Sept. 20, 1966 E. A. BUNT ETAL 3,274,424

DISCONTINUOUS ELECTRODE ARC PLASMA GENERATOR

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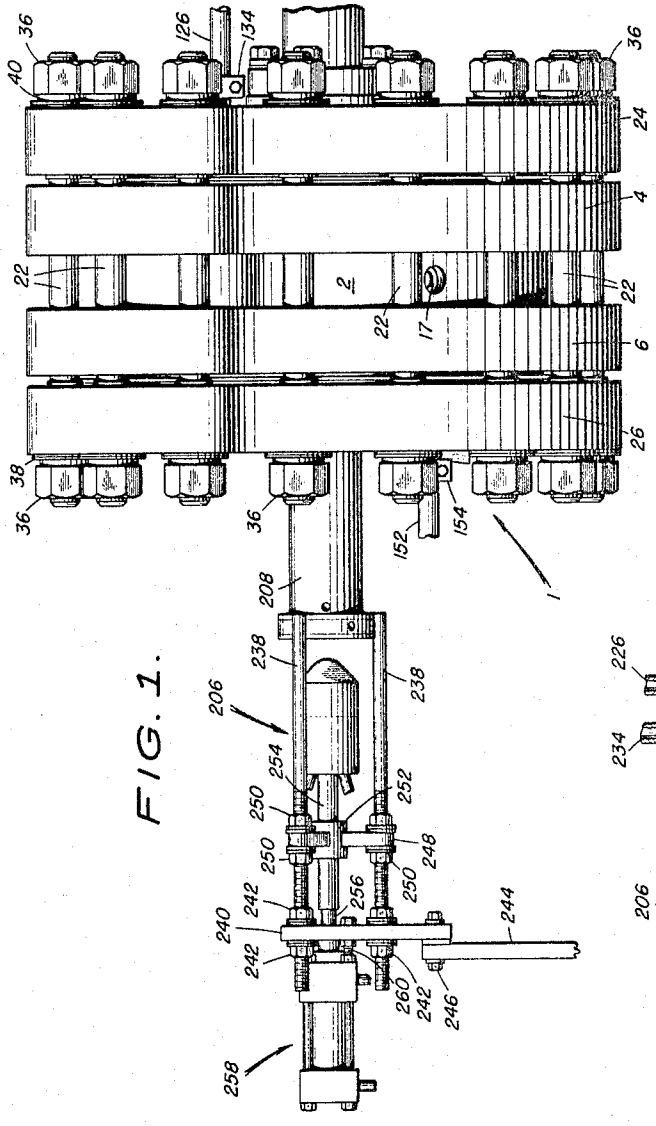


FIG. 1.

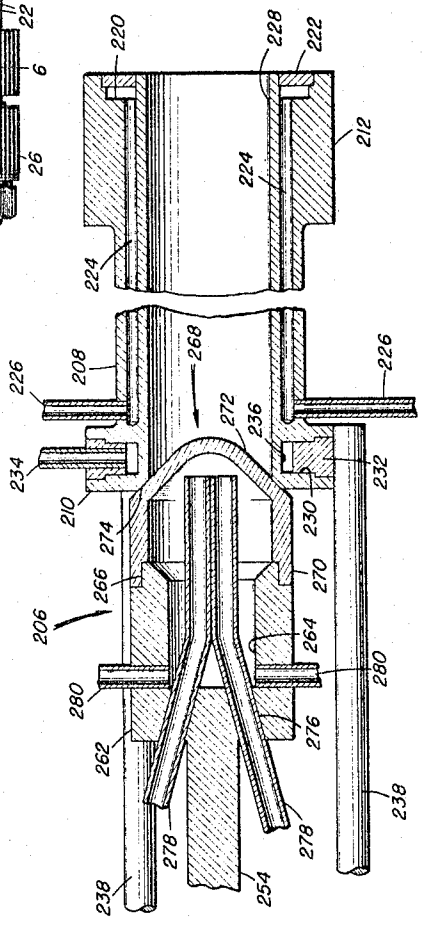


FIG. 2.

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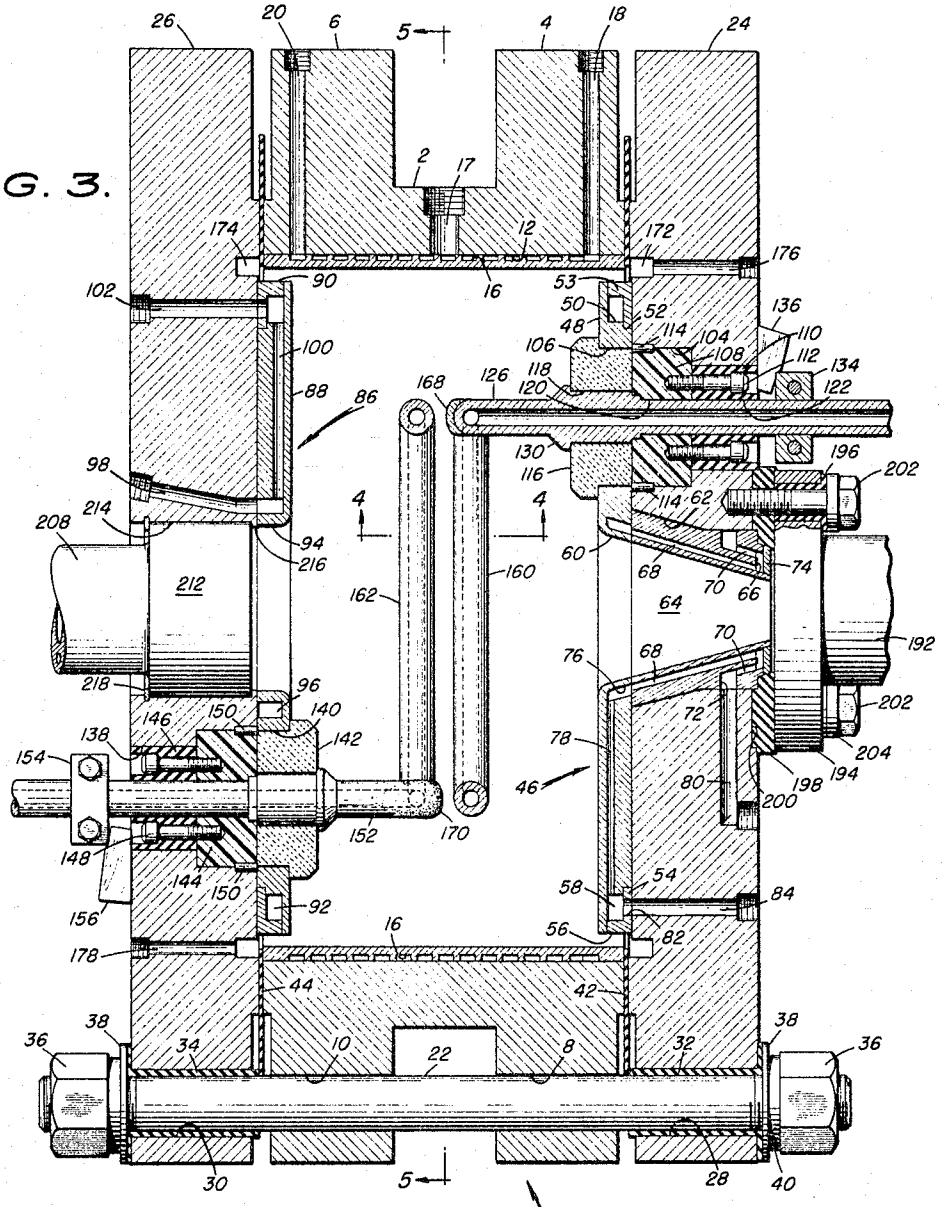
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DISCONTINUOUS ELECTRODE ARC PLASMA GENERATOR

Filed Jan. 10, 1963 3 Sheets-Sheet 2

FIG. 3.



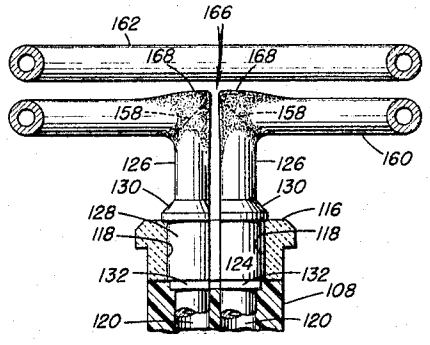


FIG. 4.

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DISCONTINUOUS ELECTRODE ARC PLASMA GENERATOR

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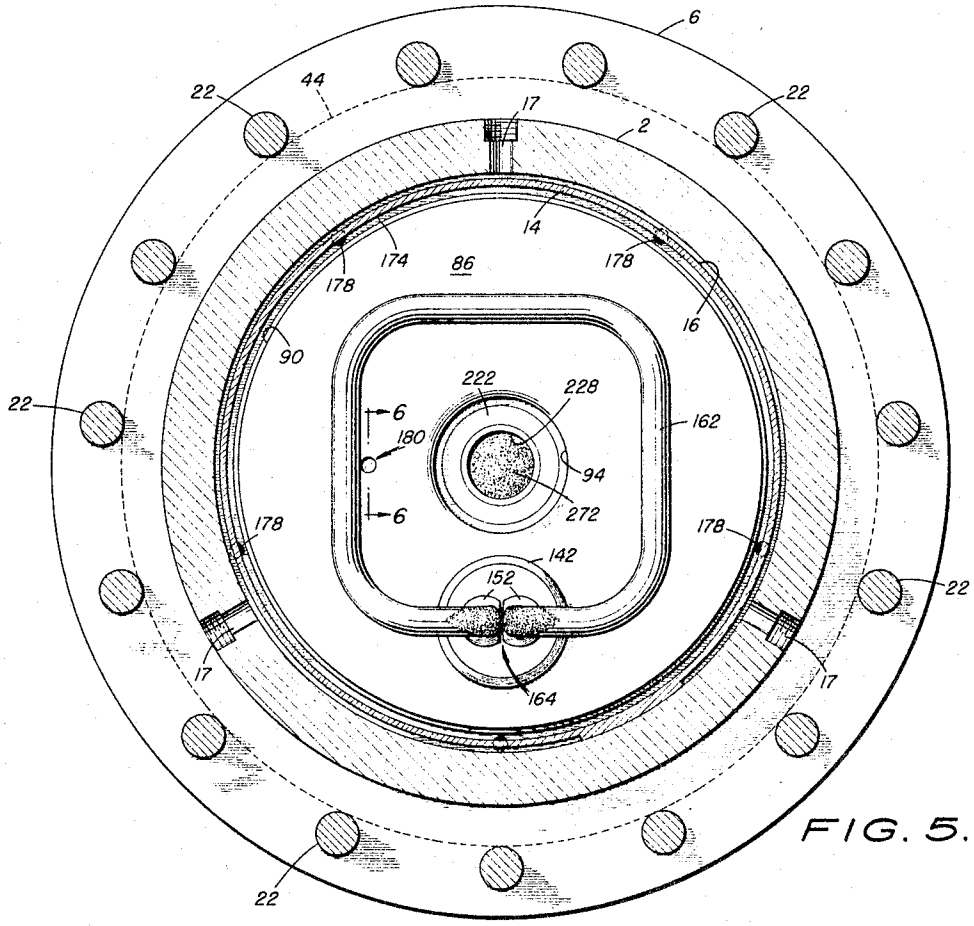


FIG. 5.

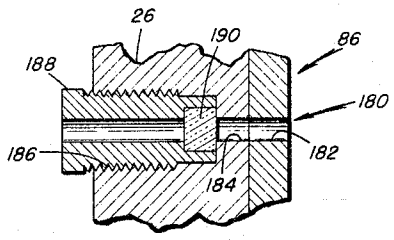


FIG. 6.

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3,274,424

DISCONTINUOUS ELECTRODE ARC PLASMA GENERATOR

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11 Claims. (Cl. 313—231)

This invention relates generally to arc plasma generators; more specifically, it relates to an improved, continuously operated arc plasma generator incorporating a novel electrode construction and novel apparatus to facilitate starting thereof, and to a method for starting said generator at relatively high chamber pressures and in the presence of gases entering the chamber at relatively high rates of mass flow.

The arc plasma generator of the invention is designed to provide a plasma discharge, which for purposes of this invention is defined as a partially ionized, gaseous-like mass derived by passing air or a similar substance through a high energy electric arc. The plasma discharge from the generator is therefore a collection of neutral particles, ionized particles, and free electrons, all of which are free to move and have mutual collisions. The temperature of the discharge produced by the generator is of the same order as the indicated temperature at the surface of the sun.

Numerous applications have been found for the plasma discharge of an arc plasma generator, including the testing, cutting and welding of materials, metal spraying, chemical processing, and as a heat source for equipment such as windtunnel facilities capable of simulating hypersonic flight. Because the subject plasma generator is capable of operating well above the maximum capabilities of existing chemical and storage heaters, such as heaters of the pebble bed type, it presents new capabilities for both industrial and scientific purposes.

Several general types of arc plasma generators have been devised, the type to which this invention relates typically comprising a pressure vessel containing a chamber within which is mounted at least a pair of substantially identical, parallel, closely spaced ring-like electrodes, said electrodes being insulated from each other and from the vessel. A high voltage is applied to the electrodes, and an arc is struck therebetween. A suitable pressurized gas is admitted to the chamber, is passed through the arc, whereby it is transformed into plasma, and is then discharged from the vessel through a suitable orifice.

Two confronting, closely spaced electrodes are utilized in the instant invention, each lying almost entirely within a single plane. Each of the ring-like electrodes is of the split ring type; that is, each has a discontinuity therein, the discontinuity in one electrode being disposed to confront a continuous surface on the other electrode. While the use of such discontinuous electrodes has been suggested, until the present invention the presence of the discontinuity in each electrode has created a problem which has severely limited the operating life thereof.

The two electrodes in the subject device are hollow, circular in cross-section, and according to the teachings of the invention are each bent into a generally rectangular configuration. A pair of hollow supporting tubes are secured to each electrode, one at each of the ends thereof positioned on each side of the discontinuity therein. The supporting tubes project normally from the plane of their respective electrodes, and serve the duel necessary functions of supporting the electrodes and providing a channel to supply a flow of cooling fluid to the interiors thereof.

In D.C. operation of the generator one of the electrodes is made positive and the other negative, and an arc is struck therebetween. The current flowing through the electrodes creates a magnetic field thereabout, which acts to propel the arc around the confronting peripheries of the two electrodes at a very high rate of speed. This high-speed travel of the very high temperature arc is necessary to the life of the electrodes, for if the arc were to rest at any one point on the electrode surfaces for more than a fraction of a second the intense heat would quickly erode and burn through the electrode, thus causing breakdown.

In the past the discontinuities in electrodes of this type have created obstacles to the rapidly moving arc, and as a result the arc has hesitated during each pass on the electrode surfaces on either side of the discontinuities; this condition particularly occurs during A.C. operation of the electrodes. The slight hesitation occurring during each revolution of the arc results after many revolutions in a build-up of temperature at the discontinuities, and premature failure of the electrodes after a relatively short running time thus occurs. The tendency for the arc to dwell at the electrode discontinuities has been overcome by the electrode construction of the present invention, wherein the electrode surfaces on each side of the discontinuities are built up in the form of a ramp.

The immediate effect of the ramps in the present invention is to reduce the spacing between the electrodes on either side of each discontinuity, whereby a reduction occurs in voltage requirements. The reduction in voltage results in an increased flow of current through the electrodes in the vicinity of the ramps (assuming a drooping load line for the power supply), which thus causes an increase in the strength of the magnetic field in those regions. The increased magnetic field in turn causes the already rapidly moving arc to be accelerated sufficiently as it approaches a discontinuity so that it effectively jumps thereover without hesitation. By substantially eliminating dwell of the arc at the discontinuities therein the present invention greatly prolongs the life expectancy of a set of electrodes, and thus makes possible relatively long continuous periods of operation for the plasma generator.

Until the present invention the configuration into which the electrodes are bent has been considered a matter of choice, there having been no recognized controlling advantage to any particular configuration. Because of ease in fabrication, circular electrode configurations have been the most common. However, it has been found that in confronting circular electrodes, especially those of relatively small diameters of the order of six inches, the arc will frequently cease its movement, or dwell, and thus cause a breakdown of operation. It has now been discovered that such dwelling of the arc can be prevented by utilizing a proper configuration for the electrode loops.

The detachment of the travelling arc from the electrode surfaces in small circular electrode devices has been traced to the circular configuration of said electrodes. It has been found that there is radial asymmetry of the self-induced magnetic field between the inside and the outside of the electrode circle, and that this asymmetry contributes to the arc bowing radially outward as it travels its circular course. When the arc bows outwardly its length increases, and occasionally it will become attached to nearby surfaces; either of these effects will slow or stop the arc movement, and will hence often catastrophically increase erosion of the electrodes at the point where the arc hesitates.

Outward bowing of the arc has been controlled in the subject invention by constructing the electrodes in straight sections joined by curved sections, a typical configuration being a square having rounded corners. The field distributions around the straight sections of the square loop

are symmetrical, and the presence of the 90 degree rounded corners is insufficient to cause catastrophic outward bowing of the arc; thus, the problems associated with uncontrolled bowing of the arc have been solved, and an electrode construction has been provided which is capable of providing continuous operation for relatively long periods of time.

In certain applications of arc plasma generators it is desirable to strike the arc, and thus commence operation of the generator, while the arc chamber is pressurized and while gas is flowing into said chamber. However, in the past it has been found in arc plasma generators of the type to which this invention relates that under these conditions the arc would frequently blow out almost immediately after it was struck.

It has now been discovered that the cause for this blowing out, or extinguishing, of the arc is a sharp pressure rise occurring at the instant the arc is struck, which pressure rise is of such a short duration and of such a large magnitude that it is normally unmeasurable. The instantaneous pressure rise requires an instantaneous increase of like magnitude in the voltage sustaining the arc, which voltage demand can normally not be met; thus, the arc is extinguished.

In the plasma generator of the present invention the extinguishing of the arc has been controlled by mounting an adjustable orifice valve in the pressure vessel. According to the novel arc starting method of the invention, gas flow at the desired rate of mass flow is initiated into the arc chamber after said valve has been opened to place the chamber in communication with a large ballast volume, such as the atmosphere. The arc is then struck in the usual manner, the critical period for pressure rise occurs, and after a brief interval (one second or a little longer) the valve is closed; by utilizing the large ballast volume during the striking of the arc the instantaneous pressure rise is controlled to such an extent that the surging voltage demand can easily be met. Thus, the arc plasma generator of the invention may be readily started without danger of the arc being extinguished.

It is noted that the utility of the plug valve method of starting is particularly good when a relatively large rate of gas mass flow (of the order of one lb. per second) is required to flow through the arc, as a high mass flow augments the required voltage. If sufficiently high voltage is not available, successful starting can also be effected by firing on a temporarily reduced mass flow; this, however, unnecessarily increases the enthalpy and temperature of the gas beyond operating requirements and may even lead to breakdown of the cooling walls. All of this is avoided in the present invention by keeping the mass flow constant and using the plug valve to discharge the pressure pulse occurring upon firing of the arc.

It is an object of this invention to provide an arc plasma generator especially adapted for D.C. operation, and so constructed as to be capable of continuous operation at relatively high temperatures and chamber pressures for comparatively long periods of time.

A further object of the present invention is to provide a discontinuous electrode pair for use in an arc plasma generator, so constructed as to permit very high speed movement of an arc struck between said electrodes without the occurrence of excessive outward bowing of said arc.

Another object of the subject invention is to provide a discontinuous electrode pair for use in an arc plasma generator, so constructed that an arc struck between and travelling the peripheries of said electrodes will pass without hesitation over the discontinuities therein.

It is also an object of this invention to provide an arc plasma generator having a pair of opposed, ring-like electrodes, and so constructed that an arc struck between said electrodes may be moved about the peripheries thereof by the effect of magnetic fields induced in said electrodes by the flow of electricity therethrough.

A further object of the present invention is to provide an arc plasma generator so constructed that it may be operated in the presence of relatively high chamber pressures.

Another object of this invention is to provide a method for starting an arc plasma generator in the presence of relatively high chamber pressures and gases flowing into said chamber at relatively high rates of mass flow.

Other objects and many of the attendant advantages of this invention will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

FIG. 1 is a side elevation of the arc plasma generator of the invention, showing the variable orifice starting valve in its fully open position;

FIG. 2 is an enlarged longitudinal section through the variable orifice starting valve, the valve being shown in its fully closed position;

FIG. 3 is a detail section taken generally along the longitudinal axis of the arc plasma generator, showing in particular the construction of the electrodes and the manner in which they are supported;

FIG. 4 is a section taken generally at **4—4** in FIG. 3, and shows the construction of the ramps on one of the electrodes and the manner in which said electrode is mounted;

FIG. 5 is a cross-section taken along the line **5—5** in FIG. 3, and showing in particular the configuration of one of the electrodes and the position of the viewing port in the end of the pressure vessel; and

FIG. 6 is an enlarged detail section taken at **6—6** in FIG. 5, showing the construction of the viewing window.

The arc plasma generator of the present invention comprises a cylindrical vessel closed at both ends by a pair of bolted-in-place closure plates, the internal surfaces of the vessel and the closure plates being fitted with cooling jackets. A fluid-cooled exit nozzle is mounted centrally within the forward closure plate, and the aft closure plate has a variable area starting valve mounted thereon. The vessel and the closure plates together define an arc chamber, and port means are provided in the two closure plates for admitting gas into said chamber.

Disposed within the arc chamber are a pair of hollow, ring-like electrodes constructed of copper or some other suitable conductive material, each electrode having a discontinuity in one of its sides and both electrodes being bent into identical rectangular configurations. A pair of hollow supporting tubes are connected to each electrode on either side of said discontinuity, and project normally from the plane of their associated electrode and away from the other electrode through suitably insulated openings in their respective adjacent closure plates. The surfaces of the electrodes on both sides of the discontinuities are built up to define ramps, and the two electrodes are placed in closely spaced, parallel relationship with the discontinuities disposed 180 degrees apart and with the ramps on each electrode facing the unbroken surface of the adjacent electrode.

Referring now to the drawings, a generally cylindrical pressure vessel is shown at **1**, and includes a cylindrical vessel **2** having radially projecting forward and aft flanges **4** and **6** on the opposite ends thereof, said flanges having a plurality of circumferentially-spaced, confronting bores **8** and **10**, respectively, extending therethrough. The vessel **2** has a cylindrical opening **12** extending therethrough, and a water jacket **14** is fitted within said opening and is secured in position, as by welding.

The water jacket **14** has an axial length corresponding to that of the vessel **2**, and has a helical, rectangular groove **16** in its outer surface. The vessel **2** has a plurality of radially-directed, circumferentially-spaced bores **17** therein which communicate with the space defined between the water jacket **14** and the vessel **2**, and which are threaded at their outer ends for connection to a source

of cooling water. The flanges 4 and 6, respectively, have a plurality of circumferentially-spaced, radially extending bores 18 and 20 therein, each threaded at its outer end; the bores 18 and 20 communicate with the opposite ends of the groove 16, and respectively function to conduct cooling water or other fluid from the ends of said helical groove after it has been admitted thereinto through the bores 17. Thus, by maintaining a flow of coolant through the space defined by the walls of the groove 16 and the vessel 2 the inner, exposed surface of the jacket 14 may be maintained at a temperature sufficiently low to prevent failure thereof.

Attached to the opposite ends of the vessel 2 by bolts 22 are a forward closure plate 24 and an aft closure plate 26, said plates respectively having a plurality of circumferentially-spaced bores 28 and 30 therein positioned in registry with the bores 8 and 10. The bores 28 and 30 are fitted with flanged insulator sleeves 32 and 34, respectively. The bolts 22 extend through said sleeves, through the bores 8 and 10, and are secured in position by nuts 36 threaded onto the opposite ends thereof; washers 38 and 40 are positioned between each nut 36 and the flange of its associated insulator sleeve 32 or 34. An annular seal 42 constructed of a suitable insulating material is disposed between the plate 24 and the forward end face of the vessel 2, and an identical annular seal 44 is clamped between the other end face of said vessel and the aft plate 26. The outer diameters of the seals 42 and 44 are such that said seals just engage the circle of bolts 22, whereby the seals are automatically centered (FIG. 5); the inner diameters of said two annular seals are just slightly greater than the inner diameter of the cylindrical cooling jacket 14. The insulator sleeves 32 and 34 and the annular seals 42 and 44 thus serve to electrically isolate the two closure plates and the vessel from each other.

The front closure plate 24 has a circular water jacket 46 secured thereto, the external diameter of said jacket being substantially less than the inner diameter of the cylindrical water jacket 14. The water jacket 46 includes an annular disk 48 having first and second reduced-in-diameter cylindrical rim portions 50 and 52 thereon, the rim portion 52 being smaller in diameter than the rim portion 50 and being disposed to extend toward the closure plate 24. An annular ring 53 comprising an annular radial portion 54 and a cylindrical rim 56 is received on the second cylindrical rim portion 52 of the disk 48 and is brazed thereto, whereby to define an annular flow channel 58 within the water jacket 46.

The disk 48 has a frusto-conical central opening 60 therein positioned to confront a bore 62 positioned centrally of closure plate 24, said bore 62 including a rear frusto-conical portion and a front cylindrical portion. A convergent nozzle 64, having a frusto-conical bore therethrough and an external configuration corresponding to that of the bore 62, is received within said bore, and has an annular flow groove 66 in the front face thereof. An inner plurality of circumferentially-spaced bores 68 extend through said nozzle parallel to and just under the frusto-conical bore therethrough, and an outer plurality of circumferentially-spaced bores 70 extend through the forward portion of said nozzle from the flow groove 66 to a circumferential flow groove 72 in the outer surface thereof. The flow groove 66 is closed by a welded-in-position annular plate 74.

The disk 48 has a frusto-conical flow channel 76 therein disposed about the bore 60, and said channel 76 is connected with the peripheral flow channel 58 by a plurality of circumferentially-spaced, radially directed bores 78. The circumferential groove 72 is positioned to confront the inner end of a plurality of elbow-shaped bores 80 in the closure plate 24, and the radial portion 54 of the annular ring secured to the disk 48 has a plurality of circumferentially-spaced bores 82 therein positioned to confront axially directed bores 84 in said plate 24. Thus,

cooling fluid may be admitted into the cooling jacket 46 through the bores 80, flow through the groove 72, bores 70, groove 66, bores 68, groove 76, bores 78, and out through the bores 84.

The aft closure plate 26 has a cooling jacket 86 secured thereto, said jacket being constructed similarly to and having a diameter identical to that of the jacket 46. The jacket 86 includes a circular disk 88 and an annular ring 90, said ring defining with the stepped periphery of said disk an annular flow channel 92. The disk 88 has a central bore 94 therethrough, and an annular groove 96 surrounds said bore and is positioned to confront a plurality of circumferentially-spaced, angled bores 98 in the closure plate 26. The flow channel 92 and the annular groove 96 are connected by a plurality of radially-extending, circumferentially-spaced bores 100 in the disk 88, and said flow channel 92 is in communication with a plurality of axially-extending, circumferentially-spaced bores 102 in the closure plate 26; thus, cooling fluid may enter the cooling jacket 86 through either the bores 102 or the bores 98, and may be exhausted therefrom through the other of said bores.

The front closure plate 24 has a stepped cylindrical bore 104 therethrough directly above the bore 62, and the disk 48 has a cylindrical bore 106 therethrough in alignment with and having the same diameter as the relatively large diameter portion of said bore 104. Disposed within the relatively large portion of the bore 104 is a first cylindrical block 108 of a suitable insulating material, such as Lucite. A second cylindrical block 110 constructed of a suitable insulating material, such as Bakelite, is disposed within the reduced diameter portion of said bore 104 and is secured to the first block 108 by a plurality of screws 112. The block 108 and the bore 104 have a pair of diametrically opposed, confronting keyways therein at the aft end thereof, and a key 114 is disposed within each pair of confronting keyways to prevent said block 108 from rotating relative to the plate 24.

The reason for utilizing Lucite for the block 108 is that this material will not form a conductive coating if it should burn in the presence of the very high arc temperatures, which coating could short out the electrodes. It has been found that nearly all other known machinable insulating materials will form such a coating in some instances.

Fitted into the opening 106 in the water jacket 46 is a flanged covering disk 116 constructed of a suitable refractory insulating material, such as boron nitride or fuzed silicon quartz. The covering disk 116 has a pair of identical parallel circular bores 118 extending therethrough (best seen in FIG. 4), the parallel longitudinal axes of said bores being spaced apart a distance substantially less than the combined radii thereof, whereby said bores communicate with each other throughout their length. The two interconnected insulation blocks 108 and 110 have a pair of identical, parallel bores 120 and 122, respectively, extending therethrough, said bores being smaller in diameter than and lying concentrically about the central axes of the bores 118. The rear end face of the insulation block 108 has a rectangular recess 124 therein (FIG. 4), the length and width of which is such that it extends beyond the bores 120 but lies within the maximum cross-sectional dimensions of the interconnected bores 118.

Extending through the aligned, parallel bores 118, 120 and 122 are a pair of hollow cylindrical electrode supports 126, each of said electrode supports having an enlarged collar 128 thereon of a size corresponding to the diameter of its associated bore 118; the collars 128 do not extend completely around their associated electrode supports, but rather terminate at a plane on each support drawn tangent to the confronting surfaces of said supports. Each collar 128 has a radially directed flange 130 on its aft end, and a rectangular boss 132 on its front

face of a size to be received snugly within the rectangular recess **124**; the rectangular bosses **132** function to restrain the electrode supports against rotation relative to the front closure plate **24**. One of the electrode supports **126** has a clamp-type electrical connector **134** secured therto, and a wedge **136** of wood or other suitable material is driven between said connector and the front face of the plate **24** for holding the supports in position.

The aft closure plate **26** has a stepped cylindrical opening **138** extending therethrough at a position just below the bore **94**; the openings **104** and **138** are positioned diametrically from each other, and the central axes of the two openings are spaced identical distances from the longitudinal central axis of the pressure vessel **2**. The water jacket **86** has a bore **140** therethrough corresponding to the bore **106**, and a covering disk **142** is positioned therein. The bore **138** has a pair of insulation blocks **144** and **146** therein interconnected by screws **148** and keyed by keys **150** to the plate **26**, said blocks being identical to the interconnected, keyed blocks **108** and **110**. The blocks **108** and **110** have a pair of aligned bores therein which confront a pair of bores in the disk **142**, and a pair of hollow electrode supports **152** identical to the supports **126** are mounted therein in a manner identical to that described for said supports **126**. The covering disks **116** and **142** both function merely to cover and protect the insulation blocks **108** and **144**, respectively. A clamp-type electrical connector **154** is connected to one of the protruding supports **152**, and a wedge **156** is driven between said connector and the plate **26**.

The ends **158** of the two supports **126** and the like ends of the two supports **152** which project within the pressure vessel **2** are bevelled along vertical planes at a 45 degree angle, as is indicated by broken lines in FIG. 4 for the supports **126**. Welded to the bevelled ends of the electrode supports **126** is a discontinuous, hollow, circular in cross-section electrode **160**, an identical electrode **162** being secured to the electrode supports **152**.

The configurations of the two electrodes are identical, and hence only that of the electrode **162** (FIG. 5) will be described in detail. The electrode **162** is bent from a cylindrical tube to generally define a square, and includes four substantially straight sections joined at their corners by rounded sections. The two ends of the tube confront each other medially of one of the sides of the square, and define a discontinuity **164** therebetween. The two ends of the tube are bevelled to mate with the bevelled ends of the two support tubes **152**, and are welded thereto so that the electrode lies in a plane disposed perpendicularly to the central axis of the pressure vessel **2**. The opposite ends of the tube forming the electrode **160** are welded to the supporting tubes **126** (FIG. 4), and define a discontinuity **166** therebetween.

The two identical electrodes **160** and **162** are disposed in confronting, closely spaced, parallel relationship, as is best shown in FIG. **3**. The surfaces of the electrode **160** disposed on either side of the discontinuity **166** and which confront the unbroken surface of the electrode **162** have weld metal **168** deposited thereon, shaped to define ramps inclined upwardly toward said discontinuity. Similar weld deposits **170** are disposed on the electrode **162**, and define similarly shaped ramps on either side of the discontinuities therein. As was described hereinabove, the ramps **168** and **170** respectively function to cause an arc structure between and travelling the opposed peripheries of the two electrodes to pass without hesitation over the discontinuities **164** and **166**.

Means must be provided in the invention for admitting gas into the chamber within which the opposed electrodes are contained. To satisfy this need, the closure plates **24** and **26** are respectively provided with annular manifold grooves **172** and **174**, said grooves being positioned to open into the annular space between the cylindrical water jacket **14** and the disk-shaped water jackets **46** and **86**, respectively. A plurality of circumferentially-spaced bores **176** and **178** in the plates **24** and **26**, respectively, communicate said annular manifold grooves with the exterior of the pressure vessel, and function to admit gas into said grooves and hence into the arc chamber. The use of annular manifold grooves for injecting gas into the chamber, together with their positions at the outer peripheral corners of said chamber, insure an undisturbed flow of gas thereinto, whereby smooth operation of the unit is facilitated.

It often is desirable to know the rate at which an arc struck between the opposed electrodes is travelling around the confronting surfaces thereof. A window **180** is thus provided in the aft closure plate **26** for viewing the arc, and is positioned medially of and radially just inside one of the vertical sides of the electrode **162** (FIGS. 5 and 6).

The construction of the window **180** is shown in detail in FIG. 6, and includes aligned bores **182** and **184** in the water jacket **86** and the closure plate **26**, respectively. An enlarged, threaded bore **186** is positioned in the plate **26** concentrically of the bores **182** and **184**, and has a hollow carrier sleeve **188** threaded thereinto. The sleeve **188** has a cylindrical recess in the front face thereof, within which is disposed a transparent window **190** constructed of quartz or a similar heat-resistant substance. In use, a photo-counter or similar device is positioned to confront the bore within the sleeve **188**, and records each passage of an arc past the window unit **180**, thus furnishing a value for the number of revolutions made per unit of time by said arc around the opposed electrode surfaces.

The forward plate **24** has the entrance duct **192** of a hypersonic windtunnel or other apparatus secured thereto concentrically of the convergent nozzle **64**, said duct having a flange **194** thereon. The flange **194** has a plurality of circumferentially-spaced bores therethrough, within each of which is fitted a flanged sleeve **196** of insulating material. An annular block of insulation material **198** is positioned between the flange **194** and the front face of the plate **24**, the latter having an annular groove **200** therein for receiving a like-shaped annular projection on said block **198**. The duct **192** is secured in position by a plurality of bolts **202** and washers **204**, the sleeves **196** and the block **198** functioning to electrically insulate the duct from the closure plate **24**.

To operate the plasma arc generator of the invention the cooling jackets **14**, **46** and **86** and the two electrodes are supplied with a flow of cooling water, and gas under pressure is made to flow into the arc chamber through the annular grooves **172** and **174**. One of the electrical connectors **134** and **154** is then made positive and the other negative, whereby the two electrodes **160** and **162** are oppositely charged; the discontinuous construction of the electrodes coupled with the connection of only one of the electrode supports of each pair to the energy source is made to insure that current will flow continuously through each electrode only in one direction, the current flow being oppositely directed in the two electrodes. An arc is then struck between the two electrodes, as by a previously installed shorting wire, the and the generator commences operation.

As has been previously described, the magnetic fields induced about the electrodes by the flow of current therethrough cause the arc to rotate about the opposed peripheries of the electrodes. When the arc reaches the gap the spacing between the electrodes is narrowed by the ramps, and the voltage demands temporarily lessen together with an accompanying momentary increase in the flow of current through the electrodes; the increase in current flow increases the strength of the magnetic fields, and hence momentarily accelerates the arc to where it readily bridges without hesitation the discontinuity by jumping thereacross through the surrounding ionized gas cloud. As the arc rotates between the electrodes, the gas admitted into the chamber through the grooves **172** and **174** passes therethrough, is transformed into

plasma, and then exits into the duct **192** through the nozzle **64**.

While arc plasma generators similar to that of the invention have been found to operate satisfactorily once they have been started, in the past certain difficulties have been encountered in the starting process. Specifically, it has been found that in the presence of relatively high chamber pressures and mass rates of gas flow the arc would be struck, and would then very often become extinguished. It has now been discovered that the cause for the extinguishing of the arc is the existence of a substantially unrecordable sharp pressure pulse on firing, which pulse creates an accompanying sharp voltage demand that normally cannot be met by the source. The present invention provides apparatus and a method of operation for overcoming this starting difficulty.

Referring now to FIGS. 1–3, a variable orifice valve assembly is indicated at **206**, and includes a cylindrical housing **208** having a flange **210** on its aft end and a cylindrical collar **212** on the forward end thereof. As is best shown in FIG. 3, the collar **212** is of a size to be snugly received within a centrally-disposed socket **214** in the aft closure plate **26**, said collar resting against radially-directed lip **216** at the forward end of said socket and being secured in position by a snap ring **218** received within an annular groove in the wall defining said socket.

The housing **208** has an annular groove **220** in the forward end face thereof, which is closed by a welded-in-position annular plate **222** received within a second, shallower annular groove in said end face. A plurality of axially directed, circumferentially-spaced bores **224** extend through said housing, and are in communication at their aft ends with conduits **226**. One half of the conduits **226** normally function as fluid inlets and the other half as fluid outlets, and thus cooling fluid may be made to flow through said housing.

The aft flange **210** has a peripheral, stepped groove **230** therein, which is closed by a welded-in-position, stepped annular band **232**. A plurality of circumferentially-spaced conduits **234** are secured within bores in the band **232**, and function to pass cooling water through the annular channel **236** within said flange. The conduits **226** and **234** are omitted from FIG. 1 for purposes of clarity.

Welded to the flange **210** and extending rearwardly therefrom are three equally-spaced, parallel support rods, **238**, each terminating in a threaded portion at its aft end. The free ends of the rods **238** extend through bores in a mounting plate **240**, said plate being clamped in position by nuts **242** threaded on said rods and disposed on both sides thereof. A supporting plate **244** is secured to the mounting plate **240** by bolts **246**, and extends downwardly to a suitable base for furnishing vertical support to the valve assembly **206**.

A three-arm spider **248** is supported on the rods **238**, each of said arms having a bore therethrough at its radially outer end through which one of said rods passes. The spider is secured in position by nuts **250** threaded on the support rods, and includes a central hub **252** having a bore therethrough for slidably receiving a valve stem **254**. The valve stem **254** is connected at its aft end to the actuator shaft **256** of a double-acting hydraulic cylinder assembly **258**, said assembly **258** being mounted on the plate **240** by stud bolts **260** and said shaft **256** extending through a bore (not shown) in said plate.

The valve stem **254** terminates at its froward end in a relatively large cylindrical head **262**, said head having a recess **264** therein and a peripheral groove **266** in its exterior surface at the forward end thereof. A cup-shaped, hollow valve cap **268** is received on the forward end of the head **262** and is secured thereto, as by welding. The cap **268** includes a cylindrical portion **270** and a frusto-conical nose portion **272** terminating in a rounded tip. The taper on the nose portion **272** corresponds to the taper of a frusto-conical valve seat **274** formed in the aft end face of the housing **208** about the bore **228**.

The valve head **262** has a pair of angled bores **276** extending through the rear end thereof, within which are secured a pair of angled tubes **278**; the tubes **278** lie immediately adjacent and extend parallel to each other within the valve head, and project forwardly nearly into contact with the inner surface of the frusto-conical cap portion **272**. The valve head **262** also has a pair of diametrically opposed, radially-directed bores near the aft end thereof, within which are secured conduits **280** (not shown in FIG. 1). Cooling water is injected into the valve head through the tubes **278**, is discharged against the frusto-conical nose surface on the cap **268**, and then flows out of said head through the conduits **280**; thus, the valve head is cooled and is protected against being melted by the high temperature gases existing within the arc chamber, particularly when these gases are flowing out through the orifice before the cap has shut tightly.

The valve head **262** may be moved axially by the double-acting hydraulic cylinder **258** from its fully open position, shown in FIG. 1, to the fully closed position shown in FIG. 2. As the frusto-conical cap **272** moves toward and away from the frusto-conical seat **274** a variable area orifice is provided, which orifice places the interior of the pressure vessel **2** in communication with the atmosphere through opening **94** and bore **228**. By properly operating the double-acting hydraulic cylinder **258** immediately after the arc is struck, premature extinguishing, or blowout, of the arc during starting may be eliminated.

In operation, the hydraulic cylinder **258** is first activated to move the valve head **262** away from the valve seat **274** until the area of the variable orifice defined therebetween is at a maximum, thus placing the arc chamber in communication with the large ballast volume which is the atmosphere. Gas is then admitted into the arc chamber through the annular grooves **172** and **174** at a relatively high rate of mass flow, say one lb. per second. The arc is then struck between the electrodes, and immediately thereafter the hydraulic cylinder is actuated to close the variable area starting orifice; the valve head is moved at a uniform rate such that the orifice is completely closed after a period of a few seconds, two seconds being a typical closure period. If required, the mass flow rate of the gas may then be increased to any other desired operating value, thereby establishing the desired operating pressure within the arc chamber.

The arc plasma generator starting method just described eliminates premature extinguishing of the arc immediately after it is struck by opening the arc chamber to the large ballast volume of the atmosphere during the period when the arc is struck and is becoming established; the pressure surge at striking is thus damped, and the accompanying surge in voltage requirements is kept down to an easily satisfied level. The maintenance of gas flow into the arc chamber during the starting process insures proper operation of the generator, and makes possible the rapid achieving of operational arc chamber pressures.

It is thus seen that an arc plasma generator construction and method of operation have been provided which satisfy all the objects set forth for the invention, and which provide a reliable plasma generator that may be operated continuously for relatively long periods of time.

Obviously, many modifications and variations of the present invention are possible in the light of the above teachings. It should therefore be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. An arc plasma generator, comprising:

a pressure vessel defining a chamber therein,

a pair of identical, ring-like electrodes supported within said chamber in confronting relationship, each electrode having a discontinuity therein and the dis-

continuity in one electrode being displaced from the discontinuity in the other electrode,

means for supplying electric current to said electrodes, and

ramp means on each electrode on both sides of the discontinuity therein and disposed to project toward the confronting surface of the other electrode so as to decrease the arcing distance between said electrodes.

2. An arc plasma generator as recited in claim 1, including additionally

means for admitting gas into said pressure vessel, and

means for cooling said electrodes and the inner surfaces of said vessel.

3. An arc plasma generator as recited in claim 1, including additionally

a variable orifice valve means mounted on said pressure vessel for communicating said chamber with the atmosphere, and

means for opening and closing said variable orifice valve means at a uniform rate.

4. An arc plasma generator, comprising

a pressure vessel defining a chamber therein,

a pair of identical, ring-like electrodes supported within said chamber in confronting relationship and each comprising a plurality of straight sections joined at their ends by curved sections, one of said straight sections of each electrode having a discontinuity therein, the discontinuity in one electrode being displaced from the discontinuity in the other electrode, and

means for supplying electric current to said electrodes.

5. An arc plasma generator as recited in claim 4, including additionally

means for admitting gas into said pressure vessel, and

means for cooling said electrodes and the inner surfaces of said vessel.

6. An arc plasma generator as recited in claim 4, including additionally

a variable orifice valve means mounted on said pressure vessel for communicating said chamber with the atmosphere, and

means for opening and closing said variable orifice valve means at a uniform rate.

7. An arc plasma generator, comprising:

a pressure vessel defining a chamber therein,

a pair of identical, ring-like electrodes supported within said chamber in confronting relationship and each comprising a plurality of straight sections joined at their ends by curved sections, one of said straight sections of each electrode having a discontinuity therein, the discontinuity in one electrode being displaced from the discontinuity in the other electrode,

means for supplying electric current to said electrodes, and

ramp means on each electrode on both sides of the discontinuity therein, said ramp means sloping upwardly toward said discontinuity and being disposed to project toward the confronting surface of the other electrode.

8. An arc plasma generator as recited in claim 7, wherein additionally

said pressure vessel has a pair of peripheral annular grooves therein positioned at the opposite ends of and opening into said chamber, and port means for admitting gas into said grooves and thus into said chamber.

9. An arc plasma generator as recited in claim 7, wherein additionally

said electrodes are hollow and are connected with a source of fluid coolant, and including additionally

cooling jacket means on the inner surfaces of said pressure vessel, said cooling jacket means containing channels for conducting a fluid coolant therethrough.

10. An arc plasma generator as recited in claim 7, including additionally

a variable orifice valve means mounted on said pressure vessel for communicating said chamber with the atmosphere, and

means for opening and closing said variable orifice valve means at a uniform rate.

11. An arc plasma generator as recited in claim 7, wherein additionally

the discontinuity in one of said electrodes is displaced 180 degrees from the discontinuity in the other electrode.

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