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Foster

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[54] **CORONA DISCHARGE VOLTAGE REGULATOR**

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[52] **U.S. Cl.** **313/216,** 313/214, 313/217, 313/220

[51] **Int. Cl.** **H01j 17/04**

[58] **Field of Search**.......313/210, 214, 216, 217, 220

[56] **References Cited**

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[57] **ABSTRACT**

The voltage regulator is a two-electrode device having a conductive cylinder which serves as a cathode and encloses an anode supported coaxially of and in insulated relation with respect to the cathode. The anode has corona discharge elements of unique configuration and their dimensioning, along with the pressure of the enclosed gas, is selected to establish well-defined electric fields within the regulator giving rise to corona or glow discharge in the presence of a predetermined anode-cathode voltage established by connecting the device to a voltage supply that is to be regulated.

12 Claims, 7 Drawing Figures

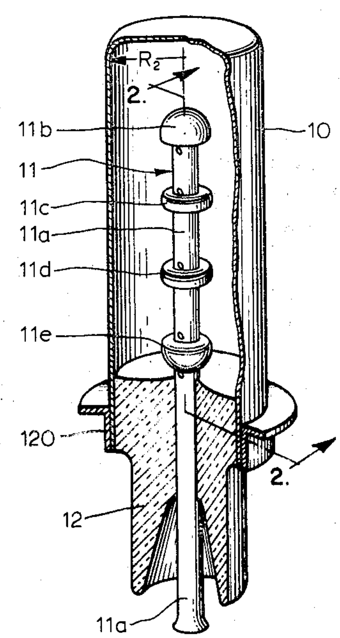


FIG. 1

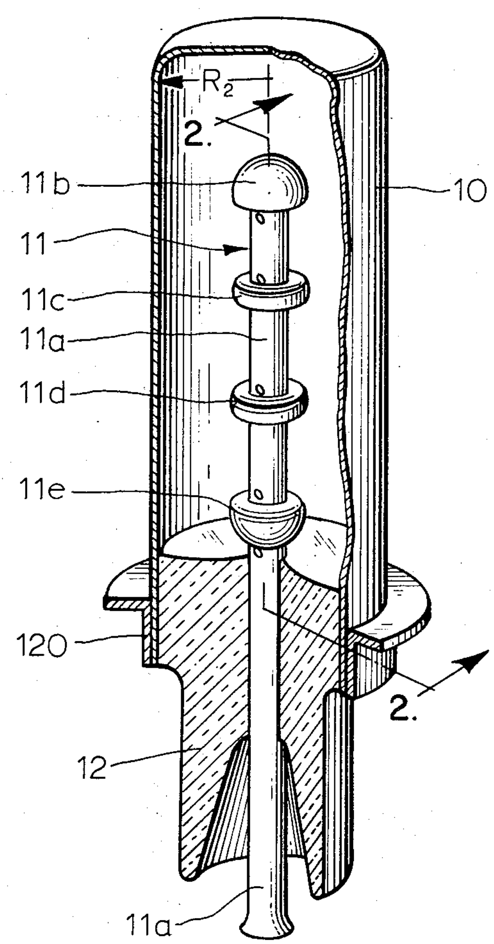


FIG. 2

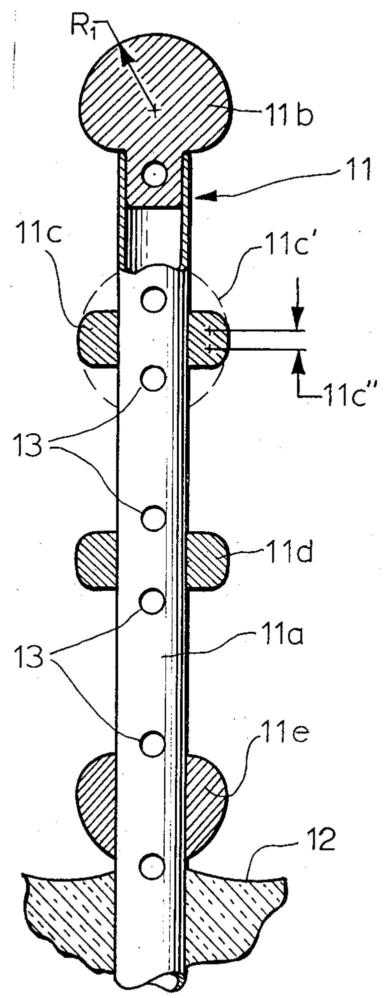


FIG. 3A

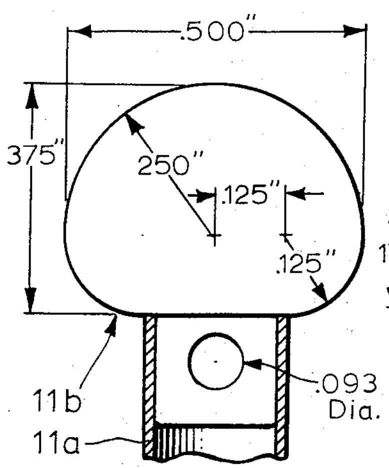


FIG. 3B

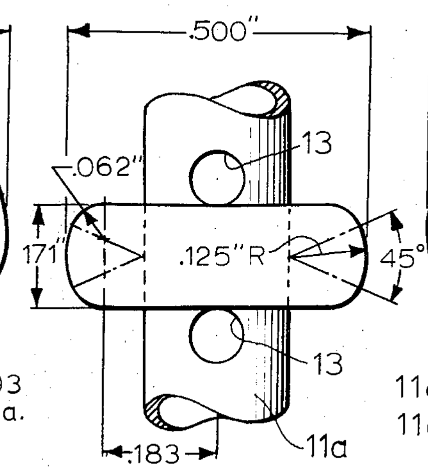
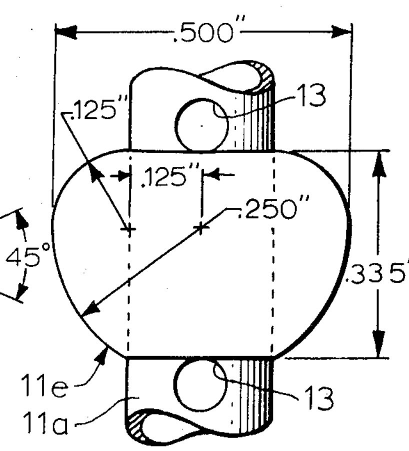


FIG. 3C



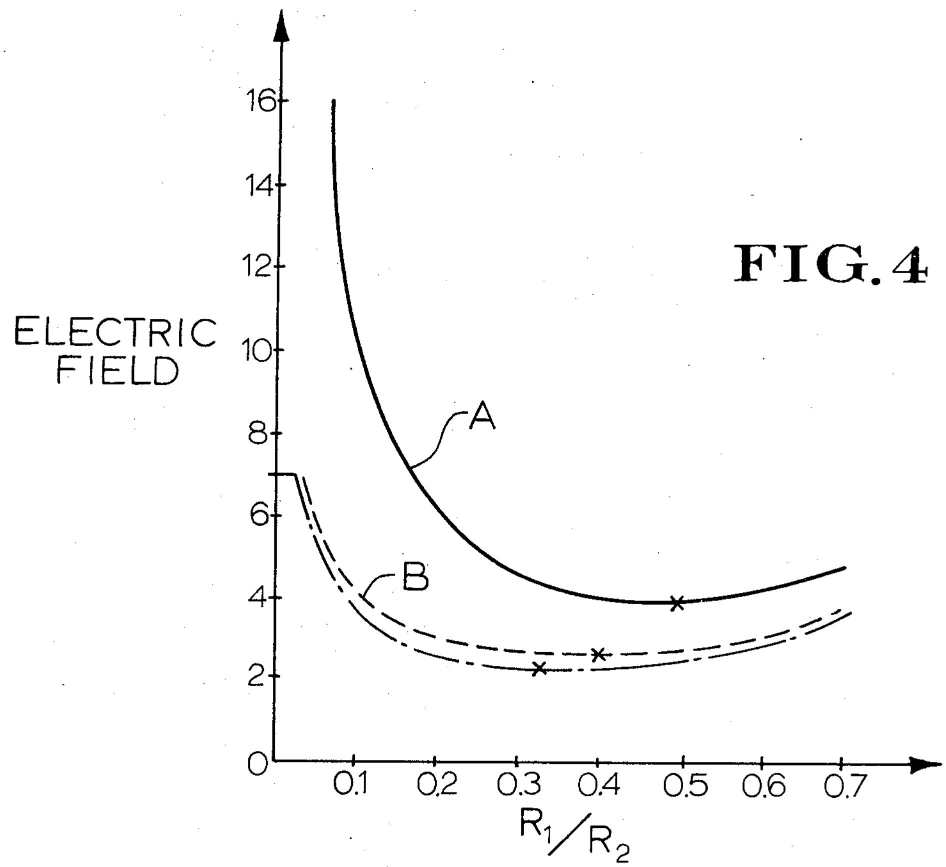

16
14
12
ELECTRIC FIELD
10
8
6
4
2
0
A
B
0.1
0.2
0.3
0.4
0.5
0.6
0.7
R_1/R_2

FIG. 4

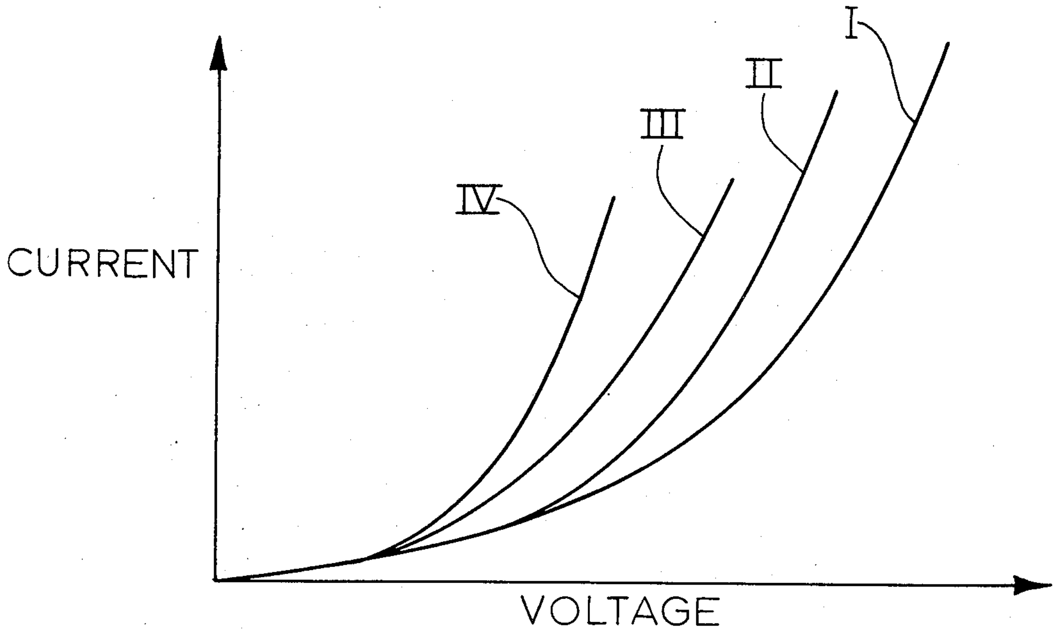

CURRENT
VOLTAGE
I
II
III
IV

FIG. 5

CORONA DISCHARGE VOLTAGE REGULATOR

BACKGROUND OF THE INVENTION

A number of different devices have been proposed heretofore to achieve voltage regulation although they have not met with complete success. A particularly well-know device is the so-called shunt regulator which is essentially a three-element vacuum tube device connected to the terminals of the voltage supply. A control voltage is developed which reflects changes in the load imposed on the voltage supply and this control voltage is applied to the control electrode of the vacuum tube device to cause the impedance of that device to vary with changes in load to the end that a constant load is maintained on the voltage supply with consequently well regulated terminal voltage. One inherent defect of this type regulator is apparent when one considers the result in the face of a heater failure. This establishes what is referred to as a runaway condition in which the terminal voltage of the supply may increase inordinately.

A very different type of device is known which has the capability of providing effective voltage regulation while avoiding the tendency to runaway conditions even in the face of failure. This is a so-called gas regulator but the structures heretofore utilized have been inadequate and have not attained the perfection in performance of which they are capable. Such a device is of the two-element variety, having a conductive cylinder which serves as the cathode and encloses a rod-type anode supported coaxially with respect to the cathode and insulated therefrom. The devices proposed heretofore have been subject to unpredictable performance and flashover or arc discharge because the structural details have not provided the well-defined electric fields necessary to predictable and controlled operation of the device.

It is accordingly an object of the invention to provide a new and improved corona discharge voltage regulator.

It is another object of the invention to provide a voltage regulator which minimizes or avoids the aforediscussed shortcomings of prior regulators.

SUMMARY OF THE INVENTION

A corona discharge voltage regulator, embodying the present invention comprises a closed envelope filled with an ionizable gas at a predetermined pressure. The envelope has a cylindrical conductive wall section of radius R_2 constituting a cathode electrode to be maintained at a fixed reference potential. An anode electrode is supported coaxially within, and in spaced relation with respect to, the cathode to provide a discharge space therebetween. The anode has a core or rod section which projects from one end of the envelope for connection with a voltage source to be regulated. A corona discharge element is provided at least at the opposite end of the anode core and has the configuration of a spherical section with a radius R_1 which is large compared with the cross-sectional dimension of the anode core to confine corona discharge within the regulator to the surface area of that element as distinguished from the core. The radius of the cathode and the radius of the discharge element are so related that the ratio R_1/R_2 has a value which is within a range over which the field gradient at the surface of the discharge element decreases toward a minimum with increasing values of R_1/R_2, but is less than the value at which that minimum occurs. Moreover, the pressure of the gas within the envelope is selected to achieve ionization and corona discharge between the discharge element and the cathode in the presence of a voltage difference between the anode and cathode electrodes corresponding to the value of terminal voltage desired for the voltage source being regulated.

BRIEF DESCRIPTION OF THE DRAWING

The features of the present invention which are believed to be novel are set forth with particularity in the appended claims. The invention, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawing, in the several figures of which like reference numerals identify like elements, and in which:

FIG. 1 is a view, partially in cross section, of a corona discharge voltage regulator constructed in accordance with the invention;

FIG. 2 is a cross-sectional view taken along line 2—2 of FIG. 1;

FIGS. 3*a*, 3*b* and 3*c* are detailed structural views on an enlarged scale showing respective dimensions of portions of the anode electrode; and

FIGS. 4 and 5 are characteristic curves used in describing the construction and operation of the regulator of FIGS. 1–2.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now more particularly to FIGS. 1–2, the voltage regulator there represented comprises a closed envelope filled with an ionizable gas at a predetermined selected pressure and having a cylindrical conductive wall section constituting a cathode electrode to be maintained at a fixed reference potential by, for example, being coupled to ground. As illustrated, the envelope is a conductive cathode cylinder 10 of radius R_2 open at one end to permit insertion of an anode electrode 11 and the formation of a coaxial seal between these electrodes (described in detail below) so that the device may retain a gaseous atmosphere at a desired pressure.

Anode 11 is supported coaxially within, and in spaced relation with respect to, cathode cylinder 10 by means of a header 12, preferably of glass such as Type No. 0122 manufactured by Corning Glass Works, through which a coaxial seal is established between the open end of cathode cylinder 10 and an extension of the central core 11*a* or rod component of anode 11. Accordingly, the electrode arrangement provides a discharge space between the cathode and anode and the anode core projects at one end from the cathode cylinder for connection with a high voltage source that is to be regulated.

While various gaseous mixtures may be employed, it has been found sufficient to charge the envelope with hydrogen. In constructing prototype devices, cathode cylinder 10 was deep drawn and formed of cold rolled steel which is acceptable for many, if not most, installations of the regulator in electrical systems. It has been found, however, that under certain ambient conditions such as high operating temperatures, there may be a tendency for an inexpensive steel cathode envelope **10** to permit some of the hydrogen gas to escape. This gives rise to what is known as "slumping," a condition in which the regulator drops the terminal voltage of the control supply from a desired nominal value to a reduced value. This may be just as objectionable as permitting the terminal voltage to increase to an undesired value and may be avoided either by using a conductive cylinder constructed of material (e.g., copper) which does not permit the escape of hydrogen or, alternatively and more attractively from the standpoint of cost, a steel cylinder may be employed if suitably coated or cladded to retain the desired gas pressure within the regulator under all operating conditions including those of high ambient temperature. It has been determined that a copper coating or cladding, on either the inside, the outside or both surfaces of cylinder **10**, if of sufficient thickness avoids all tendency to slumping. The thickness of the coating layer is very small relative to the thickness of the cathode cylinder and may, for example, be 0.030 inch. Other suitable cladding materials include aluminum and gold. An advantage to an external coating of copper is that it may be blackened by thermal or chemical oxidation which is desirable to enhance heat dissipation. If cost considerations permit, the cathode cylinder may of course be constructed of solid copper.

In a preferred embodiment, to preclude gas leakage at the header-cylinder sealing interface, the cathode cylinder **10** is composed of steel coated internally with a sealing film of oxidized chromium. The oxide layer may be formed by depositing chromium on the inside of the cathode cylinder **10** in the region where a seal is needed, after which the cathode cylinder **10** is supported in an appropriate fixture and fired, e.g., for 15 minutes at 1,000° C in a wet hydrogen atmosphere. Firing causes the header **12** to soften and conform to the cathode cylinder **10**. The oxide bonds to the glass header **12** and to the metal cathode cylinder **10** to form a vacuum-tight seal.

To enhance the integrity of the seal, it is preferred to constrict the cylinder **10** around the header **12** by means of a compression band **120** serving also for mounting the device on an associated high voltage cage.

In a preferred embodiment, to preclude gas leakage through the walls of the cylinder **10**, an external coating of appropriately baked stove-type enamel having a relatively high glass content may be employed.

Anode electrode **11** is a unique structure in that it has a number of corona discharge elements of such configuration as required to establish well-defined electric fields and of such number as to shape the regulation characteristic for the performance desired. In fact, and as described hereafter, an acceptable regulator may utilize only one such element. In any event, these elements of the anode, however many are used, are dimensioned and configured to the end that the rod or core **11***a* has no significant role in the glow or corona discharge phenomena by which regulation is achieved and, of equal importance, localized fields of high concentration, which lead to arc discharges in prior art devices, are obviated. This desired result is achieved not only by dimensioning and configuring the anode electrode but also through appropriate selection of the anode material.

One corona discharge element **11***b* is provided at the free end of anode **11** located within cathode cylinder **10**. It has the configuration of a spherical section with a radius R_1 that is large compared with that of core **11***a* to confine corona or glow discharges to the surface of element **11***b* as distinguished from core **11***a*.

The dimensioning of anode element **11***b* in relation to the radius of cathode cylinder **10** is also of great importance in respect of the operation of the device. This will be described more particularly in relation to the curves of FIG. **4** which show the manner in which the electric field on the surface of the anode changes with changes in configuration and dimension of the anode relative to the cathode electrode. Curve A relates the electric field on the surface of anode element **11***b* with changes in the ratio R_1/R_2 for the case in which the anode and cathode elements are concentric spheres. Curve B is generally similar but for the case in which these electrodes are coaxial cylinders rather than spheres. And finally, curve C is for the arrangement in which the anode is considered a cylinder disposed over a planar cathode. These curves are simply the plots of the following equations:

CONCENTRIC SPHERES:

$$E=\frac{V_0}{R_2}\cdot\frac{R_2/R_1}{1-R_1/R_2}$$

COAXIAL CYLINDERS:

$$E=\frac{V_0}{R_2}\cdot\frac{R_2/R_1}{\text{In }(R_2/R_1)}$$

CYLINDER OVER PLANE:

$$E=\frac{V_0}{R_2}\cdot\frac{\frac{R_2}{R_1}\sqrt{\frac{R_2/R_{1+1}}{R_2/R_{1-1}}}}{\cosh^{-1}(R_2/R_1)}$$

where, E is the electric field at the surface of the smaller element and V_o is the potential of that element, assuming the other element to be at ground potential. It will be observed that each of curves A–C has a minimum point, that is to say, there is a range over which the field gradient at the surface of the anode element decreases toward a minimum with increasing values of the ratio R_1/R_2 while for further increases in that ratio, the field gradient starts to increase. To achieve stable operation of the device, the anode and cathode electrodes are dimensioned so that the ratio R_1/R_2 falls to the left of the minimum point of the relevant one of curves A–C.

A specific structure of anode **11** was arrived at emperically, using as a starting point a spherical configuration for element **11***b* at the free end of the anode, that is to say, the end enclosed within cathode envelope **10**. Curve A of FIG. **4** applies to that structure and it was dimensioned for stable operation.

If anode **11** has simply the single element **11***b*, the regulation curve I of FIG. **5** is obtained and it is apparent that the regulation is not particularly steep. The other members of the family of curves in FIG. **5** show the manner in which the knee of the regulation curve may be sharpened by increasing the number of anode elements that are employed. Curve IV, for example, may be considered to represent an arrangement as in FIGS. **1–2** having four anode elements designated **11***b* to **11***e*.

The structure can be made with each of these elements having a generally spherical configuration as indicated for element **11***b* and also as shown in dotted outline at **11***c'* for element **11***c* in FIGS. 1–2. The field condition in this case and its change with dimensioning of the anode relative to the cathode is again represented by curve A of FIG. 4. Experience establishes, however, that in the operation of such a device, where all anode elements are essentially spherical in construction, the glow discharge from an intermediate element, such as **11***c'* is confined to a narrow surface portion such as that shown by dimension lines **11***c'*. In other words, only a small ring-type segment of anode element **11***c'* contributes to the glow discharge and the regulation; the remaining surface area hardly comes into play. Accordingly, the element **11***c'* can be modified in shape to be essentially a ring as shown in solid outline **11***c*.

It has been determined that improved results are attained by constructing element **11***c* with a relatively sharp radius R_1'. While this may be a continuous curve, the actual configuration of anode element **11***c* used in current practice is detailed in the FIG. 3B. The variation in electric field with changes in dimension for this element **11***c* configuration is represented substantially by curve C of FIG. 4.

It will further be observed from FIGS. 1 and 2 that anode element **11***b* is not a spherical section in the strictly geometrical sense but actually has a sharpened curvature at what may be considered its trailing edge, that is, the surface of anode element **11***b* which faces anode element **11***c*. The detailed view of FIG. 3*a* shows representative dimensions of anode element **11***b*. Without this unusual shaping of anode element **11***b*, the corona discharge tends to be confined to the forward half of the sphere. Shaping the trailing portion of the element to the described configuration extends the discharge over a greater portion of the element surface. As so shaped, characteristic curve B of FIG. 4 is more applicable to element **11***b* than curve A.

Where the anode electrode is constructed to have several corona discharge elements, as illustrated in FIGS. 1 and 2, they should be dimensioned to exhibit the same ignition potential. In other words, when a glow discharge is established within the regulator it should be established essentially simultaneously with respect to all of the anode elements. It is also important in using a series of anode elements that they be axially separated from one another along anode core **11***a* so that the fields associated with the individual elements **11***b*, **11***c*, **11***d* and **11***e* do not interact and disturb one another. A satisfactory center-to-center element separation for a regulator having the dimensional details of FIGS. 3*a* and 3*b* has been found to be three-quarters of an inch.

As shown in FIGS. 1, 2, and 3*c*, element **11***e* is preferably configured substantially like element **11***b*, but truncated to accept core **11***a*.

The choice of material used for anode **11** is also of importance. In past voltage regulator structures the anode electrode has generally been composed of aluminum or an aluminum alloy, and in use of devices with such anode compositions, unpredictable flashover has been experienced because of a phenomenon known as whisker growth. The field gradients within the regulator are sufficiently high, especially when such devices are employed as high voltage regulators operating at voltages of 25,000 volts, for example, that metallic fibers are drawn out of the anode element which give rise to sub-elemental areas within the structure of exceedingly high electric field concentrations. In fact, the field generated by such whiskers may be so intense that an arc discharge results and all regulation is thereupon interrupted or destroyed. If the discharge is successful in burning off the metal fiber, the regulation restores itself; otherwise, the device becomes inoperative.

If the anode is made of malleable tubing, the elements **11***b*–**11***e* may be formed integrally with the anode **11** in a suitable dye setup. Attenuating the anode elements may be made separately and staked or otherwise suitably secured to an anode core such as core **11***a*.

As stated above, anode elements **11***b*–**11***e* are dimensioned to confine glow discharges necessary to the operation of the regulator to these elements as distinguished from the anode core **11***a*. Since the core **11***a* does not participate in the glow discharge, holes **13** may be provided so that the rod may function as an exhaust tubulation in evacuating cylinder **10** and in subsequently injecting a new gas supply. This is an attractive advantage of the described structure over such prior art as has its rod section participating in the glow discharge. Clearly, holes **13** constitute a discontinuity in the anode electrode **11** and if such were formed in a portion of the electrode that is active in the glow discharge, there would be a serious risk that field concentrations would occur at such holes of sufficient magnitude as to provoke destructive arc discharges. In the described structure, however, that source of operating difficulty is eliminated.

To charge the regulator enclosure, hydrogen is injected into the anode core **11***a*, after which core **11***a* is pinched off and sealed. The pressure of the contained gas determines the ignition potential of the regulator and this is so selected that corona or glow discharge occurs in the presence of a voltage difference between cathode **10** and anode **11** corresponding to the regulated value desired for the power supply to which the device is connected. For a 25 KV regulator, using hydrogen gas, a representative value of gas pressure is 17 pounds per square inch above atmospheric pressure.

In utilizing the regulator, cathode cylinder **10** is grounded or otherwise maintained at a fixed reference potential while anode electrode **11** is connected through the exposed portion of core **11***a* to the high potential terminal of the power supply that is to be regulated. For the specific regulator for which dimensional information is shown in FIGS. 3*a* and 3*b*, a glow discharge is experienced when the terminal voltage reaches a value of about 22,000 or 23,000 volts.

When the glow discharge starts, a sheath of plasma encloses all of anode elements **11***b*–**11***e* but does not encase the sections of anode core **11***a* which are interposed between the anode elements. Changes in terminal voltage of the voltage supply being regulated reflect changes in current in the regulator as required to maintain a desired maximum terminal voltage of that supply. The stiffness of the regulation or the sharpness of bend of the regulation characteristic is, as mentioned above, controllable by the number of anode elements that are employed. Experience has indicated that a 25 KV regulator utilizing anode elements corresponding to those designated **11***b*, **11***d* and **11***e* is sufficient to maintain good voltage regulation in a load having current carrying capacity of 1.5 to 2 or more illiamperes.

The device exhibits uniform ionization potential and stabilized predictable electric fields with no areas of field concentration materially higher than those otherwise existing throughout the portions of the regulator effective in achieving control or regulation. The stability of operation will be appreciated from a further discussion of the curves of FIG. 4. If the cross at each of curves A, B and C designates the ratio of R_1/R_2 for which the regulator experiences minimum electric fields, it will be recalled that the electrodes are dimensioned so that the operating point, in fact, is to the left of the point of minimum electric field. When the glow discharge is initiated and the sheath of plasma encases the anode elements, there is an effective increase in the dimension R_1. This is equivalent to moving from the operating point in the direction of the minimum point but is occasioned with a reduction in the field gradient, whereas operation on the otherside of the minimum point produces the opposite field change and leads to a runaway condition.

The device described can fail through loss of the contained gaseous medium or, expressed differently, it may let down to air. Should that happen for any reason, the voltage of the controlled source decreases and assumed a value substantially below the nominal value which the regulator is intended to establish. It has been found that with the regulator let down to air, a nominal 25,000 volts supply suffers a loss to approximately 15,000 volts. This is a change in the opposite sense to that of the prior art shunt regulation where, in the face of failure of the heater, all regulation is lost and a runaway condition with extraordinarily high voltage results.

While particular embodiments of the invention have been shown and described, it will be obvious to those skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects, and, therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of the invention.

I claim:

1. A voltage regulator comprising:

a closed envelope, filled with an ionizable gas at a predetermined pressure, having a cylindrical conductive wall section of radius R_2 constituting a cathode electrode to be maintained at a fixed reference potential;

an anode electrode supported coaxially within, and in spaced relation with respect to, said cathode providing a discharge space therebetween, and having a core which projects at one end from said envelope for connection with a voltage source to be regulated;

a corona discharge element at the opposite end of said anode core having the configuration of a spherical section with a radius R_1 large compared with that of said core to confine corona discharge to the surface area of said element, as distinguished from said core, and related to the radius of said cathode so that the ratio R_1/R_2 has a value within a range over which the field gradient at the surface of said element decreases toward a minimum with increasing values of R_1/R_2 but is less than the value at which said minimum occurs,

and the pressure of said gas being selected to achieve ionization and corona discharge between said element and said cathode in the presence of a voltage difference between said anode and cathode corresponding to the regulated value desired for said source.

2. A high-voltage regulator in accordance with claim **1** which includes at least one additional arc discharge element extending transversely of and spaced along said core from said spherically-shaped element in the direction of said one end, dimensioned to exhibit substantially the same breakdown potential as said spherically-shaped element,

and having a surface spacing R_1' with respect to said core such as that the ratio R_1'/R_2 has a value within a range over which the field gradient at the surface of said additional element decreases toward a minimum with increasing values of R_1'/R_2 but is less than the value at which said minimum occurs.

3. A high-voltage regulator in accordance with claim **2** in which said additional element is ring shaped having a ring radius approximately equal to the radius R_1 of said spherically-shaped element.

4. A high-voltage regulator in accordance with claim **2** in which said additional element has the shape of a flattened ring.

5. A high-voltage regulator in accordance with claim **4** in which said additional element is spaced along said core from said spherical element a sufficient distance that the fields established from each of said elements to said cathode in the operation of said regulator do not disturb one another.

6. A high-voltage regulator in accordance with claim **1** having a second spherically shaped corona discharge element which is spaced along said core from the first-mentioned spherically-shaped element in the direction of said one end and which is essentially a mirror image of said first-mentioned element.

7. A high-voltage regulator in accordance with claim **4** having a second spherically shaped corona discharge element which is spaced along said core from said additional element in the direction of said one end and which is essentially a mirror image of the first-mentioned spherically-shaped element.

8. A high-voltage regulator in accordance with claim **1** in which said envelope comprises a conductive shell open at one end and an insulator which closes said one end and supports said anode in coaxial relation within said shell and in which the material of said shell is substantially impervious to said gas at the operating temperature of said regulator.

9. A high-voltage regulator in accordance with claim **8** in which said shell is made of steel and is coated with another material which is substantially more impervious to said gas than steel at the operating temperature of said regulator.

10. A high-voltage regulator in accordance with claim **8** in which said anode is formed of a conductive metal which is sufficiently hard to avoid the growth of metallic fibers on the surface of said discharge element in the presence of electric fields established about said anode in the operation of said regulator.

11. A high-voltage regulator in accordance with claim **10** in which said anode is formed of stainless steel.

12. A high-voltage regulator in accordance with claim **1** in which said anode core defines a fluid passageway communicating with said discharge space within said envelope.

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