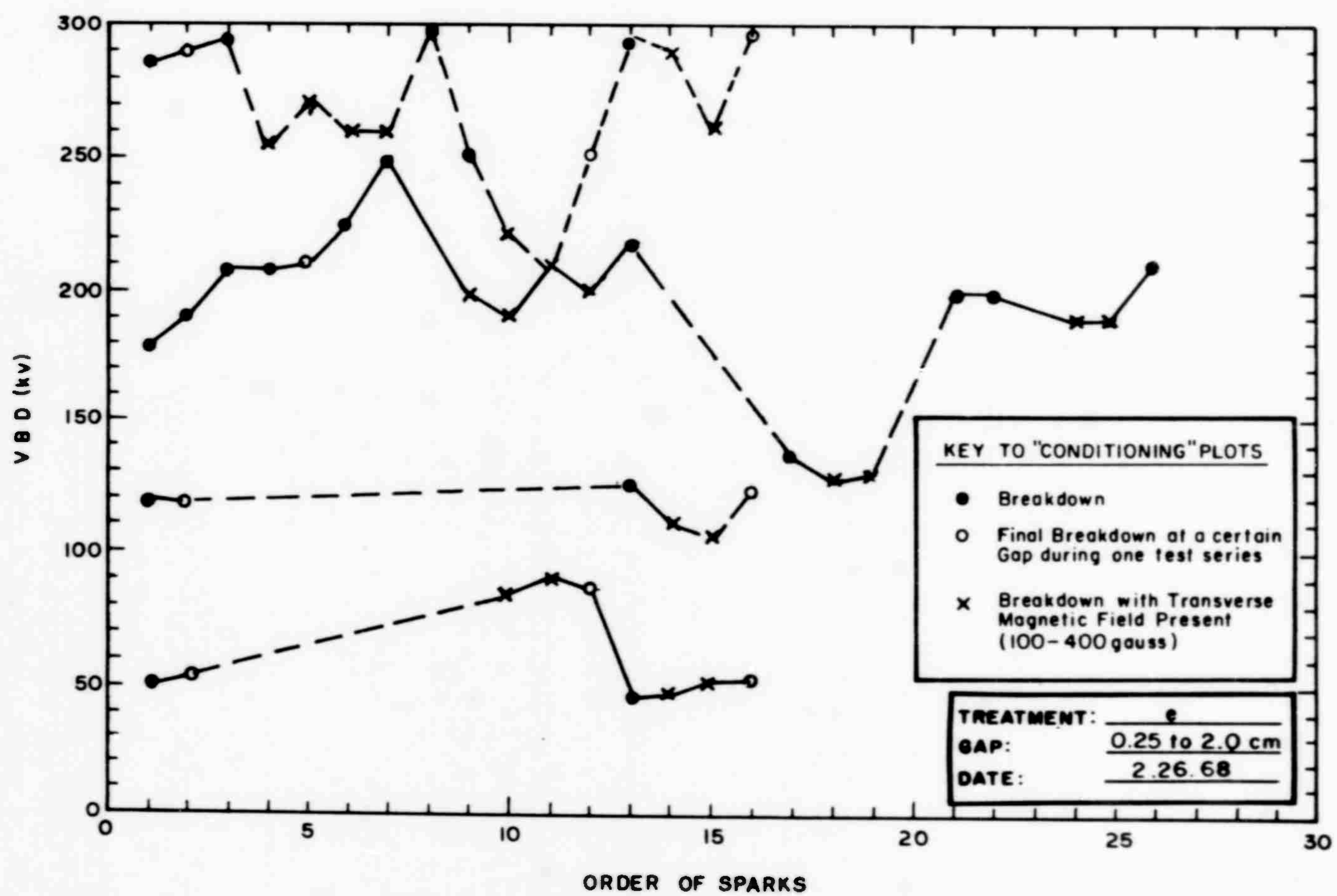

Figure 47. Breakdown Voltage Conditioning Plot for Treatment e

1-2955

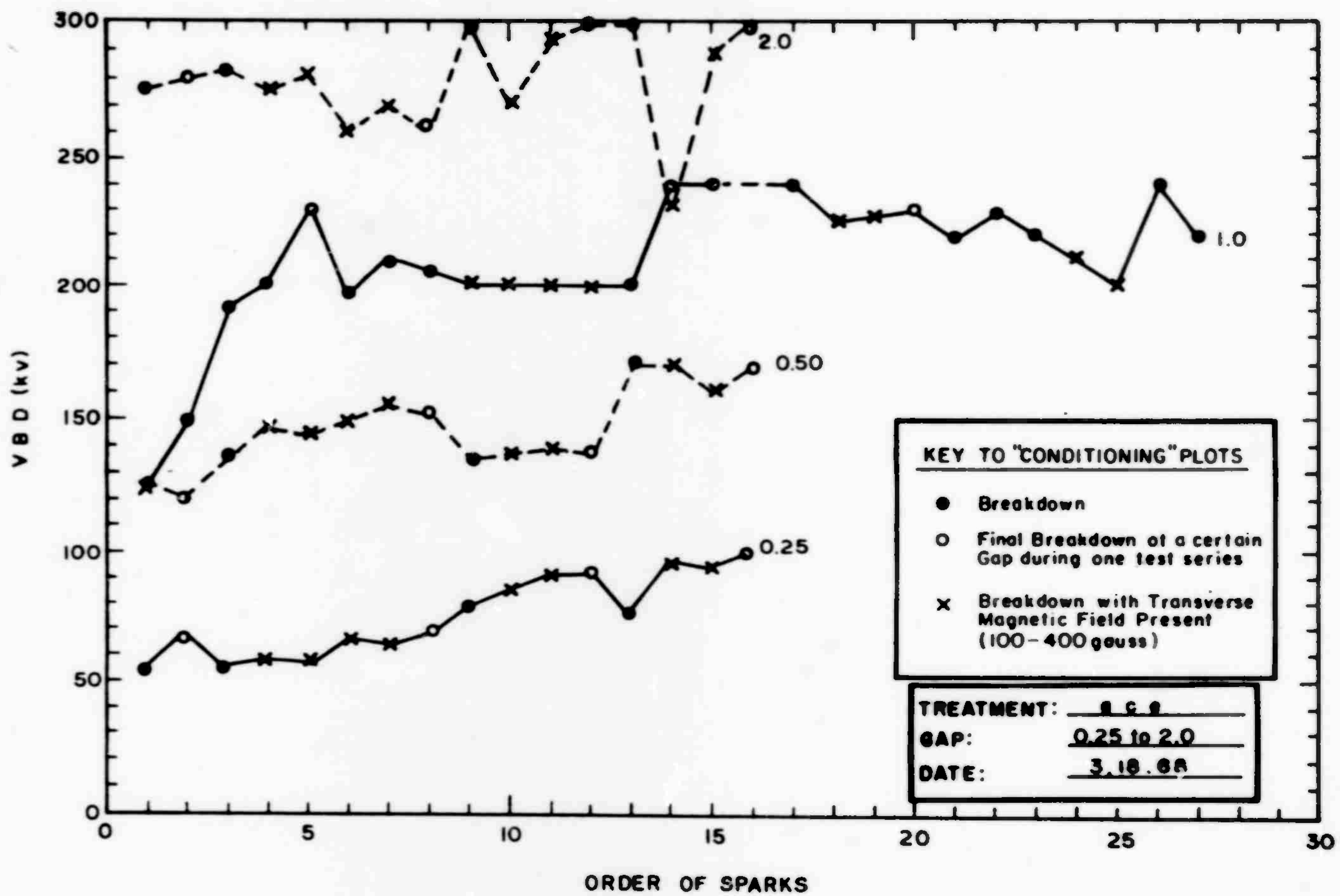

Figure 48. Breakdown Voltage Conditioning Plot for Treatment ace

1-2956

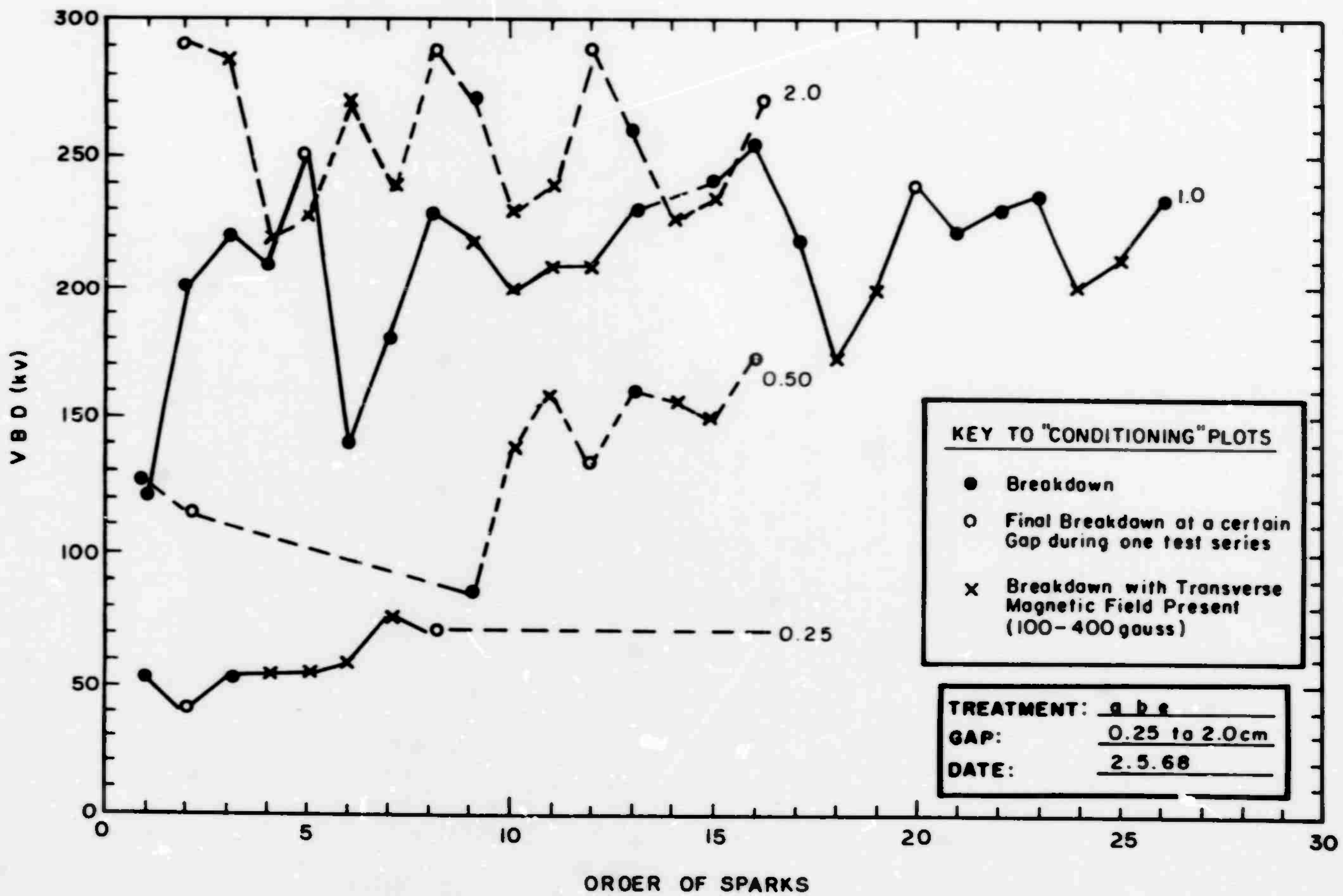

Figure 49. Breakdown Voltage Conditioning Plot for Treatment abe

1-2957

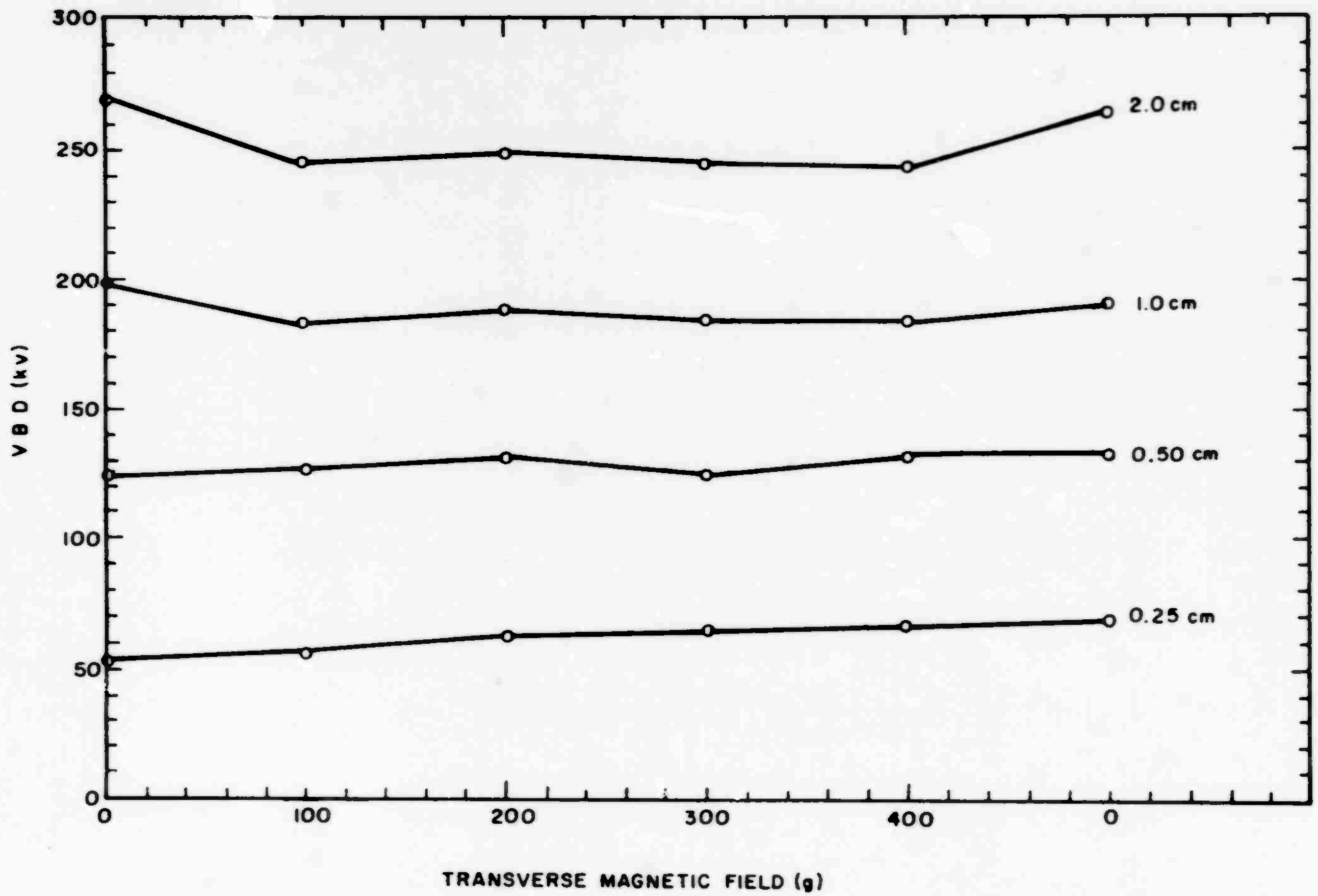

Figure 50. Average Breakdown Voltage as a Function of Transverse Magnetic Field (Second Days' Tests)

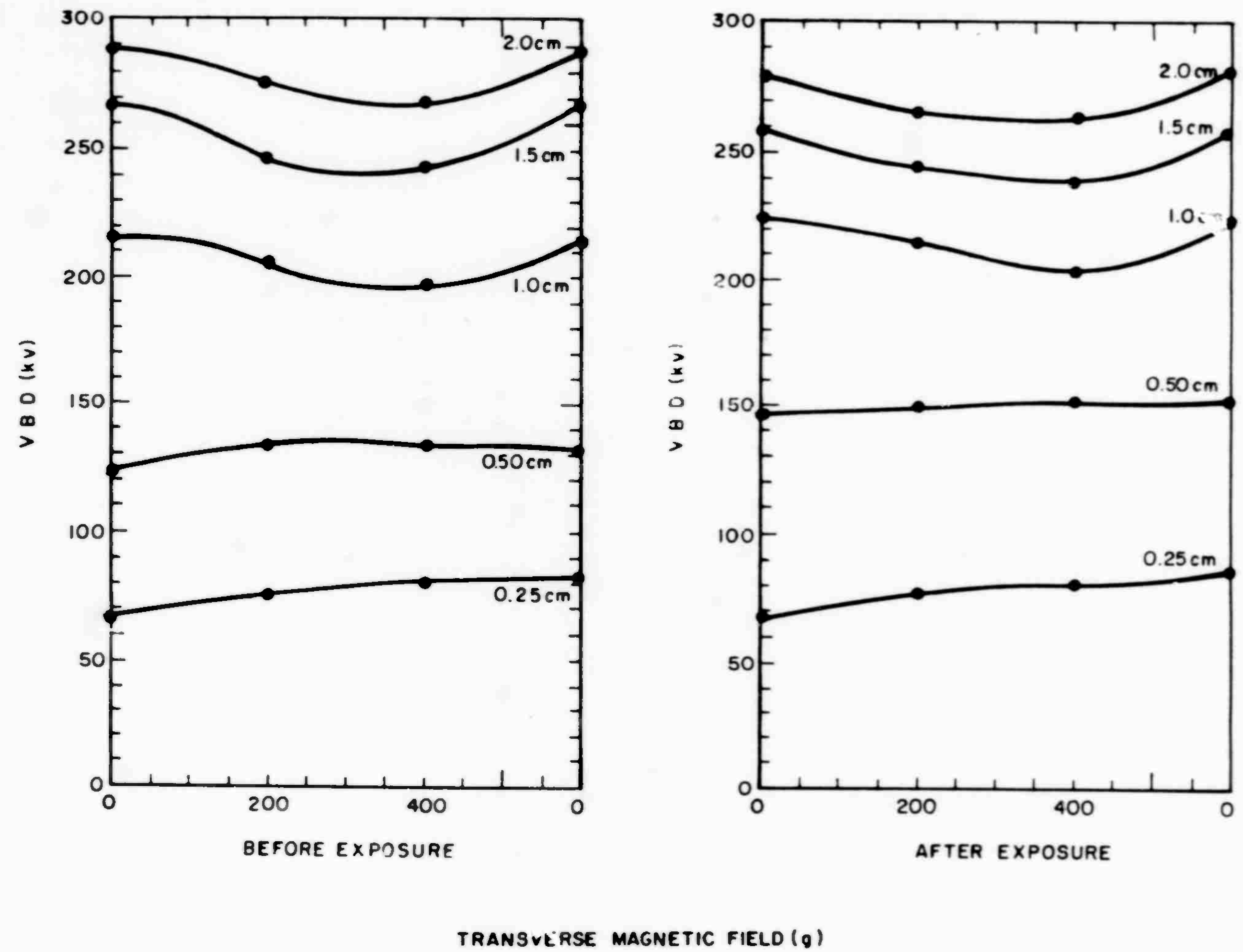

Figure 51. Average Breakdown Voltage as a Function of Transverse Magnetic Field (Third Days' Tests)

1-2958

SECTION 6

DESIGN OF "SECOND SIXTEEN" EXPERIMENT

6.1 Introduction

The First Sixteen and Second Sixteen experiments are independent but closely related parts of the overall five factor, two-level, full-factorial experiment. The factors and levels have been described in Table 1. The First Sixteen investigated the factor of anode shape at its high level which was Bruce profile. The Second Sixteen will investigate this factor at its low level which is sphere profile. The other factors remain the same.

Experimental procedure will not change as far as electrode and system preparation is concerned. The first two days' tests will be carried out in substantially the same way. However, on the third day of testing, the First Sixteen experiment investigated the effects of gas exposure on breakdown voltage. In place of these tests, the Second Sixteen will look into the effects of a dielectric envelope and energy storage with crowbarring. Three treatments have been completed so far and will be reported on in a later Quarterly Progress report.

6.2 Dielectric Envelope Tests

The presence of a dielectric envelope around the electrodes is of interest because this is the usual situation in high voltage vacuum tubes. To model this in the present experiments, a dielectric envelope assembly has been constructed that can be mounted around the electrodes in the vacuum chamber (see Quarterly Progress Report No. 3). The present pyrex dielectric envelope is 1/4 inch thick, 8 inches in diameter and 10 inches long. It is mounted upright on the anode bushing with metalized end faces for good electrical contact. A metal ring on the cathode end allows monitoring any current flowing over the envelope surfaces.

Since the envelope cannot be inserted without opening the vacuum chamber to atmosphere, the following procedure is used to separate the effects of the dielectric envelope from the effects of exposure to atmosphere:

(1) series of breakdowns before exposure;

(2) chamber is exposed to atmosphere and pumped down, another series of breakdowns after exposure;

(3) chamber opened and dielectric envelope inserted, pumped down, final series of breakdowns with dielectric envelope.

Preliminary results indicate that it is difficult to distinguish between exposure and envelope effects. In addition, flashover of the envelope often occurs before gap breakdown at the larger gap settings. It is expected that these problems can be overcome by maintaining a flexible approach.

6.3 Energy Storage and Crowbarring

The "conditioning" effects of a vacuum arc are dependent to a large extent on the parameters of the external electrical circuit. Specifically on the energy available to the arc once breakdown has taken place. Presently, there seems to be no clear evidence as to the time energy profile required for optimum conditioning. To investigate this, an energy storage and crowbar system, as described in Section 2.5 of this report, has been constructed. This system will make possible application to the gap of varying amounts of energy for different time intervals. A maximum of 7000 joules is available and a minimum crowbarring time of 600 ns has been achieved.

The specific test procedures will evolve during the tests. Present results, although not suitable for detailed reporting, indicate that the presence of energy storage and crowbarring does have an effect on the breakdown voltage levels obtained during a series of sparks.

SECTION 7

FUTURE EFFORT

The following tasks are planned for the next quarter:

- Continue with remaining treatments.
- Investigate effect of dielectric envelope.
- Investigate effect of energy storage with crowbarring.
- Regular maintenance of main chamber, pumps, electrode firing system, instrumentation, high voltage power supply, magnets and their supplies.
- Design, fabricate and install new electrode heater assemblies.
- Continue analysis of First Sixteen.
- Report on theoretical model of breakdown process.
- Initiate design of next experiment.

SECTION 8

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
P. C. Bolin	-	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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5. AUTHOR(S) (First name, middle initial, last name)

W. R. Bell, P. C. Bolin, M. J. Mulcahy, F. Y. Tse and A. Watson

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13. ABSTRACT

This report describes the fifteenth quarter of a study of high voltage breakdown in vacuum. The study has particular relevance to problems encountered in the development of high power vacuum tubes.

During the present period the first sixteen treatments and four repeat treatments of a 32 treatment experiment were completed. This five-factor, two-level, full-factorial experiment investigates the influence on vacuum breakdown of anode material, cathode material, anode size, anode shape and electrode treatment. At present the first half of this experiment is complete; and since one factor (anode shape) was held constant during these treatments, the results can be analyzed as a four factor, full factorial experiment. The experimental results and a preliminary analysis are contained in this report. The effects of gas exposure and a transverse magnetic field were also studied by a technique of stacking.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Conditioning Procedure						
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Partial Pressure and Gap Current						
Etching						