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ELECTRODE DAMAGE CAUSED
BY SPARKS IN VACUUM

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November 4, 1960

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Contents

Abstract	5
1. Introduction	7
2. Review	7
3. Test Objective	8
4. Apparatus and Electrodes	8
5. Tests--First Series	
A. Test Results for 60 Sparks at Approximately 20 Joules each	11
B. Discharge at Air Pressure	11
C. Discharge at 1×10^{-3} torr of Argon	11
D. Discussion of First Series of Tests	11
E. Voltage Transients	19
6. Tests--Second Series	
A. Tests with High Stored Energy	19
B. Gas Released by a Spark	19
C. Arc Energy Calculation	29
D. Effect of Surface Roughness	30
7. Conclusions	30
Acknowledgments	31
References	31

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ABSTRACT

Tests were performed to determine what range of series resistance is required to protect electrodes in a vacuum from electrical discharges. Twelve hundred joules of energy stored in an external capacitor were used. A typical installation would be the high voltage electrodes of a parallel-plate beam separator operating at (+) and (-) 600 kv.

It was determined that damage to electrodes was not the main factor to consider when choosing the external resistor.

Maximum discharge current was limited to a value well below the expected chopping current. This allows the arc to go out immediately and possibly not restrike, giving more full-voltage operating time even with a high spark rate. A high resistance also decreases the amount of metal evaporated from electrodes, which otherwise might be deposited on insulators and give trouble.

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1. INTRODUCTION

Progress in developing glass cathode parallel-plate spectrometers¹ has resulted in a need for 600-kv power supplies.

The glass cathode inhibits electron emission at points of high gradient. Suppression of electron emission allows higher voltage gradients to be held than is possible with metal cathodes. Stainless steel anodes were used because the power density for collected electrons is high enough to cause glass electrodes to crack.

Experiments are now being organized to use ± 600 kv on the plates for a total of 1200 kv in the spectrometer. A 2-in. separation of the plates is planned. Some of the conclusions I had reached in 1959² regarding spark damage on electrodes were still unsubstantiated; we needed more information regarding spark damage in a vacuum before we could build a reliable protection circuit for the spectrometer electrodes.

2. REVIEW

A survey of current literature regarding spark damage in a vacuum, and its control, was not very rewarding. There are several articles regarding theories of arc breakdown and how to hold maximum voltage gradients on gaps and across insulators,^{3,4,5,6} but only a few mention the damage resulting from a discharge. The article by A. S. Denholm was most informative,⁵ although he used a maximum stored energy of only 24 joules at 70 kv. The National Nuclear Energy Series volume on High Voltage Problems by J. D. Trimmer and H. Pearlman (1951), dealt with higher energies, but was mainly concerned with cable and insulator breakdown rather than resultant damage.

The 600-kv power supplies now being constructed will have a combined stored energy of 2400 joules when connected to a spectrometer. This is a much higher stored energy than covered by any literature on arc damage; therefore, we decided to perform some experiments to point the way for the design of suitable protection.

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Fig. 1. Series resistor R_2 and capacitor C_1 .

3. TEST OBJECTIVE

We wished to determine what effect different series resistors would have on the amount of electrode damage caused by a spark in the vacuum, and to correlate this information with various stored energies that might be available for typical spectrometer installations.

4. APPARATUS AND ELECTRODES

A small oil-diffusion-pumped liquid-air-trapped vacuum system was used for the tests. An untrapped ion gauge was used for all pressure measurements.

The volume of the tank on the spark-gap side of the air-operated vacuum gate was 60 liters. Some of the stored energy capacitors and series resistors are shown in Fig. 1.

High voltage was supplied by a 300-kv 1-ma electrostatic generator built by Soci Anonyme des Machines Electrostatiques of Grenoble, France.

Stainless steel electrodes were used for these tests. They were shaped like a doughnut with one side flattened and had previously been used as insulator skirts. They were located one above the other, anode on top (Fig. 2), and displaced so that only a small portion of the doughnut shape would be involved during a spark.

The electrodes could be rotated with the tank open to air to expose new surfaces for subsequent tests. Before they were placed in the chamber they were buffed with No. 600 grit wet, washed thoroughly with a detergent, and then rinsed with acetone.

A 13/64-in. gap (5.1 mm) was used which gave a breakdown voltage of about 130 to 160 kv for most of the tests. This voltage was chosen as an easy one for the stored-energy capacitors to handle in open air structure. RG-19/U was used for high-voltage connections between the various units.

Capacitors used for stored energy were 0.167 mf, 0.033 mf, and 1500 μ mf of cable. The limiting resistors ranged from 0 to 20×10^6 ohms. The maximum stored energy was 1400 joules.

The gap capacity of 600 μ mf represents 5 joules. Nominal care was taken in the gap assembly. We were interested in electrode damage resulting from sparks, and not necessarily the maximum voltage that a gap will hold.

A compensated high-voltage divider was used to measure the voltage of the gap. Response of the divider was about 26×10^{-6} sec. This limited our voltage measurements to time constants of 250×10^{-6} sec or more, which proved satisfactory for the range of capacity and resistance of interest.

Current measurements were taken with an air toroid for 10^{-9} sec times, and with a 1-ohm noninductive resistor for the slower and lower current measurements.

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Fig. 2. Electrode arrangement with sandblasted surfaces shown.

5. TESTS — FIRST SERIES

A. Test Results for 60 Sparks at Approximately 40 Joules Each

The first series of tests (see Fig. 3), was designed to obtain some qualitative information on spark damage caused by 60 sparks. R_2 was given values of zero, 55,000 ohms, and 600,000 ohms respectively, in three separate tests.

Examination of the damaged areas (Figs. 4, 5, and 6) showed only a small correlation to the value of the series resistor. The upper (+) electrodes showed many pits and craters; small balls and depressions about 0.02 mm in diameter covered the damaged areas.

The lower (-) electrode showed very few pits or craters, but did show a thin deposit of a dark substance that might have been from oil vapors in the tank. This coating could also have resulted from some sputtering from the (+) electrode.

The first tests were made when the test chamber had been pumped down to about 3×10^{-6} torr (mm of Hg) pressure. It was noted that normally a spark would not occur until the gradient was raised sufficiently to cause about 500×10^{-6} amp of current to flow. With this current flowing, the tank pressure measured approximately 20×10^{-6} torr. The pressure rise is probably due to outgassing of the surfaces.

B. Discharge at Air Pressure

The same 13/64-in. gap was sparked at air pressure. The gap broke down at 21 kv (approx 0.4 joule). The resulting damage was considerably more severe than from vacuum sparks, and involved both electrodes equally (see Fig. 7). The points left were jagged and rough. Oxidation probably contributed greatly to the damage.

C. Discharge at 1×10^{-3} torr in Argon

The same setup was used to check the effect on gap performance and damage of argon at 1×10^{-3} torr. Only one test was made with $R_2 = 0$ ohms and $C = 2100$ μ pf. The electrode damage was no different from those in the first tests run at 3×10^{-6} torr (see Fig. 8). The gap held about the same voltage as at lower pressure tests, but the spark always occurred with less than 100 μ a of steady drain.

D. Discussion of First Series of Tests

We were surprised to find so little correlation between the limiting resistor and resultant damage. It was thought that each spark might only discharge the gap capacity, and that the added series resistor might only determine whether and how soon the arc would restrike. Testing this possibility, I connected the high voltage directly to the gap with a short cable. Total capacity was about 400 μ pf, or 4.5 joules at 150 kv. Figure 9 shows the electrodes after about 170 sparks; again the amount of damage and size of irregularities were about the same as before. A thin (+) electrode

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Fig. 3. High-voltage test equipment; maximum stored energy, 20 joules.

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Fig. 4. Sixty sparks: $R_2 = 0$ ohms, 40 joules.

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Fig. 5. Sixty sparks: $R_2 = 55 \text{ k ohms}$, 40 joules.

ZN-2646

Fig. 6. Sixty sparks: $R_2 = 600$ k ohms, 40 joules.

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Fig. 7. More than 60 sparks in air: $R_2 = 0$ ohms, approx
0.4 joules at 21 kv.

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Fig. 8. Sixty sparks: $R_2 = 0$ ohms, approx 40 joules. Tank was at 1×10^{-3} torr pressure of argon.

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Fig. 9. One hundred-seventy sparks; $C_2 = 400 \mu\text{mf}$, 150 kv.
Added short cable running from power to test chamber.

(0.010 in.) was also tried, to be sure that the mass of the electrodes used was not influencing the results. The same damage resulted.

A single large crater appeared approx 0.25 mm in diameter and about 1/10 as deep. It may be that the influence of electromagnetic forces on a molten bit of steel allows only a certain maximum size of ball to exist. Rapid outgassing of the molten metal could further disperse the material. The high gap pressure in its vicinity may allow the arc to wander around and thereby spread damage over a larger area.

E. Voltage Transients

A 1-ft length of high-voltage cable next to the vacuum tank was used as a high-voltage divider to measure high-frequency transients involved with a vacuum spark. Rise times of less than 10×10^{-9} sec were measured.

6. TESTS — SECOND SERIES

A. Tests With High Stored Energy

A series of tests was next set up to observe the damage for just a few sparks with a maximum stored energy of 1620 joules. See Fig. 10 for the circuit diagram, and Figs. 11 through 18 for pictures of the resultant damage. Only (+) electrodes are shown because the (-) electrodes showed no large damage.

The pictures indicate that on a single-spark basis, high series resistance does minimize the resultant area of damage of one spark.

The current value below which a vacuum discharge goes out is called the chopping current.⁵ Our tests with a 13/64-in. gap showed chopping current from 0.5 to 1.5 amp. Tests on a 2-in. gap showed similar chopping currents. Measurements on a spectrometer during operation at ± 240 kv showed chopping currents of 2 to 3 amp.

At pressures above 1.5×10^{-3} torr, the arc current did not exhibit the phenomenon of chopping off, but instead decayed to practically zero current.

Voltage drop of a 13/64-in. discharge in a vacuum can range from 2 to 5 kv. A 2-in. gap showed arc drops from 4 to 25 kv. The voltage established at the beginning of the spark held reasonably constant until the arc was extinguished. High values of series resistance (e.g., 1 to 20×10^6 ohms) tended toward high arc drops, but not consistently.

B. Gas Released by a Spark

The gas released by a spark consists of both condensable material, such as metal vapor, and noncondensable gases absorbed in the metal.

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Fig. 10. High-voltage test equipment; maximum stored energy 1620 joules.

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Fig. 11. Two sparks: $R_2 = 0$, $C_1 = 0$.

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Fig. 12. Spark damage: approx 7 sparks, $R_2 = 0$ ohms,
 $C = 0.033 \times 10^{-6}$ farad.

ZN-2651

Fig. 13. Spark damage: 4 sparks, $R_2 = 22$ k ohms,
 $C = 0.033 \times 10^{-6}$ farad.

ZN-2641

Fig. 14. Spark damage: 3 sparks, $R_2 = 50 \text{ k ohms}$,
 $C_1 = 0.033 \times 10^{-6} \text{ farad}$.

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Fig. 15. Spark damage: 7 sparks, $R_2 = 0.0$ ohms,
 $C_1 = 0.166 \times 10^{-6}$ farad.

ZN-2652

Fig. 16. Spark damage: 2 sparks, $R_2 = 22$ k ohms,
 $C_1 = 0.166 \times 10^{-6}$ farad.

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Fig. 17. Spark damage: 13 sparks, $R_2 = 50$ k ohms,
 $C_1 = 0.166 \times 10^{-8}$ farad.

ZN-2642

Fig. 18. Spark damage: 3 sparks, $R_2 = 20 \times 10^6$ ohms,
 $C_1 = 0.166 \times 10^{-6}$ farad.

The noncondensable gas released can be measured by noting the pressure change caused by a vacuum spark in a sealed tank. It was thought that the gas released in our 60-liter test chamber might correlate with the amount of electrode damage noted during the tests.

The first tests were with the 0.033×10^{-6} -f capacitor and 12,000-ohm series resistance. A typical pressure change for one 140-kv spark was from 60×10^{-6} torr to 160×10^{-6} torr.

Subsequent tests showed that with 0.167×10^{-6} f and 20×10^6 ohms there was an almost negligible pressure change. A resistance of 1×10^6 ohms showed a change of about 2×10^{-6} torr from a base pressure of 60×10^{-6} torr and 70,000 ohms resistance showed a change of about 10×10^{-6} torr from a base of 70×10^{-6} torr. Indeed, there seemed to be a correlation between arc damage and gas released.

C. Arc Energy Calculation

Using the facts that arc drop V_{arc} is constant for the duration of a spark, and that current cuts off at some value I_c , one can calculate the energy dissipated in the arc as follows:

$$E_{\text{arc}} = \int_{t_0}^{t_1} V_{\text{arc}} I_0 \exp[-t/(R_2 C_1)] dt \quad (1)$$

$$\begin{aligned} &= V_{\text{arc}} (V_0/R_2) \int_{t_0}^{t_1} \exp[-t/(R_2 C_1)] dt \\ &= V_{\text{arc}} (V_0/R_2) \frac{1 - \exp[-t/(R_2 C_1)]}{1/(R_2 C_1)} \end{aligned} \quad (2)$$

where

E = energy in the arc,	t_1 = time to current chopping,
V_0 = initial voltage,	R_2 = resistance in series with
V_{arc} = arc drop,	stored energy,
I_0 = initial peak current,	C_1 = capacitor for stored energy,
I_c = chopping current,	$V_0 = V_{\text{arc}}$.

For an exponential decay the current is $i = I_0 \exp(-t/R_2 C_1)$ at that value of t for $i = I_c$. Then

$$I_c/I_0 = \exp(-t/R_2 C_1). \quad (3)$$

Substituting (3) into (2), we then have

$$E = V_{\text{arc}} V_0 C_1 (1 - I_c/I_0), \text{ or } E = V_{\text{arc}} Q_1 (1 - I_c/I_0), \quad (4)$$

where Q_1 is the charge stored in C_1 , $Q_1 = V_0 C_1$.

From Eq. (4) it can be concluded that energy loss in a vacuum spark will be reasonably constant for different values of series resistances, until it is high enough to limit I_0 to about 1/2 amp.

It would require much more investigation to determine how much arc energy shows up as energy that will damage electrodes. For the present, it is assumed that the energy causing electrode damage is some constant fraction of the total energy in the arc.

D. Effect of Surface Roughness

We used highly polished electrodes for this series of tests. Polishing stainless electrodes can considerably increase the cost of high-voltage apparatus.

A short test of the effect of the surface condition seemed in order. A comparative test was made using $R_2 = 300$ k ohms, $C_1 = 0.033$ mf, gap = 13/64 in. Polished surfaces were raised to 150 kv in about 3 sparks and in a short time (2 min). Surfaces roughened with 80D garnet paper were raised to 150 kv after about 11 sparks, about three times as long as with the polished surfaces. Surfaces roughened with No. 38 grit by using a sand blast had the first spark at about the same voltage (90 kv) as the other two tests, but never held more than 120 kv. It is concluded that surface roughness has some influence on the voltage-holding capabilities of a 13/64-in. gap, but not a large one. For larger gaps, the influence might be even less.

7. CONCLUSIONS

The energy into a vacuum discharge from an external capacitor can be minimized by using a series resistor that will limit peak current to less than the chopping current. One-half amp should be a safe value.

The high series resistance also minimizes the amount of gas released during a spark, and causes a second spark immediately following the first to be less probable.

Although the breakdown voltage of a 13/64-in. gap was not significantly changed by sparking with no series resistor and 1600 joules of stored energy, it is desirable to have a high series resistance to limit the amount of metal vapors that may deposit on insulators and give subsequent trouble.

High series resistances should give more reliable spectrometer operation because a single spark does not completely discharge the power supply output capacitor. This has been borne out in the operation of the

present spectrometers, where we have empirically settled on a series resistor greater than 100,000 ohms for 240-kv operation.

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