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VOLTAGE STABILIZATION BY MEANS OF THE CORONA DISCHARGE BETWEEN COAXIAL CYLINDERS

by

I. H. Blifford, R. G. Arnold and H. Friedman

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Approved by:

E. O. Hulburt
Superintendent
Optics Division

Commodore H. A. Schade, USN
Director
Naval Research Laboratory

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ABSTRACT

The positive-wire continuous-corona discharge between coaxial cylinders provides adequate regulation for use with G-M counters, cathode-ray devices, and electron diffraction cameras. The supply voltage is applied to the corona tube through a resistance R_s. If R_c is the slope of the corona current-voltage characteristic, the stabilization ratio is $R_c/(R_s + R_c)$. Both the firing voltage and R_c depend on the nature and pressure of the gas, and on the electrode dimensions. R_c was about 100,000 ohms for a 1000-volt hydrogen-filled regulator tube having the following dimensions: length, 10 cms; cathode diameter, 1.0 cm; anode diameter, 0.050 cm. The stabilization ratio was one percent at 100 microamperes load. A 3-inch cathode and 3/8-inch anode, 20 inches long, were used in a 40,000-volt regulator which gave a stabilization ratio of 2 percent at 100 microamperes. An electronic stabilizer employing this tube as the reference potential for a degenerative triode amplifier, regulated to 0.1 percent at 40,000 volts, for loads up to 10 milliamperes.

PROBLEM STATUS

This is an interim report. Work on the basic problem is continuing.

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INTRODUCTION

Glow discharge tubes are commonly used to regulate potentials up to 150 volts. For the stabilization of higher voltages, many low-voltage regulator tubes connected in series or vacuum-tube electronic stabilizer circuits are necessary. The corona-discharge type of regulator tube, described below, can be used to stabilize higher voltages in the same manner that glow tubes are utilized for low voltages. At low current requirements, they compare favorably with the vacuum-tube types of voltage regulators, which usually involve relatively complicated circuits. Voltage regulator tubes employing the corona-discharge principle consist of a pair of coaxial cylinders in an atmosphere of hydrogen or air. For voltages up to about 10,000 volts, they need be no larger than ordinary receiving tubes and are equally rugged in construction. These tubes are suitable for use in power supplies for Geiger-Mueller counters, image tubes, cathode-ray tubes and, in fact, any device requiring less than a milliampere of current.

The firing voltage of the corona-tube regulator may be raised by increasing the electrode radii or by using higher gas pressures. Potentials as high as 40 kilovolts are easily stabilized with larger tubes filled almost to atmospheric pressure with hydrogen or air. It is also possible to use several smaller corona tubes in series, for instance, five 10-kilovolt tubes to regulate at 50 kilovolts. If relatively large currents must be drawn from the supply, a corona tube may be used as a reference potential for the simplest type of electronic regulator -- the single-tube degenerative triode circuit.*,† This method can provide over-all stabilization, sufficient for X-ray and electron diffraction instruments, and electron microscopes.

THE CORONA CHARACTERISTIC

When voltage is applied across a pair of well separated coaxial cylinders, the field is concentrated about the smaller electrode. In the absence of external ionizing radiation, the current flow through the gas is extremely small until the potential at the wire reaches a value $+V_{minimum}$ with respect to the outer cylinder. At V_{min}, a self-sustained corona is established which is manifested by the formation of a luminous sheath about the anode and by the passage of a current, I_{min}, measured in microamperes. As the voltage is increased beyond V_{min}, the current increases until at a sufficiently higher voltage the entire gap breaks into a glow.

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* W. B. Lewis "Electrical Counting" MacMillan Co., p. 58, 1943

† S. C. Brown, R. S. I. 17, 543, 1946

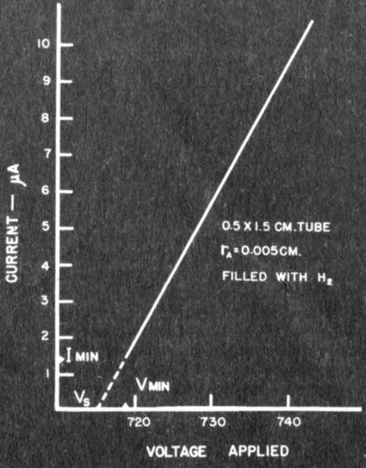

Figure 1 The Corona Characteristic.

The starting voltage of the corona discharge in a cylindrical tube counter filled with a monatomic or diatomic gas is quite sharply defined. If the voltage supply is connected directly across the electrodes without including a series quenching resistor, a corona "characteristic" similar to Figure 1 is observed. Between V_{min} and a slightly lower voltage, V_s, the discharge is not self-sustaining and breaks off after a mean lifetime that approaches zero as V approaches V_s. If ionizing radiation is supplied from an external source, or if the cathode is illuminated by ultraviolet light, the unstable corona can be stabilized down to V_s. Below V_s no corona discharge is possible.

The slope, R_c, of the corona characteristic has the dimensions of a resistance and, for small overvoltages, $V - V_s$, is approximately constant. The corona equation may therefore be written

$$V - V_s = R_c I, \qquad (1)$$

where I is the corona current. If, now a resistance R_s is included in series with the tube and voltage supply (Figure 2) the corona discharge tube behaves like a voltage stabilizer. The ratio of the change in voltage across the corona discharge, to the change in applied voltage is given by

$$S = \frac{\Delta V_{stabilized}}{\Delta V_{applied}} = \frac{R_c}{R_s + R_c}, \qquad (2)$$

where S defines the stabilization ratio. For the ordinary variety of hydrogen-filled counter tubes, R_c is about a megohm. With a series resistance of 100 megohms, a stabilization ratio of about one percent can be obtained, if such a counter tube is used as a voltage regulator. According to equation (2) the regulation can be improved by increasing R_s. This is illustrated in Figure 3 which shows the stabilization obtained with a particular tube for various values of R_s. But there are disadvantages to making R_s very large. For a given load resistance R_L, the discharge will not strike unless

$$V_{applied} > \left(\frac{R_s + R_L}{R_L}\right) V_{stabilized},$$

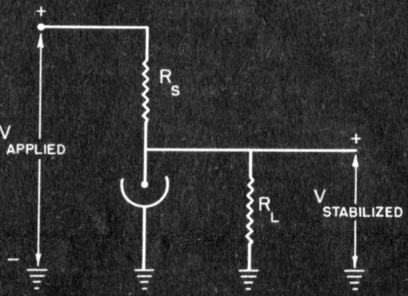

Figure 2. Basic Circuit of Corona-Tube Regulator

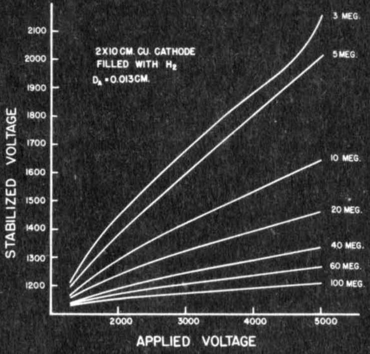

Figure 3. Effect of Series Resistance on Stabilization

with the result that a large overvoltage is required to fire the tube if R_s is large compared to R_L. By proper choice of tube dimensions, however, R_c can easily be reduced to 100,000 ohms or less, with a corresponding reduction in the required size of R_s.

STARTING VOLTAGE AND RESISTANCE OF THE CORONA

The theory of the dependence of V_s and R_c on tube dimensions and gas pressure was worked out in detail by Werner[‡] in connection with the discharge mechanism of counter tubes, and was later extended by Loeb.[§] The use of the corona discharge for voltage stabilization was first described by Medicus,[**] who did not, however, attempt to realize the conditions necessary to give the best performance.

On the assumption that the requirement for the self-sustained discharge is first satisfied when an electron falls through a potential difference U during the last n free paths on its way to the anode, Werner derived the following expression for the starting voltage of the corona:

$$V_s = \frac{U \ln (r_c/r_a)}{\ln (r_z/r_a)}, \tag{3}$$

where r_c and r_a are the cathode and anode radii respectively, and r_z is the radius of the zone of intense ionization encompassing the final $\underline{n}$ free paths. The relationship between $\underline{r_z}$, $\underline{n}$, and the pressure, $\underline{P}$, is given by

$$r_z = \frac{nk}{P} + r_a \tag{4}$$

[‡] S. Werner. Zeits, f. Physik, 90, 384 (1934)

[§] L. B. Loeb, Electrical Discharge in Gases, John Wiley Publishers, 1939

[**] G. Medicus, Zeits, f. tech. Physik, 14, 304 (1933)

where k is the electron mean free path at unit pressure. U and n are constants for any given gas and do not depend on the material of the electrodes.

Werner (Cf. fn. ‡.) verified the form of equation (3) for hydrogen. The constants U and n were evaluated by substituting measured starting voltages, V_s, at two different pressures. Values of 413 volts and 72 mean free paths, for U and n respectively, gave the best correlation between equation (3) and the experimental curves. It was further noted, that the results were unaltered when highly photosensitive alkali cathodes were substituted for the usual copper or iron. Haines†† repeated these measurements with a number of gases and reported values of U and nk for hydrogen, air, argon and helium in various states of purity.

Werner and Haines each confined most of his measurements to pressures less than 100 millimeters of mercury and anode radii less than 0.125 millimeters. In the present experiments, the measurements were carried out to higher pressures and larger anode radii. Figure 4 shows the experimental values of the firing voltage, V_s, in hydrogen as a function of pressure for several anode radii and a constant cathode radius of one centimeter. In Figure 5 the curves for hydrogen are compared with those for helium and argon. Equation (3) fitted these results reasonably well only in the lower pressure range and for large values of r_c/r_a.

Above the starting voltage V_s, the positive-ion space charge in the vicinity of the anode effectively limits the current within the tube as the voltage is raised. To a first approximation, (Cf. fn. §.) omitting space-charge distortions and assuming r_a small compared to r_c, the corona resistance per unit length is given by

$$R_c = \frac{p\, r_c^2}{2KV} \ln \frac{r_c}{r_a} \tag{5}$$

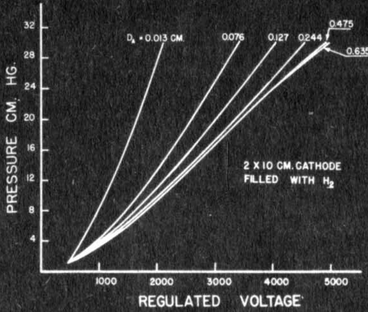

Figure 4 Variation of Firing Voltage Pressure and Anode Radius

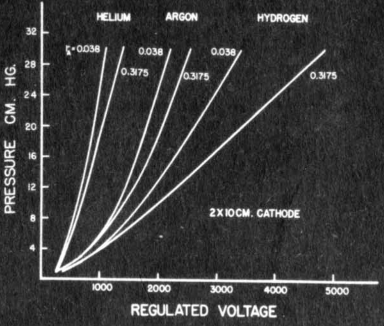

Figure 5 Dependence of Firing Voltage on Pressure for Various Gases

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†† C. L. Haines, R. S. I. 7, 411, 1936

Equation (5) indicates that the corona resistance, R_c, depends on the pressure and positive-ion mobility of the gas, and on the electrode dimensions.

To minimize R_c, a gas should be selected which produces the required firing voltage at a relatively low pressure, and has a high positive ion mobility. Hydrogen offers the best combination of mobility and starting-voltage-versus-pressure characteristic. Air is almost as effective because its higher starting voltage compensates to a large extent for the lower ionic mobility.

It also follows from equation (5) that the larger anode diameters should produce lower values of R_c if the cathode diameter remains fixed. As the ratio of anode to cathode radius is increased, however, the range between the inception of corona and the breakdown into glow or spark discharge decreases. Brown (Cf. fn.†.) pointed out the existance of a limiting ratio, 0.37, of the radii of coaxial cylinders, beyond which the corona region of the discharge does not appear.

Since R_c is the resistance for unit length of the discharge, it is possible to reduce further the corona resistance by increasing the length of the tube. As an alternative to increasing the length, a number of short discharge tubes may be combined in a single envelope and the electrodes connected in parallel.

The experimental results of a study of regulation characteristics at a given stabilized voltage, as related to electrode dimensions and type of gas, are presented in Figure 6. Figure 7 is a photograph of a rugged type of tube, whose performance is described in Table I. The cathode was a copper cylinder 2.54 centimeters in diameter and ten centimeters in length, which was joined to the hard glass anode supports by Housekeeper seals. The anode was a stainless steel tube 6.4 millimeters in diameter. If the tube is filled with hydrogen the pressure may be selected to produce any starting voltage between the minimum breakdown potential of about 360 volts and a maximum of about 9000 volts at one atmosphere. The temperature coefficient of a tube of this type is practically negligible. No aging was observed when proper cleaning and out-gassing techniques were used in preparing the tubes.

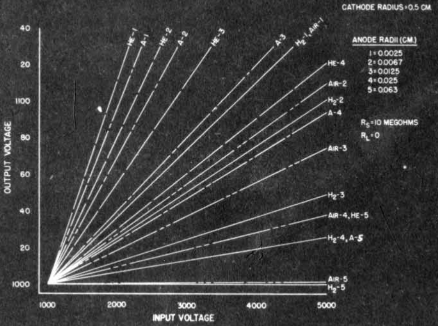

Figure 6. Regulation Curves for Various Gases.
The Pressure in Each Case was Adjusted to
Produce a Starting Voltage of about 1000 volts.

TABLE I

Characteristics of Hydrogen Filled Corona Tube Regulator

	V_s = 1150 volts	r_a = 0.32 cm	R_c = 1.27 cm
Load Current (Microamperes)	Series Resistance R_s (megohms)	Input Voltage at initiation of corona discharge	Stabilization ratio (percent)
1000	1	2400	1.4
200	1	1500	1.7
	5	2200	.6
100	1	1400	2.1
	5	2200	.6
50	1	1280	2.8
	5	2000	.5
10	10	1400	.4
	100	1800	$<.1$
2	10	1250	.4
	100	1800	$<.1$

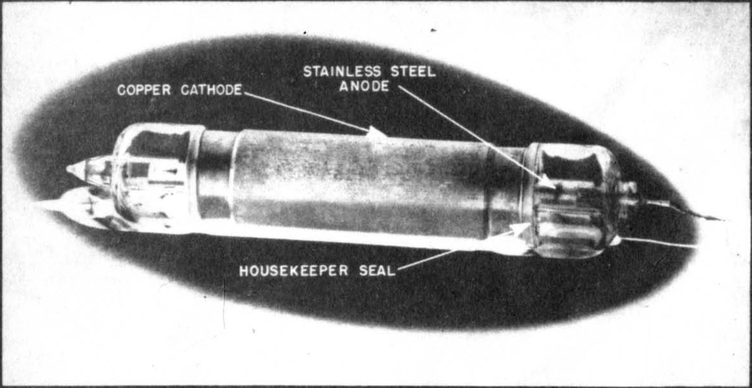

Figure 7. Corona Tube

APPLICATION OF THE CORONA TUBE REGULATOR

An example of the possibilities of applying the corona tube regulator in portable Geiger counter power supplies is its use in connection with the well-known vibrator-transformer method of obtaining high voltage from low-voltage batteries. The vibrator acts as an electromechanical switch to make and break the current in the primary of a transformer having a high secondary-to-primary turn ratio. In a circuit (Figure 8) described by Morton and Flory, ‡‡ 5000 volts output was obtained from a three-volt flashlight battery supply. The primary circuit was tuned so as to produce an effective peak primary voltage ten to twenty times the battery voltage and the secondary circuit delivered 100 microamperes at 5000 volts. By feeding the output of this vibrator-transformer high-voltage generator into a corona-discharge regulator tube, the voltage was stabilized sufficiently for operation of a Geiger-Mueller counter. Although the input to the regulator fell from 5000 to 1200 volts as the batteries ran down, the stabilized output dropped only ten volts, from 1000 to 990 volts.

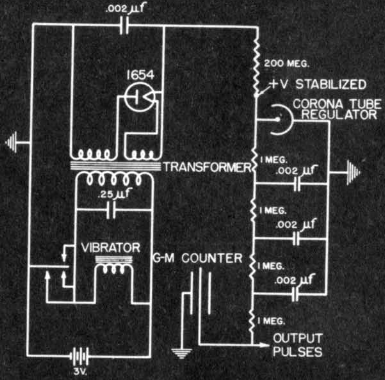

Figure 8. Vibrator-Transformer Type of High-Voltage Generator Employing Corona Tube Regulator

When a variable stabilized voltage is desired, a corona-tube regulator can be equipped with a sylphon bellows to readjust the pressure.

The corona stabilization method can be applied to much higher voltage ranges than have been mentioned thus far. Figure 9 shows the pressure dependence of the starting voltage up to 40 kv for a much larger tube than those previously discussed. By using a cathode twenty inches long and three inches in diameter, and an anode 13/32 inch in diameter, stabilization ratios of less than one percent were obtained at current loads of 10 microamperes.

If the corona discharge is used as the reference potential for a degenerative triode voltage regulator such as that described by Brown (Cf. fn. †.) and shown in Figure 10, the stabilization ratio is given very nearly by the reciprocal of the amplification factor of the triode. The current limitations of such a stabilizer are determined only by the plate dissipation of the triode. A number of triodes in parallel may be combined

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‡‡ G. A. Morton and L. B. Flory, Electronics, Sept. 1946

to increase the current capacity. To regulate the high voltage for an X-ray tube at 40,000 volts when the input varied in the range from 40.000 to 50,000 volts, a combination of three type-811 tubes was used. The stabilization ratio was about 0.5 percent at a current drain of 10 milliamperes. By using a saturable-reactor regulation transformer in the input to the high-voltage transformer, an over-all stability of about 0.01 percent was achieved. The constancy of the output voltage was determined entirely by the stability of the reference potential of the corona tube, and was virtually independent of load.

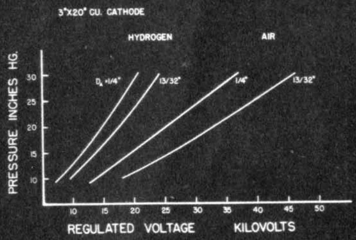
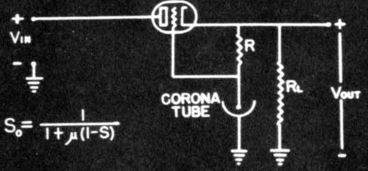


Figure 9. Firing Voltage Versus Pressure for Air and Hydrogen

Figure 10. Regulator Circuit Employing Corona Tube as Reference Potential



$$S_o = \frac{1}{1+\mu(1-S)}$$

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