Jan. 18, 1966 E. E. HAFKEMEYER, JR., ETAL 3,230,410

ARC DISCHARGE DEVICE WITH TRIGGERING ELECTRODE

Filed Dec. 29, 1960

Fig. 1

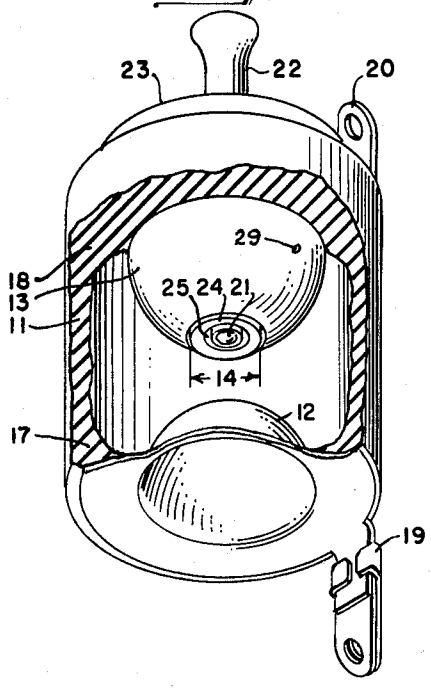
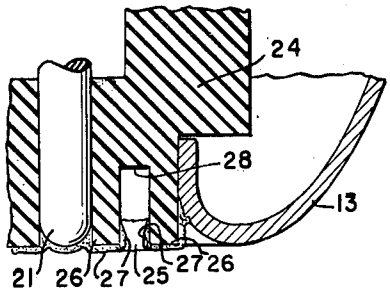


Fig. 4



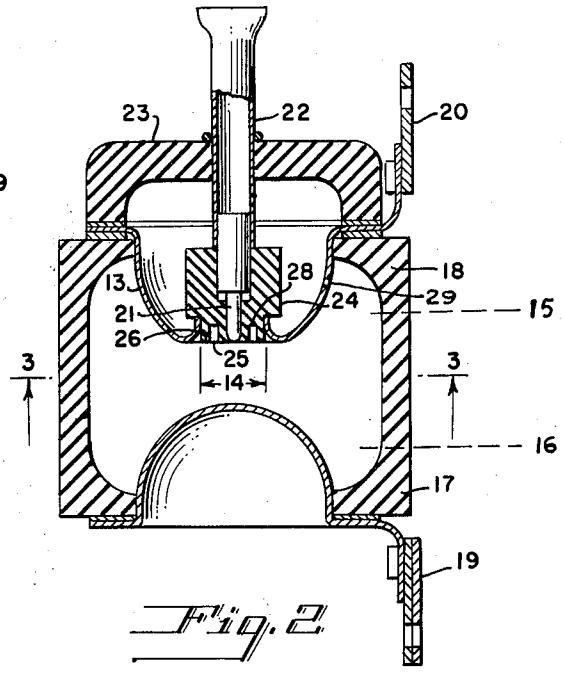
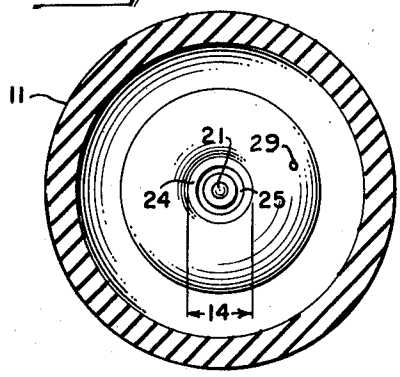


Fig. 2

Fig. 3



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ARC DISCHARGE DEVICE WITH TRIGGERING ELECTRODE

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This invention relates to arc discharge devices and more particularly, to triggered spark gap tubes.

The triggered spark gap is an arc discharge device that functions as a high voltage switch; it employs the electrical breakdown of a gas within the tube in order to provide conduction. Triggered spark gaps have been used for switching up to at least 30,000 volts. They are especially useful in electrical circuits that require extreme fast and very reliable switching functions. Typical applications are those wherein switching times must be less, and often considerably less, than one microsecond. One such application of the triggered spark gap is disclosed in the United States Patent No. 2,867,728 to H. C. Pollock, for "Logging Apparatus," which issued on January 6, 1959. Shown therein is a circuit wherein the spark gap is utilized for pulsing a source of neutrons used for lithological logging analyses. The specific requirement of the logging apparatus of that patent is for a high voltage pulse which is a small fraction of a microsecond. The triggered spark gap is well suited for this type of switching function.

In essence, the triggered spark gap is a tube, the interior of which is filled with a gas which is capable of ionization when an appropriate voltage is applied between certain of the electrodes. The triggered spark gap tube comprises three electrodes. Two of them act as the contacts of a switch, and the third acts to close this elemental switch by virtue of breaking down or ionizing, with a preparatory or initiating pulse, the gas disposed between the third electrode and one of the other two electrodes. The two electrodes which act as the contacts of the switch are called dome electrodes because they are hollow hemispherical shapes. The dome electrodes are disposed opposite one another, and are spaced apart (and insulated from each other) by a distance which is appropriate for the voltage of interest. The third electrode (which is shaped like a tube or rod and is called the trigger electrode) projects just through, and is insulated from, the surface of one of the two dome electrodes. When the spark gap is to be switched, a short pulse is applied between the trigger and one of the two dome electrodes. This difference of potential is sufficient to break down the gas between these two closely spaced electrodes, whereby ionization takes place therebetween. One of the theories advanced to explain the triggering of the triggered spark gap is that the ultraviolet radiation which is generated by this localized breakdown serves to trigger the ionization of the rest of the gas between the two dome electrodes. This results in an avalanche breakdown or ionization of the gas between the dome electrodes. The ionized gas serves as a conductor thereby to effectively close the switch. The term "breakdown" as applied to spark gaps means electrical conduction of the gas between the electrodes. In this way, the triggered spark gap acts as a high voltage switch.

Three of the most important conditions for successful operation of a spark gap should be understood for this discussion. The first condition is that breakdown (i.e., conduction) must *not* occur as long as the potential applied between the dome electrodes is below a certain value. This value is frequently called the "hold-off" value. Spark gaps may be constructed having hold-off values ranging from 500 to at least 30,000 volts. The trigger electrode is not energized while the "hold-off" value is being determined or while the spark gap is being subjected to a specified "hold-off" test.

Secondly, breakdown between the dome electrodes *must* occur when the potential across them is greater than a certain minimum value. In other words, if the difference of potential between the two dome electrodes is great enough, the gas therebetween should break down, and conduction between the electrodes should follow. The value at which the breakdown should occur (keeping in mind that the trigger electrode is not energized at this time either) is often termed the minimum static breakdown voltage. The static breakdown voltage of spark gaps is usually not less than 25% greater than the hold-off value.

Thirdly, the breakdown *must* occur when the potential applied across the two dome electrodes is within a certain specified range between the hold-off and static breakdown values when the trigger electrode is energized. Furthermore, this breakdown must occur within a certain, and very short, period of time after the trigger electrode is energized. This delay period between application of the pulse to the trigger electrode and the breakdown between the two dome electrodes is called the delay time. This is usually a fraction of a microsecond. The average time variation that a spark gap tube may exhibit in its delay time during a series of pulses is called "jitter."

Not only is the triggered spark gap a high voltage switch, but the current that is switched can be considerable. Since it is an arc discharge device, its conduction current is limited only by the constants of the external circuit. Such operation results in very high temperatures at the cathode dome electrode because of the high current density, and also in intense ionic bombardment of the cathode because of the high voltages. These two effects result in an erosion of the cathode dome electrode due to the vaporization of the cathode metal as a result of the high temperatures and also due to the ionic bombardment. There is a subsequent and inevitable deposition of the vaporized electrode metal elsewhere (and undesirably) on the interior surfaces of the spark gap tube. The combined result of high temperature and ionic bombardment on the cathode dome electrode is, for our purposes here, termed "sputtering."

A metallic coating on the insulating materials that separate the three electrodes within the spark gap affects the electrical characteristics of the spark gap in an undesirable way. Typically, a thin conductive coating forms on the insulator that separates the two dome electrodes, and also on the insulator that separates the trigger electrode with its coupled dome electrode. The dome electrode triggered with the trigger electrode acts as the cathode in normal operation and is usually called the cathode electrode or trigger dome electrode. The other of the two dome electrodes is termed the main dome electrode.

Clearly, the more often the tube is fired or pulsed, the more sputtering results, and as time goes on, the greater the erosion of the trigger dome electrode and deposition of the eroded metallic material on the insulation of the spark gap. In this way, sputtering not only causes unacceptable performance of the tube with respect to the hold-off value and the delay time, but the life of the tube is greatly reduced.

Indeed, sputtering has been so great a problem that prior to the utilization of the principles of the instant invention in connection with spark gaps, more than twenty-five percent of the tubes produced had to be rejected as unacceptable for failing the hold-off, static breakdown, or delay and jitter tests, or because the life of the tube was too short. With the applications of the principles in accordance with the instant invention, however, rejection of manufactured tubes has been reduced to about ten percent.

It is the primary object of this invention, therefore, to provide an improved arc discharge tube characterized by longer life and better performance characteristics than has heretofore been possible, and which for any specified performance characteristic, may be manufactured to satisfy those characteristics with a higher production yield than has been heretofore possible.

The above object has been satisfied in accordance with with the principles of the invention in a two-fold manner. Firstly, in accordance with the principles of the invention, it was discovered that sputtering of the electrodes and deposition of the eroded metal onto the insulating material could be considerably reduced such that hold-off problems became insignificant. This is accomplished by contouring the inside face of the insulator separating the two dome electrodes to conform in shape to the electric field pattern between the two dome electrodes (that would exist in free space) when voltage is applied thereto.

Secondly, it has been found that by cutting a groove or gap in the insulator separating the trigger electrode from the trigger dome electrode, the possibility of a conductive short therebetween is substantially eliminated, even when there is considerable sputtering and deposition of eroded metal on the insulator between the trigger and trigger dome.

The novel features believed to be characteristic of the invention are set forth with particularity in the appended claims. The invention itself, however, both as to its organization and method of operation, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings.

In the drawings:

FIGURE 1 is a perspective view with portions cut away of a triggered spark gap tube in accordance with the invention;

FIGURE 2 is a longitudinal cross section of the triggered spark gap of FIGURE 1 taken through a plane including the longitudinal axis of the tube, so as to highlight the shape of the contoured inner surface of the insulator between the two dome electrodes;

FIGURE 3 is a cross section of the triggered spark gap of FIGURES 1 and 2 taken along lines 3—3, so as to highlight the grooved insulator between the trigger electrode and the trigger dome electrode; and

FIGURE 4 is a portion of the tube showing the trigger, the trigger dome, and the grooved insulator therebetween after the tube has been pulsed many times.

Referring with particular attention at this point to FIGURES 1 and 2, there is shown a triggered spark gap tube in accordance with the principles of the invention. So that a frame of reference may be had, the external diameter of the cylindrical body insulator **11** of the tube of FIGURE 1 would be characteristically approximately .675 of an inch for a typical tube. The cylindrical insulating body of tube **11** is preferably a ceramic material percent Al_2O_3, with the remaining five percent comprising to which the metal electrodes may be brazed. A particularly satisfactory type of ceramic comprises ninety-five Cr_2O_3, SiO_2, MgO and CaO. A commercially available ceramic having this composition goes under the trade name of Diamonite P3142–1, although we are not restricting the ceramic either to this type or to this chemical composition. It need only satisfy the requirement that it

be a good insulator, strong, and easily adaptable for brazing to metals such as tantalum or molybdenum.

The major functions of the ceramic body insulator **11** are: the formation of the envelope of the tube so that the gas may be contained therein at a desired pressure; and the electrical separation and insulation of the two dome electrodes **12** and **13**. At the lower portion of the ceramic body insulator **11** is a hollow hemispherical metallic electrode **12**. This is the main dome electrode and in its usual operation normally has applied to it a positive potential relative to the dome electrode **13**. Located at the top portion of insulator **11** is the trigger dome electrode **13** which is in many respects similar to main dome electrode **12**, except that in the central portion of the hemisphere, an aperture **14** is defined therein for purposes that will be described below.

Each of dome electrodes **12** and **13** has a collar forming a base to afford means for brazing to the bottom and top edges of the ceramic body insulator **11**. Disposed between the collar of main dome **12** and insulator **11** is a thin washer of brazing metal used for brazing the collar of the electrode **12** to the bottom edge of the cylindrical body insulator **11**. In similar fashion, the collar of the trigger dome is brazed to the top edge of the cylindrical insulator **11** through the medium of a thin metallic washer of the same metal as that used for securing electrode **12** to the ceramic body insulator **11**. Except for the aperture **14** located in the center of trigger dome **13**, and a small hole **29** to permit easy loading of gas during the gas filling process, the unitary structure formed by the body insulator **11** and the electrodes **12** and **13** would be air tight. The general configuration resulting is that the two hollow hemispheres **12** and **13** are disposed inside the hollow insulator **11**, with the hollow hemispherical main dome **12** being disposed concave downward and trigger dome **13** concave upward. The distance in the tube between the closest points or the surfaces of domes **12** and **13** determines the breakdown voltage of the tube (in conjunction with the type of gas filling the tube and its pressure).

Of considerable importance is the shape or contour of the inner surface of the ceramic body insulator **11**. This shape may best be seen in FIGURE 2, which shows a cross-sectional view of the triggered spark gap shown in perspective in FIGURE 1. This cross-sectional view is taken by passing an imaginary plane diametrally through the triggered spark gap, so as to coincide with, and be parallel to, the longitudinal axis of the cylindrically shaped ceramic body insulator **11**. The contour of the inner face of the body insulator **11** is of importance for reasons that will be described more fully below. A description of the shape itself is all that will be described at this point.

The outside surface of insulator **11** defines a right cylindrical shape. The inner surface of insulator **11** defines a right cylindrical surface only along approximately the middle half of the insulator, i.e., between the imaginary lines **15–16**. Above line **15** and below line **16**, the inner surface radically departs from the straight right cylindrical surface of its middle portion. This is due to the ring-like extensions **17** and **18** to the bottom and top edges of the insulator **11**, respectively. The bottom (outside) face of ring **17**, and the top (outside) face of ring **18** form the flat surfaces to which the collars of the insulators **12** and **13** are brazed, respectively. The inside surfaces of ring-like extensions **17** and **18** (i.e., the surfaces inside the tube) are shaped in a special way. As seen in the cross-sectional view of FIGURE 2, the inside surface of ring **17** is defined by a curved line which commences at main dome **12** and proceeds along an arc of a circle (having a radius of curvature which is the same for both **17** and the top ring **18**) to meet the middle portion of the inner cylindrical surface of insulator **11** substantially tangentially. The cylindrical surfaces of **17** and **18** are not deliberately in intimate contact with electrodes **12** and **13**, but due only to mechanical toler-

ances. The inner surface of ring 18 is similarly arranged relative to trigger dome 13. This internal shaping of the body insulator 11 relative to the dome electrodes 12 and 13 is to simulate (at the inner surface of insulator 11) the electric field pattern between the domes 12 and 13 when the domes 12 and 13 are mounted in free space and a potential is applied therebetween. Thus, immediately adjacent the inner surface of insulator 11, the lines of electrical force commencing and terminating on domes 12 and 13 are of substantially the same shape as the inner surface of the insulator 11.

Attached to the brazed collars of dome electrodes 12 and 13 respectively are electrical terminals 19 and 20 respectively, to which may be applied the potential which is to be switched by the spark gap.

Trigger dome electrode 13 and main dome electrode 12 are made of a material characterized by a high melting point and low vapor pressure. This is necessary, because when the spark gap is activated, its internal temperature may reach to approximately 6,000° C. Tantalum is a metal which well satisfies these requirements and the additional requirement that it be easily brazed to the ceramic insulator 11. Molybdenum, tungsten and columbium are examples of other metals which may be used because they have similar properties.

The third electrode of the spark gap is the trigger electrode 21 (as distinguished from the trigger dome electrode 13). It is disposed in the aperture 14 formed in trigger dome electrode 13. The trigger electrode 21 is disposed coaxially with the cylindrical portion of insulator 11. Extending upwardly from the trigger electrode 21 is a trigger tube 22 within which the trigger electrode 21 fits. A ceramic cap insulator 23, with a hole through its center for receiving the trigger tube 22, is mounted on top of the spark gap, so that the rim portion of cap insulator 23 may be brazed to the top surface of the collar of trigger dome electrode 13. A thin washer-like element is disposed between the rim of cap 23 and the collar of dome 13 to provide the material necessary for brazing the two together. The hole through the center of ceramic cap insulator 23 is closed by brazing its boundary to the outer periphery of trigger tube 22 with a thin wire of brazing material. By virtue of the ceramic cap 23 being brazed at these areas, the entire volume within the spark gap body itself is air tight. This volume is filled with nitrogen at a pressure of from approximately one-half of an atmosphere to one atmosphere. The precise pressure of the nitrogen (in conjunction with the spacing between the trigger dome 13 and the main dome electrode 12) determines the breakdown potential of the spark gap. Other gases and combinations of gases, such as helium/nitrogen and krypton 85/nitrogen may be used.

Trigger electrode 21 is preferably of tungsten, which also has a low vapor pressure and high melting point. Ceramic cap insulator 23 may be of the same material as the body insulator 11. The trigger tube 22 is preferably of Kovar or nickel, although materials such as copper or combinations such as copper/Kovar may be used.

Although trigger electrode 21 is disposed in the aperture 14 of trigger dome electrode 13, it does not fill the aperture. Surrounding trigger electrode 21 and contiguous thereto, and otherwise filling the aperture 14, is an insulator 24 hereinafter referred to as the trigger insulator. Trigger insulator 24 is a ceramic material which may be of the same type as the body insulator 11 and/or ceramic cap insulator 23.

Of considerable importance is the fact that trigger insulator 24 is grooved. The annular gap or groove 25 is in the face 26 of the insulator which is perpendicular to the longitudinal axis of trigger electrode 21, and faces main dome electrode 12. The nature of the annular groove 25 may perhaps best be seen from the view shown in FIGURE 3, which is a transverse cross-section taken along a plane perpendicular to the longitudinal axis of body insulator 11, e.g., along line 3—3 of FIGURE 2. Groove 25 is circular in form with trigger electrode 21 as its center. Thus, groove 25 forms a circle which is concentric with the boundary of aperture 14 in trigger dome electrode 13. So that appropriate proportions may be visualized keeping in mind that the external diameter of the body insulator 11 may be approximately .675 of an inch), the width of groove 25 may be approximately .015 of an inch (the width being the dimension in the plane of face 26 of insulator 24). The depth of groove 25 may be approximately .030 to .045 of an inch. The importance and function of groove 25 in the operation of the spark gap will be discussed in some detail below.

The lower tip of trigger electrode 21 is round in shape to form a bullet-like head. It is also highly desirable to uniformly roughen the surface of trigger dome electrode 13 prior to use. This helps decrease sputtering of the cathode electrode metal. It is important that the roughening be done uniformly over the surface of dome 13.

Nitrogen gas may be introduced into the body of the spark gap through a hole in the side of tube 22 and a hole 29 in dome electrode 13.

The operation of the triggered spark gap and the problems involved in such operation may now be properly comprehended. In operation, a voltage is applied across the main dome electrode 12 (the anode) and the trigger dome electrode 13 (the cathode). This voltage is somewhat less than that required to cause normal or static breakdown. Another voltage is then applied between trigger electrode 21 and the trigger dome 13 to initiate breakdown between the dome electrodes 12 and 13. In the gas discharge that occurs, electrons are emitted from trigger dome 13, and electron-ion pairs are formed in the nitrogen gas between the electrodes. The current density at the cathode 13, during the arc discharge, is extremely high and causes some vaporization of the cathode material. This, in conjunction with the ionic bombardment of the cathode, results in an erosion of the cathode material and eventual deposition of the eroded metallic material elsewhere in the interior of the spark gap tube. Typically, the metallic deposition, which in the example given is tantalum, forms on the inside surfaces of ceramic body insulator 11, and also on the face 26 of insulator 34.

Prior to the instant invention, the metallic vaporization and subsequent deposition was so thick that there was a change in the inter-electrode resistance as a function of length of operation. The deposited metallic film also distorted the electric field adjacent to the electrodes and while the film was being formed, some gas molecules were undoubtedly trapped by the Blodgett-Vander slice phenomenon. The latter effect causes the reduction of gas pressure through "clean-up." The longer the tube was operated and the more the cathode electrode was eroded, the greater the amount of metallic deposit formed, and consequently the greater were the harmful effects. Needless to say, heavy deposition of tantalum on the inside face of the body insulator between the main and trigger domes drastically affected the hold-off performance of the tube. Similarly, metallic deposition across the insulator spacing the trigger electrode from the trigger dome electrode had a considerable effect upon the resistance therebetween, and therefore affected delay time and jitter.

These past undesirable effects are completely eliminated by the circular groove 25 in the trigger insulator 24 disposed between the trigger electrode 21 and trigger dome electrode 13 and minimized by the special contoured shape of the inner surface of the body insulator 11.

Consider first the function of the annular groove 25 in the trigger insulator 24. It has been ascertained that with the groove 25 disposed between trigger 21 and the trigger dome 13, any deposition that there may be of material on the insulator 24 fails to form a completed electrical path between the electrodes. Although eroded metal may, in fact, form on the insulator 24 between trigger 21 and dome 13, and although the deposited metal may penetrate into groove 25 along its sides (see FIG-

URE 4) it has been clearly ascertained that the vaporized metal does not, and apparently cannot, penetrate all the way to the bottom edge 2 of groove 25.

As may be seen in the enlarged view of FIGURE 4, a thin metallic film 27 has been formed, due to erosion of the electrode 13. This thin film commences at the trigger tube electrode 21 and crosses over face 26 of insulator 24 to the region of groove 25. Similarly, there is a thin deposition of metal commencing at trigger dome 13 and passing over the face of insulator 24 to groove 25. It may be noted that the deposition of metal takes place on the two inside parallel surfaces of groove 25, but does not enter into the groove very deeply. In fact, the entrance of the deposited metal is no more than about one-third the total depth of the groove. The remote wall or base 28 of the groove is entirely free of any deposited metal. Therefore, electrodes 21 and 13 remain insulated from each other.

Why the vaporized metal does not peentrate all the way into groove 25 is not clear. One plausible explanation is that the nitrogen gas is compressed in groove 25 by, and serves to act as a cushion against, the ionic bombardment and metallic vapor trying to enter the groove. Thus, the tendency of the ions and metallic vapor to push into the groove 25 is resisted by a type of cushioning due to compression of the nitrogen against the remote wall 28 of the groove.

Minimization of metallic vaporization from the cathode electrode 13 is accomplished by the spatial configuration and relation of electrodes 12 and 13 and the contoured inner surface of body insulator 11. If a uniform electrical field pattern exists between dome electrodes 12 and 13, then the discharge phenomenon that takes place therebetween would not tend to be concentrated in one particular area. Thus, if the two electrodes were suspended in free space and the geometry of the electrical field pattern therebetween were not distorted or compressed in any way because of any boundary conditions other than those defined by the conductive surfaces of the electrodes themselves, then there would be no tendency for the discharge to establish itself at any particular place on the electrodes. Once, however, there is an enclosure formed about the electrode, as, for example, by the body insulator 11, problems arise with respect to the uniformity of the electrical field distribution between the electrodes.

The body insulator is a dielectric material which, in the example given for the insulator 12, may have a dielectric constant of 9. The inside of the tube is filled with nitrogen and so the dielectric constant within the tube and immediately adjacent the inside face of insulator 11 is approximately that of free space, or one. Thus, a dielectric interface is defined at the inside surface of insulator 11. Such an interface tends to distort the normal electric field pattern between electrodes 12 and 13. Such a distortion could, and it is believed in the past it has, resulted in an undesirable concentration of electric lines of force in restricted areas of the electrodes. As a consequence, the initiation of breakdown has occurred in an unpredictable, undesirable manner. In accordance with the principles of the invention, however, the inside face of the body insulator 11 has been contoured and shaped to conform to the geometry of the electrical lines of force that would normally appear between the electrodes 12 and 13 if they were, in fact, suspended in free space and not bonded. Furthermore, the walls formed by the body insulator 11 have been spaced as far from the electrodes as possible, consistent with other practical structural and mechanical factors. By making the bounding dielectric interface conform to the shape of the electrical field pattern at the interface, the electrical field pattern is left relatively undistorted. This, it is believed, avoids the generation of unusually high temperatures in isolated regions on the cathode electrode and thus tends to greatly minimize the amount of metallic deposit on the insulators within the tube. The shape of the inner face of the body insulator is such that a line drawn on it from one electrode to the other electrode describes the path of an electrical line of force at that region between the two electrodes. It is a curved line because the two electrodes are hemispherical in shape, and as is known in the art, the electrical lines of force commencing from either of the two conductive boundaries must be at right angles to the surfaces thereof.

The above heuristic explanation for the improvement in operation due to contouring the inside surface of insulator 11 is the best presently available. However, no definitive theory has been developed which explains the success of the invention.

Contouring the inner surface of insulator 11 in this manner provides a non-electrical advantage as well. The rim-like portions 17 and 18 of insulator 11 used to form the appropriate contour also provide thickened portions at the top and bottom of the insulator. This adds mechanical strength to the tube envelope and aids in the brazing of the dome electrodes 12 and 13 to insulator 11.

While particular embodiments of the invention are shown, it will be understood that many modifications may be made without departing from the spirit thereof, and it is contemplated by the appended claims to cover any such modifications as fall within the true spirit and scope of the invention.

What we claim is:

1. An arc discharge device comprising a pair of shaped electrodes spaced from each other which define an electric field pattern when said electrodes are in free space and a potential is applied between them, an insulator physically separating and insulating said electrodes from each other and encompassing a portion of the electric field between said electrodes, said insulator having a surface contoured to substantially conform with the shape of said electric field pattern when said electrodes are in free space.

2. An arc discharge device comprising a pair of spaced electrodes, each of which is hollow and approximately hemispherical in shape, said electrodes being disposed facing each other concave outward, a hollow ceramic insulator having a cylindrical external surface, said insulator being disposed to insulate said electrodes from each other, said insulator having an inner surface contoured to conform with the shape of the electric field pattern between said electrodes when said electrodes are suspended in free space and a portential is applied therebetween.

3. An arc discharge device as recited in claim 2 wherein the shape of the inner surface of said hollow cylinder is defined as follows, an imaginary plane passing longitudinally and diametrally through said insulator intersects said inner surface along a line having non-linear portions with each end of said line terminating at one of said electrodes.

4. An arc discharge device as recited in claim 3 wherein said non-linear portions of said line are adjacent said electrodes and are non-linear in the following sense, each non-linear portion is an arc of a circle having substantially the same radius of curvature as the other.

5. An arc discharge device as recited in claim 3 wherein a line tangent to one end length of said line is substantially perpendicular to a line tangent to the surface of the hemispherical electrode at the point where said end of said line terminates on said electrode.

6. A triggered spark gap tube comprising first and second hollow and substantially hemispherical electrodes, a hollow ceramic insulator with a right cylindrical external surface, said first and second electrodes being secured in the top and bottom ends respectively of said hollow insulator with the concave sides of said first and second insulators being disposed concave upward and concave downward respectively, a gas insulator filling the volume formed by said electrodes and said ceramic insulator, the interface formed by said ceramic and gas insulators de-

fining a surface similar in shape to the electric field pattern that would exist at that surface if said electrodes were suspended in free space and a potential applied therebetween.

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