

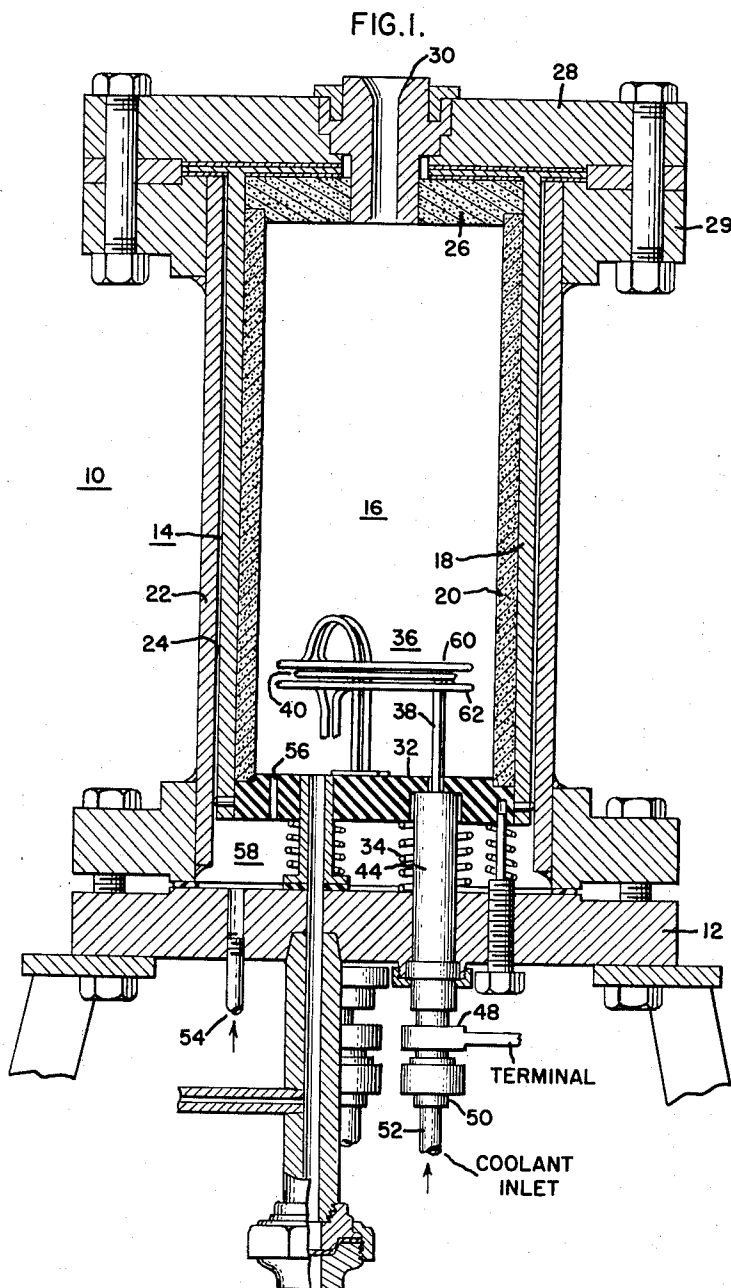
Dec. 13, 1960

H. N. SCHNEIDER ET AL
ARC PLASMA GENERATOR

2,964,679

Filed June 26, 1959

3 Sheets-Sheet 1



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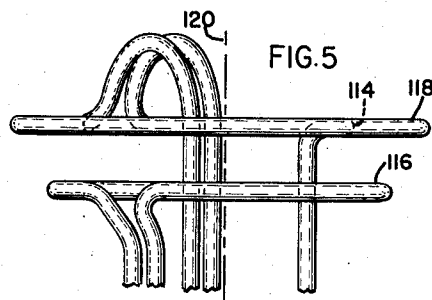
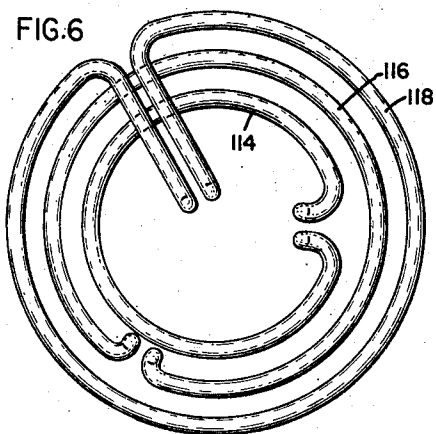
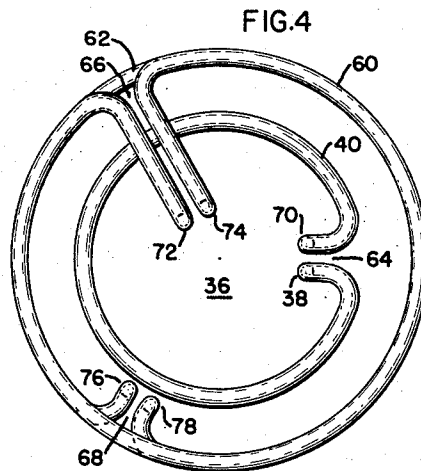
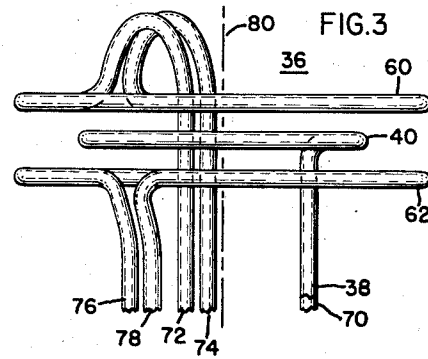
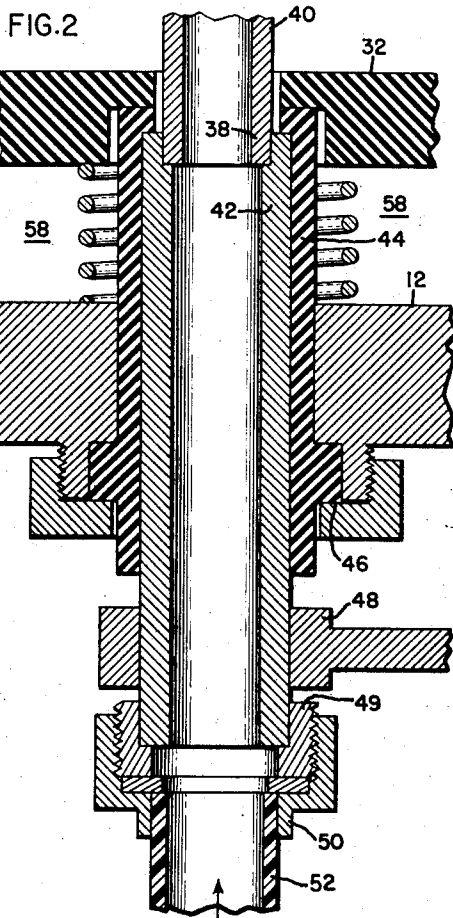
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3 Sheets-Sheet 2



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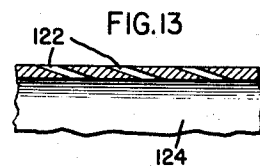
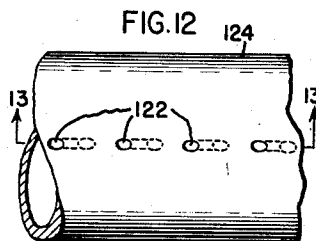
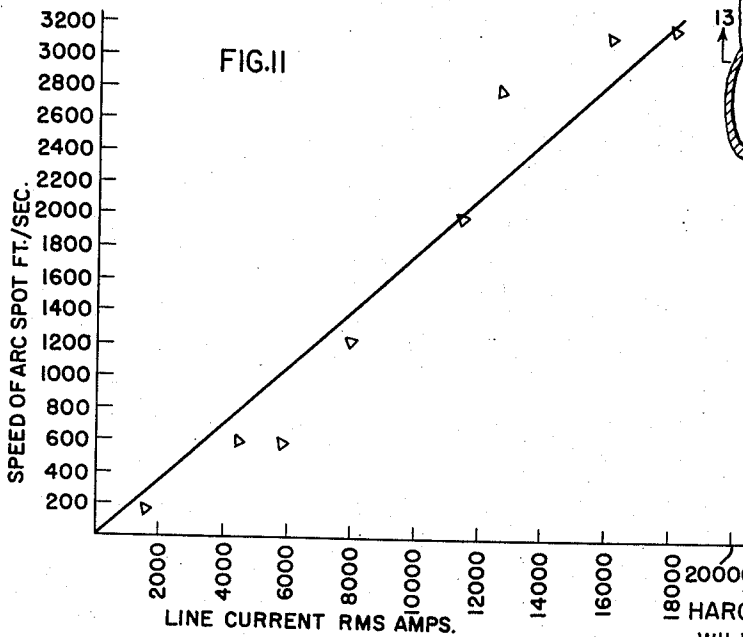
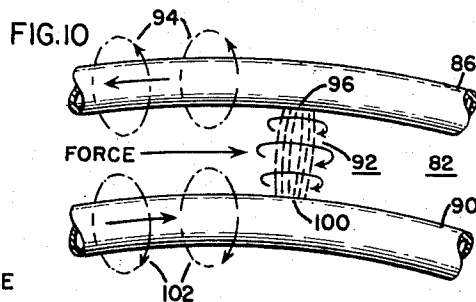
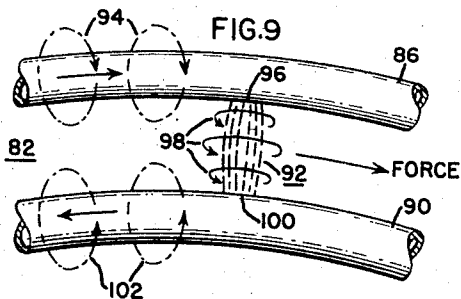
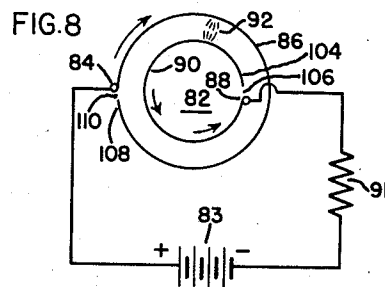
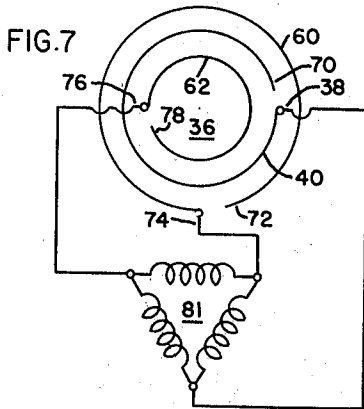
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ARC PLASMA GENERATOR

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3 Sheets-Sheet 3



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2,964,679

ARC PLASMA GENERATOR

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20 Claims. (Cl. 315—111)

This invention generally relates to improvements in plasma generators and more particularly to a plasma generator for producing a large volume of high temperature plasma from sustained high power electric arcs.

For purposes of the present invention, the term plasma, or arc plasma, means a partially ionized mass derived from air, or special gases such as oxygen, nitrogen, helium, etc., or from vaporized solids such as copper, iron, graphite, etc., or a mixture thereof, which is in such an extremely heated and excited condition that it does not obey the laws for low temperature ideal gases, $PV=RT$. It is known that the measurable temperature at the surface of the sun is about 10,000° F. or 5,800° Kelvin. The temperature of the plasma produced by an arc plasma generator, according to the present invention, is in this order of magnitude and is, therefore, capable of vaporizing any known material. For this reason, the plasma produced by such a generator may be advantageously employed for testing materials, particularly in the simulation of the conditions encountered in high-speed aerodynamics. Plasma generators may also be used for cutting, welding, metal spraying, and chemical processing. In the chemical processing area, arc plasma generators open the possibility for the production of new alloys and compositions and the processing of less commonly used materials.

Prior art arc plasma generators have produced a limited volume of plasma by continuously discharging an electric arc in a plenum chamber filled with a suitable working fluid; i.e., the material from which the plasma is to be produced. Where the electrical power inputs to such generators are in the lower kilowatt ranges, solid or liquid cooled electrodes have been employed with reasonably good results. However, such arc plasma generators cannot be scaled up to heat larger masses of working fluids by arcs in the megawatt (10^6 watts) power ranges with satisfactory results. One of the reasons why scaled up versions cannot be satisfactorily used with greater power inputs is that the rate of electrode erosion increases rapidly as the magnitude of the electric arc current increases. The rapid rate of erosion of the electrodes is indicated by the fact that in some megawatt plasma generators of conventional design, from 8% to 30% by weight of the plasma is derived from the electrodes. The rapid erosion of the electrodes, unless they are continuously replaced, reduces the operating time of such generators to a period of the order of one to two seconds, after which it is necessary to shut down the generator and replace the electrodes.

The high rate of erosion of the electrodes is due to the power input, the heat flux, transferred to the electrode at the arc spot. The magnitude of this power is of the order of 1.67×10^8 B.t.u. per hour per square foot for an arc current of 3500 amperes. The magnitude of the power transferred to an electrode at the arc spot, the place where the electric arc originates or terminates at an electrode, is so much greater than the power that can be dissipated by radiation, conduction, and convection, that the

2

only way the excess power can be dissipated is through the evaporation of the electrodes. It is estimated that only 10% of the heat flux transferred to an electrode at the arc spot can be dissipated by radiation from a tungsten electrode, approximately 1% to 2% can be dissipated by radiation from a molybdenum electrode, and only .1% can be dissipated by the same mechanism from a copper electrode. It requires approximately 12 microseconds for an arc having a power input of 1.67×10^8 B.t.u. per hour per square foot to raise the surface temperature of a water cooled copper electrode to its melting point. No known materials can have such extremely large amounts of power in the form of heat applied to them for more than a very short period of time without being destroyed.

One prior art solution to the problem of obtaining a longer period of operation for high power arc plasma generators has been to provide a mechanism to replace the electrodes as they are consumed. However, this solution does not reduce the amount of contamination of the plasma by material derived from the electrodes.

The present invention provides a solution to the problems of obtaining longer operating periods and of simultaneously minimizing contamination of the plasma by providing a unique structural arrangement of the electrodes and manner of connecting them to the source of electrical energy which causes the arcs which heat the working fluid to move rapidly over the surface of the electrodes so that the power applied to the electrodes is distributed over a substantial area of the surface of the electrodes. As a result, the power input from an electric arc even of megawatt power levels, is not applied to a given area of the electrode surface for a sufficient period of time to raise the surface temperature of the electrode to its melting point. When the electrodes are cooled internally, the temperature of the electrodes reaches an equilibrium temperature (after a short period of operation) which is below the melting point of the materials most suitable for use as an electrode, such as copper, molybdenum, etc. As a result, the rate of erosion of the electrodes is quite small. However, after an arc plasma generator embodying the present invention has been operated for a substantial period, it is observed that the surfaces of the electrodes have an etched appearance. It appears that there is a slight loss of material from the surface of the electrodes at the arc track, the area of an electrode over which arc spots pass, but there is no evidence of melting, as such, of the electrodes. The mechanism, or cause, of the etch appearance is not fully understood at this time.

It is accordingly an object of this invention to provide an extremely high current arc plasma generator capable of operation for a sustained period of time.

Another object of this invention is to provide such an arc plasma generator which is capable of producing a large volume of high temperature plasma over a sustained period of time.

It is another object to provide a high power arc plasma generator which has a substantially longer period of operation between shutdowns for repair and replacement of the electrodes.

It is another object of this invention to provide an arc plasma generator which will operate satisfactorily when connected to either an A.C. or a D.C. source of electrical power.

It is still another object of this invention to provide an arc plasma generator having a low rate of electrode erosion.

It is still another object of this invention to provide an arc plasma generator which produces large volumes of high temperature plasma in which the percentage of contamination by electrode materials is minimized.

Other objects and many of the intended advantages

will be more readily comprehended by those skilled in the art after a consideration of the following detailed description of the invention and the drawing wherein:

Figure 1 is a cross sectional view of one embodiment of the present invention;

Figure 2 is an enlarged sectional view illustrating the manner of mounting an electrode in the device of Figure 1;

Figure 3 is an enlarged elevation of the electrode arrangements illustrated in Figure 1;

Figure 4 is a plan view of the electrode arrangement illustrated in Figure 3;

Figure 5 is an elevation of an alternative electrode arrangement;

Figure 6 is a plan view of the electrode arrangement of Figure 5;

Figure 7 is a schematic wiring diagram showing one manner of connecting three electrodes to a three phase source of A.C. electrical energy;

Figure 8 is a schematic wiring diagram illustrating a manner of connecting two electrodes to a D.C. source of electrical energy;

Figures 9 and 10 are schematic views illustrating the relation between current flow through a pair of electrodes and the direction of movement of the arc;

Figure 11 is a chart illustrating relationship between current and speed of an arc spot over an electrode;

Figure 12 illustrates a modified form of electrode structure;

Figure 13 is a section taken on line 13—13 of Figure 12.

In Figure 1 there is illustrated a plasma generator 10 which is comprised of a base portion 12 and an inner cylindrical housing 14. Within cylindrical housing 14 there is defined a plenum chamber 16 within which the plasma is produced. Housing 14 is made up of a metal cylinder 18 of steel, for example, which is lined with high temperature resistant, or refractory, material 20, such as graphite, ceramic fire brick, etc. Inner metallic cylinder 18 is in turn located within an outer cylinder 22 which is made from a strong material such as steel and of sufficient thickness to safely contain the maximum pressures encountered during operation of plasma generator 10. A gap 24 is formed between the outer wall of cylinder 18 and the inner wall of cylinder 22 to reduce the amount of heat transferred from inner cylinder 18 to outer cylinder 22. Gap 24 may be occupied by the working fluid, which may be either a gas or a liquid, such as compressed air, water, liquid oxygen, liquid nitrogen, etc., to help maintain the temperature of the outer cylinder 22 sufficiently low so that its strength will not be adversely affected. The upper end of plenum chamber 16 is closed by a thick block of refractory material 26 which is held in place by a heavy metallic plate 28 of steel, for example, which is illustrated as being bolted to outer cylinder 22. Nozzle 30 which is secured to plate 28 permits the plasma produced within plenum chamber 16 to escape from the chamber. The lower end, or bottom of plenum chamber 16 is closed by bottom plate 32 which is preferably made of a suitable electrical insulating material such as a sheet of pressed asbestos having an inorganic binder, an example of which is marketed under the trade name, "Transite." Base 12 is illustrated as being secured to outer cylinder 22 by a plurality of bolts. Bottom plate 32 is resiliently pressed against the bottom of liner 20 by a plurality of springs 34. Electrode structure 36 of generator 10 is secured to base 12, but extends through bottom plate 32 into plenum chamber 16.

In Figure 2, the means for mounting extension 38 of electrode 40 of electrode structure 36 is illustrated. Extension 38 of hollow electrode 40 is preferably brazed to hollow cylindrical connector 42 to form a fluid tight connection. In a preferred embodiment, electrode 40, extension 38, and connector 42 are made of copper. Connector 42 is provided with a protective insulating cover

44 made from a suitable plastic laminate material, such as filled phenol formaldehyde, an example of which is marketed under the trade name, "Textolite," which has a press fit with connector 42. A shoulder 46 on cover 44 provides the means for firmly securing connector 42 to base 12 and thus to firmly position electrode 40. Clamp 48, which may also be brazed on connector 42, provides the means for making an electrical circuit between electrode 40 and the source of electrical power, which is not illustrated, by suitable electrical conductors which are also not illustrated. To the lower end of connector 42, there is brazed a threaded adaptor 49 so that the nozzle 50 of hose 52 may be secured to connector 42. Hose 52 which is made of a suitable electrical nonconductive material such as neoprene, rubber, etc., is either connected to a pressurized source of the coolant, water in a preferred example, or is used to conduct the coolant from electrode 40. Hose 52 is long enough so that the electrical impedance of a circuit through the coolant, water, is much greater than the impedance between electrodes when generator 10 is in operation.

In Figure 1, the working fluid, compressed air in a preferred example, is supplied to plenum chamber 16 through one or more openings 54 in base 12 and through openings 56 in bottom plate 32 into plenum chamber 16. The openings 56 may be formed at an angle so that the working fluid will be given an initial circular component of motion as it enters plenum chamber 16. The space 58 between the base 12 and bottom plate 32 into which the working fluid is introduced is in communication with the gap 24 between cylinders 18 and 22. As a result, only a very slight pressure differential will exist across metal cylinder 18 and bottom plate 32, and the pressure produced in plenum chamber 16 when the generator 10 is in operation will be acting against base 12 and the outer wall member 22, rather than against inner housing 14 and bottom plate 32. The working fluid flowing through bottom plate 32 prevents the high temperature occurring in plenum chamber 16 from destroying plate 32.

A perusal of Figures 3 and 4 shows that each of the electrodes 40, 60, and 62 is almost a closed loop, with each electrode having a small segment 64, 66, 68, omitted. The ends, terminals, or extensions, 38, 70; 72, 74; 76, 78; of electrodes 40, 60, 62, provide the physical means for mounting the electrodes, for connecting the electrodes to a source of electric power, and for circulating a coolant through them.

It can be seen from Figure 3 that the planes in which electrodes 40, 60, 62, lie are substantially parallel to one another, and that the centers of the substantially circular electrodes lie on line 80 which is substantially normal to the planes determined by the electrodes. From Figure 3, it can also be seen that the intersection of the centers of electrodes 40, 60, 62, and a plane through line 80 substantially determine an equiangular, or equilateral, triangle. The extensions of electrodes 40, 60, 62, and the electrodes themselves are so designed and located with respect to each other and the walls of plenum chamber 16 that arcs will primarily occur between electrodes 40, 60, 62. Since the extension of each electrode, such as extensions 38, 70, of electrode 40, are always at almost the same electrical potential, the width of the gap between them may be quite small.

Figure 7 is a schematic diagram illustrating how the three electrodes 40, 60, and 62 are connected to a source 81 of three phase A.C. current. Figure 8 is a schematic diagram of a two electrode structure 82 which is connected to a source of direct current 83, to facilitate explaining the theory of operation of the invention, and to illustrate that the electrode structure constituting the invention can be used with sources of electrical energy other than three phase A.C. sources, such other sources being D.C., pulsating D.C., or single phase A.C. After an explanation of the forces which act to rapidly advance an arc around the electrodes has been made with respect

to the two electrode structure 82 of Figure 8, it will be relatively simple to extend this explanation to the three electrode structure 36 illustrated in Figure 7.

In Figure 8, the positive terminal of a source 83, which is illustrated as being a battery, is connected to terminal 84 of electrode 86, and the negative terminal of source 83 is connected to terminal 88 of electrode 90 through ballast resistor 91. If an arc 92 exists between electrodes 86 and 90, then conventional current will flow as indicated by the arrows from terminal 84 of electrode 86 to that portion of electrode 86 where arc 92 originates, through arc 92 to electrode 90, and through electrode 90 to its terminal 88 which is connected to the negative terminal of source 83. It should be noted that only terminals 84 and 88 of electrodes 86 and 90 are connected to the source of current 83.

Figure 9 is a greatly enlarged fragmentary view of the electrode structure 82 of Figure 8 in which the magnetic lines of force 94 associated with the current flow in electrode 86 from terminal 84 to the arc spot 96 are indicated. Also, the magnetic lines of force 98 due to the current flow constituting arc 92 and the magnetic lines of force 102 due to the current flow returning through electrode 90 to terminal 88 are illustrated. It should be noted that the magnetic lines of force 94, 102, are in the same direction between electrodes 86 and 90 on that side of arc 92 in which current is flowing through electrodes 86, 90, and thus increase the intensity of the magnetic field between them. The magnetic lines of force 98 due to arc 92 also increase the intensity of the magnetic field between electrodes 86, 90, on that side of arc 92 in which current is flowing through electrodes 86 and 90. No current flows on the other side of arc 92 in electrodes 86, 90, so that the magnetic field between them is only that contributed by the lines of magnetic force associated with arc 92. The interactions of these magnetic fields with the arc current produces a net force acting on arc 92 which tends to drive arc 92 clockwise, or from left to right in Figure 9.

In Figure 10, the direction of current flow through electrode 90, arc 92, and electrode 86, and the magnetic lines of force associated with it, is illustrated, assuming that terminal 84 of electrode 86 was connected to the negative terminal of the source of potential 83, and that terminal 88 of electrode 90 was connected to the positive terminal. Again, it can be seen that the magnetic fields due to the current flowing in that portion of electrodes 86 and 90 between arc 92 and terminals 84, and 88 will exert a net force on the magnetic field associated with arc 92 tending to drive arc 92 clockwise, or from left to right. Thus, it can be seen that it is not the instantaneous direction of flow of current through the electrodes that determines the direction of motion of arc 92.

If the source 83 of electrical energy were connected to terminals 104, 108, of electrodes 90, 86, in Figure 8, instead of terminals 88, 84, then an arc between electrodes 86, 90, would be driven or rotated in a counterclockwise direction due to the interactions of the magnetic fields associated with current flow in electrodes 86, 90, and the arc, as described above. This would be true irrespective of how terminals 104, 108, were connected to source 83. Thus, in order for the electromagnetic forces to cause the arc between two electrodes to move in a given direction, i.e., clockwise, or counterclockwise, it is necessary that current flowing to and from the arc, flow through those parts of the electrodes that are, or lie on, the same side of the arc. Variations in the direction and magnitude of current flow will not vary the direction of motion of the arc.

When electrode structure 82 is connected to source 83, as illustrated in Figure 8, and when arc 92 has advanced clockwise to the end 104 of electrode 90, which is open-circuited, it readily jumps gap 106. The length of gap 106 is made as small as is reasonably possible, it only

being necessary that it be of sufficient length that current will not flow from both ends of electrode 90 toward the arc spot. The length of the gaps between the ends of electrodes is not, however, a critical factor in the operation of generator 10. The reason arc 92 jumps gap 106 so readily is that the ionized gases associated with the arc readily permit arc 92 to reform with arc spot 100 initially at the end 88 of electrode which is connected to power source 83. There is substantially no interruption of the arc current as arc 92 jumps gap 106. The same thing happens when the arc 92 has advanced to the point where it reaches the open-circuited end, or terminal, 108 of electrode 86. It is necessary that there be gaps in electrodes, such as gaps 106, 110, in electrodes 90, 86, in order that the electromagnetic effects associated with current flow in the electrodes will advance the arcs along the electrodes. To minimize any tendency toward intermittent operation, the electrodes are generally arranged so that the gaps in them are substantially uniformly distributed as seen in Figure 8 although again this is not a critical limitation.

In Figure 7, electrode structure 36 is illustrated schematically as being connected to a source of three phase A.C. power 81. As was pointed out above, it is not the instant polarity, or direction of current flow which determines the directions of motion of an arc between electrodes, but rather the arc will move along the electrodes in a direction away from the parts of electrodes through which current is flowing, or from the terminals which are connected to the source of power. In Figure 7, terminals, or extensions 38, 74, 76, of electrodes 40, 60, 62, are illustrated as being connected to source 81, and terminals 70, 72, 78, of electrodes 40, 60, 62, are open-circuited. Thus, any arcs that occur between electrodes 40, 60, 62, will be advanced in a clockwise direction. If terminals 70, 72, 78, of electrodes 40, 60, 62, were connected to source 81 and terminals 38, 74, 76, were open-circuited, then arcs between electrodes 40, 60, 62, would move in a counterclockwise direction.

In a three electrode structure connected to a three phase source of A.C., there is always at least one arc between the electrodes. Thus, there is always a copious supply of ions to aid the arcs in reforming, or jumping across the open segment in each loop electrode, or restarting when the current through one electrode has just passed through its zero value. The direction of rotation of the working fluid within the plenum chamber and the direction of rotation of the arcs are generally made the same.

Figure 11 is a chart showing the relationship between the speed in feet per second of the arc spot as a function of line current R.M.S. The data for Figure 11 was obtained using solid copper electrodes having a configuration substantially similar to that of electrode structure illustrated in Figures 3 and 4. For relatively low current values of around 2000 amperes, the arc was advanced at a speed of approximately 200 feet per second. For currents of 18,000 amperes, the arc spot will be advanced at a velocity of approximately 3200 feet per second. The relationship between line current and velocity of the arc spot is approximately linear, assuming that the distance between electrodes is constant and substantially uniform.

While uniform spacing between electrodes results in the speed of the arc spot being a substantially linear function of the magnitude of the line current, uniform spacing between electrodes is not a critical factor which is necessary to satisfy to obtain successful operation of an arc plasma generator. Uniform spacing between electrodes, however, has the advantage of facilitating design and construction of arc plasma generators and of optimizing their performance. The commonest form for electrodes to assume to provide as small a gap as possible, maximum physical strength, and to facilitate obtaining uniform spacing, is the circle. However, there are other forms that the electrodes can assume and still provide

the desired characteristics, such as the elliptical and numerous arbitrary forms.

It should be noted that when the velocity of the arc spot is 3200 feet per second and if the electrodes have a circumference of three feet for example, and if 60 cycle A.C. is connected to the electrodes, then an arc will complete approximately nine revolutions per half cycle. Thus, during some revolutions of the arc, the direction a magnitude of current flows can be considered to be substantially uniform.

Three electrodes are needed when an arc plasma generator is energized by a three phase source of A.C. If an arc plasma generator is to be energized by a six phase source of A.C., for example, then six electrodes would be required. Thus, when an arc plasma generator is to be supplied with multiphase A.C., there is provided an electrode for each phase.

In Figures 5 and 6, there is illustrated an alternative arrangement of three electrodes 114, 116, and 118. In this particular arrangement, substantially circular electrodes 114 and 118 are in the same plane and have a common center. Substantially circular electrode 116 is located in a plane parallel to the planes determined by electrodes 114 and 118 but below them. The center of electrode 116 lies on line 120, which is normal to the plane of electrodes 114, 118, and through the center of electrodes 114, 118. As a result, the minimum distances between electrodes 114, 116, 118, are substantially equal. It is obvious that there are other arrangements which permit three electrodes to be mounted within plasma generator 10 so that they are substantially equidistant from one another. However, the terminals or extensions of the electrodes should be located and arranged so that arcs will not form between the extensions of the electrodes, between the extensions of the electrodes and any of the other electrodes, and between the extensions and the side walls of the plenum chamber of the generator.

In Figure 12, there is illustrated a modification of electrode construction in which plurality of openings 122 are formed in the walls of the electrodes such as electrode 124 for example. In this manner, the coolant for electrode 124 is introduced into the plenum chamber and the fluid flowing through electrode 124 can provide a portion of the working fluid. In this modification, the coolant and working fluid are generally the same. The openings 124 are at such an angle to the surface of electrode 124 to facilitate rotation of the working fluid within the plenum chamber. The direction of rotation of the fluid is the same direction of rotation of the arcs between the electrodes. This particular electrode modification has the advantage of being more efficient, since the heat absorbed by the coolant preheats the working fluid. Further, the additional rotation imparted to the working fluid due to the orientation of openings 122 helps to keep the working fluid between the arc and the side walls of the plenum chamber and to reduce the heat flux applied to the side walls of the plenum chamber.

In one embodiment of the invention, the electrodes were arranged as illustrated in Figures 3 and 4. The electrodes were made of $\frac{3}{4}$ inch copper tubing having walls 0.093 inch thick, the outside diameter of electrodes 60, 62, was approximately 10 inches, and the diameter of the plenum chamber was 11 inches. The voltage at the source of the three phase A.C. electrical power was 1200 v. R.M.S., and the magnitude of the current supplied was from 3000 to 8000 amperes R.M.S. The voltage across the arcs ranged from 200 to 400 volts R.M.S. when the generator was running. The minimum power supplied under these conditions was 3500 kw. The energy of the plasma produced was approximately 500 kw. The amount of contamination of the working fluid, the ambient atmosphere, by material derived from the electrodes, was approximately 0.3%. The materials, dimensions, voltages and currents listed above are included by

way of example only, as being suitable for the device illustrated. It is to be understood that arc plasma generators may be constructed in accordance with the invention which vary from the particular specifications listed above.

Generally, the peak voltage applied between electrodes is insufficient in the absence of ionized gases in the plenum chamber to establish arcs between the electrodes. When it is desired to start up a plasma generator, a single strand of fine silver wire, .007 inch in diameter for example, is wrapped around the three electrodes so that it touches all three. When the electrodes are connected to the source of power, the wire is vaporized and produces sufficient ions to start the generator running.

The data for the chart of Figure 11 was obtained using solid copper electrodes having a configuration substantially such as is illustrated in Figures 3 and 4. With solid electrodes, an equilibrium temperature below the melting point of copper for example is not reached. After relatively short periods of operation, the solid electrodes melt. With cooled hollow electrodes, an equilibrium temperature below the melting point of copper is reached and maintained. As a consequence, the operating period of a plasma generator is now of the order of two minutes. The length of the operating period is, of course, a function of the power level at which the generator is operated.

From the foregoing, it is clear that this invention provides an arc plasma generator which has means for rapidly advancing one or more large amperage arcs between two or more electrodes. The rate of advance, or the speed, of the arc is such that the arc spot does not dwell at any one point of the electrode structure for a sufficient period of time to raise the temperature at the arc spots above the melting point of the material. Further, by the use of suitable coolants, the average temperature of the electrodes may be maintained below the melting point of such suitable materials as copper, tungsten, etc. The electrodes have comparatively a substantial operating life, and the contamination of the plasma by materials from the electrodes is practically eliminated. Further, because this electrode structure adapts itself equally well to either D.C. or A.C. power sources, a plasma generator having electrode structure as taught and claimed herein has the advantage that it is readily adaptable to the power source available. Since generally the tremendous amounts of power required by large arc plasma generators are more readily available from A.C. sources, there is no need to provide apparatus capable of producing large amounts of D.C. power, which would be the case where an arc plasma generator requires D.C. sources of energy. Further, this particular invention has made it possible to make very high energy arc plasma generators which are capable of using normal atmosphere as the working fluid.

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

What is claimed is:

1. In an electrical arc device, a pair of loop electrodes, each of said electrodes having a pair of closely spaced terminals, means for mounting said electrodes so that they are spaced a substantially uniform distance from one another, and means for connecting one terminal of each electrode to a source of electrical energy, the other terminal of each electrode being open-circuited, the terminals of the electrodes connected to the source of energy being chosen so that the intensity of the magnetic field due to the current of an arc between the electrodes adds to the intensity of the magnetic fields in the space between the electrodes due to current flowing in the electrodes; whereby arcs between the electrodes are caused to move

away from the terminals connected to the source of energy at a speed which is a function of the magnitude of the arc current.

2. In an arc plasma generator, "n" loop electrodes, each of said electrodes having a pair of closely spaced terminals, means for mounting said electrodes so that they are spaced from one another approximately uniform distances, and means for connecting one terminal of each electrode to one phase of a source of electrical power having "n" phases, where "n" is an integer equal to or greater than two, the other terminal of each electrode being open-circuited, the terminals of the electrodes connected to the source of energy being chosen so that arcs between electrodes are caused to move along the electrodes away from the terminals connected to the source of energy at a speed which is a function of the magnitude of the arc current.

3. In an arc plasma generator, a plurality of substantially circular electrodes, each electrode having a small omitted segment, each of said electrodes having a pair of terminals at the ends of the electrodes, means for mounting said electrodes so that they are substantially uniformly spaced from each other, and means for connecting one terminal of each electrode to a source of electrical energy, the other terminal of each electrode being open-circuited, the terminals of electrodes connected to the source of energy being chosen so that the electromagnetic forces established by an arc between two electrodes causes the arc to move along the electrodes in a direction away from the terminals connected to the source of energy.

4. In an arc plasma generator, three loop electrodes, each of said electrodes having a pair of closely spaced terminals at the ends of said electrodes, means for mounting said electrodes so that they are substantially equidistant from each other, and means for connecting one terminal of each electrode to a source of electrical energy, the other terminal of each electrode being open-circuited, the terminals of electrodes connected to the source of energy being chosen so that the electromagnetic forces resulting from arcs between said electrodes cause the arcs to move along the electrodes in a direction away from the terminals of the electrodes that are connected to the source of electrical energy.

5. In an arc plasma generator, a pair of electrodes, each of said electrodes being substantially circular with a small segment of the electrode omitted, means for mounting said electrodes so that they are substantially equidistant from each other, and means for connecting each electrode to a source of electrical energy so that the electromagnetic forces associated with an arc between the electrodes and the current flow to and from the arc in said electrodes causes the arc to move in a given direction around the electrodes at a speed which is a function of the magnitude of the arc current.

6. In an arc plasma generator, three electrodes, each of said electrodes being substantially circular with a small segment omitted, means for mounting said electrodes so that they are substantially equidistant from each other, and means for connecting each electrode to a source of three phase electrical energy so that the electromagnetic forces due to arcs between electrodes and the current flow in said electrodes due to said arcs, causes the arcs to rotate in the same direction.

7. In an arc plasma generator, a pair of electrodes, each of said electrodes being in the form of an open loop with the ends of each of the loops being closely adjacent to each other, means for mounting said electrodes so that they are substantially equidistant from each other, and means for connecting one end of each electrode to a direct current source of electrical power, the end of each electrode connected to the source of power being selected so that the portions of the electrodes through which current flows are on the same side of the arc.

8. In an arc plasma generator, three electrodes, each of said electrodes being in the form of an open loop with the ends of each of the loops being closely adjacent to each other, means for mounting said electrodes so that they are substantially equidistant from each other, means for connecting one end of each electrode to a source of three phase alternating current electrical energy, the end of each electrode connected to the source being selected so that the portions of the electrodes through which current flows due to arcs between electrodes are on the same side of the arcs; whereby, the arc moves in the same direction.

9. In an arc plasma generator, a pair of hollow tubular electrodes, each of said electrodes being in the form of a substantially circular open loop with extensions at the ends of each electrode, the extensions of each electrode being closely spaced from one another, means in cooperation with said extensions for mounting said electrodes so that the loop portions of the electrodes are substantially equidistant from one another, means for connecting one extension of each electrode to a source of electrical energy, the other extension being substantially open circuited, the extension of each electrode connected to the source of electrical energy being chosen so that the portions of the electrodes through which current flows to or away from an arc between the loop portions is always on one side of the arc, and means for circulating a coolant through each of said electrodes.

10. In an arc plasma generator, three hollow tubular electrodes, each of said electrodes being of a form of an open substantially circular loop with extensions at the ends of each of the electrodes, the extensions of each electrode being closely spaced from one another, means in cooperation with said extensions for mounting said electrodes so that the loop portions of the electrodes are substantially equidistant from one another, means for connecting one extension of each electrode to a source of three phase alternating current electrical energy, the other extension being substantially open-circuited, said extensions being selected so that the portions of the electrodes through which current flows to or away from arcs between the electrodes is on one side of the arcs, and means for circulating a coolant through said electrodes.

11. An arc plasma generator comprising means forming a plenum chamber having an outlet, a pair of electrodes, at least one of said electrodes being in the form of an open loop and having end portions which are separated from each other a relatively small distance, means for mounting said electrodes in the plenum chamber so that the spacing between the electrodes is substantially uniform, means for connecting one end portion of the open loop electrode to a source of electric power, the other end portion of the open loop electrode being open-circuited, and means for connecting the other electrode to the source of electric power, and means for injecting a working fluid into said plenum chamber.

12. An arc plasma generator comprising means forming a plenum chamber, a pair of hollow electrodes, each electrode being substantially circular with a small segment eliminated, means for mounting said electrodes in the plenum chamber so that the electrodes are substantially uniformly spaced from one another, means for internally cooling the electrodes, and means for connecting one end of each of the electrodes to a source of electrical power, the terminal of each electrode connected to the source of power being chosen so that the portions of the electrodes through which current flows are on the same side of an arc between electrodes, the other end of each electrode being open-circuited, and means for injecting a working fluid into the plenum chamber.

13. An arc plasma generator comprising means forming a plenum chamber, three hollow electrodes, each electrode being substantially circular with a small seg-

ment eliminated, means for mounting said electrodes in the plenum chamber so that the electrodes are substantially uniformly spaced from one another, means for internally cooling the electrodes, and means for connecting one end of each of the electrodes to a source of three phase alternating current, the terminal connected to the source being chosen so that the portions of the electrodes through which current flows are on the same side of any arc between electrodes, the other end of each electrode being open-circuited, and means for injecting a working fluid into the plenum chamber.

14. An arc plasma generator comprising means forming a plenum chamber, three hollow electrodes, each electrode being in the form of an open loop, means for mounting said electrodes in the plenum chamber so that the electrodes are substantially uniformly spaced from one another, means for circulating a coolant through the electrodes, and means for connecting one end of each electrode to a source of electrical power, the terminal connected to the source of power being chosen so that the portions of the electrodes through which current flows always are on the same side of any arcs between them, the other end of the electrodes being open-circuited, and means for injecting a working fluid into the plenum chamber.

15. An arc plasma generator comprising means forming a plenum chamber having an outlet, a pair of electrodes, each electrode being in the form of an open loop, means for mounting said electrodes in the plenum chamber so that the electrodes are substantially uniformly spaced from one another, means for circulating a liquid coolant through the electrodes, and means for connecting one end of each electrode to a source of electrical power, the terminal connected to the source of power being chosen so that the portions of the electrodes through which current flows are on the same side of any arc between them, the other end of the electrodes being open-circuited, and means for injecting a working fluid into the plenum chamber.

16. An arc plasma generator comprising an inner open-ended cylindrical housing having an inner metallic cylinder, the inner walls of which are lined with a high temperature resistant material; an outer metallic cylinder mounted around said inner cylinder and spaced therefrom to form a gap; a plate member, one side of which is lined with a high temperature resistant material closing one end of the inner housing and being removably secured to the outer cylinder; a bottom plate of electrically nonconductive material closing the other end of the inner housing to form a plenum chamber within the inner housing; a metallic base removably connected to the outer cylinder to close the other end of the outer cylinder, and defining a space between the bottom plate and the metallic base, which space is in communication with the gap between the inner housing and the outer cylinder; three substantially circular electrodes, each electrode having a small segment omitted, being formed of an electrically conductive material, being hollow, having extensions at each end of the electrodes defining the omitted segment, determining a plane and having a center; connector means, secured to the base, for mounting each extension of each of the three electrodes, the connectors being located, and the diameters of the electrodes being chosen, so that the electrodes are positioned within the plenum chamber so that the centers of the electrodes lie on a line substantially normal to the planes of the electrodes and so that the intersection of a plane through the line, determined by the centers of the electrodes, and the electrodes determines a substantially equiangular triangle; said connector means providing means for circulating a coolant through the electrodes and for connecting one extension of each electrode to a source of electrical power, the other extension of each electrode

being open-circuited, the extension of each electrode which is connected to the source of power being chosen so that arcs between electrodes rotate in a direction around the electrodes toward the open-circuited extensions; means for supplying a working fluid under pressure to the space between the base and the bottom plate; passages in the bottom plate through which the working fluid enters the plenum chamber; and a nozzle in the plate member for providing a passage through which plasma produced by the generator leaves the plenum chamber.

17. An arc plasma generator as defined in claim 16 in which the diameters of two of the electrodes are substantially equal.

18. An arc plasma generator as defined in claim 16 in which the planes of two of the electrodes are substantially coincident.

19. An arc plasma generator as defined in claim 16 in which the electrodes have openings formed therein which permit the coolant to enter the plenum chamber, said electrodes being oriented to cause the coolant to have a component of rotation in the same direction as the arcs between electrodes also rotate.

20. An arc plasma generator comprising an inner open-ended cylindrical housing comprising an inner metallic cylinder, the inner walls of which are lined with a refractory material; an outer metallic cylinder mounted around said inner cylinder and spaced therefrom to form a gap; a plate member, one side of which is lined with a high temperature resistant material closing one end of the inner housing and being removably secured to the outer cylinder; a bottom plate of electrically nonconductive material closing the other end of the inner housing to form a plenum chamber within the inner housing; a metallic base removably connected to the outer cylinder to close the other end of the outer cylinder, and defining a space between the bottom plate and the metallic base, which space is in communication with the gap between the inner housing and the outer cylinder; three substantially circular electrodes, each electrode having a small segment omitted, each electrode being formed of copper, being hollow, having integral extensions at each end of the electrodes defining the segment omitted, determining a plane and having a center; copper connector means removably secured to and electrically insulated from the base for mounting each extension of each of the three electrodes, the connectors being located and the diameters of the electrodes being chosen so that the electrodes are positioned within the plenum chamber so that the centers of the electrodes lie on a line normal to the planes of the electrodes, and so that the intersection of a plane through the line determined by the centers of the electrodes and the electrodes substantially determines an equilateral triangle, said connector means providing means for circulating water through the electrodes and for connecting one extension of each electrode to a source of three phase electrical power, the extension connected to the source of power being chosen so that the interactions of electromagnetic fields due to arcs between electrodes, and current flow in the electrodes causes the arcs to rotate in a given direction; means for supplying air under pressure to the space between the base and the bottom plate, openings in the bottom plate through which the air enters the plenum chamber, said openings being oriented to cause the air entering the plenum chamber to have a circular component; and a nozzle in the plate member for providing an opening through which plasma produced by the generator escapes from the plenum chamber.

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