NRL REPORT 3635

HIGH-VOLTAGE STABILIZATION BY MEANS OF THE CORONA DISCHARGE BETWEEN COAXIAL CYLINDERS

NAVAL RESEARCH LABORATORY

WASHINGTON, D.C.

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HIGH-VOLTAGE STABILIZATION BY MEANS OF THE CORONA DISCHARGE BETWEEN COAXIAL CYLINDERS

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ABSTRACT

The corona discharge between coaxial cylinders affords a practical means for stabilizing high voltages in a manner analogous to the stabilization of low voltages by the familiar glow-tube regulator. The corona regulator is particularly suitable for stabilizing voltages above several hundred volts at currents below one milliampere. It is accordingly well adapted for controlling the beam focusing and accelerating potentials of cathode-ray beam devices such as oscilloscope, iconoscope, and kinescope tubes, of electron diffraction cameras, and for stabilizing Geiger tube voltage sources.

Some of the theoretical aspects of the corona discharge region as related to voltage stabilization are reviewed. Circuit design relationships are considered in detail and are developed to an extent sufficient for adapting particular corona regulator tube characteristics to specific performance requirements. Examples of constructional features and performance characteristics of typical high-voltage regulating tubes are presented.

PROBLEM STATUS

This is an interim report; work is continuing on the problem.

AUTHORIZATION

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HIGH-VOLTAGE STABILIZATION BY MEANS OF THE CORONA DISCHARGE BETWEEN COAXIAL CYLINDERS

INTRODUCTION

The corona discharge between coaxial cylinders affords a practical basis for stabilizing voltages at currents below one milliampere, above the voltage limits of conventional glow tube regulators. A degree of stabilization comparable to that obtainable from electronic regulating circuits may be realized in a simple and straightforward manner.

The design of voltage regulator tubes, based on the corona discharge characteristic between coaxial cylinders, has been the subject of investigation at the Naval Research Laboratory for the past few years. Some early results were described in a previous NRL report[1*]. The theory and performance of corona discharge tubes are discussed more completely in a later NRL report[2], which contained the basis for the specifications established for the Navy type BS-101 tubes now being manufactured by several sources. Some of the more general aspects of this report have appeared in a recent issue of Electronics.[3] Although the emphasis thus far has been on the manufacture of tubes for Radiac devices such as Geiger Counter and Scintillation Counter survey instruments, the tubes are equally useful for a much wider field of application in connection with the control of high voltage focusing and accelerating potentials of cathode-ray beam devices such as television tubes, oscilloscope tubes, electron microscopes, and X-ray tubes.

A simple theory describing the corona discharge between coaxial cylinders has been treated in several papers by various investigators. The relationships most pertinent to the present problem were covered in the works of Werner[4] and Loeb,[5] and an early description of the application of the self-sustained corona discharge to voltage regulation appeared in a brief note published by Medicus in 1933.[6] Although the earlier NRL reports described most of the general features of corona regulator tubes, little attention was given toward deriving rigorous circuit design relationships for a variety of applications. It is the purpose of this paper to present circuit design relationships which permit the fitting of particular corona regulator tube characteristics to specific load-current and other performance requirements. As background for this work, a brief review of previous work is presented together with examples of constructional features and performance characteristics of some typical high voltage regulating tubes.

CORONA DISCHARGE BETWEEN COAXIAL CYLINDERS

When voltage from a low impedance source is impressed upon a pair of coaxial cylinders in a gas filling, consisting of a wire anode of small diameter and a comparatively large diameter cathode, the field will be most intense about the wire. In the absence of external ionizing radiation, the current flow through the gas will at first be small. As the voltage is raised, a critical value will be reached, Vmin, at which a self sustained corona is established. This is characterized by the formation

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*Superscript numbers to words in the text represent references at the end of this report.

of a luminous sheath about the anode and a discharge current measured in microamperes. As the impressed voltage is further raised above Vmin, the discharge current increases continuously until the gap breaks into a complete glow.

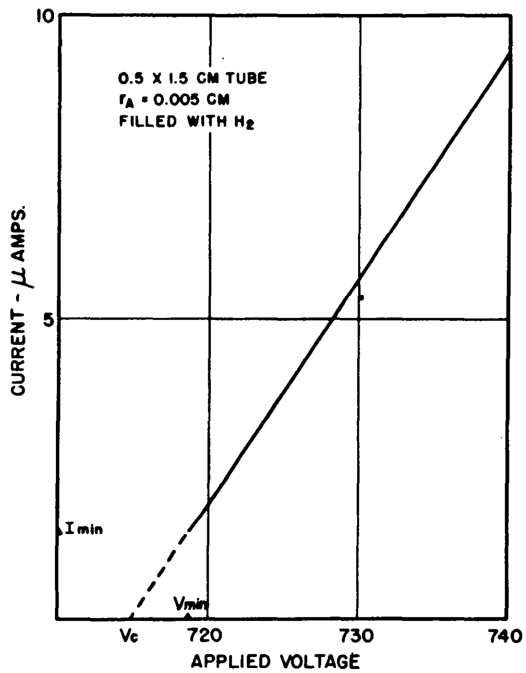

Figure 1. Corona Discharge Characteristic

The starting voltage in this type of tube structure filled with a monatomic or a diatomic gas is sharply defined. If the voltage supply is connected directly across the tube electrodes, a corona characteristic similar to Figure 1 is observed. Below Vmin the discharge is unstable. If ionizing radiation is supplied from an external source, the unstable corona can be stabilized down to V_C. Below this value no corona discharge is possible.

The slope of the corona characteristic has the dimensions of a resistance R_C and in the idealized case, it can be written as

$$V_R = IR_C + V_C , \qquad (1)$$

where V_C and R_C are constants and V_R is the voltage across the tube while passing a current, I.

If a resistance 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

$$S = \frac{\Delta V \text{ stabilized}}{\Delta V \text{ applied}} = \frac{R_C}{R_C + R_S} , \qquad (2)$$

where S defines a very simple form of stabilization constant. As far as input voltage fluctuations are concerned, this equation shows that the output voltage changes become smaller as R_S is increased. As R_S is increased however, the applied voltage must be increased proportionately for the discharge to strike. The overvoltage necessary for firing the tube becomes large as R_S becomes greater than the load resistance, R_L. By a proper choice of tube dimensions R_C can be reduced to 100,000 ohms, or less, which is sufficient for many practical applications. Figure 3 shows the effect of series resistance on the stabilization for a particular tube.

$$V_R = I\,R_C + V_C$$

$$E_1 = I\,(R_C + R_S) + V_C$$

$$\frac{\Delta V_R}{\Delta E_1} = \frac{R_C}{R_C + R_S} = S$$

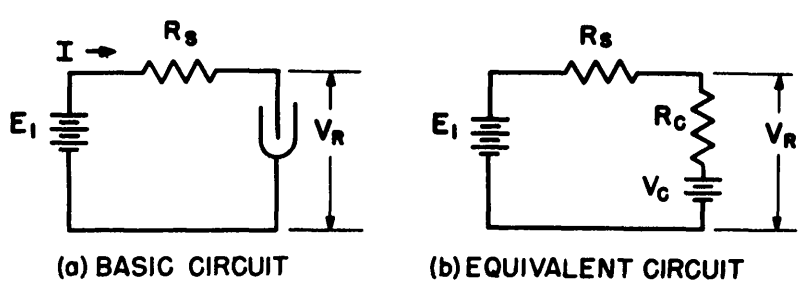

Figure 2. Corona Tube Voltage Regulator Circuit

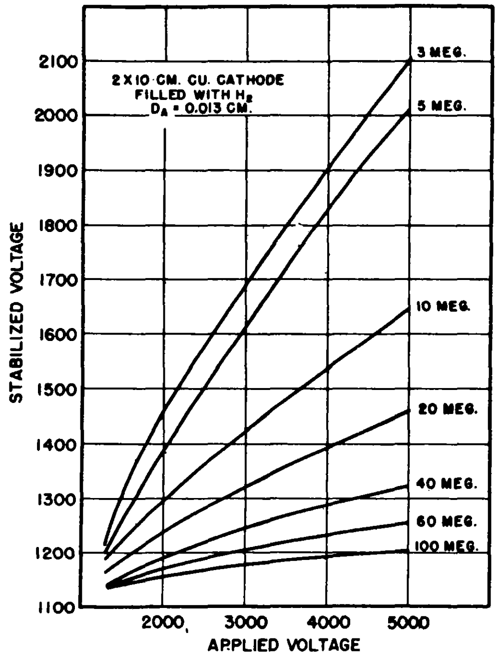

Figure 3. Effect of Series Resistance upon Stabilization

STRIKING VOLTAGE AND SLOPE RESISTANCE

The influence of tube dimensions and gas filling upon V_C and R_C was worked out by Werner[4] in connection with the discharge mechanism of counter tubes. This work was later extended by Loeb.[5]

Werner obtained the following expression for the corona starting voltage:

$$V_C = U \log \left[(r_C - \frac{nk}{P}) \frac{1}{r_a} - 1 \right], \qquad (3)$$

where r_c and r_a are the cathode and anode radii respectively, k is the electron mean free path at unit pressure, P is the actual pressure and U is a critical potential difference that an electron must fall through during the last n free paths on its way to the anode.

Assuming r_a to be small compared to r_c, the corona resistance per unit length, according to Loeb, is given approximately by

$$Rc = \frac{Prc^2}{2KV_R} \log \frac{(r_c)}{r_a}, \qquad (4)$$

where K is the positive ion mobility at unity pressure and V_R is the voltage across the tube terminals (equation 1).

It follows from this equation that R_C may be kept small by choosing a gas which produces the required corona 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 relationship. Air is almost as effective (Figure 4) because its higher starting voltage compensates to a large extent for the lower ionic mobility. It is also evident from this equation that R_C may be reduced by increasing the ratio r_a/r_C. As this ratio is increased however, the length of the corona region decreases. Finally, when the ratio of the coaxial cylinder radii reaches 0.37, or greater values, the corona region disappears completely and the discharge goes directly into the glow region.[7]

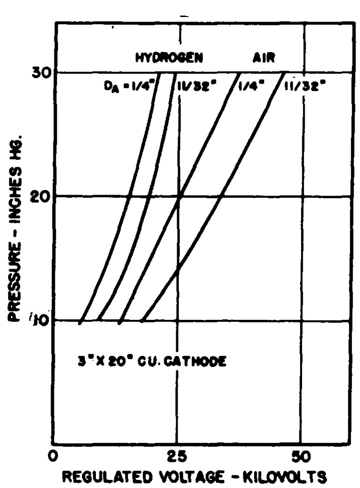

Figure 4. Firing Voltage versus Pressure for Air and Hydrogen

The slope resistance R_C may be further reduced by increasing the length of the tube and by combining within a single envelope, a number of short discharge tubes with the electrode elements in parallel.

For a further discussion of the preceding equations, reference is made to the NRL report[2] which has been the principal source for the material thus far presented. It also contains additional curves that disclose effects produced by the gas filling and tube geometry upon the corona tube performance.[5] The following discussion will be confined to new experimental material and to recently completed circuit analysis.

STABILITY REQUIREMENTS

To obtain stable performance from a corona voltage regulating tube, the total circuit capacitance in shunt with the tube must lie within well defined limits. This is due to the influence of the tube discharge current upon the striking voltage as developed in the circuit. When the tube fires, the initial value of striking voltage is lowered by an amount which is dependent upon the ratio of the discharge pulse charge to the capacitance of the circuit in shunt with the tube. This may be expressed as

$$V_2 = E_S - \frac{q_o}{C} , \tag{5}$$

where:
- q_o = Discharge pulse charge.
- C = Capacitance in shunt with the tube.
- E_S = Striking voltage.
- V_2 = Voltage at termination of discharge pulse.

When the total effective circuit capacitance, C, in shunt with a corona discharge tube is too small, the tube voltage during discharge will drop below the value necessary for maintaining the Townsend avalanche. The discharge will thereby become interrupted and will result in pulsing of the circuit current. Such pulsed operation may be avoided by adding sufficient capacitance in shunt with the tube to prevent V_2 from falling below the corona threshold value.

If the shunt circuit capacitance is excessive, the discharge pulse will be incapable of reducing the voltage in the circuit from the initial striking value E_S to an ultimate value within the corona region. The discharge will then be confined to the heavy current region of the firing characteristic and will result in IR drop quenching of the discharge by the series stabilizing resistance. In consequence, the discharge will again be interrupted.

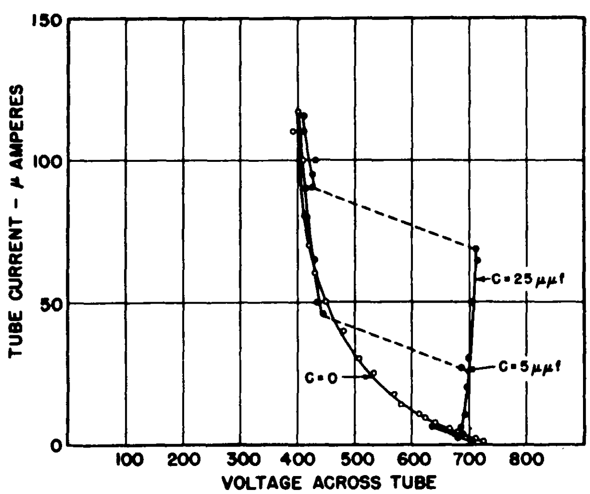

Figure 5. Continuous and Pulsed Operation of Corona Regulator Tube

In Figure 5, are illustrated two distinct modes of operation obtained with a typical corona tube voltage stabilizing circuit. For no externally added capacitance in shunt with the regulating tube, the discharge current has negative slope and it is pulsed. This mode of operation is obviously unsuitable for voltage stabilization purposes. The addition of sufficient capacitance, however, causes the discharge characteristic to revert to the positive slope, corona-discharge mode of operation, associated with a continuous flow of discharge current.

During pulsed operation, as a result of insufficient stabilizing capacitance, the charge per pulse remains constant and the repetition rate varies directly with the circuit current. This is illustrated in Figure 6.

The limiting conditions necessary for stable corona operation, may be conveniently expressed in terms of the ratio of charge per discharge pulse to the shunt circuit charge. Rearranging equation (5), there is obtained

$$\eta = \frac{q_o}{Q} = \frac{C_c}{C} = \frac{E_S - V_R}{V_R} , \tag{6}$$

where:
- V_R = Regulated voltage ($V_2 = V_R$, for stable operation).
- E_S = Striking voltage.
- q_o = Charge per pulse = $\frac{I_{Ave}}{f}$
- Q = CV_R
- C = Shunt circuit capacitance.
- C_c = Effective corona tube capacitance = $\frac{q_o}{V_R}$.
- I_{Ave} = Discharge current, average.
- f = Pulse frequency.

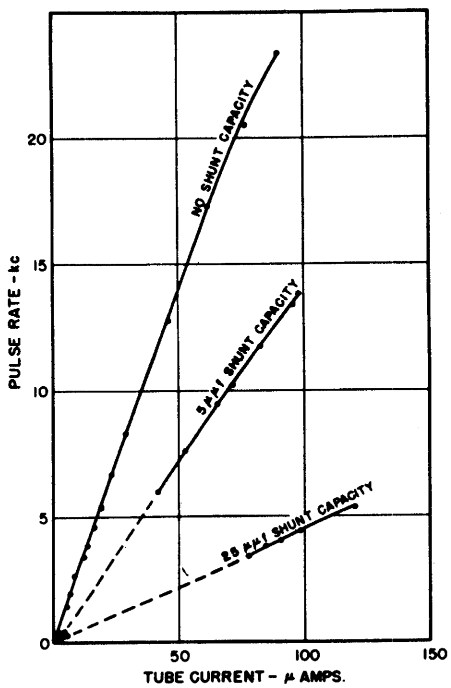

Figure 6. Pulse Rate versus Corona Tube Discharge Current

In Figure 7 are shown maximum and minimum values for the charge ratio η as a function of the discharge current I_{Ave}, as obtained by measurement of a particular tube type. From this figure, values for the shunt circuit capacitance limits may be computed with the aid of equation (6).

Upon satisfying the above requirements, a corona voltage stabilizer will be found to perform reliably, whether involving a single tube, or various possible series tube combinations for obtaining higher voltages.

CIRCUIT DESIGN CRITERIA

The stabilization figure, S, thus far referred to is a convenient factor, but it is an over simplified parameter inasmuch as it does not take into account the influence of load current upon the operation of a corona regulator.

Over-all circuit relationships may be derived as follows, starting with initial conditions as described by Hoyle and others.[8-10]

k = Fractional change in supply voltage.

R_c = Corona tube slope resistance.

R_S = Series resistance.

E_1 = Applied voltage.

$I_{C_{Max}}$ = Maximum Corona tube current.

$I_{C_{min}}$ = Minimum Corona tube current.

$I_{L_{Max}}$ = Maximum load current.

V_R = Regulated voltage.

V_C = Corona threshold voltage.

For minimum corona tube current

$$E_1(1-k) = V_{R1} + R_S\,(I_{L_{Max}} + I_{C_{min}}) \qquad (7)$$

And for maximum tube current

$$E_1(1+k) = V_{R2} + R_S\, I_{C_{Max}} \qquad (8)$$

Let. $\Delta V_R = V_{R2} - V_{R1}$

From these relations the output voltage stability coefficient β may be computed:

$$\beta = \frac{\Delta V_R}{\Delta V_{R_1}} = \frac{R_c(I_{C_{Max}} - I_{C_{min}})}{I_{C_{min}} R_c + V_C}. \tag{9}$$

From (1), (7) and (8) there also follows:

$$E_1 = \frac{V_C + I_{C_{min}} R_C + R_S (I_{L_{Max}} + I_{C_{min}})}{1 - k}, \tag{10}$$

$$R_S = \frac{[\beta (1-k) - 2k][V_C + I_{C_{min}} R_C]}{(1 + k)(I_{L_{Max}} + I_{C_{min}}) - (1-k) I_{C_{Max}}}. \tag{11}$$

Equations (9), (10) and (11) may be reduced to normalized form through use of the defining identities,

$$\Psi \equiv \frac{I_{C_{min}}}{I_{C_{Max}}}, \qquad \alpha \equiv \frac{I_o}{I_{C_{Max}}},$$

$$I_o \equiv \frac{V_C}{R_C}, \qquad h \equiv \frac{I_{L_{Max}}}{I_{C_{Max}}},$$

$$d \equiv \frac{R_C}{R_S}, \qquad \nu \equiv \frac{V_C}{E_1},$$

resulting in

$$\psi = \frac{1 - \beta\alpha}{1 + \beta}, \tag{12}$$

$$d = \frac{2 - (h + \Psi + 1)(1 + k)}{(\alpha + \Psi)[k(\beta + 2) - \beta]}, \tag{13}$$

$$\nu = \frac{1 - k}{1 + \left(\frac{1}{\alpha d}\right)[\Psi(1 + d) + h]}, \tag{14}$$

Equations (12), (13) and (14) furnish a practical means for computing E_1 and R_1 in terms of particular tube characteristics, load current and stability requirements.

MINIMUM INPUT VOLTAGE SOLUTION

In the preceding formulas, $I_{C_{Max}}$ has been used as an independent variable. A solution is accordingly provided which operates downwards from $I_{C_{Max}}$ on the corona slope resistance characteristic. By rearranging terms and introducing one more defining identity,

$$\omega \equiv \frac{I_o}{I_{C_{min}}},$$

a solution may be obtained working upwards from $I_{C_{min}}$ on the slope-resistance characteristic. Such a solution will require the smallest value of input voltage to conform with the initial performance requirements.

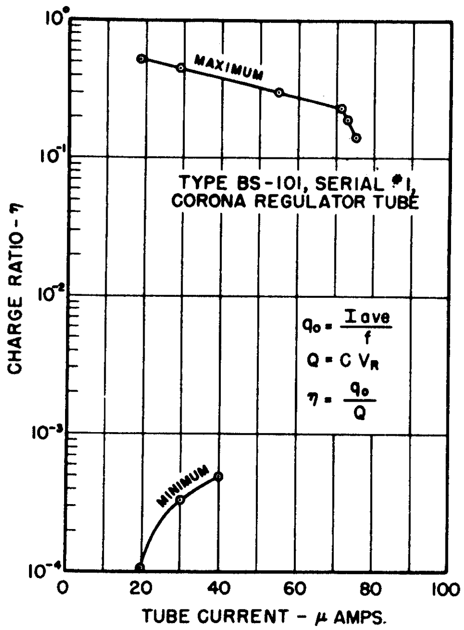

Figure 7. Maximum and Minimum Charge Ratio Limits, for Stable Operation, versus Corona Tube Current

Rewriting the previous expressions in terms of $I_{C_{min}}$, there is obtained:

$$h = \psi\left(\frac{I_{L_{Max}}}{I_{C_{min}}}\right) ,$$

$$\alpha = \psi\,\omega ,$$

whereby equation (12) becomes

$$(12)' \qquad \psi = \frac{1}{1 + \beta(1 + \omega)} .$$

The use of this equation in combination with equations (13) and (14) furnishes the required solution.

MINIMUM INPUT POWER SOLUTION

A solution for E_1 and R_1 may be obtained for particular tube characteristics and regulation requirements, corresponding to greatest economy of input power, by determining the value of h which satisfies maximum efficiency conditions.

$$\text{Eff.} = \frac{\text{Maximum Load Power}}{\text{Maximum Input Power}} = \frac{V_R\, I_{L_{Max}}}{E_1 (1 + k)\, I_{C_{Max}}} \quad (15)$$

$$\text{Eff.} = \frac{hA - h^2B}{hC + D}$$

$$A = \frac{2-(1-k)(1+\psi)}{(\alpha+\psi)\left[k(\beta+2)-\beta\right]} \quad (16)$$

$$B = \frac{1 + k}{(\alpha+\psi)\left[k(\beta+2)-\beta\right]}$$

$$C = \frac{1 - (\alpha+\psi)\, B}{S\alpha}$$

$$D = \frac{\psi + \alpha\, L}{S\alpha}$$

$$L = \frac{2 - (1 + k)(1 + \psi)}{(\alpha+\psi)\left[k(\beta + 2) - \beta\right]}$$

$$S = \frac{(V_C + R_C\, \psi\, I_{C_{Max}})(1-k)}{V_C(1 + k)}$$

which reduces to

$$h = -x \mp \sqrt{x(x + z)} , \quad (17)$$

where

$$x = \psi\left[1 + \frac{\psi(1 + k)}{(k-1)(1 + \alpha)}\right] - \frac{\alpha}{1 + \alpha} , \text{ and}$$

$$z = \left(\frac{1 - k}{1 + k}\right) - \psi .$$

The use of h from equation (17) in equations (13) and (14) leads to a solution for the initial conditions which requires minimum input power.

Figures 8 to 10 are graphical plots of some of the preceding relationships in a form suitable for design applications.

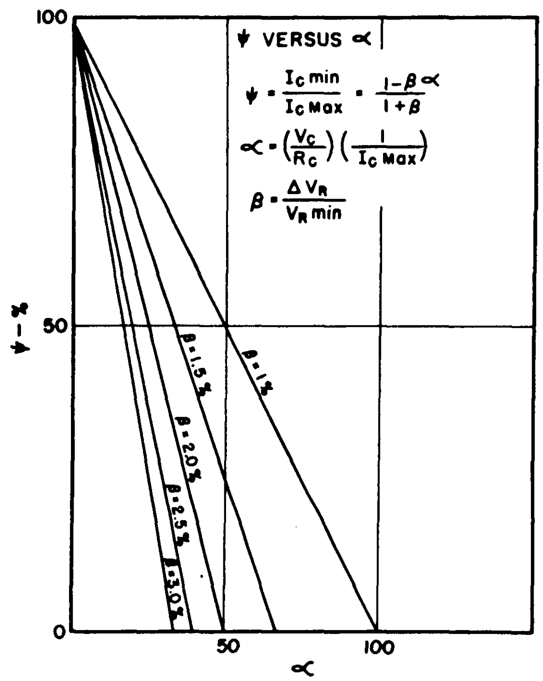

Figure 8. Design Sheet for Corona Regulator Circuit, ψ versus α.

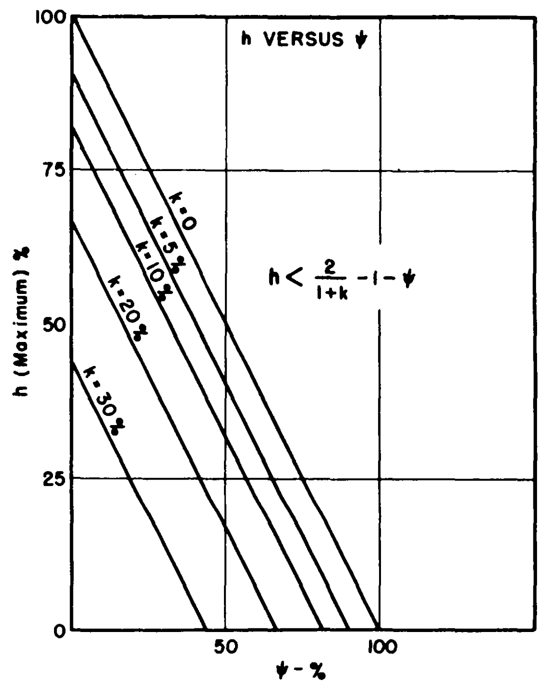

Figure 9. Design Sheet for Corona Regulator Circuit, h versus ψ.

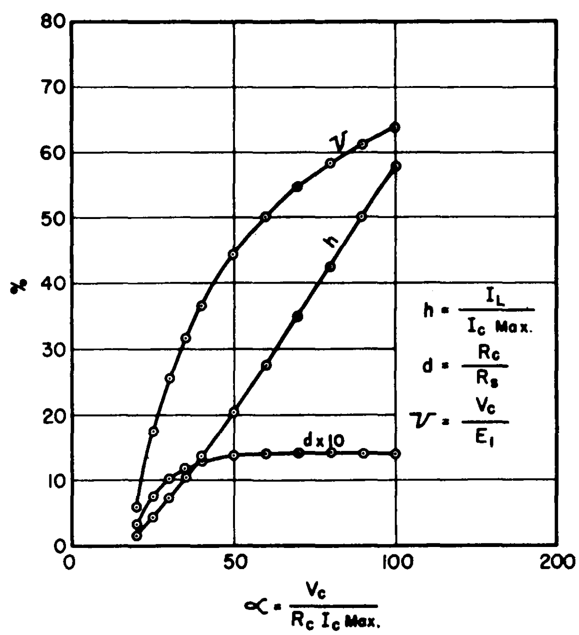

Figure 10. Corona Regulator Circuit Relationships for Maximum Efficiency. ($k = 10\%$, $\beta = 1\%$).

	EXAMPLE NO.1		EXAMPLE NO.2		EXAMPLE NO.3	
	INITIAL CONDITIONS	MEASURED VALUES	INITIAL CONDITIONS	MEASURED VALUES	INITIAL CONDITIONS	MEASURED VALUES
k	20 %	20 %	10%	10%	10%	10%
V_C	680 V		680 V		680 V	
R_C	229K		223 K		229 K	
I_C Max. (μA)	50.0	51.0	53.0	51.2	40.0	40.2
β	1%	0.7 %	1.46 %	1.46 %	1%	1.17 %
	CALCULATED VALUES	MEASURED VALUES	CALCULATED VALUES	MEASURED VALUES		
I_C min. (μA)	20.1	20.0	8.1	7.5	10.1	8.6
I_L (μA)	7.6	7.6	24.5	24.2	10.0	10.1
E_1	2300 V	2300 V	1140 V	1140 V	966 V	966 V
V_{R1}		686 V		682 V		682 V
V_{R2}		691 V		692 V		690 V
R_S	41.4 M	41.5 M	10.5 M	10.5 M	9.35 M	9.28 M

Table I Comparison of Computed and Measured Performance of Corona Voltage Stabilizer.

Table I shows results obtained for several computed design conditions together with the corresponding performance that was measured with the actual circuits. By means of either the design equations or the graphs, it has been found possible to predict performance of corona-tube voltage stabilizing circuits consistently to within 2 percent of the physically measured values. This order of agreement also denotes the justification involved in replacing the discharge characteristic with equivalent fixed circuit elements for design purposes.

TUBE CONSTRUCTION AND PERFORMANCE

Laboratory models of corona regulating tubes have been made in a wide variety of sizes, utilizing various electrode materials, gas fillings and types of construction. Satisfactory tubes have been used employing brass cathode cylinders measuring 3 feet in length and 1/2 foot in diameter, for operation of 40,000-volt X-ray equipment. More recently, efforts have been directed towards the development of tubes of small physical dimensions. These will be the subject of a forthcoming report. From this work, excellent tubes have been constructed in subminiature sizes, suitable for operation up to 2000 volts.[11] One of these, constructed of chrome-iron and a soft glass envelope, used a cathode 3/16-inch long and 1/8-inch inner diameter. The maximum diameter of this tube was 3/16 inch and its over-all length, when sealed off, was less than one inch. Figure 11 shows the performance obtained for this tube. It regulates in the vicinity of 1800 volts at tube currents up to 200 microamperes.

In Figure 12 is shown a photograph of a production type, 700 volt, corona regulator tube of miniature type construction. Adjacent to it is shown a standard miniature, Type OB-2, tube. The anode connection in the corona tube is made to a cap located on top of the glass envelope and the cathode connection is made through pins in the 7-pin miniature base. This tube has a useful life well upwards of 1000 hours, at a regulating current of 50 microamperes. The filling consists of a mixture of hydrogen plus helium, and the tube is suitable for use over a nominal ambient temperature range of -50°C to +75°C. The influence of temperature upon the operation of a tube of this type, is shown in Figure 13. The temperature coefficient, from this figure, is approximately 0.2 volt per degree centigrade and is equivalent to a voltage stability of 0.03 of 1 percent per degree centigrade.

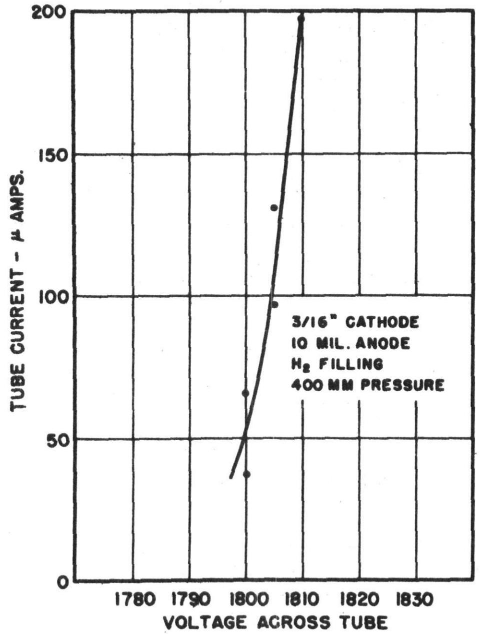

Figure 11. Discharge Characteristic of Sub-Miniature Tube.

To obtain good performance from a corona regulator tube, regardless of the size or type of construction employed, the elements must be in coaxial alignment. Either an eccentricity in centering of the anode or non-parallelism of the cylinder axes will prevent the discharge from being uniformly distributed over the length and surface of the anode. Such a condition raises the slope resistance, R_C, and may result in abrupt discontinuities in the discharge characteristic. Coaxial cylinder alignment is therefore essential for efficient performance. When properly constructed with electrodes outgassed and suitably cleaned before filling, the coaxial-cylinder corona voltage stabilizer is capable of good dependability, long life and a high degree of permanence.

ACKNOWLEDGMENTS

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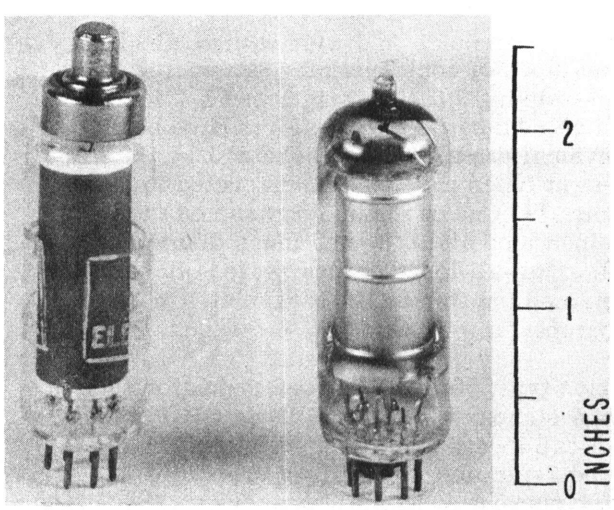

Figure 12. Miniature Type Voltage Regulators BS-101 Corona Tube and OB-2 Glow Tube.

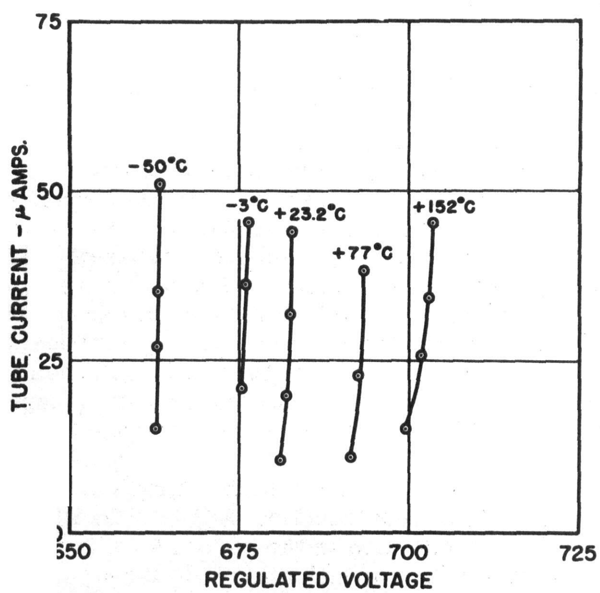

Figure 13. Temperature Influence upon Discharge Characteristic of Miniature, Type BS-101, Corona Voltage Regulator Tube

APPENDIX

GASEOUS DISCHARGE THEORY OF THE CORONA REGION

In accordance with theory relating to the conduction of electricity in gases, a gas under ordinary conditions contains very few free electrons. When a low voltage exists between two electrodes in a gaseous medium, any free electrons near the electrodes are set in motion. As the potential is increased, the velocity and hence the kinetic energy of the electrons is increased. The moving electrons collide with atoms of the gas, but as long as the kinetic energy is below a critical minimum value, the impact is elastic and the electrons are reflected without loss of energy. If at the time of impact the kinetic energy is greater than the critical value, the collisions become inelastic and free electrons are detached from the atoms of the gas leaving positively charged ions. The gas is then said to be ionized by collision. If the free electrons produced by the collision process acquire sufficient energy to also produce ionization in the gas, an ionization chain, or avalanche, will be formed. Under favorable conditions, the discharge may spread throughout the length of the anode and it may be sustained. Over the corona region, the discharge current for a particular electrode voltage is limited by the positive ion space charge formed in the ionization process.

When excited gas atoms return to the neutral state, ultra-violet quanta are released with energies below the ionization potential for the gas. The ultra-violet photons do, however, have sufficient energy to release photo-electrons from the cathode. The discharge will spread at a rate determined by the photon transit time and the lifetime of the excited gas particle. In the case of the coaxial-cylinder voltage regulator, ultra-violet radiation represents the principal agency for furnishing a supply of free electrons in sufficient quantity to sustain the avalanche process. The requirement for each avalanche to initiate photoelectrically another avalanche may be expressed quantitatively by means of the second Townsend coefficient γ:

$$n\gamma = 1 \, , \tag{A}$$

where n is the number of ion pairs formed per Townsend avalanche and γ is the number of photoelectrons ejected per ion pair.[12] The corona region represents the first portion of the general gas discharge characteristic in which the discharge is implemented by photoelectric emission and the discharge current is limited by positive ion space charge.

* * *

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