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HIGH VOLTAGE BREAKDOWN STUDY

W. R. Bell, et al

Ion Physics Corporation
Burlington, Massachusetts

December 1969

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HIGH VOLTAGE BREAKDOWN STUDY

NINETEENTH QUARTERLY PROGRESS REPORT

16 MAY 1969 through 15 AUGUST 1969

Prepared by:

ION PHYSICS CORPORATION

BURLINGTON, MASSACHUSETTS

DECEMBER 1969

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December 1969

HIGH VOLTAGE BREAKDOWN STUDY

Nineteenth Quarterly Progress Report
16 May 1969 through 15 August 1969

Report No. 19

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ION PHYSICS CORPORATION
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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 kV without breakdown.

ABSTRACT

The nineteenth quarter of a study of high voltage breakdown in vacuum is reported. Results of an Energy Conditioning Experiment relating to extended high energy discharge series, prebreakdown current, voltage collapse, and breakdown current pulses are analyzed. It was found that titanium alloy electrodes perform significantly better than material combinations with a copper anode when tested under high energy discharge conditions. The design and initial results of a Barium Contamination experiment are reported. In this experiment, barium is evaporated from a typical barium oxide cathode near the electrodes. Preliminary withstand tests are also reported.

LECTURES, CONFERENCES AND PUBLICATIONS

Lectures and Conferences

10 June 1969

M. M. Chrepta visited Ion Physics Corporation to review overall results of the Energy Conditioning Study and to discuss the Barium Contamination Study.

17 June 1969

H. Doolittle visited Ion Physics Corporation to discuss the Energy Conditioning Study with particular reference to Withstand Tests. Typical Barium Cathodes as used by Machlett Laboratories were made available and design of the Barium Contamination Study as discussed.

23 June 1969

Professor H. Freeman visited Ion Physics Corporation to discuss Factorial and Statistical aspects of the program.

6 August 1969

H. Doolittle and B. Singer visited Ion Physics Corporation to discuss the use of the Barium Cathodes supplied by Machlett Laboratories. Further results of the Energy Conditioning Study were discussed.

Publications

There were no publications during this period.

SECTION 1

INTRODUCTION

The work reported herein covers the nineteenth quarter of a study of high voltage breakdown in vacuum, with particular application to problems encountered in the development of high power vacuum tubes.

Further results and analysis of an Energy Conditioning Study are reported. This experiment investigated in a factorial design, the factors of energy conditioning, electrode size and cathode material (titanium or nickel) for Bruce Profile (Uniform Field) geometry electrodes. The anode was generally OFHC copper. The effects of extended high energy discharge series are discussed. It was found that titanium anode and cathode gave substantially better performance than the copper anode-nickel cathode combination. Prebreakdown current, breakdown voltage collapse and breakdown current pulse characteristics are discussed. Two treatments which included a dielectric envelope around the electrodes are reported. Preliminary withstand tests are considered.

A Barium Contamination Study was initiated during this quarter and one treatment with OFHC copper electrodes was completed. The results were unexpected in that the effect of Barium Contamination did not show up strongly until many breakdowns had occurred after contamination. In addition, there was no permanent degrading effect on either breakdown voltage or emission characteristics.

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SECTION 2

300 kV TEST VEHICLE

2.1 Vacuum Chamber and System

A thorough cleaning of the entire vacuum system at the end of the energy conditioning study was carried out on 9-13 June 1969 and the pressure after bakeout returned to the high 10^{-9} torr or low 10^{-8} torr range. The new modified bakeout mantle has been used for more than five treatments and has performed satisfactorily.

2.2 Barium Contamination Study

The Barium Contamination device (see Quarterly Progress Report No. 18, Section 2.4) has been installed and used twice. At the end of the second bake, a small leak developed at the copper conflat gasket that mates the contamination device to the loading port flange. This is thought to have been due to relaxation of the stainless steel bolts and is not expected to occur again.

2.3 General

All other aspects of system performance have been normal.

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SECTION 3

ENERGY CONDITIONING STUDY

3.1 Introduction

The major portions of the Energy Conditioning Study have been reported in Quarterly Progress Reports No. 17 and 18. Here, results of several non-standard test sequences dealing with the effect of an extended series of high energy discharges and the proximity of a dielectr·· envelope are presented. Voltage collapse and breakdown current waveforms are analyzed and related to circuit parameters and their characteristic effects on breakdown voltage. Prebreakdown current phenomena are reported and discussed. "Withstand" properties, i. e. the ability of electrodes to sustain high voltages for long time intervals, are discussed and preliminary results given. The effects of a dielectric envelope in a limited number of tests appeared to be negligible.

3.2 Effect of Extended Series of High Energy Discharges

A limited number of high energy discharges (R_S = 0 ohms, total series resistance of 24 ohms, energy storage 0.15 μF) have been shown in the basic energy conditioning study to be severely damaging. Low breakdown voltages and high emission currents resulted. However, in order to be able to complete the conditioning sequence for purposes of factorial analysis, the degree of damage at any one time was limited to that produced by nine high energy discharges. Subsequent tests have extended the high energy discharge series to hundreds of breakdowns and marked differences between electrode materials have appeared. In particular, a titanium alloy anode can tolerate such a discharge series with little or no long term deterioration.

Figure 3 of the 18th Quarterly Progress Report shows the effect of 230 high energy discharges on electrodes consisting of a copper anode and a nickel cathode. The breakdown voltage level drops from 210 kV for the preceding 30 kohm series resistance sequence to minimum levels of 85 to 95 kV with most breakdowns within 10 kV of 175 kV. At the same time, the emission level, as characterized by the voltage level necessary for 10^{-6} amperes of prebreakdown current, increased greatly. Indeed, frequently 2×10^{-3} amperes, namely the limit of the power supply was drawn for several minutes prior to breakdown. At this point, a thermal complication has been introduced into the determination of breakdown voltage, since at voltages of 200 kV with 2×10^{-3} amperes of electronic current, the heat flow into the anode is 400 watts. This level will in a short time lead to heating of the entire anode (to a red heat in one case) with localized heating to melting or vaporization levels. Thus, breakdown becomes strongly time dependent. In any case, both breakdown voltage and prebreakdown current levels characterize this copper anode-nickel cathode

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electrode system as severely damaged by the extended series of high energy discharges.

The response of a pair of identical electrodes to high energy discharges with crowbarring after ~ 500 ns was found to be similar to that of the pair without crowbarring. Figure 1 gives the results of this test. It is evident that the crowbarring is not sufficiently rapid to limit damage. This is discussed further in Section 3. 3 where the breakdown voltage collapse and current pulse are related to circuit parameters and crowbarring.

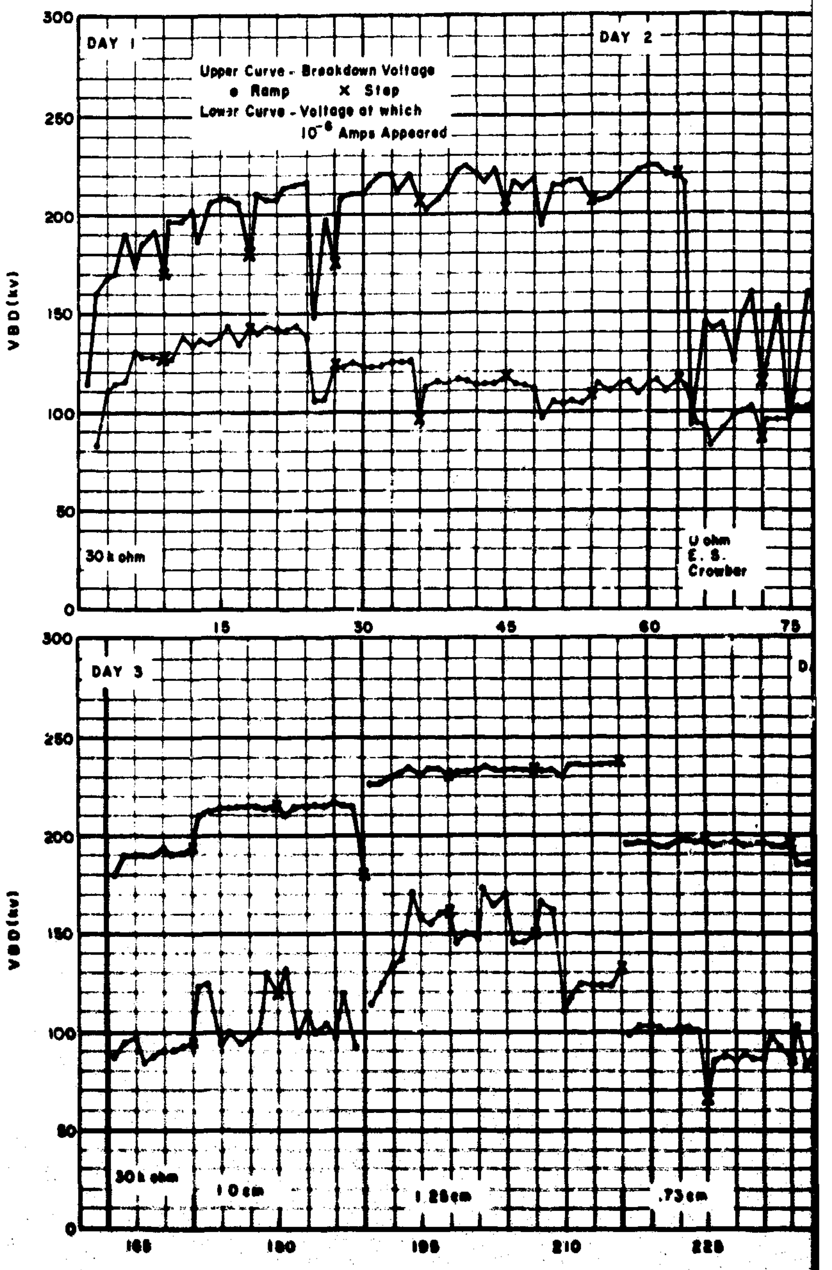
Titanium alloy electrodes tolerated better the high energy discharges as shown in Figure 2. While initially upon introduction of the high energy discharges there is a substantial reduction in breakdown voltage and a marked increase in emission level, after a conditioning period performance improved so that breakdown was generally above 200 kV with reasonable emission levels (10^{-6} amperes at ~ 160 kV).

3. 3 Prebreakdown Current

Interelectrode current preceding breakdown was monitored with an electrometer and found to vary from less than 10^{-9} amperes to 2×10^{-3} amperes. Low current levels were usually unstable and were encountered during the early stages of conditioning and the moderate energy discharge series (R_S = 1000 ohms, Energy Storage = 0. 15 μF). Currents of above 10^{-8} amperes were usually constant at a given voltage. During most of the conditioning sequence, stable prebreakdown currents from 10^{-6} to 10^{-3} amperes preceded breakdown.

The dependence of prebreakdown current upon voltage was usually of an exponential nature and conformed roughly to the Fowler-Nordheim equation indicating field emission from cathode protrusions. In addition, the approximately linear change in the voltage necessary for 10^{-6} amperes as the gap is changed and the correlation of emission level and computed field enhancement factor β also point to field emission as the primary source of prebreakdown current. These features will be presented later.

A more important consideration is the relation between prebreakdown current and subsequent breakdown voltage. The strong correlation between changes in the 10^{-6} ampere voltage level and changes in breakdown voltage (as shown in the conditioning curves of Quarterly Progress Reports No. 17 and 18 and in Figures 5 through 7 of this report) suggests that prebreakdown current is an important factor in the breakdown mechanism. However, the lack of any consistent correlation between the level of prebreakdown current and the level of the breakdown voltage would imply that total prebreakdown current may not be a major initiating factor in breakdown. Theory would either identify field emission produced thermal instabilities as the initiating



DAY 1
DAY 2
Upper Curve - Breakdown Voltage
• Ramp   X Step
Lower Curve - Voltage at which
10^{-6} Amps Appeared
VBD(kv)
30 k ohm
0 ohm
E. S.
Crowbar
DAY 3
30 k ohm
1.0 cm
1.28 cm
.73 cm

1-4359

A

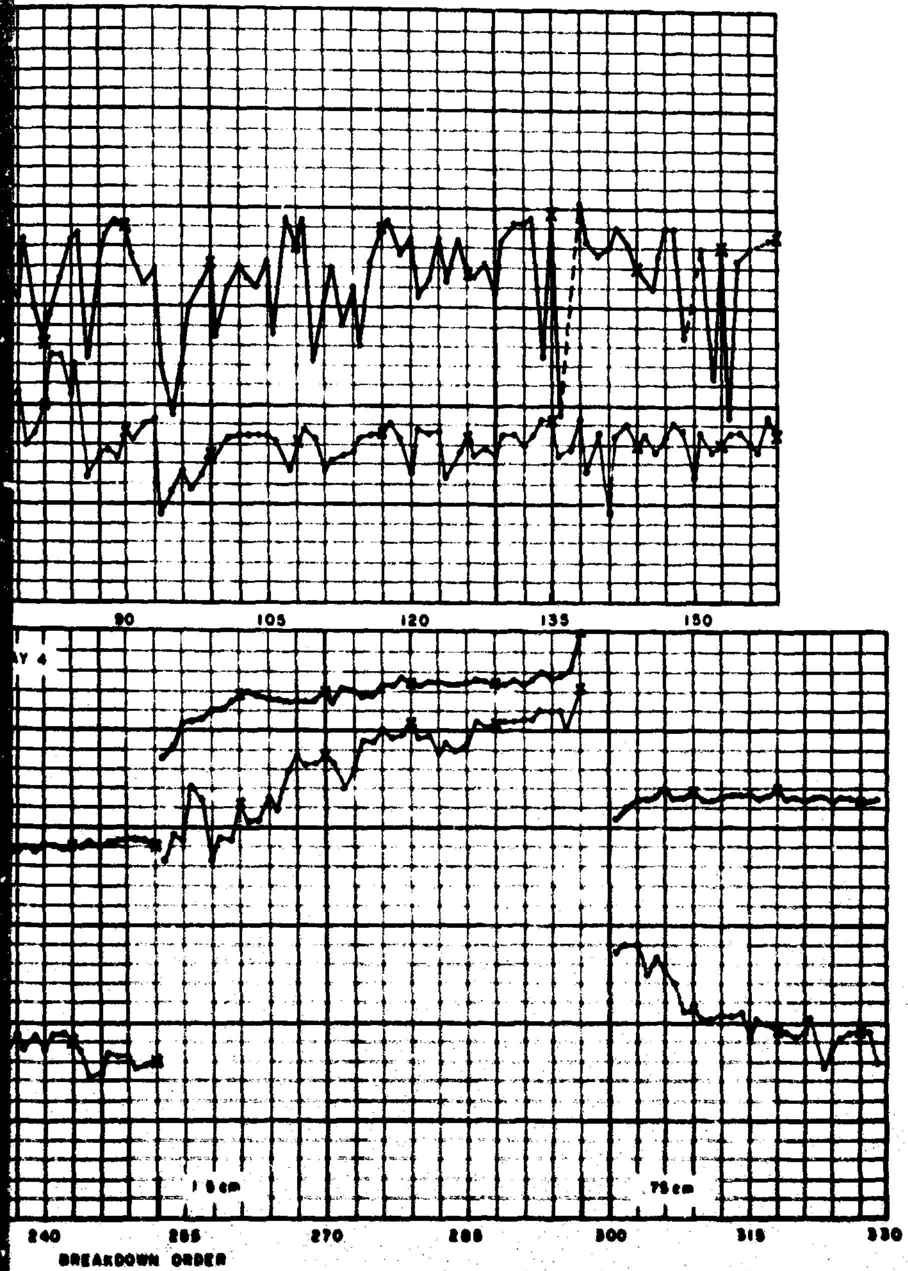
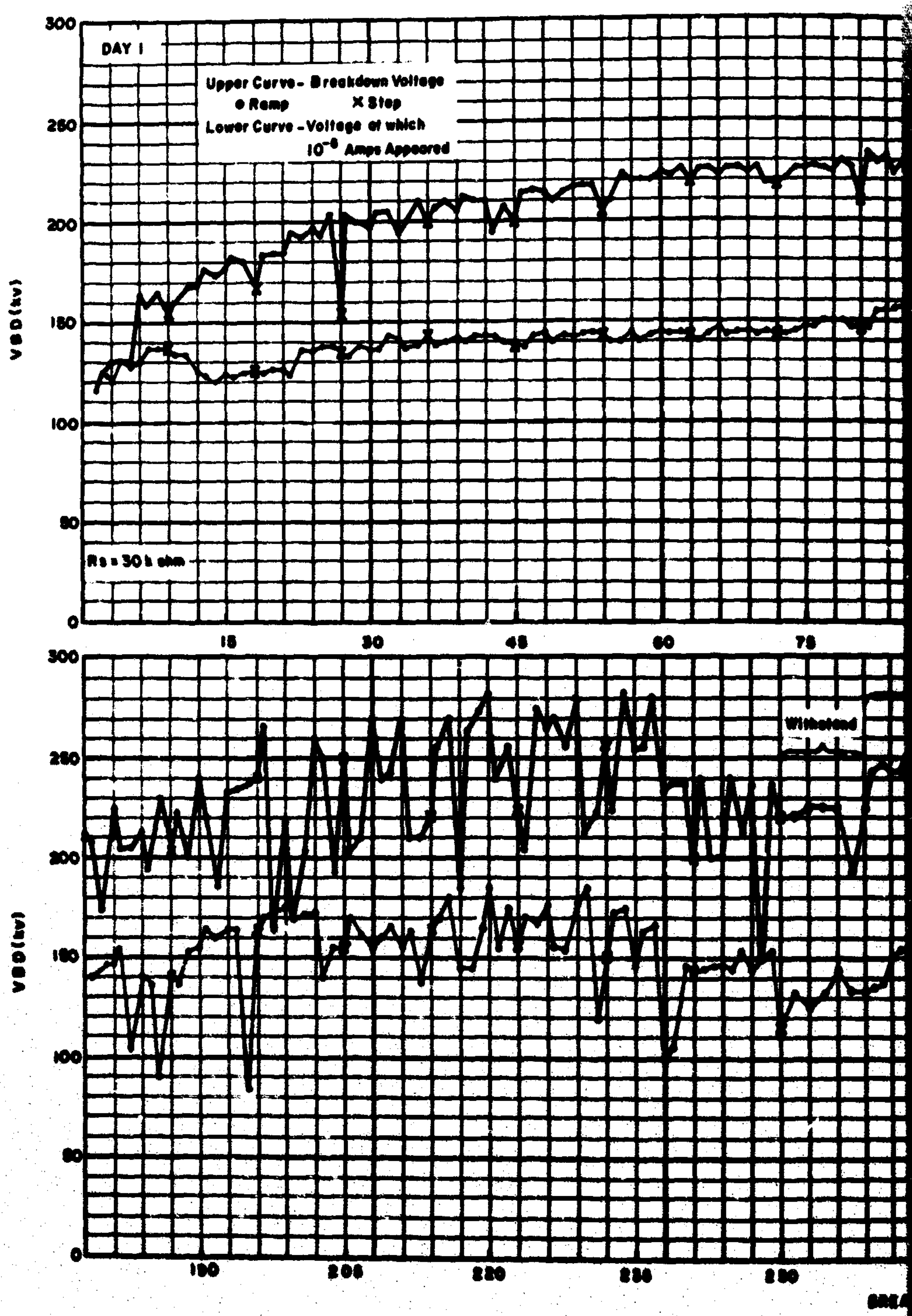


Figure 1. Conditioning Curve for Treatment ab: HEC 4-Inch Diameter Bruce Profile Electrodes - Copper Anode Nickel Cathode - With Extended Series of High Energy Discharges With Crowbarring

B



DAY I
Upper Curve - Breakdown Voltage
● Ramp × Step
Lower Curve - Voltage at which
10^{-6} Amps Appeared
Rs = 30 k ohm
VBD(kv)
Withstand

1-4263

A

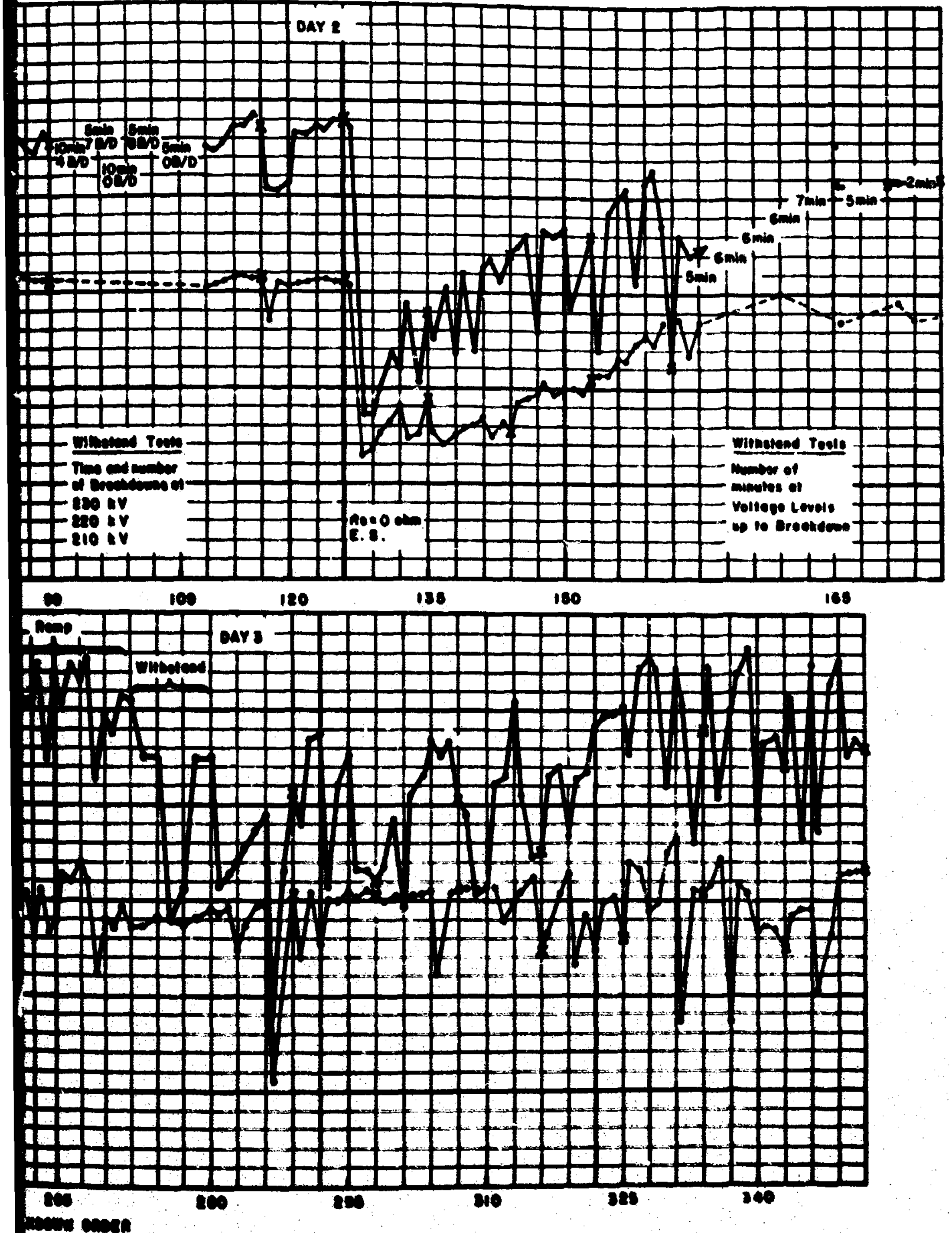
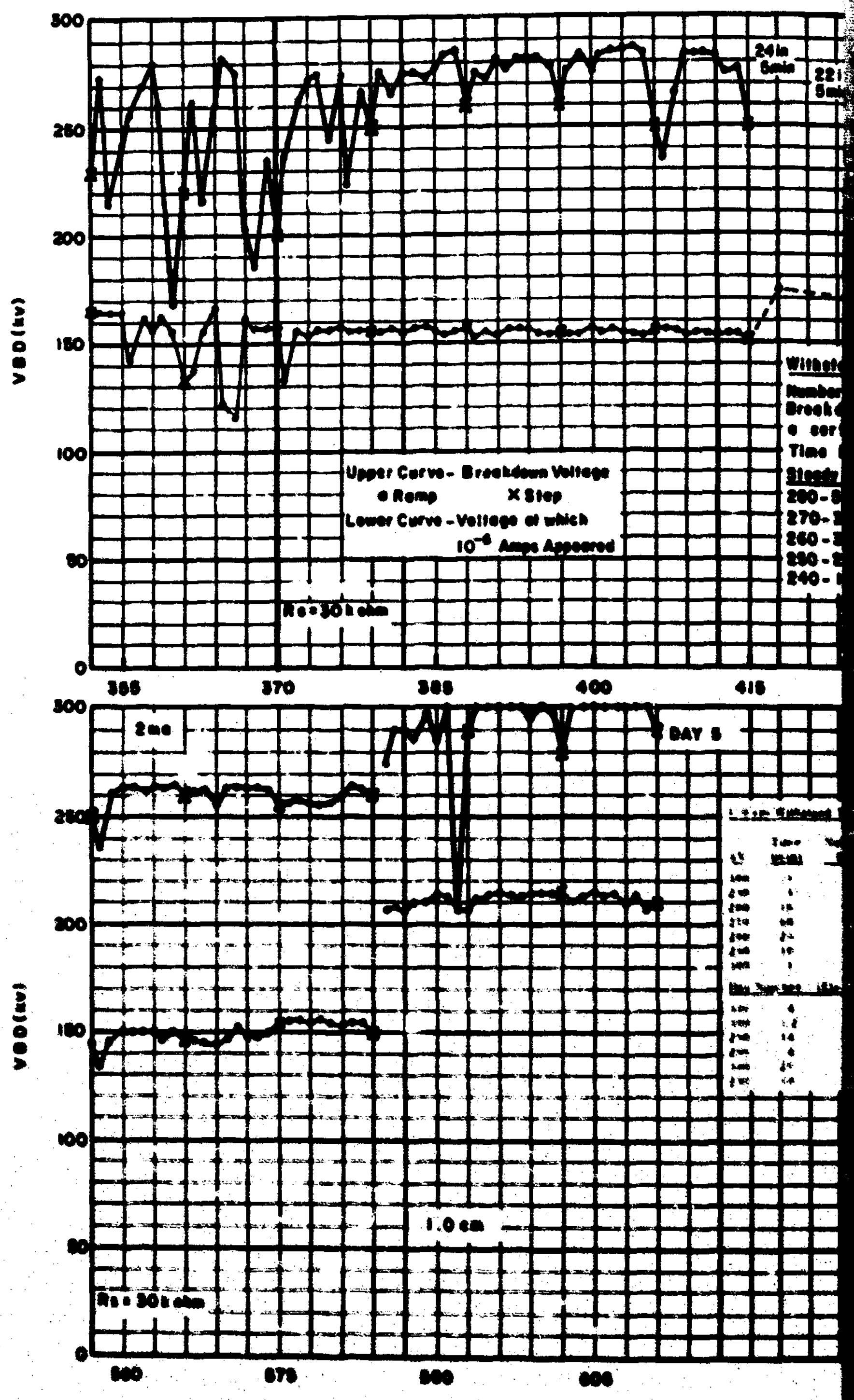


Figure 2. Conditioning Curve for Treatment ab:Ti2 - 4-Inch Diameter Bruce Profile Electrodes - Ti-7Al-4Mo Anode and Cathode with Extended Series of High Energy Discharges

B



VBD(kv)
Upper Curve - Breakdown Voltage
● Ramp ✕ Step
Lower Curve - Voltage at which
10^{-6} Amps Appeared
Rs = 30 k ohm
355
370
385
400
415
2mc
DAY 5
1.0 cm
Rs = 30 k ohm
VBD(kv)

1-4263

A

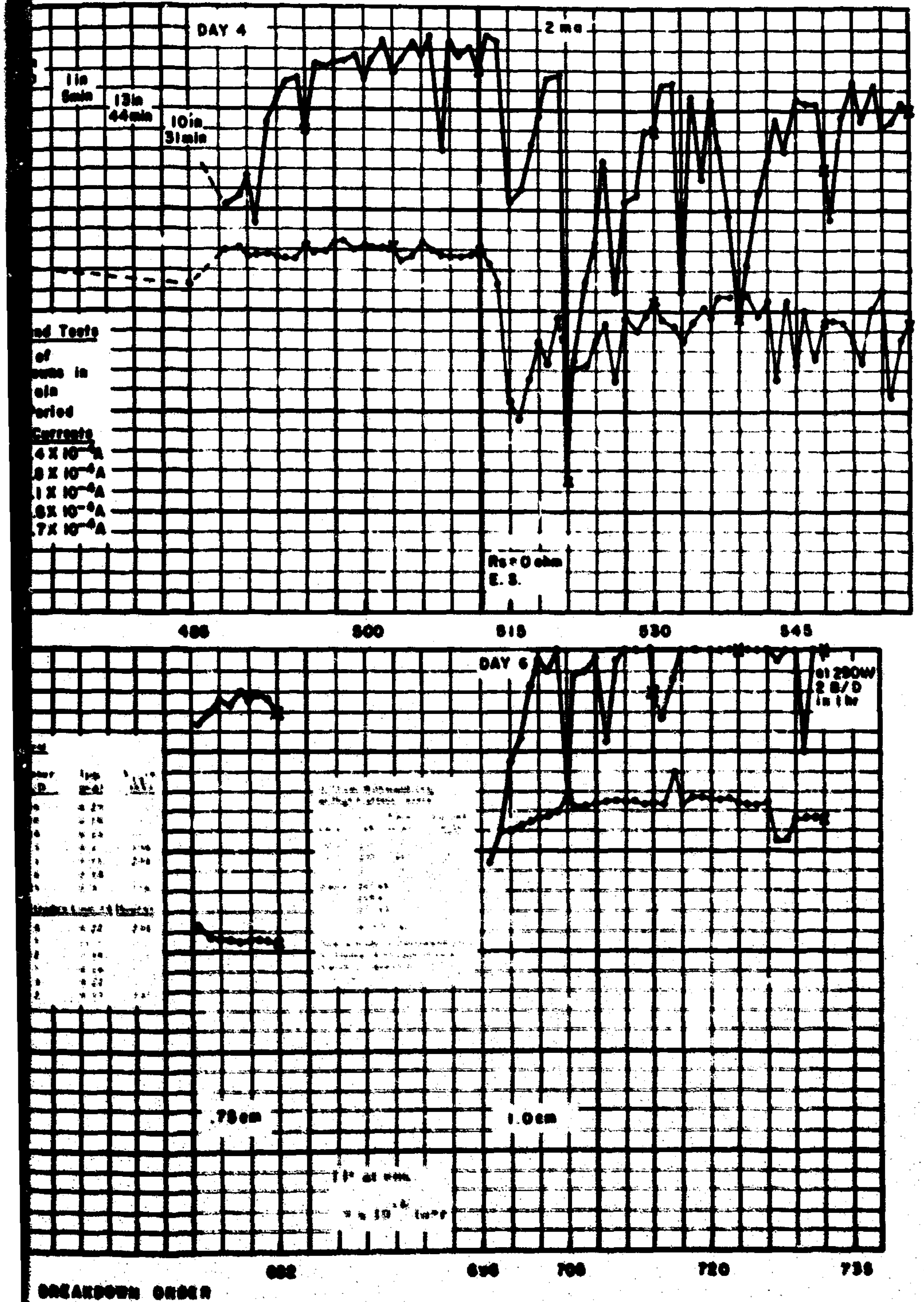


Figure 2. Continued

P

event, or hypothesize that particles or "clumps" electrostatically accelerated across the gap precipitate breakdown. In the first case, the lack of correlation between prebreakdown current level and breakdown voltage can be explained by noting that the measured current is the total current from many emitting sites (although a few may be dominant) while breakdown is dependent on the conditions at only one site, thus a protrusion that is emitting only a small fraction of the total current might be the first to go unstable due to its geometry. The second theory would view the steady field emissinn currents preceding breakdown as unrelated to the initiating event which involves macroparticles. It is not unreasonable to assume that a breakdown which results in a strongly emitting surface might also tend to produce more suitable "clumps, thus a change to a more highly emitting state would usually be accompanied by lower breakdown voltages.

Until decisive experiments have clearly identified the relevant mechanisms, a physical explanation of the relation between prebreakdown current and breakdown voltage will be tentative at best. It is clear, however, that prebreakdown current behavior is an important consideration in vacuum insulation since the current levels often reached prior to breakdown can be more than 2 x 10^{-3} amperes. This represents a considerable source of anode heating (400 watts at 200 kV and 2 mA) which must be dissipated if uncontrolled temperature effects are to be avoided.

For this reason, the prebreakdown current phenomena will now be discussed as a function of voltage, gap, conditioning, and electrode material.

For each breakdown, an approximate measure of the emission characteristics prior to breakdown has been reported by including the voltage at which 10^{-6} amperes of prebreakdown current appeared. These values are given in the conditioning curves of Quarterly Progress Reports No. 17 and 18. A more detailed recrod of prebreakdown current was obtained for approximately 20% of the breakdowns by noting the 10^{-7} and 10^{-5} ampere voltage levels. These values can then be used to estimate the field emission parameters according to the Fowler-Nordheim equation:

$$I = A \left(\beta \frac{V}{d}\right)^2 \exp \frac{-Bd}{\beta V} \qquad V = \text{Voltage}, \quad d = \text{Gap}$$

where A includes the emitting area and B is approximately a constant depending in part upon the work function ϕ. A Fowler-Nordheim plot of log I/V^2 vs $1/V$ is then a straight line if the currents are of field emission origin and several emitting sites are dominant (i. e. there is an equivalent field enhancement factor β). That such is approximately the case for the conditions of this experiment is indicated by Figures 3 and 4 which give detailed Fowler-Nordheim

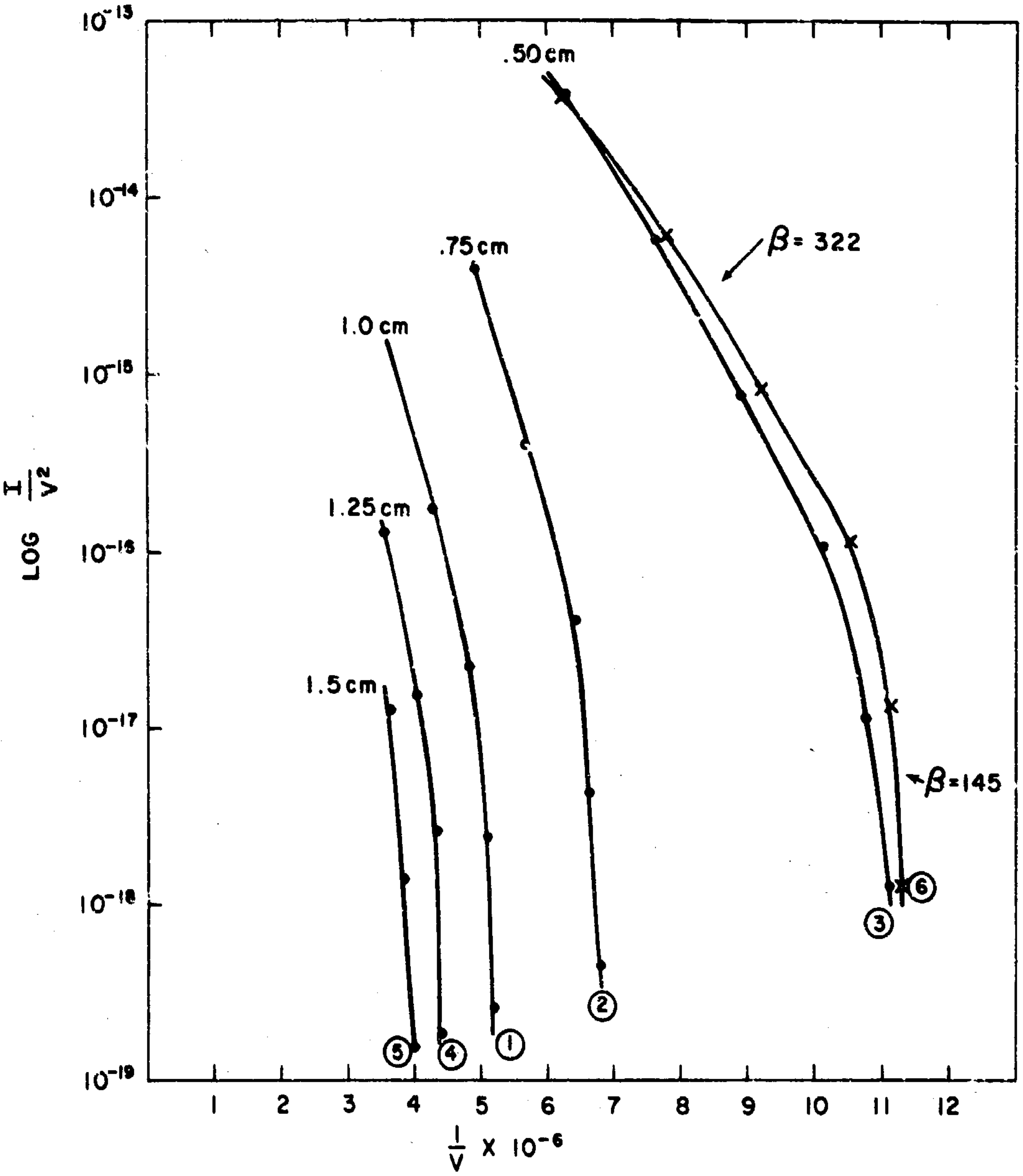


Figure 3. Fowler-Nordheim Plot for Treatment ab: Ti2 4-Inch Diameter Bruce Profile Vacuum Fired Titanium Electrodes

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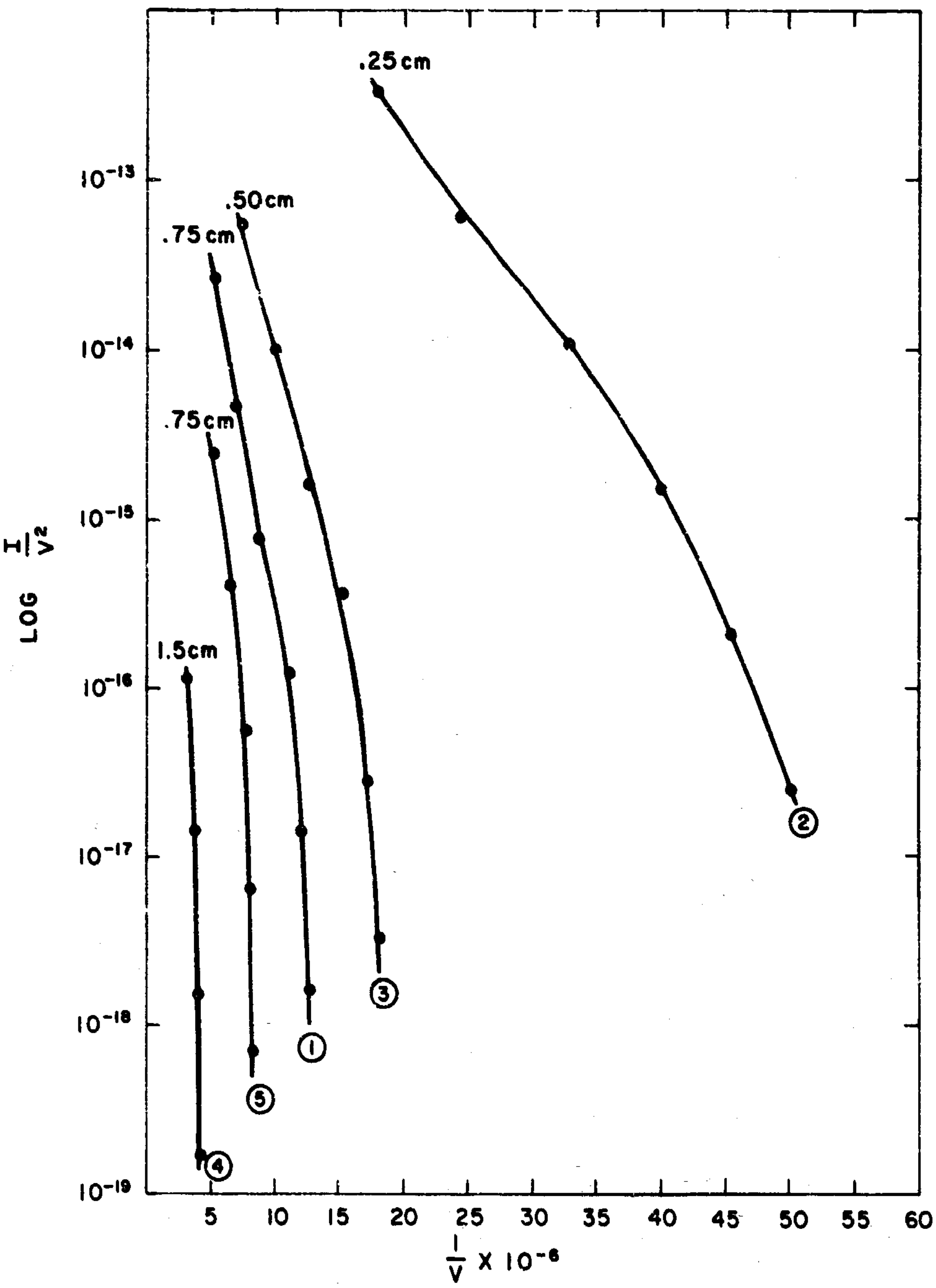


Figure 4. Fowler-Nordheim Plot for Treatment ab: HEC 4-Inch Diameter Bruce Profile Vacuum Fired Electrodes Copper Anode, Nickel Cathode

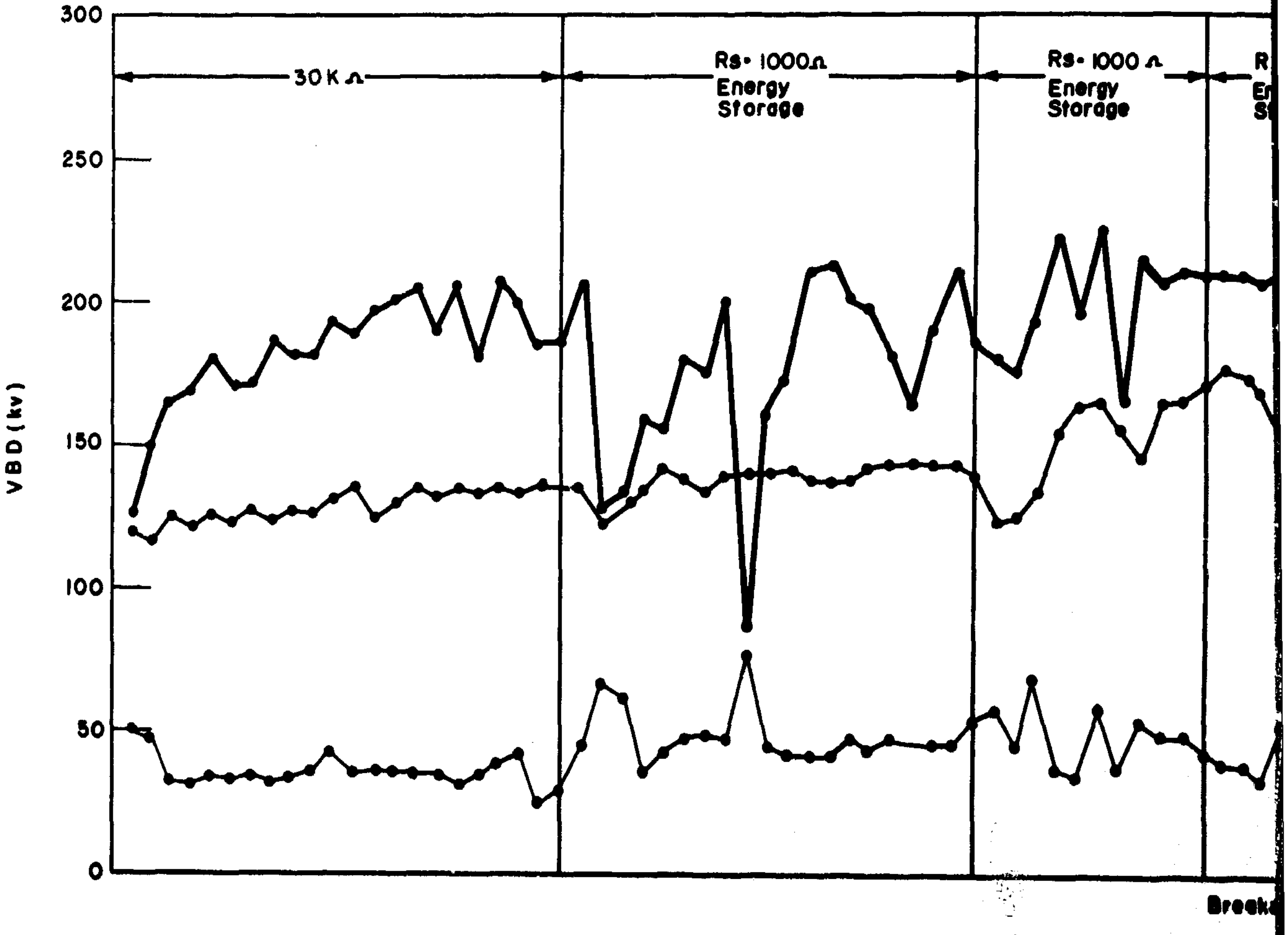
1-4045

plots for well conditioned electrodes typical of the experiment. A distinctive feature is a bend in the curves at about the 10^{-6} ampere current level. Below that current level the slope of the Fowler-Nordheim plot would give an equivalent field enhancement factor β of 145 for the 0.50 cm gap of Figure 3. Above 10^{-6} amperes, the slope changes and an increased β of 322 is calculated for the same gap. In this case, a repeat run at 0.50 cm after a number of runs to breakdown at other gaps yields much the same slopes and thus this behavior of β is reproducible. The conclusion is that at some current level the field enhancement factor increases. The contribution of ionic space change has been suggested by Watson as a possible explanation of this effect. A complete discussion is given in an addendum to the Fourteenth Quarter Progress Report. Similar bending at smaller gaps has been reported by Utsumi(1) and Tomaschke(2) no explanation was suggested and this behavior was not typical.

Breakdowns for which the 10^{-7}, 10^{-6}, and 10^{-5} ampere voltage levels were noted (~ 20% of the total) have been utilized to obtain estimates of the equivalent field enhancement factor β preceding each breakdown. These were computed with the aid of a time-sharing computer for a work function of 4 eV, a gap of 0.75 cm, and a least squares fit to the data. The results for representative treatments are given in Figures 5 through 7. It can be seen that a decreasing β is usually accompanied by an increase in the voltage necessary for 10^{-6} amperes. The range of β from 100 to 400 is consistent with values typically reported by other workers. Due to the bend in the Fowler-Nordheim curves around 10^{-6} amperes these β values are only approximate and represent the average slope over the whole range of current.

At the end of the standard conditioning sequence most treatments were subjected to breakdown over a range of gap from 0.25 cm to 2.0 cm. These measurements have been reported in the conditioning curves for each treatment. The voltage at which 10^{-6} amperes of prebreakdown current appeared can be used to calculate the dependence of emission characteristics upon gap. Field emission would show a linear dependence since Bruce Profile geometry produces a uniform field in which the field strength E is a linear function of gap. That such dependence is approximately followed is evident in Figure 8 which gives averaged voltage levels for 10^{-6} amperes as a function of gap for representative treatments.

The variation in prebreakdown current with conditioning is primarily a function of the type of discharge. Low energy discharges generally produce low emission levels (i.e. the voltage for 10^{-6} amperes is high and the last measurable current prior to breakdown is low, usually 10^{-5} to 10^{-4} amperes). Moderate energy discharges (R_S = 1000 ohms with 0.15 µF of energy storage) do not significantly change prebreakdown current levels. On the other hand, high energy discharge conditioning (R_S = 0 ohms with 0.15 µF of energy storage) substantially increases the prebreakdown current level in that the voltage necessary for 10^{-6} amperes drops by as much as 50% and often the current just prior to breakdown exceeds 2×10^{-3} amperes.



300
250
200
150
100
50
0
VBD (kv)
30 K Ω
Rs = 1000 Ω
Energy
Storage
Rs = 1000 Ω
Energy
Storage

1-3826

A

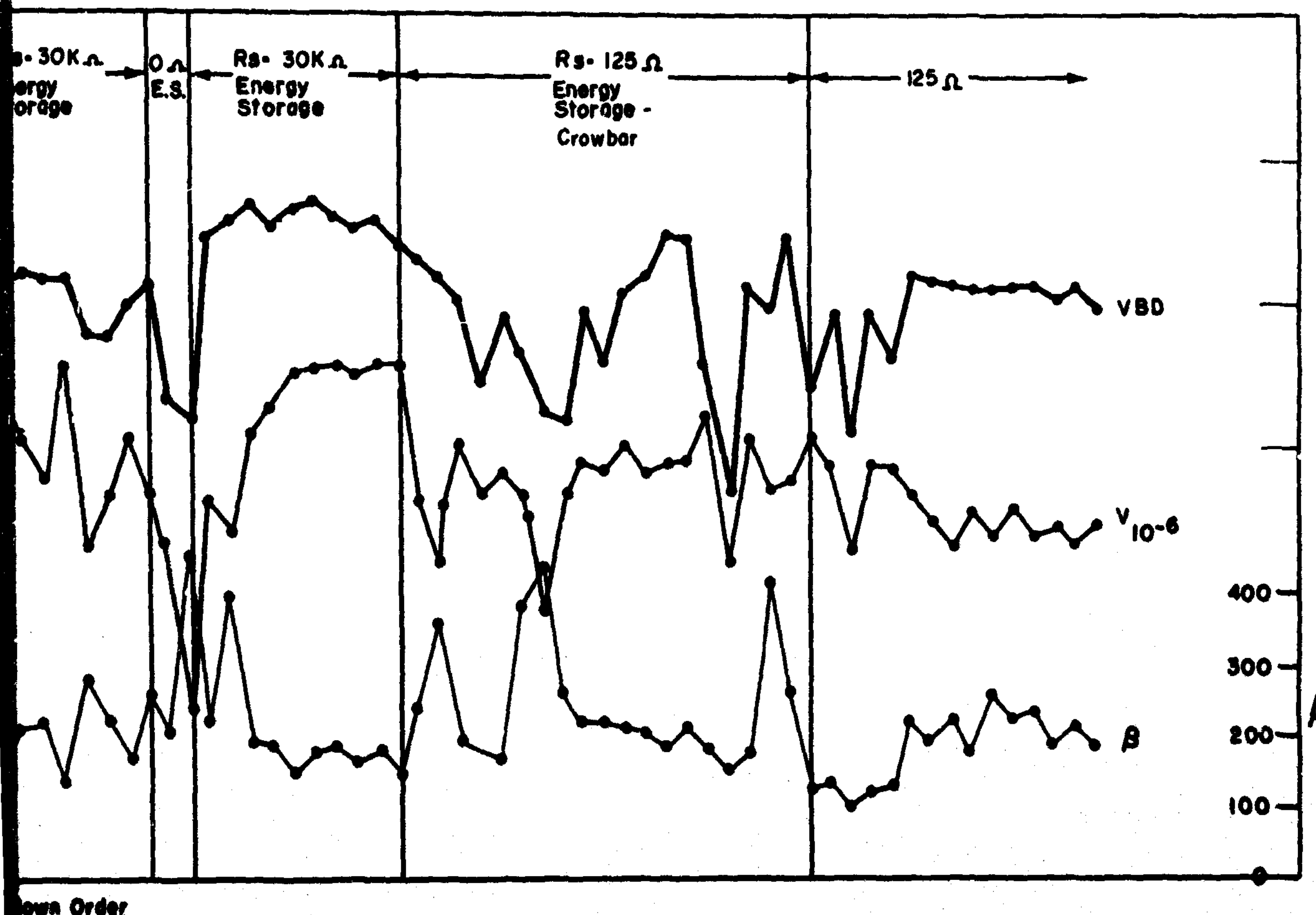
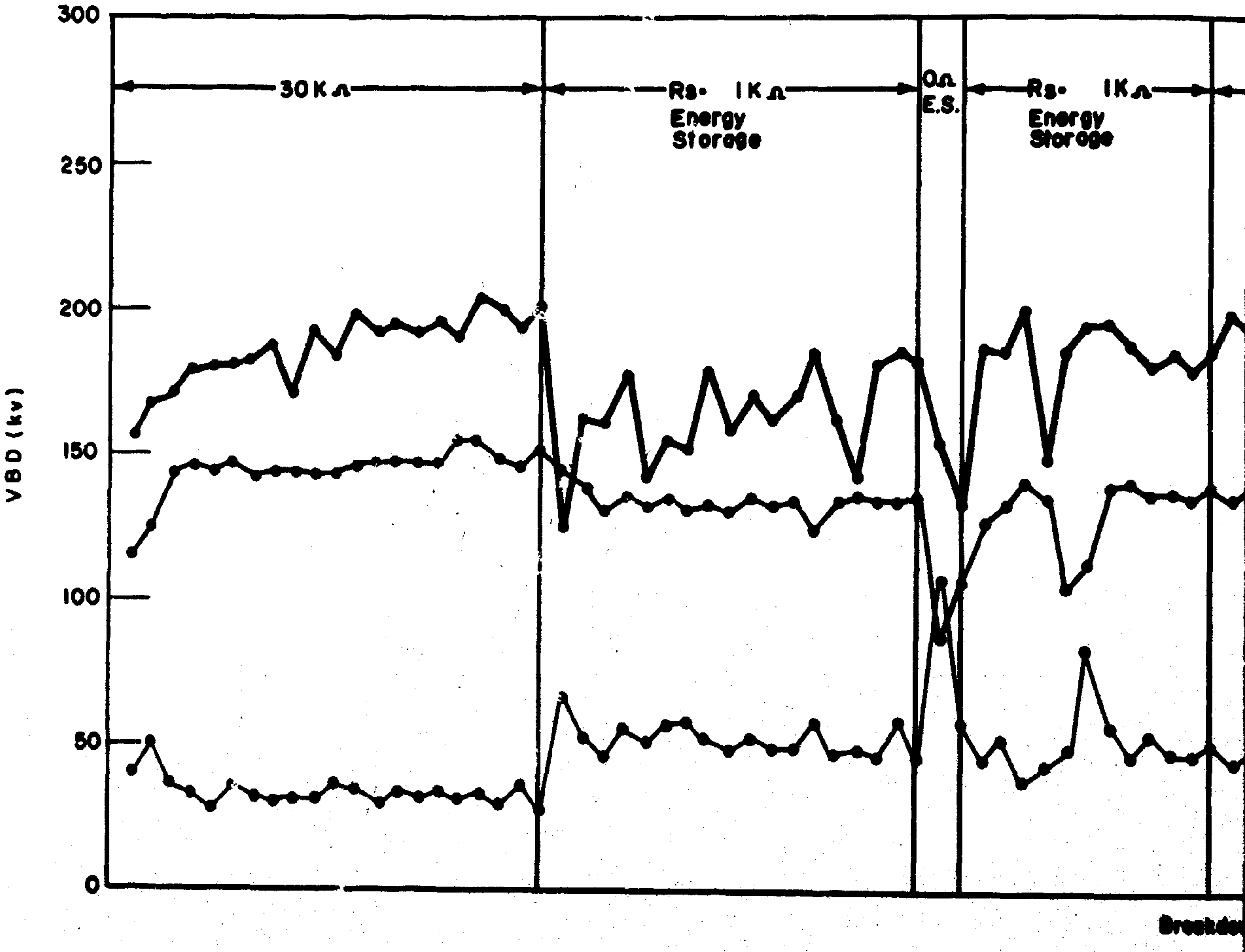


Figure 5. Correlation of Curves for Breakdown Voltage, 10^{-6} A Voltage Level, and Computed Field Enhancement Factor β for Treatment abc - Energy Conditioning Study

B


300
250
200
150
100
50
0
VBD (kv)
30 K Ω
Rs = 1K Ω
Energy
Storage
0 Ω
E.S.
Rs = 1K Ω
Energy
Storage

1-3830

A

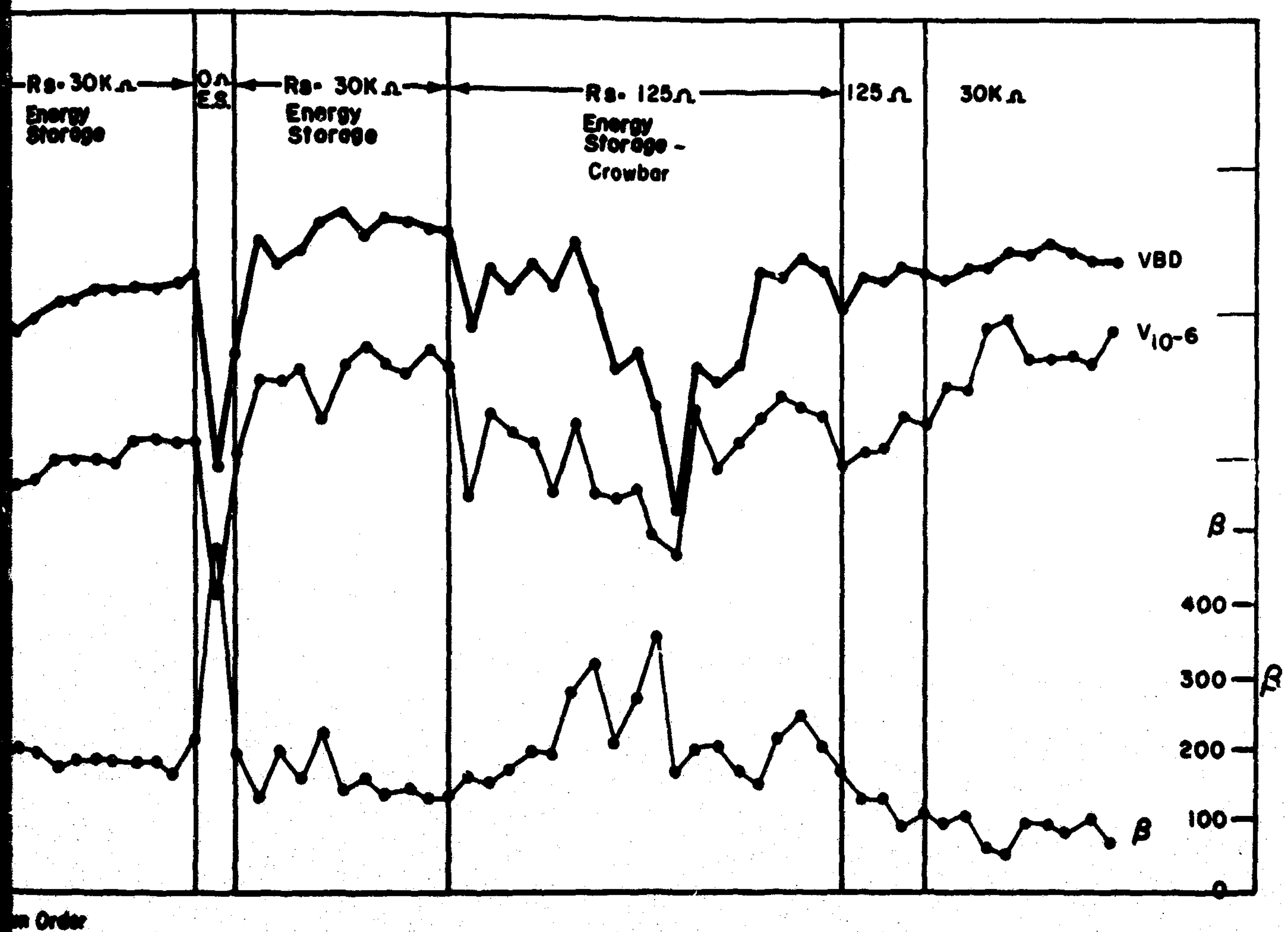
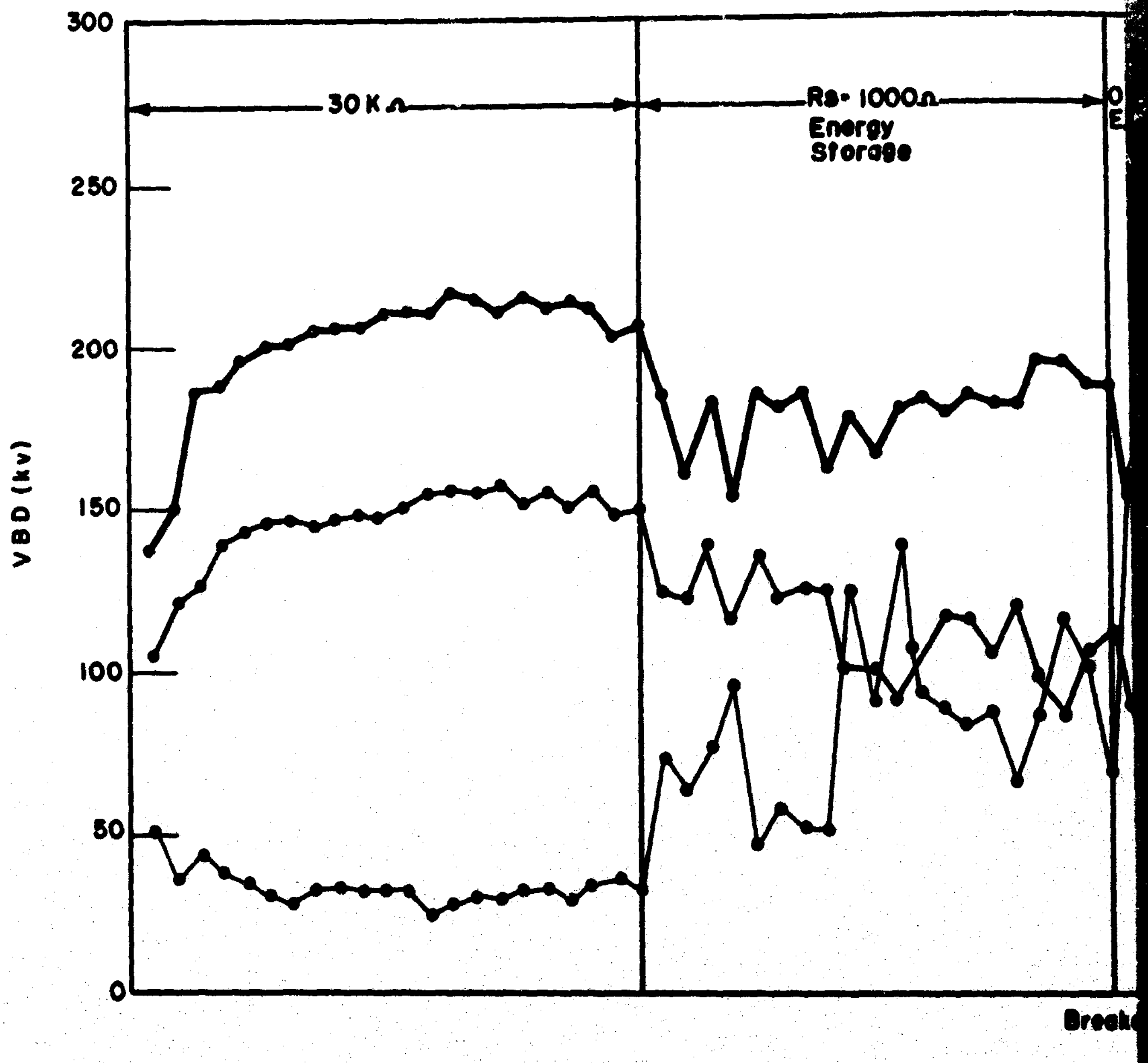


Figure 6. Correlation of Curves for Breakdown Voltage, 10^{-6} Ampere Voltage Level, and Computed Field Enhancement Factor β for Treatment abc (R) - Energy Conditioning Study

13



1-3829

A

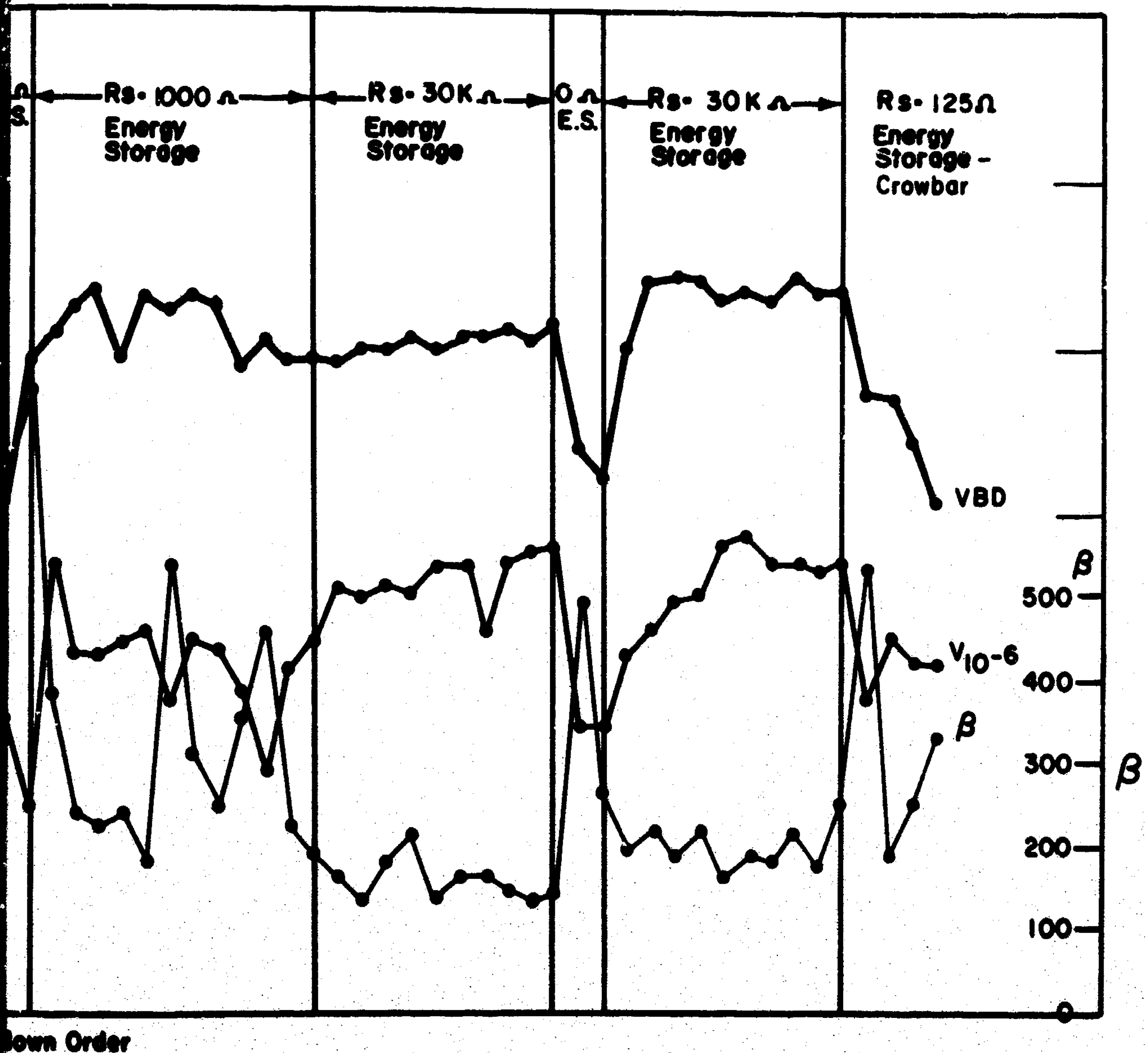


Figure 7. Correlation of Curves for Breakdown Voltage, 10^{-6} Ampere Voltage Level, and Computed Field Enhancement Factor β for Treatment ab: Cu - Energy Conditioning Study

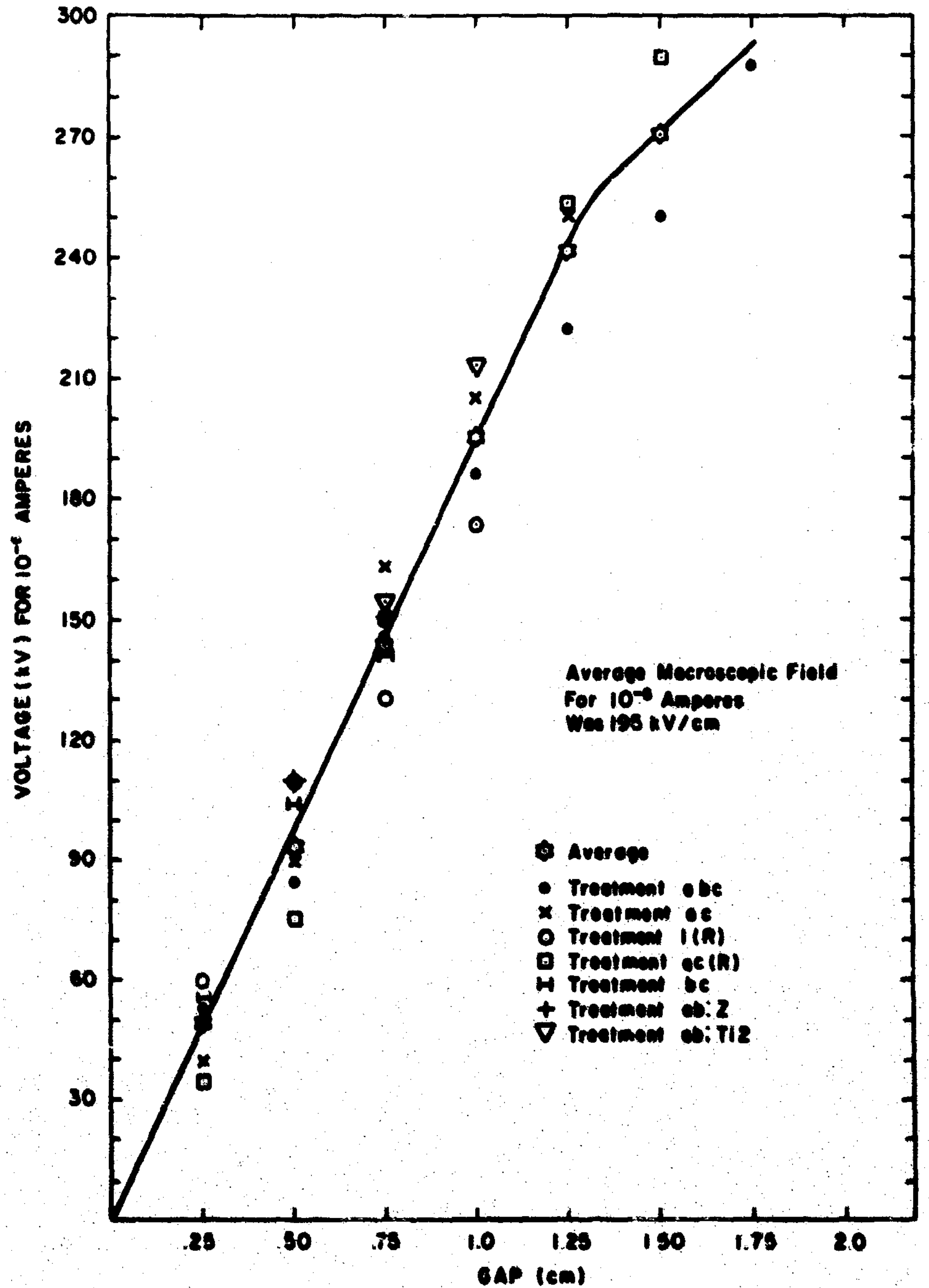


Figure 8. Dependence of Voltage for 10^{-6} Amperes of Prebreakdown Current Upon Gap for Representative Treatments - Measurements are for Well-Conditioned Electrodes

1-4046

At this point, electrode material must be considered in interaction with conditioning and prebreakdown current level. The above conclusions refer to the main part of the experimental program in which the anode was OFHC copper and the cathode was either nickel or Ti-7Al-4Mo. As has been noted, these electrode material combinations were subject to deterioration in performance when subjected to high energy discharge. An extension of the basic factorial design tested electrode combinations in which the anode was also a refractory metal (nickel or Ti alloy). These materials, while initially responding in the same way as electrodes with copper anodes, would, after many high energy discharges, reach performance levels which were higher than had previously been achieved. Thus, in applications where high energy discharges must be tolerated, electrode material can be expected to be extremely important.

3.4 Discharge Characteristics

3.4.1 Introduction

DC vacuum breakdown is defined as the collapse of the gap voltage to near zero. This occurs as capacitive energy is discharged to ground by currents of the order of hundreds of amperes. The rate at which the voltage collapses (or alternately the current flow) depends on two major factors:

(1) Amount and availability of capacitive energy - i.e. the external electric circuit.

(2) Effective instantaneous impedance of the developing vacuum discharge.

Since the material which eventually constitutes the plasma generated upon breakdown must come from the electrodes in vacuum breakdown, the vacuum discharge, relative to breakdown in other media, has a rather slow development, passing through two distinct phases in times of the order of hundreds of nanoseconds. These can conveniently be classified as:

(1) Initial High Impedance Spark Phase

During the initial 100 to 500 ns considerable current flow (hundreds of amperes) occurs while significant voltage is still across the gap. Thus, power input to both the discharge and the electrode surfaces is very high, reaching values of 10^7 joules/s. However, since the duration of this phase is very short, the total energy dissipated is of the order of 1 to 10 J. The effective impedance of the vacuum gap during this phase is $\sim$ 1000 ohms.

(2) Low Impedance Arc Phase

Once the required plasma has been generated by the spark phase, an arc discharge characterized by high currents (hundreds or thousands of amperes) at low voltages occurs. The magnitude and duration of this arc is determined only by the external electric circuit. If sufficient charge is not available, it may never develop. In vacuum, the arc extinguishes very rapidly if the current drops below 5 to 0.5 amperes, the exact value depending on electrode material and gap.

The complex physical mechanisms active during these initial phases have so far received little attention, especially at high voltages. One pertinent study by Epstein, et. al.[3] of plasma processes in a 60 kV vacuum spark found the following sequence. The total current rises monotonically to thousands of amperes. During the early stages of the discharge, a large fraction of the current consists of electrons which are accelerated to the full gap voltage. A plasma which neutralizes the space change develops, allowing the current to rise to high values. Plasma oscillation and intense microwave radiation appear as a result of the interaction of the fast electron stream with the plasma. The electrons lose energy during this stage and eventually a quiescent plasma occurs until a new fast electron stream appears. This alternation of fast electron stream interaction with plasma, energy loss, quiescent plasma, new fast electron stream continues for about 500 ns. Then the impedance of the discharge collapses. This collapse is brought about when a dense plasma vaporized from the anode by incident electron streams arrives at the cathode. These mechanisms are capable of explaining the major features of the discharges observed in the present experiment.

3.4.2 Experimental Observations

Voltage collapse was monitored with a capacitive voltage divider and an oscilloscope. This has been described in detail in Quarterly Progress Reports No. 10 and 17. It is coupled to the high voltage bushing on the gas side and is isolated from the electrodes by only about 20 inches of large diameter conductor. Thus, the voltage collapse waveform is an accurate representation of voltage across the gap, with transit time isolation of not more than 2 to 5 ns.

The breakdown current pulse is observed on the cathode size with a resistive monitor of 0.1 ohms or 0.03 ohms, depending on the maximum current expected. This monitor has been described in Quarterly Progress Report No. 17 and is of low inductance construction.

Typical voltage collapse and breakdown current waveforms are given in Figure 9. The pertinent circuit is given in Figure 10. This circuit

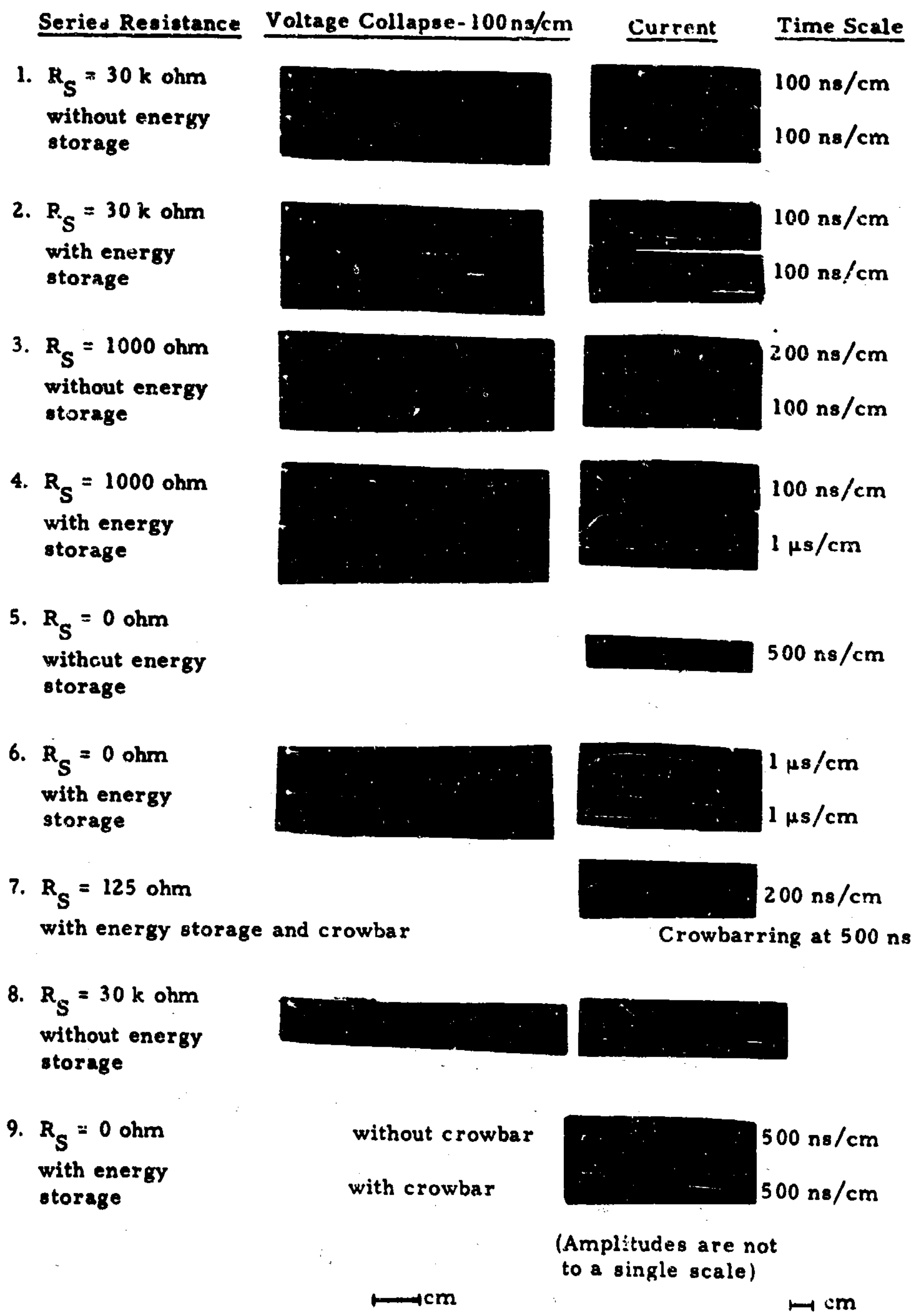
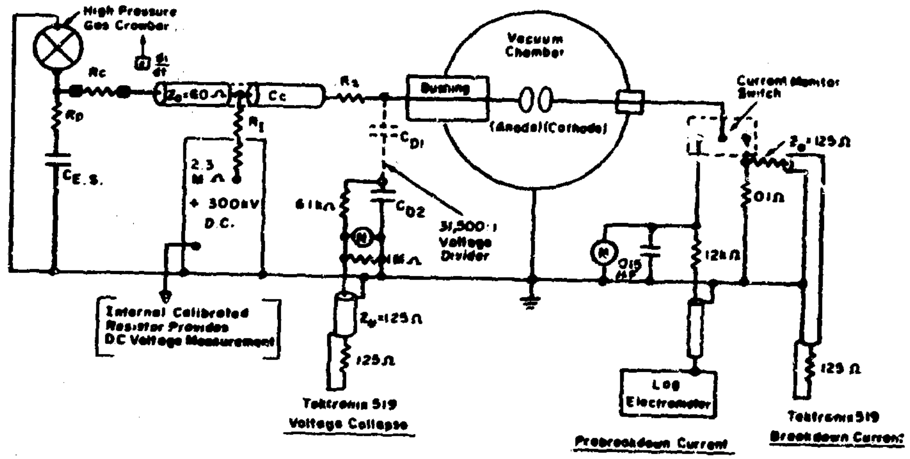


Figure 9. Typical Discharge Waveforms

2-1416



R_s	=	Series Resistance
R_c	=	Crowbarring Resistance (20 ohm) (Removeable)
R_p	=	Protective Resistance (4 ohm)
$C_{E.S.}$	=	Energy Storage Capacitance (0.15 μf)
C_{D1}	=	Voltage Divider Capacitance (1.9 pF)
C_{D2}	=	Voltage Divider Capacitance (1200 pF)
R_I	=	Power Supply Isolation Resistance (2.3 Mohm)
C_c	=	Cable Capacitance (~900 pF)

Figure 10. Schematic of Electrical Test and Instrumentation Circuits

1-3556a

reduces to the simplified circuits of Figure 11 for various combinations of energy storage and series resistance.

3.4.3 Discharge with 30 Kilohm Series Resistance

With a series resistance of 30 kilohms, the typical discharge consists of a rapid buildup of current to about 160 amperes in less than 10 ns. This is followed by a decay of current to near zero in about 500 ns. At the same time, the gap voltage has collapsed to a low value during the first 40 to 100 ns. This behavior is independent of whether or not the energy storage capacitor bank is connected. Thus, 30 kilohms of series resistance effectively isolates the gap and associated bushing capacitance from the rest of the external circuit and the equivalent circuit of Figure 11(b) is pertinent.

The limited peak current and subsequent shape of the current decay waveform suggest that the vacuum spark, during the initial 500 ns, has a fairly high impedance. Since the voltage is initially around 200 kV and the peak current is 160 amperes, the initial impedance is around $Z = V/I = 1250$ ohms. Subsequently, the decay of current is similar to that of a capacitor through a resistor. In this case, the bushing capacitance and the spark impedance, if considered to be resistive, form an R-C circuit whose decay time constant is approximately 200 ns. If the bushing capacitance is assumed to be 150 pF, the equivalent resistance is $R = \tau/C = 1300$ ohms. Measurement of typical integrated currents (charge) supports the assumption that a capacitance of around 150 pF is being discharged from ~ 200 kV to a very low voltage.

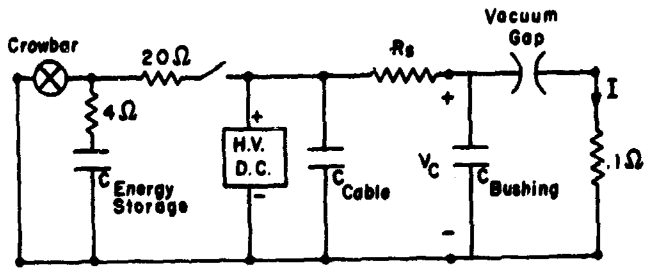
Thus, a consistent description of the high impedance discharge is that it is equivalent to the discharge of a small capacitance through a spark resistance of the order of 1000 ohms. This occurs in a time of ~ 500 ns. The energy dissipated in the gap and on the electrode surfaces during this discharge is of the order of 10 Joules..

Many details of the complex mechanisms active in the initial phases of a vacuum spark are omitted in the above model. Possible mechanisms have been mentioned in Section 3.4.1. For practical purposes, the above description is adequate.

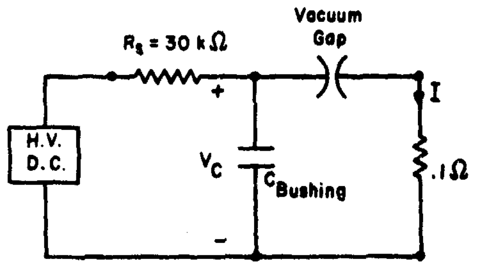
Conditioning with discharges typical of a 30 kilohm series resistance produces high stable breakdown voltage. Reasonably low prebreakdown current levels are also found. This type of discharge will be referred to as a low energy vacuum spark.

3.4.4 Discharge with 1 Kilohm Series Resistance

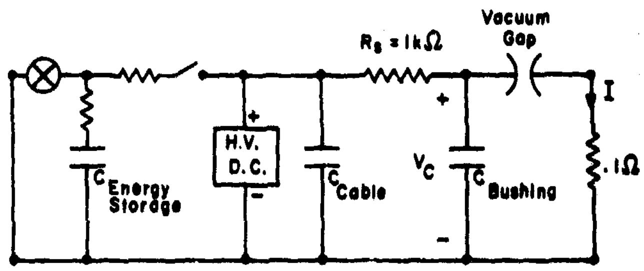
When the series resistance is 1 kilohm, the high voltage cable can now supply significant currents to the discharge. If the initial voltage is 200kV



(a) Equivalent Discharge Circuit for Energy Conditioning Study



(b) Equivalent Discharge Circuit When R_s = 30 Kilohms



(c) Equivalent Discharge Circuit When R_s = 1 Kilohm

Figure 11. Discharge Circuits for Energy Conditioning Study

1-4047

200 amperes can be delivered if the gap voltage drops to a low value. In this case, the circuit of Figure 11(c) applies and the energy storage capacitor bank becomes a critical element if connected.

Voltage collapse time is increased due to the necessity of discharging both cable and bushing capacitance. However, collapse times were approximately the same whether or not the energy storage capacitor bank was connected. This indicates that by the ime the current is being drawn from the energy storage capacitor bank, the gap impedance is very low so that currents of around 200 amperes can be passed with a low voltage drop in the gap. In other words, after about 300 ns the discharge is in the arc phase. This phase will continue for several time constants of the RC circuit formed by the 0. 15 μF capacitor bank and the 1 kilohm series resistance, that is, for times of the order of 300 μs. During this lengthy arc power dissipation in the gap and on the electrode surfaces is expected to be at a low level.

The effect of this form of discharge (R_S = kilohm with Energy Storage) is to produce erratic and often low breakdown voltages. However, the average prebreakdown current level is not change significantly. Although the energy dissipated in the gap cannot in this case be calculated, it seems reasonable to refer to this as a moderate energy discharge.

3.4.5 Discharge with 24 Ohms of Series Resistance

When the series resistor at the high voltage gas-to-vacuum bushing is replaced by a conductor, the only remaining resistance in the discharge circuit is located at the energy storage capacitor bank. There, a total resistance of 24 ohms provides for protection of the capacitor bank and effective crowbar operation. The discharge without energy storage is then the discharge of cable capacitance and, as shown in Figure 9, it exhibits a fairly long duration with minor oscillations. With energy storage the voltage collapse waveform is complicated by reflections in the unterminated cable, but appears to have settled to a lower level after about 300 ns indicating that at this time the gap impedance is low. The current, after an initial peak due to bushing capacitance discharge, builds up to a second peak in 1 to 2 μs. The current then decays with a time constant of 3. 6 μs.

The effects of this discharge on breakdown voltage and prebreakdown current levels are severe. The breakdown voltage is initially reduced by as much as a factor of 2 to 5, and the prebreakdown current at a certain voltage increases significantly. With some electrode materials, it can be expected to reach 2 mA before breakdown. Materials such as nickel and titanium, when included as anode material, have demonstrated great tolerance for such high energy discharges. After the initial drop in performance, a series of 40 to 60 discharges will lead to performance that is as good or better than that found with only low energy discharges (high impedance conditioning - R_S = 30 kilohms).

3.4.6 Crowbarring - Effect on Discharge

The high pressure gas crowbar is capable of diversion within 200ns. When applied in the system shown in Figure 10, the effects of diversion become apparent in the current waveform after about 400 to 500 ns, as shown in Figure 9. This is for a series resistance of 125 ohms which, with energy storage, is normally a damaging discharge in the sense that breakdown voltage level drops and prebreakdown current levels increase. As has been discussed in Section 3.6 of the Eighteenth Quarterly Progress Report, crowbarring was not effective in eliminating this damage. Later tests in which crowbarring was used with a 0 ohm series resistance have been given in Figure 1. It is evident that crowbarring again had no significant effect on breakdown voltage levels. In this case, diversion reduced the current waveform after about 1.5 μs as shown in Figure 9.

The conclusion is that electrode damage due to high energy discharges, measured as a deterioration in vacuum gap insulation performance, occurs during the first stages of the discharge - certainly within several microseconds. Thus, if energy is available during the first one to two microseconds, crowbarring that cuts off the energy supply at 500 to 1500 ns will not maintain high breakdown voltages. The solution is to add resistance or inductance to the system so that the energy (current) cannot reach the gap during the initial stages of the discharge. Then, crowbarring will most likely be effective.

It is again important to note that the above conclusions are based upon treatments in which the anode was copper. Treatments in which the anode is a refractory metal such as titanium alloy or nickel have shown a much better tolerance of high energy discharges as discussed in Section 3.2 In such cases, added inductance, resistance, or faster crowbarring would probably be unnecessary.

3.5 Effect of a Dielectric Envelope

In this experiment, the vacuum environment is provided by a 3 foot diameter stainless steel sphere. It is more usual in high voltage electron tubes for the vacuum chamber to be at least partially constructed of dielectric material so that it can provide some high voltage insulation and support for electrode structures. Thus, the effect on breakdown voltage of dielectric surfaces in the vicinity of the stressed gap is pertinent. To model this, a cylinder of Pyrex 7740 glass, 8 inches in diameter by 1/4 inch thick and 10 inches high has been placed around the electrodes with stress relieving end flanges as shown in Figure 12. Previously, this dielectric envelope had been installed after the usual test series. However, this required that the vacuum chamber be opened to atmosphere and it was found (see Quarterly Progress Report No. 16, Section 4.4) that the effect of exposure to atmosphere totally obscured any effects which might be due to the dielectric envelope.

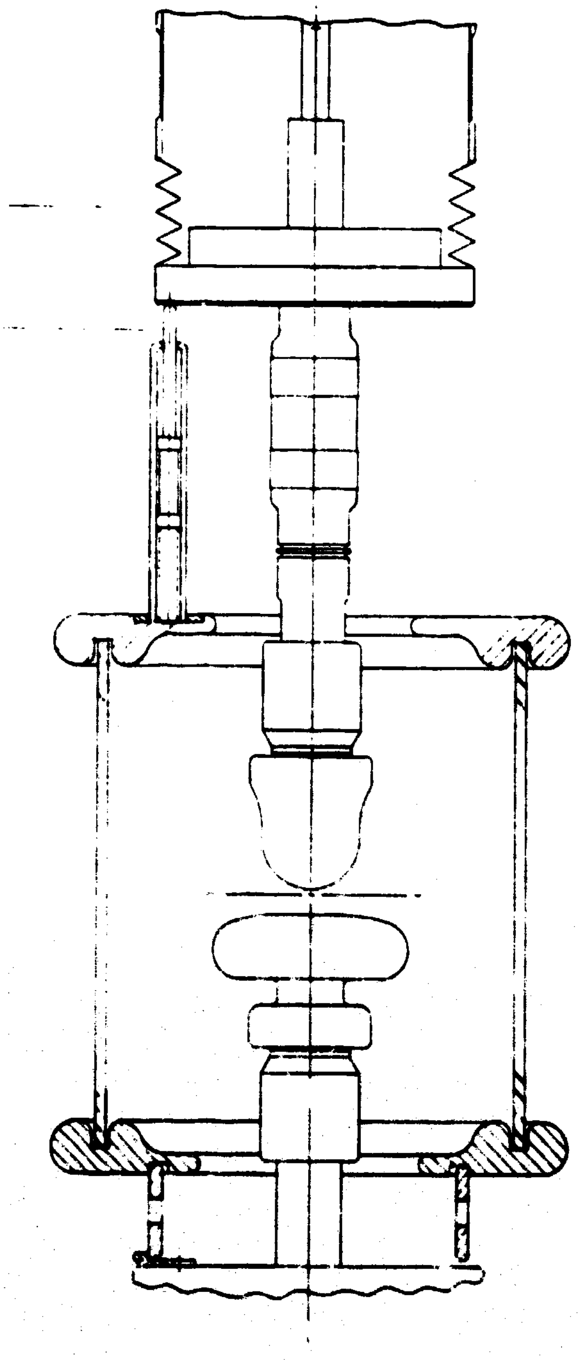


Figure 12. Dielectric Envelope Assembly

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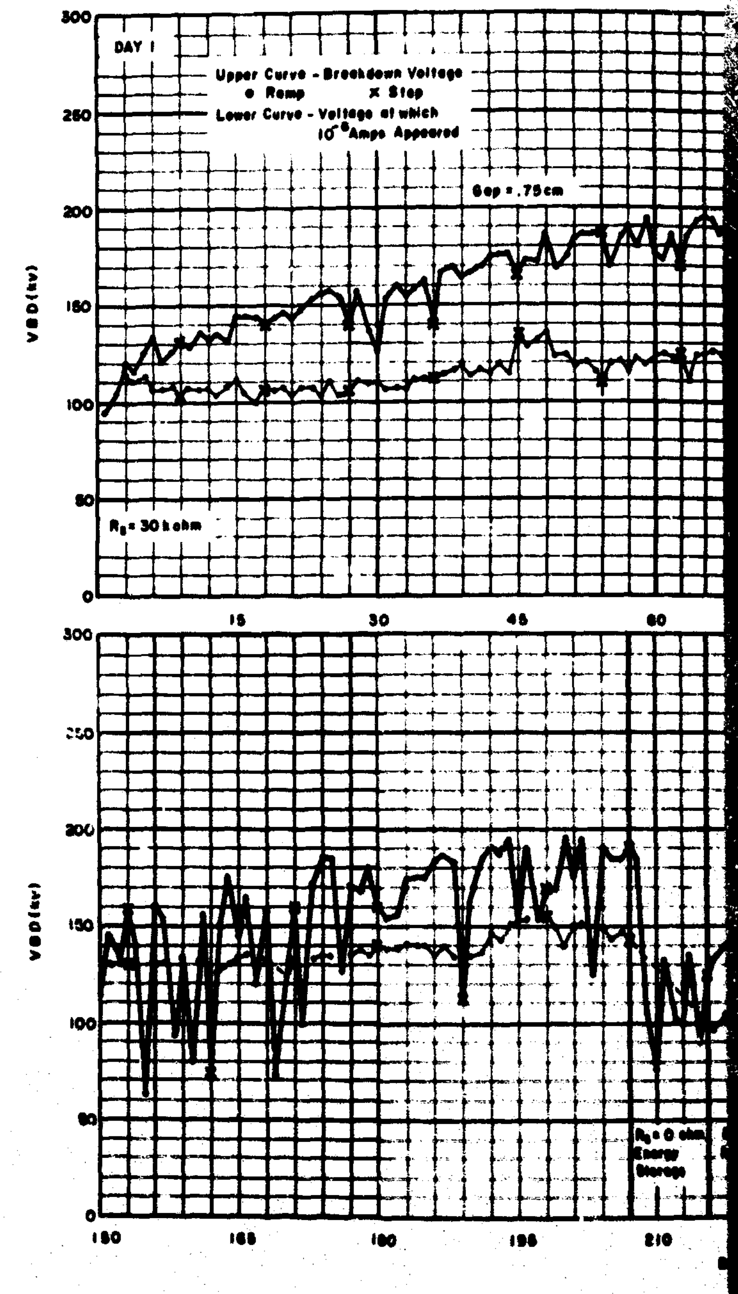

DAY 1
Upper Curve - Breakdown Voltage
● Ramp × Step
Lower Curve - Voltage at which
10^{-6} Amps Appeared
Gap = .75 cm
R_s = 30 k ohm
VBD(kv)
300
250
200
150
100
50
0
15
30
45
60
R_s = 0 ohm
Energy
Storage
150
165
180
195
210

1-4048

A

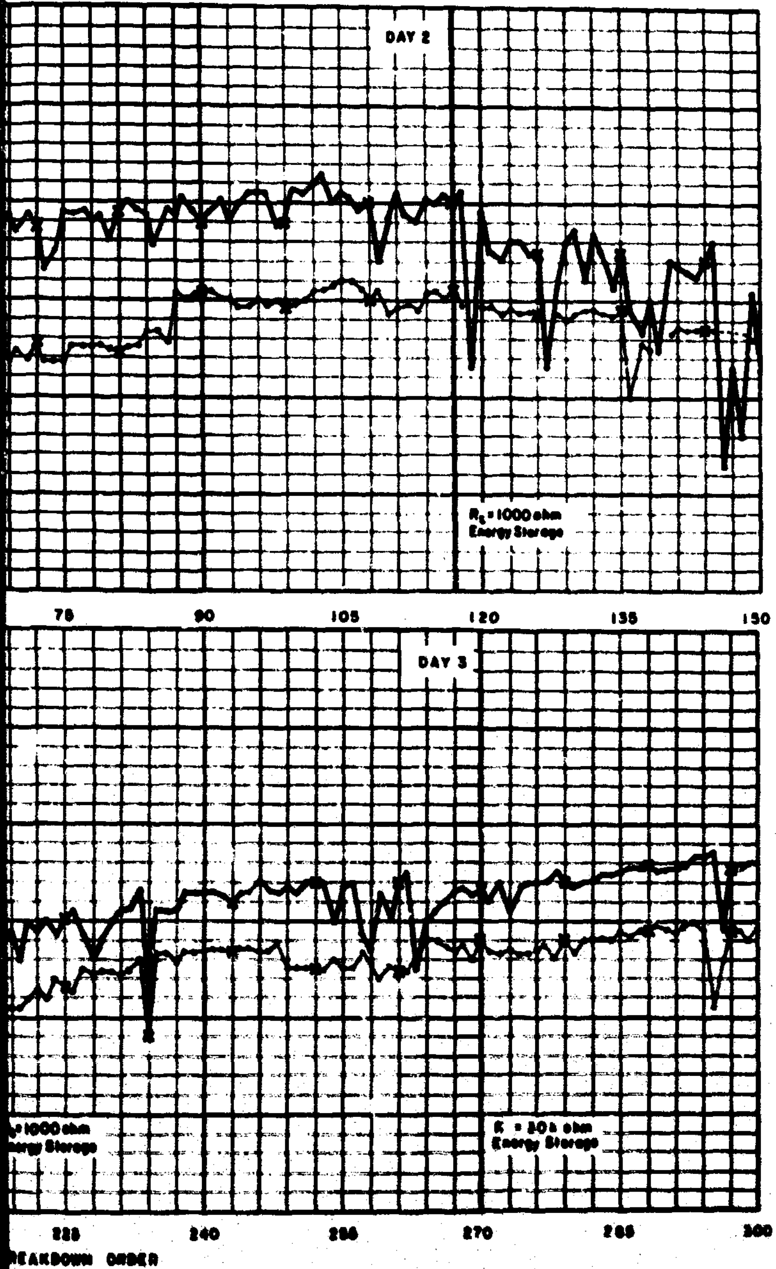
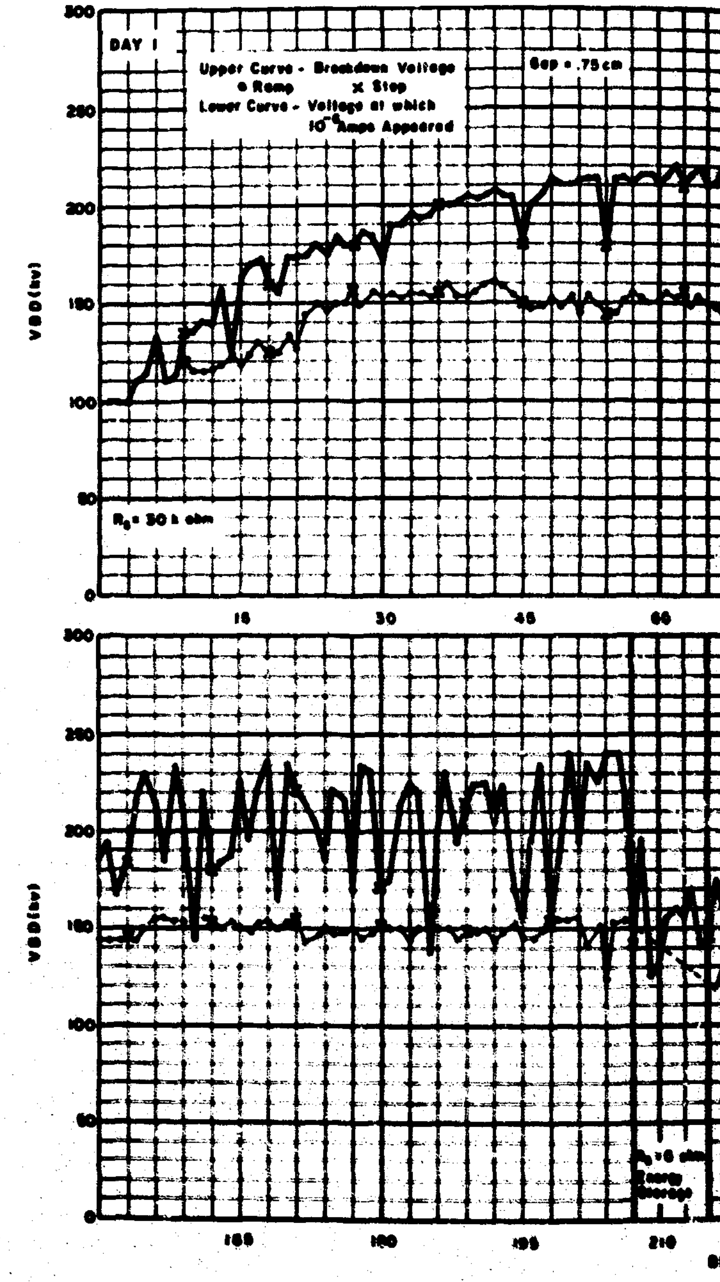


Figure 13. Energy Conditioning Curve for Treatment abc: DE1 4-Inch Diameter Bruce Profile Electrodes - Titanium Cathode Copper Anode Vacuum Fired With 10-Inch Diameter Pyrex Dielectric Envelope



DAY 1
Upper Curve - Breakdown Voltage
o Ramp x Stop
Lower Curve - Voltage at which
10^-6 Amps Appeared
Gap = .75 cm
VBD(kv)
300
250
200
150
100
50
0
15
30
45
60

1-4049

A

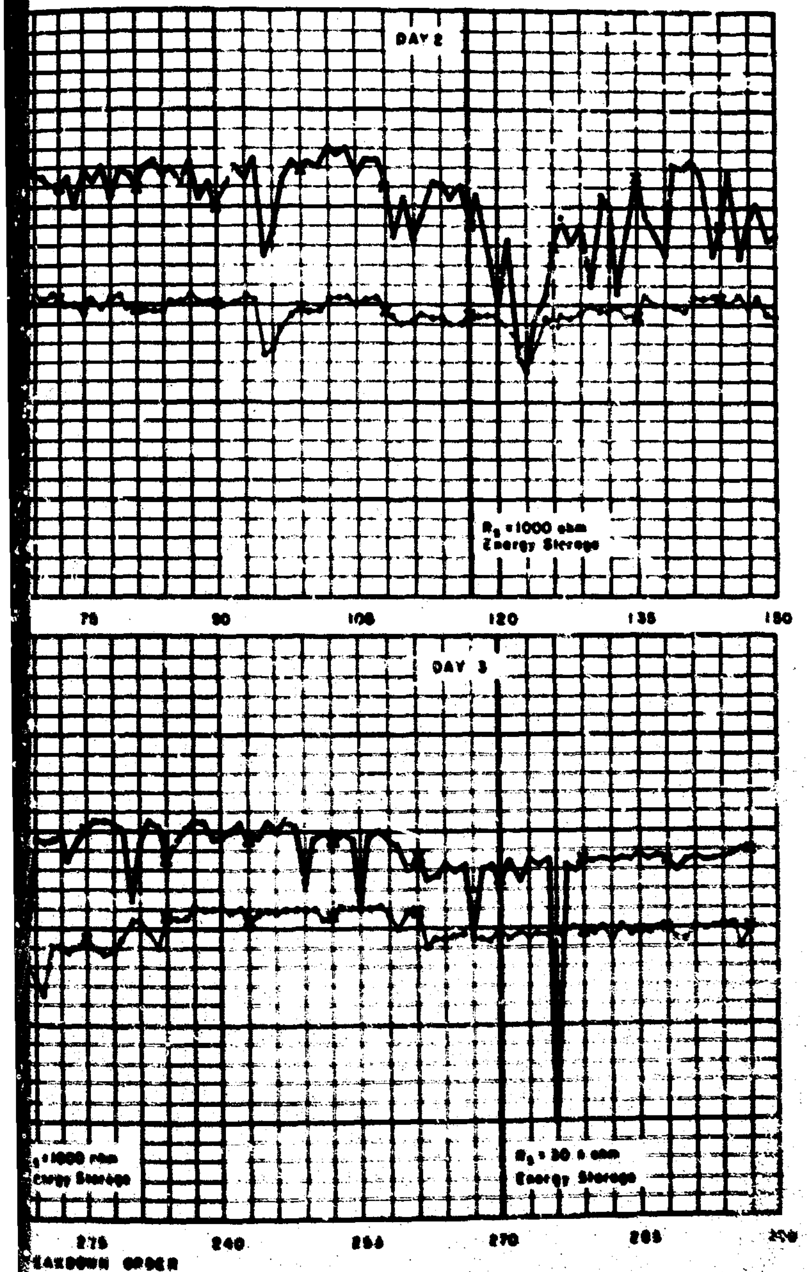


Figure 14. Energy Conditioning Curve for Treatment abc: DE2 4-Inch Diameter Bruce Profile Electrodes - Titanium Cathode Copper Anode - Vacuum Fired With 10-Inch Diameter Pyrex Dielectric Envelope

Accordingly, during the Energy Conditioning Study, an electrode combination that had been previously tested (4 inch diameter Bruce Profile Vacuum Fired Electrodes with a Titanium cathode and Copper anode was tested twice again, in this case with the dielectric envelope placed around the electrodes prior to bakeout. Thus, the effects of the dielectric envelope would not be obscured by other factors.

The results in the form of conditioning curves are given in Figures 13 and 14. These may be compared with similar curves for the identical electrode combinations of treatments abc and abc(R) as given in Figures 8 and 9 of the Eighteenth Quarterly Progress Report. Allowing for the 5 to 10% repeatability obtained in these vacuum breakdown studies there does not appear to be any significant differences between the treatments with and without the dielectric envelope. Average performance levels during the initial high impedance conditioning stage were around 210 kV. During the subsequent moderate energy conditioning series the breakdown voltage level with the dielectric envelope was in one case (abc:DE2) higher than that without; while in the other case (abc:DE1) it was lower. If the following high impedance conditioning stage, the treatments without the dielectric envelopes reached about 205 kV while those with reached only 185 to 190 kV. However, this 5 to 10% difference is probably not significant.

After the second test with the dielectric envelope, it was observed that it had partially cracked on one side. It is thought that this did not have any influence on the results. During previous tests with an unbaked enveloped, flashover often occured at 200 kV or above. With the baked envelope, no flashover was encountered even during the bushing conditioning periods of 20 minutes at 300 kV which preceded each day's testing.

3.6 Effect of Time in dc Vacuum Breakdown

Breakdown voltage is usually defined as the last measurable voltage across the gap just prior to breakdown. This convention has been followed throughout the present experimental program. In other experiments, breakdown voltage has sometimes been taken as the maximum steady voltage that could be held for a specified time period. In vacuum breakdown these definitions do not yield the same rssults, since for a given vacuum gap the breakdown voltage is apparently a strong function of the time for which the voltage is applied. This section reports some preliminary measurements of this dependence of breakdown voltage on time at voltage or rate of voltage application. It was found that while these measurements are straightforward when each discharge is of low energy, the introduction of high energy discharges renders measurement of long term withstand properties difficult and time consuming.

The withstand tests were carried out for the four inch diameter Bruce Profile nickel electrodes after completion of the normal energy conditioning sequence. A series impedance of 30 kilohms limited the intensity and duration of each discharge to such a low energy (< 10 joules) that it could be assumed that the well-conditioned electrode surfaces did not change during the test. The gap was set to 0.75 cm and the voltage steadily increased (at a rate of ~ 5 kV/s) to breakdown after which a series of step withstand tests were carried out at lower voltage levels down to a level at which no breakdown would occur over a period of several hours. Steps of 5 kV were used and the voltage was held at each level (except for the momentary drop to zero during each discharge) for a time of either 1 hour or until 10 to 20 breakdowns had occurred. The voltage levels were tested in a random sequence and periodically the ramp breakdown voltage (5 kV/s) was determined to verify that the electrodes had not changed appreciably. Each level was investigated at least twice, and the times between breakdown were apparently random at any one level.

Results are given in Figure 15. The breakdown voltage level is plotted as a function of the log of the mean time to breakdown at each voltage level. The mean time to breakdown increases rapidly as the stress is reduced, leading to an exponential withstand characteristic.

The steady prebreakdown current prior to breakdown was, even at the highest stress levels, less than 4×10^{-5} amperes. Thus, assuming as a worst case that this is due to a single field emission beam, localized power input to the anode is less than $P = VI = (2.45)(10^5)(4)(10^{-5}) = 9.8$ watts. While this would not lead to significant general heating of the anode in the time periods involved, it does suggest that a possible cause of long time dc breakdown is localized thermally generated instabilities of the anode surface. Thus, at lower stress levels, the prebreakdown current and power flow is less and the mean time to breakdown is longer. Since the prebreakdown current depends exponentially on voltage due to its field emission origin (see Section 3.3), it is reasonable that if the current is a precursor to breakdown through heating of the anode surface, then the mean time to breakdown will be exponentially dependent upon voltage level. This could occur at lower and lower stress levels until the conduction of heat away from local anode hot spots is sufficiently rapid to prevent instabilities. The mechanism of this instability has been suggested by Watson[4] to be evolution of gas from the hot spot and by Davies[5] to be the electrostatic pulling away of a thermally softened blob of anode material. At the present time there is not sufficient experimental evidence to indicate which mechanism is most likely.

For high energy discharge sequences, measurement of withstand properties becomes difficult because the electrode surfaces are changed as a result of each discharge. Thus, each measurement of time to breakdown at some stress level is for an essentially different set of electrodes. That is, some of the high energy discharges will leave behind a surface able to sustain high stresses for long time periods, while other high energy discharges will result in electrode surfaces incapable of supporting even low stress levels for

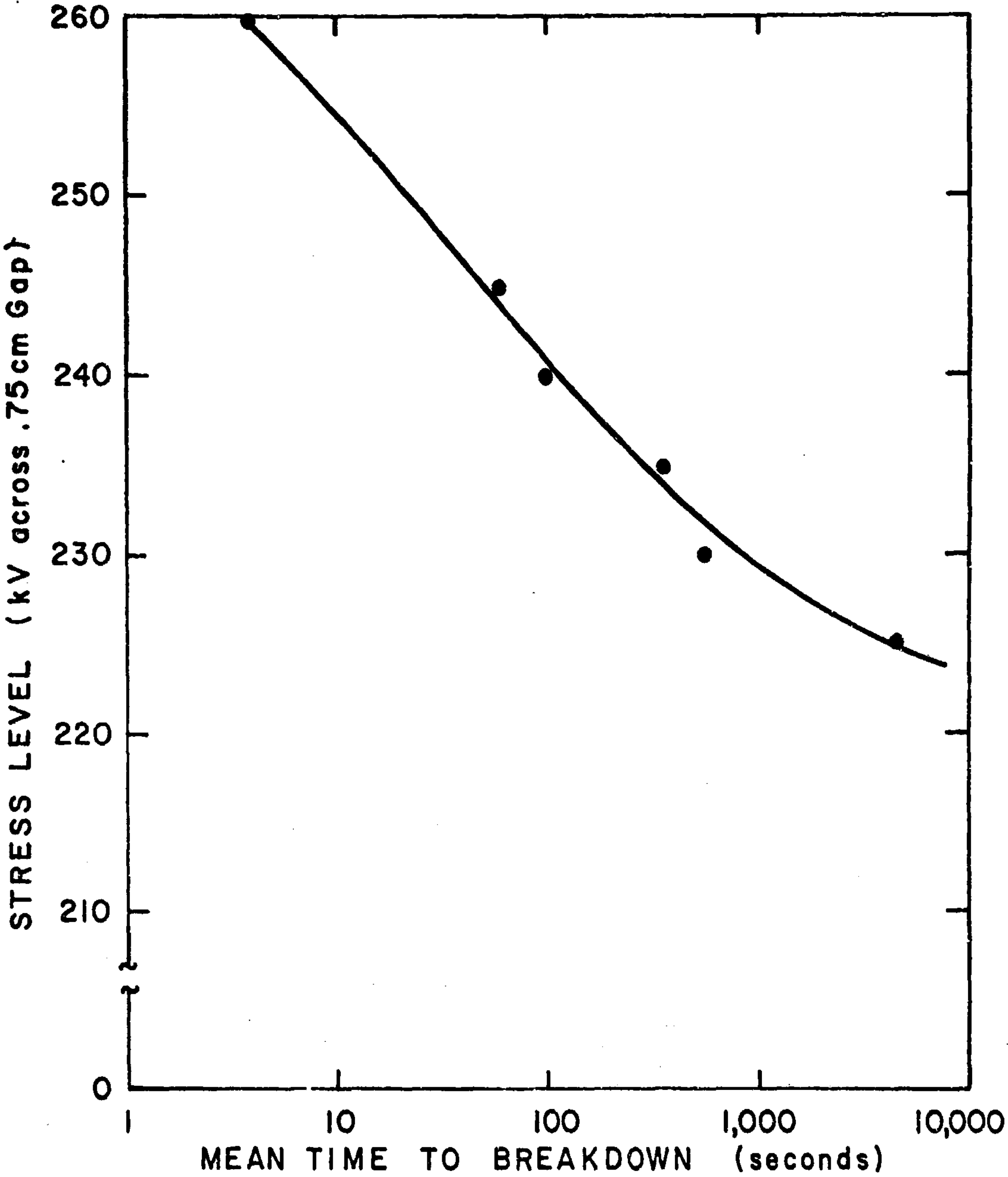


Figure 15. Typical Withstand Properties of High Impedance Conditioned Vacuum Gap - 4 Inch Diameter Uniform Field Nickel Electrodes

1-4360

short time periods. In the program to date sufficient time has not been available to allow meaningful measurements of withstand characteristics of high energy conditioned electrodes to be made. It is planned, however, that in the next quarter work on this aspect will be undertaken.

3.7 Conclusions

The effects of conditioning with high energy discharges have been found to depend to a large extent on anode material. Electrode combinations with a titanium alloy anode were not permanently degraded by high energy discharges, while those with a copper anode were severely damaged.

Accordingly, it is planned to investigate this energy conditioning effect for a range of anode material. This experiment will be carried out in parallel with this Barium Contamination experiment and should enable quantitative estimations to be made of the response of different anode materials to high energy discharges in vacuum.

SECTION 4

BARIUM CONTAMINATION AND ENERGY CONDITIONING STUDY

4.1 Introduction

Many high voltage vacuum tubes use a thermionic cathode of the Barium Oxide type to provide the necessary supply of electrons. These tubes are usually found to be limited to lower stresses than tubes not subject to decomposition and evaporation products from a hot Barium Oxide cathode. The most probable mechanism for this lowering of permissible stress is the reduction of work function of the metal surfaces when barium and/or barium oxide is depsoited. This phenomenon has been studied by Brodie at low voltages (~ 50 kV) for nickel electrodes. The present experiment extends the investigation of the effects of barium contamination to higher voltages for a wide range of materials (nickel, copper, titanium alloy, and stainless steel). In addition, the discharge energy will be varied so as to make possible a comprehensive study of the conditioning of contaminated electrodes.

The results of the one treatment completed so far using OFHC copper electrodes have shown major differences from Brodie's work. He observed, upon exposure of a vacuum gap to a hot Barium Oxide cathode, a marked decrease in breakdown voltage and an increase in prebreakdown current. While the breakdown voltage could be restored to its initial level by conditioning, the prebreakdown current was an order of magnitude or more higher as a result of barium contamination.

In the present experiment, the effect of barium appeared to be related to conditioning, in that the greater the amount of conditioning, the greater the reduction in breakdown voltage produced by the barium contamination. However, there was no permanent increase in level of prebreakdown current. The complexity of the present results indicate that this phase of the program will require a flexible approach. Thus, while the factors of material and contamination of anode or cathode or both electrodes are easily specified, the experimental sequence will need to be evolved as the experiment proceeds.

4.2 Experimental Procedure

The techniques of materials processing, prefiring and baking developed in previous experiments were used to obtain repeatable results. These techniques are discussed in previous Quarterly Progress Reports and will, thus, only be briefly outlined here (see Table 1).

Table 1. Experimental Procedure

Electrode Preparation

Machine to Bruce Profile

Hand Finish with 600 Grit SiC Paper

Clean with Solvents and Ultrasonic Process

Fire at 900° C for 6 hours in Vacuum

Load into Vacuum Chamber

System Bakeout

Chamber at 375°C for 6 hours

Electrodes at 400° C for 6 hours

Cool System for 48 Hours

Test Sequence - at 0.75 cm Gap

Condition with 30 k ohm Series Resistance

Activate Barium Oxide Cathode

Recondition - Note any changes in VBD Level

Then a series of exposures to the hot Barium Oxide Cathode followed by reconditioning each time (R_S = 30 k ohm)

Introduce High Energy Discharges into the Sequence (R_S = 0 ohm, with Energy Storage)

Barium contamination was introduced by moving a heated Barium Oxide cathode into the vicinity of the gap by means of a rod and bellows assembly. This apparatus has been described in Quarterly Progress Report No. 18, Section 2. 4. The cathode used was obtained from Machlett Laboratories and is typical of those used in high voltage vacuum tubes. The hot surface of the oxide cathode is directed at either the cathode or anode electrode of the vacuum gap. A metal shield protects the other electrode from direct contamination. A new cathode is used for each treatment.

The activation procedure is designed to convert the barium and strontium carbonates of the unused cathode to oxides and free barium in such a way that a stable and adherent layer is produced on the nickel substrate. The sequence consists of gradual heating under vacuum and is as follows:

Step	Time (min)	Filament Current Amps(rms)	
1	1	.5	
2	1	.6	
3	2	.7	
4	2	.8	
5	2	.9	
6	15	1.0	(~ 800°C)
7	3	1.1	
8	5	1.0	

Subsequent running of the oxide cathode is at either normal operating temperature (1. 0 ampere filament current) or at higher levels (up to 1. 3 amperes).

Exposure times as long as several days, with elevated temperatures used to increase the amount of contamination evolved, have been used.

4. 3 Experimental Results

One treatment was completed in this reporting period. Results in terms of breakdown voltage and voltage level for one microampere of prebreakdown current are given in the conditioning curve of Figure 16. The electrodes were 4 inch diameter Bruce Profile (Uniform Field) vacuum fired OFHC copper with a 600 grit SiC finish. The series resistance throughout this treatment was 30 kohm, and thus, all discharges were of low energy. The gap was

0. 75 cm until Day 12 when other gap settings were tested. Every third breakdown has been used in the conditioning curve so that it would be of reasonable length. Any breakdowns significantly different from adjacent breakdowns (in voltage level or prebreakdown current) have also been included.

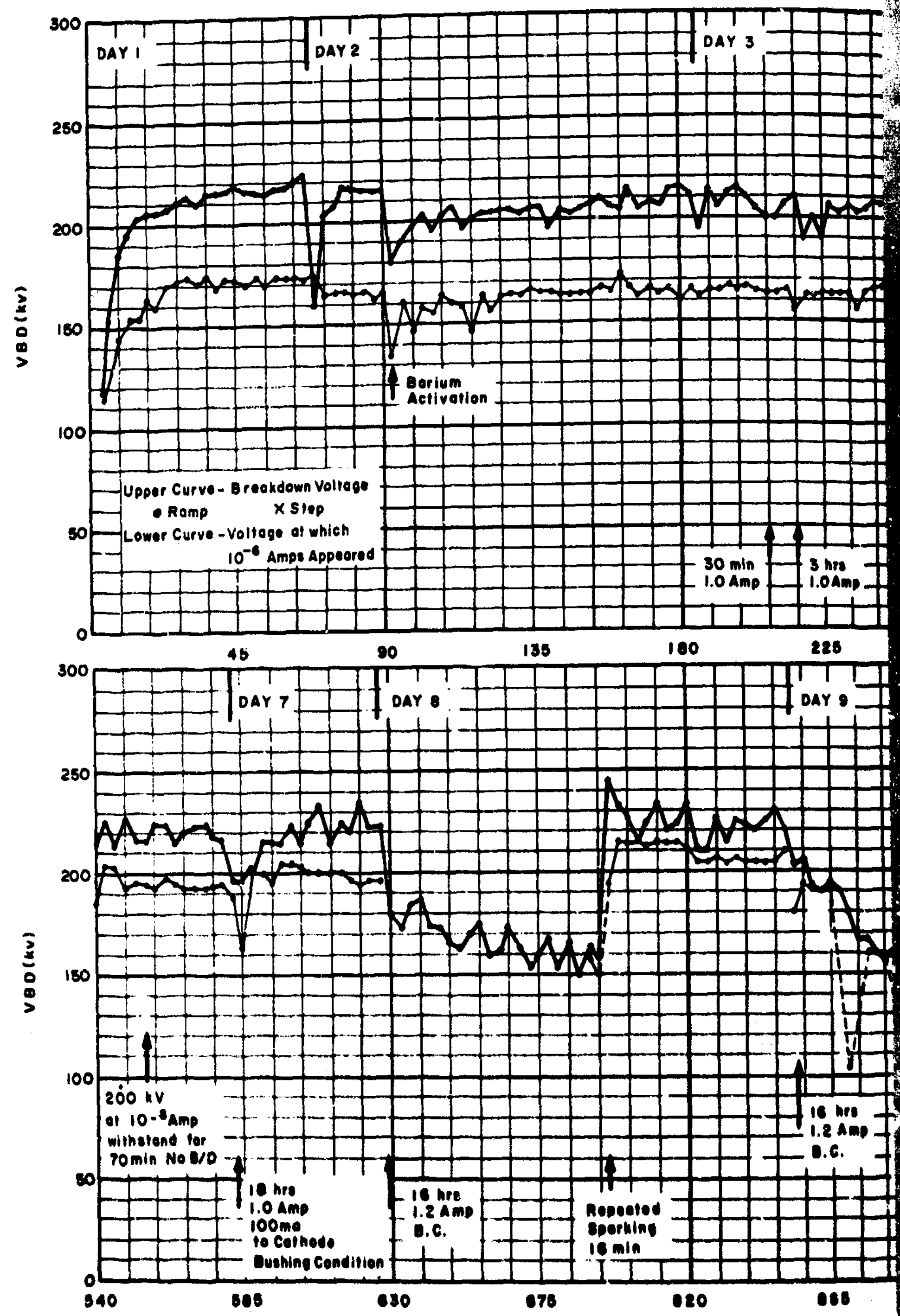
While detailed discussion and conclusions must wait until more treatments have been completed, the following observations can be made:

(1) The initial effects of barium contamination are minor and times of the order of tens of hours are required to produce contamination sufficient to cause significant changes in breakdown voltage and prebreakdown current.

(2) In many cases, the effects of the barium contamination become more noticeable as reconditioning is attempted (see breakdown No. 865 and No. 1055 of Figure 16).

(3) Repeated sparking (many sparks or breakdowns per minute) appears to remove the effects of barium contamination more readily than the usual breakdown rate of one per minute (see breakdown No. 1760 and No. 2175 of Figure 16).

(4) There is no permanent increase in prebreakdown current levels as a result of barium contamination.



DAY 1
DAY 2
DAY 3
VBD(kv)
Barium Activation
Upper Curve - Breakdown Voltage
● Ramp X Step
Lower Curve - Voltage at which
10^{-6} Amps Appeared
30 min 1.0 Amp
3 hrs 1.0 Amp
45
90
135
180
225
DAY 7
DAY 8
DAY 9
200 kV at 10^{-5} Amp withstand for 70 min No B/D
18 hrs 1.0 Amp 100ma to Cathode Bushing Condition
16 hrs 1.2 Amp B.C.
Repeated Sparking 16 min
16 hrs 1.2 Amp B.C.
540
585
630
675
720
765

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A

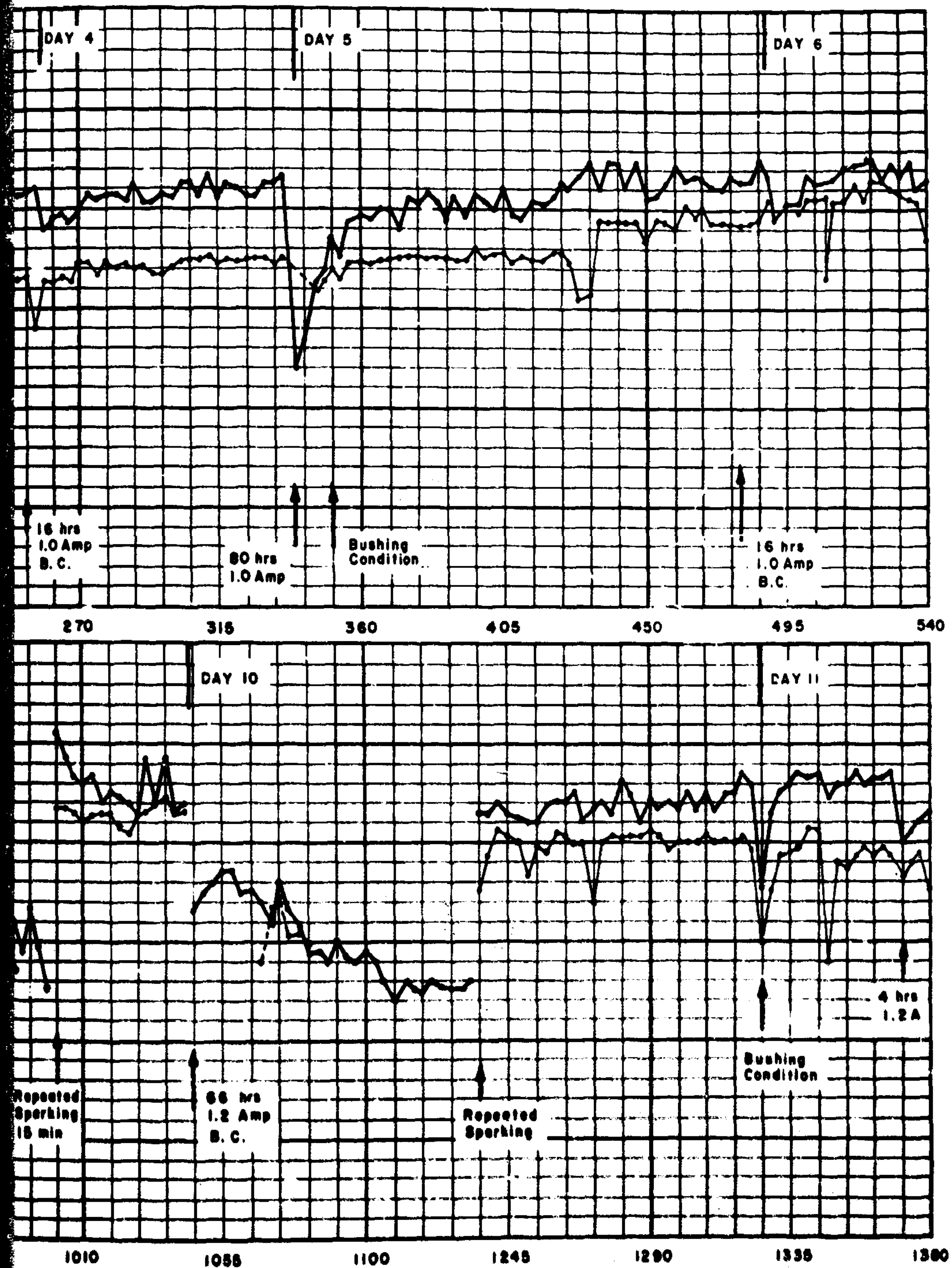
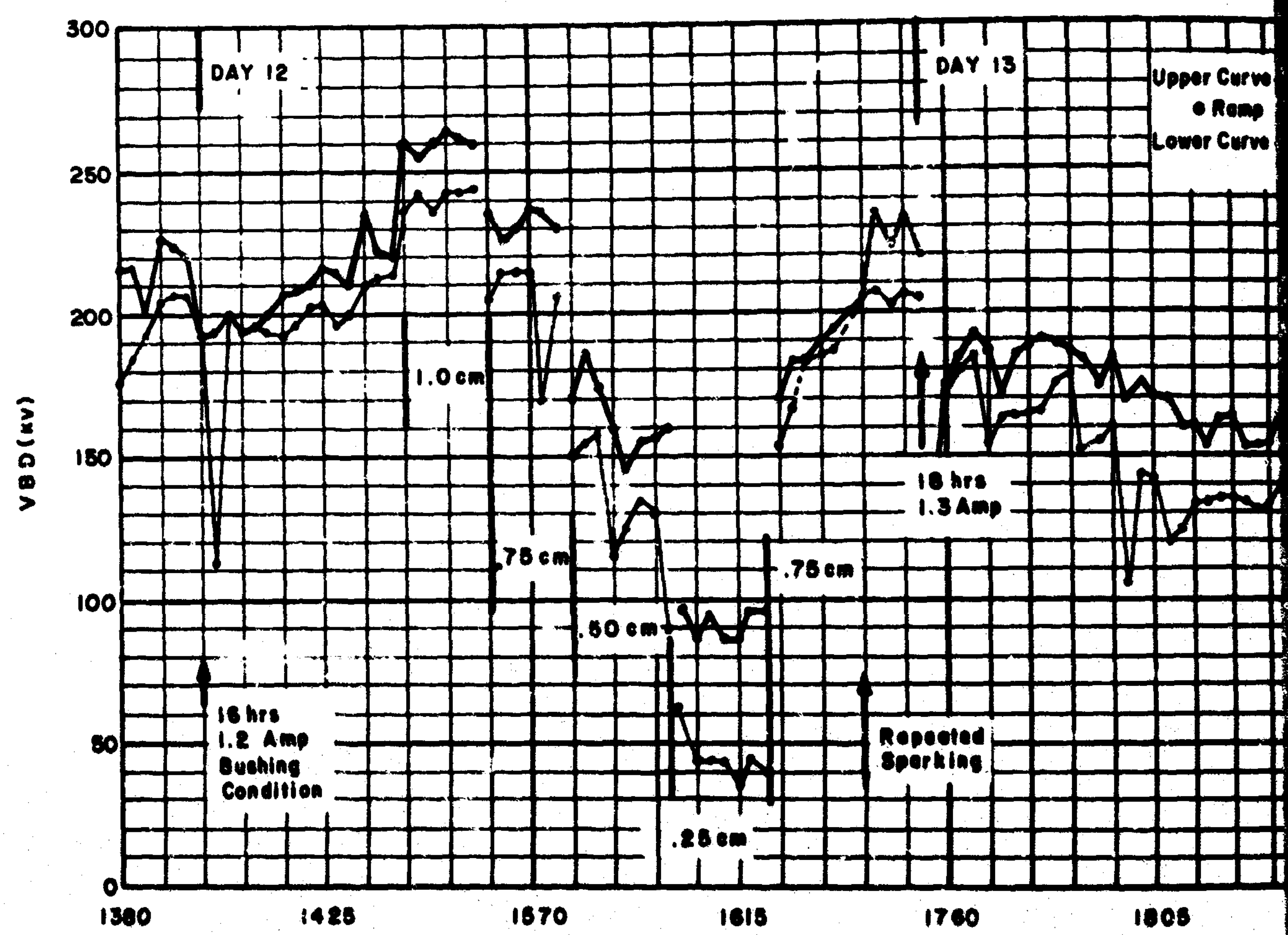


Figure 16. Conditioning Curve for Barium Contamination Treatment I - 4-Inch Diameter Bruce Profile Vacuum Fired OFHC Copper Electrodes at 0.75 cm Gap - R_s = 30 Kilohms


300
250
200
150
100
50
0
VBD (kv)
DAY 12
DAY 13
Upper Curve
e Ramp
Lower Curve
1.0 cm
.75 cm
.50 cm
.25 cm
.75 cm
16 hrs
1.2 Amp
Bushing
Condition
Repeated
Sparking
18 hrs
1.3 Amp
1380
1425
1570
1615
1760
1805

1-4272

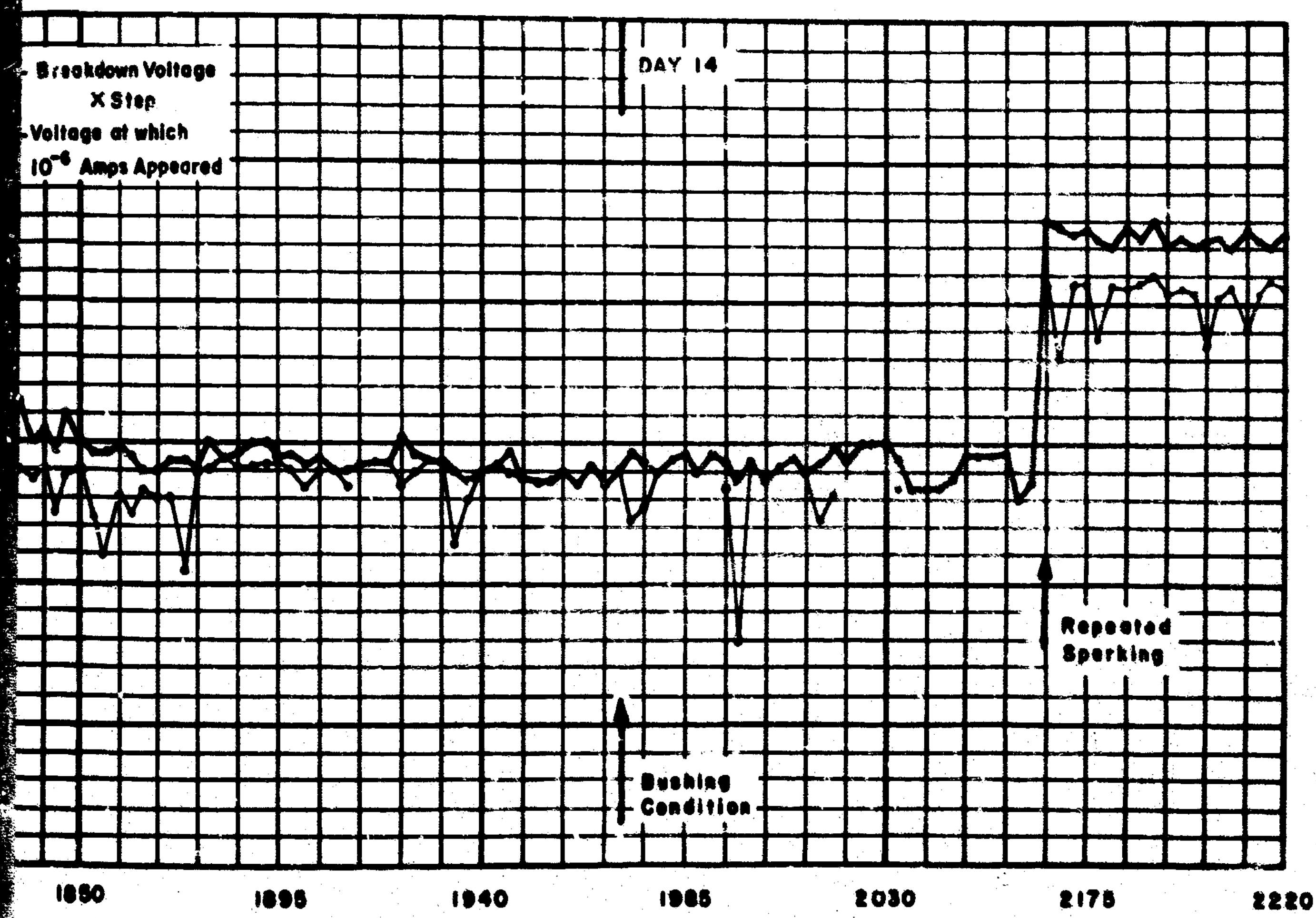


Figure 16. Continued

SECTION 5

FUTURE EFFORT

During the next quarter, effort will be directed toward:

- Completion of the Barium Contamination Study
- Continuing Analysis of the Energy Conditioning Study
- Extension of Materials Study as part of the Barium Contamination Study and as indicated by results of the Energy Conditioning Study
- Regular Maintenance of the Apparatus
- Initiation of Final Overall Analysis for a Final Report.

SECTION 6

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(4) Watson, A., Addendum to Technical Report ECOM-00394-14, High Voltage Breakdown Study, Ion Physics Corporation, Burlington, Massachusetts (October 1968).

(5) Davies, D. K. and Biondi, M. A., Journal of Applied Physics, 39, No. 7, (June 1968).

SECTION 7

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

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A. C. Stewart	Engineering Manager
W R. Bell	Senior Electrical Engineer
M. M. Thayer	Senior Metallurgist
P. C. Bolin	Project Engineer
F. Y. Tse	Electrical Engineer
R. M. Parsons	Engineering Aide
D. Bryant	Technician
R. J. Merchant	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
Dr. N. E Woldman	Consultant Metallurgy

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13. ABSTRACT

The nineteenth quarter of a study of high voltage breakdown in vacuum is reported. Results of an Energy Conditioning Experiment relating to extended high energy discharge series, prebreakdown current, voltage collapse, and breakdown current pulses are analyzed. It was found that titanium alloy electrodes perform significantly better than material combinations with a copper anode when tested under high energy discharge conditions. The design and initial results of a Barium Contamination experiment are reported. In this experiment, barium is evaporated from a typical barium oxide cathode near the electrodes. Preliminary withstand tests are also reported.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT

Security Classification