March 31, 1964 M. P. FREEMAN 3,127,502

ELECTRICAL PROPERTIES OF ABLATING SOLID MATERIALS OF LOW RESISTIVITY IN A PLASMA JET

Filed Aug. 8, 1961 2 Sheets-Sheet 1

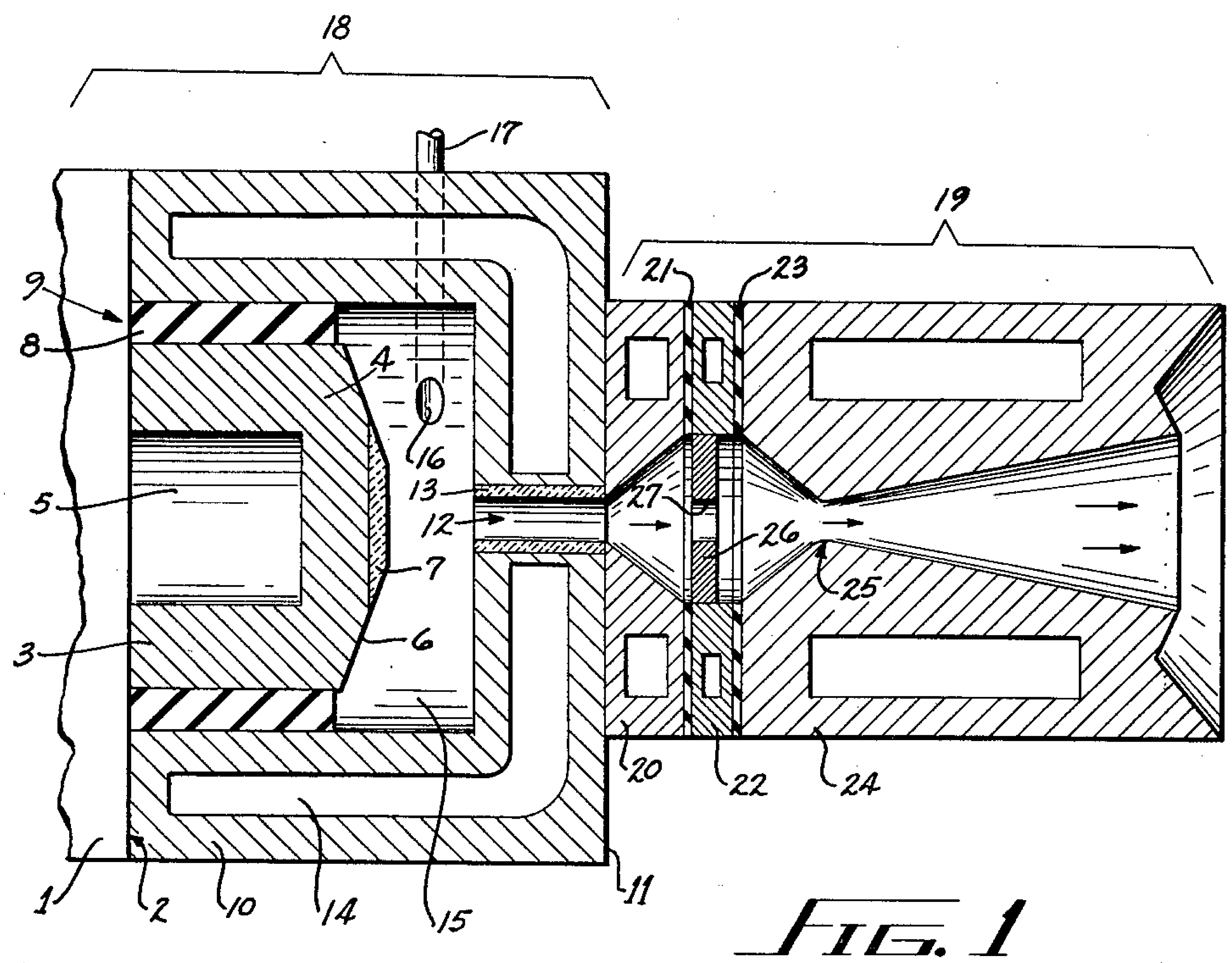

FIG. 1

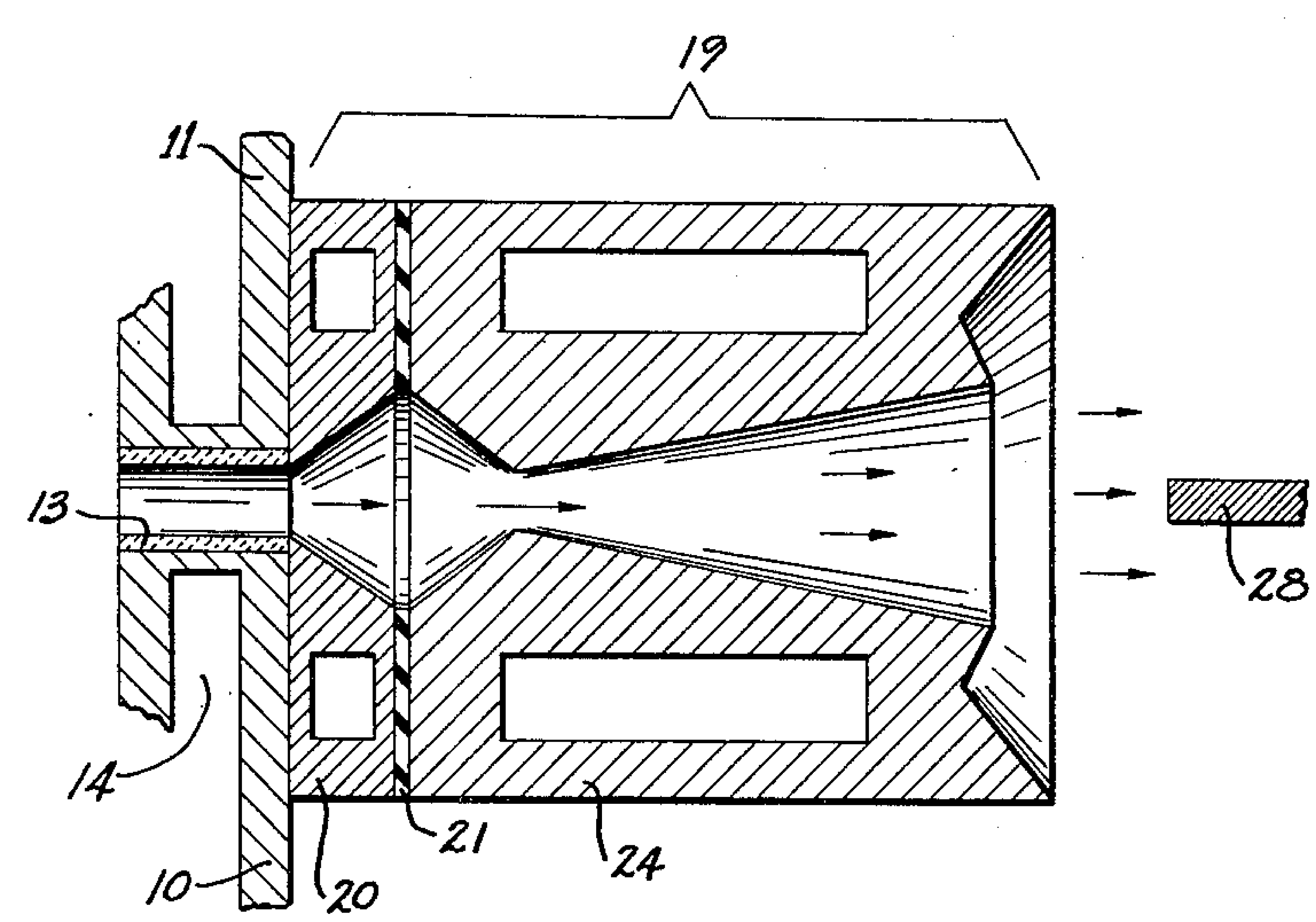

FIG. 2

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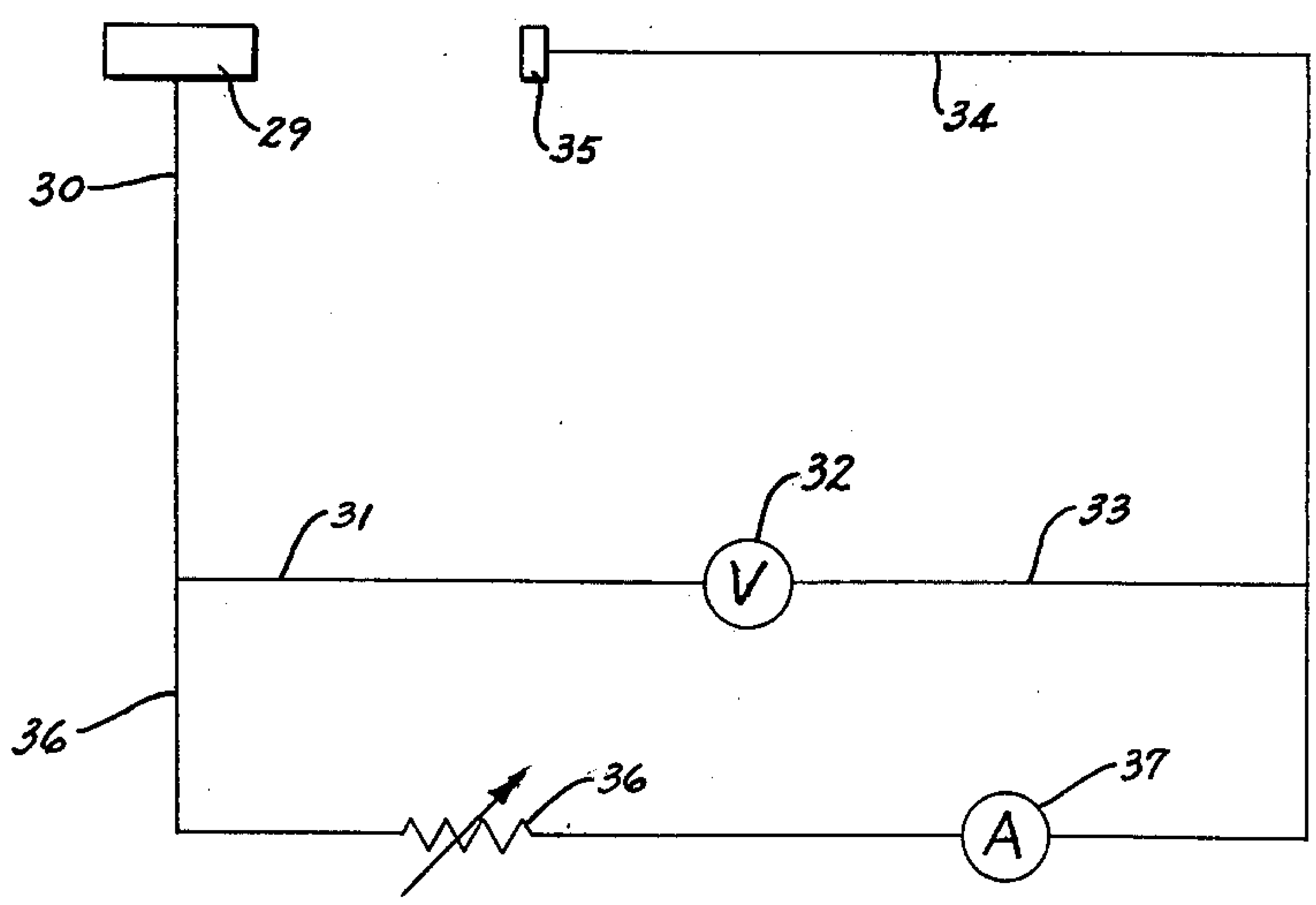

FIG. 3

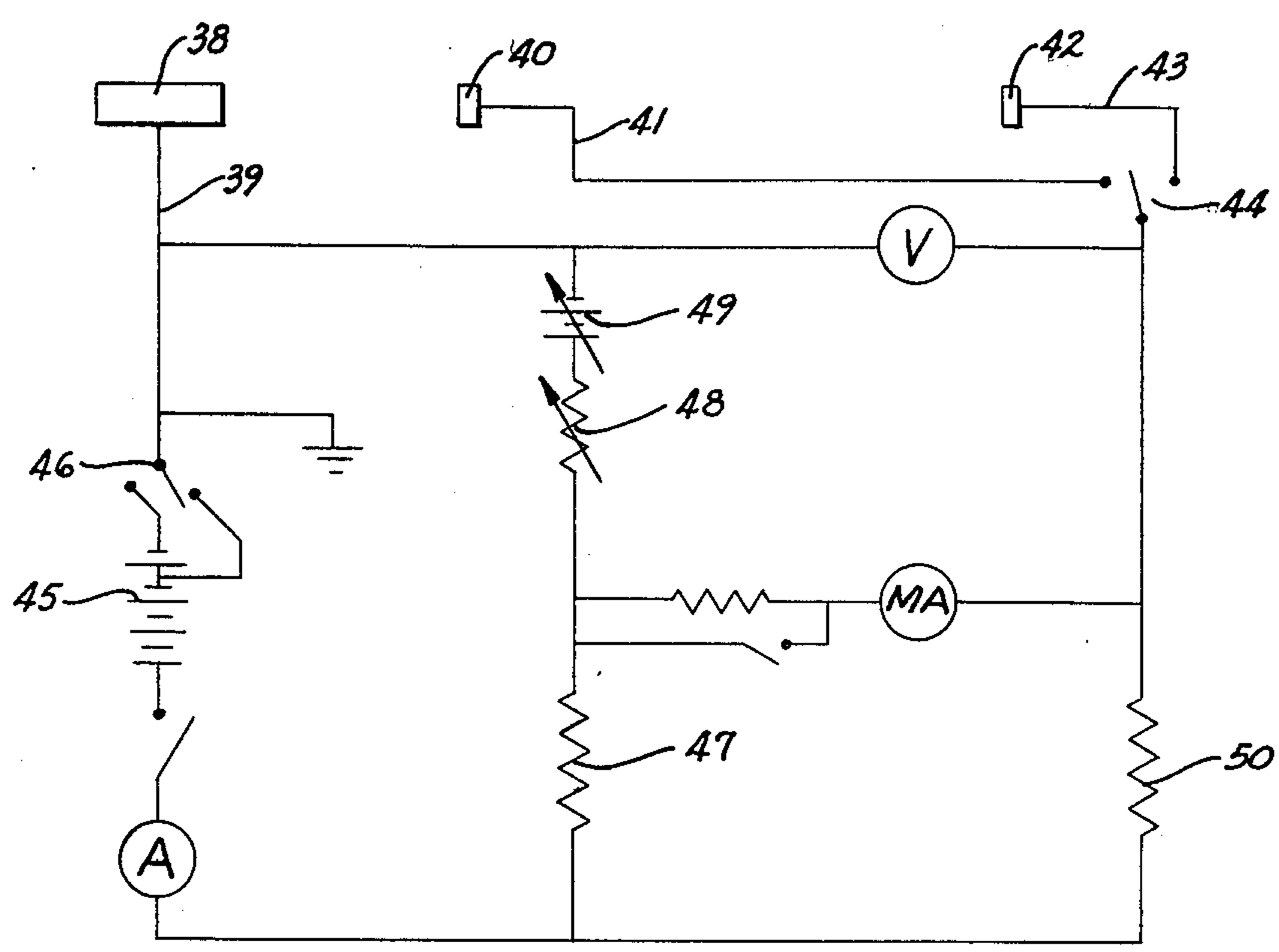

FIG. 4

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ELECTRICAL PROPERTIES OF ABLATING SOLID MATERIALS OF LOW RESISTIVITY IN A PLASMA JET

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8 Claims. (Cl. 219—121)

This invention relates to an improvement in high-temperature plasma jet generators. More particularly, it deals with measurement of the plasma temperature. Still more specifically, this invention relates to an improved method and means for measuring the specific conductivity (or resistivity) of the plasma jet stream, whereby the correlated temperature of the hot plasma can be instantly determined. The invention contemplates both the method and the apparatus therefor.

As used in the present discussion, the term "plasma" is intended to mean a hot, partially-ionized gas stream. While in any one operation the same gas or mixture of gases will constitute the plasma, in general, almost any gas, for example hydrogen, argon, nitrogen, air, a vaporized liquid and the like, may be encountered. The term "plasma jet generator," or an equivalent expression, is intended to designate any apparatus capable of forming and discharging a plasma stream or "jet." Plasma jet generators of various types are commercially available.

In general, such equipment normally includes a solid, non-consumable plenum; means for passing a stream of the chosen gas therethrough; suitable anode and cathode means; and means for imposing an electric potential across the space between the electrodes sufficient to pass a high amperage current therebetween and effect the discharge of a high energy arc; and a means, such as a non-consumable passage, to discharge the resulting plasma as a directional effluent or jet, along some predetermined path, the cross-section of the jet being defined by the geometry of the discharge passage.

Illustrative plasma jet generators are shown for example in U.S. Letters Patent Nos. 2,806,124; 2,858,411 and others. Such generators are readily capable of generating jets having extremely high temperatures in the order of from 2000° C. to some 20,000° C. Some can produce even higher temperature, up to about 50,000° C. or higher. Accordingly, such plasma jet generators are useful for many purposes, such as cutting and welding or as a source of heat in carrying out endothermic chemical reactions, particularly those which are favored by extremely high temperatures. For efficient use and proper control of a plasma reactor for its many uses, it is highly desirable to know the actual temperature of the flowing plasma with a fairly high degree of precision. Such high temperatures are difficult to measure under any circumstances and even more so in such jet streams.

Heretofore, the only accurate method of determining an average plasma temperature was by calculation of the heat balance. In this method is detailed balance of the heat content of the flowing plasma at the point of interest is made by subtracting the rate of energy loss to all cooling water supplies from the electrical power input to the device and dividing by the mass rate of flow of the effluent gas. This heat content may be readily converted to an average temperature by using any of a number of readily available Mollier charts. Only the heat balance calculation method is of unequivocal accuracy. Unfortunately, it is so laborious and slow that by the time the estimate is obtained, conditions have changed to an unknown degree. For control purposes, such a calculated result is of little or no use. Therefore, some method is needed which is faster but which does not entail a substantial sacrifice in the accuracy of the results.

It is, therefore, a major object of this invention to provide plasma jet generators with a means by which the temperature of the plasma jet can be quickly and accurately determined.

It is another object of this invention to provide a process for the determination of the temperature of a hot plasma stream.

More specifically it is the object of this invention to provide an improved means and method for quickly measuring the specific conductivity or resistivity of a hot plasma jet, whereby the correlated temperature of the hot plasma can be instantly determined.

Other objects will be apparent to those skilled in the art from the following description of the invention.

In general, these objects have been accomplished in a highly successful manner by incorporating in a plasma jet generator means for inserting a suitable electrode or "probe." One end of the probe is placed in or close to, the flowing plasma. This probe is also placed into an electrical circuit with one of the electrodes of the plasma jet. Preferably, the probe should be so connected as to serve the function of an anode when current flows through the plasma between an electrode of the plasma generator and the probe to complete the circuit.

By suitable arrangement of the external electrical circuit, some electrical characteristic of the circuit, such as the potential between the generator electrode and the probe or the current flowing in the circuit, can be accurately measured by known means such as a suitable meter. From this measurement some factor such as the specific conductivity or the specific resistivity of the flowing plasma, and hence its temperature, can be determined. The instrument or meter by which the actual reading is taken may read in any desirable units, even ones which are purely arbitrary.

The plasma jet generator is then operated under various conditions and the plasma temperature and the meter reading or its equivalent correlated by calculating the heat balance as discussed above. By taking a plurality of observations, under different conditions in the generator, a chart or a meter dial, may be readily drawn which will indicate the temperature conditions in the plasma, at any given moment.

It is obvious that under operating conditions, such a probe assembly must be so placed or constructed as to prevent immediate deterioration (i.e., ablation) under the temperatures which it will encounter. Of course, the probe material must also be an electrical conductor under operating conditions. This may be accomplished by constructing the probe of a sufficiently refractory conductive material such as graphite, tungsten, various alloys and the like and/or by providing the probe with an internal cooling means.

If the probe assembly is such that the probe or a portion thereof, is positioned in the actual path of the plasma, it will be an "ablating" probe even if equipped with cooling means. It is desirable, therefore, to provide in such a case for feeding the probe into the plasma jet at a speed proportional to the rate of ablation and thereby ensure a substantially continuing ohmic relationship between the jet and the probe. While such ablating probes are useful in accordance with this invention, a non-ablating probe is preferred wherever they are practicable.

It is an advantage of this invention, and another aspect thereof, that the probe need not necessarily be directly in the path of the plasma stream. Such a probe is referred to herein as a "non-ablating" probe. Ohmic relationship is maintained by imposing an electromotive force between the plasma stream and the non-ablating probe.

This invention will be more fully understood in conjunction with the accompanying drawings which are intended for illustrative purposes only. Therein:

FIGURE 1 is a view in cross section of one modification of the present invention; showing only the essential component features of a plasma jet generator including the probe type and its positioning;

FIGURE 2, also in section, shows part of the apparatus of FIGURE 1 but modified with respect to the type and positioning of the probe;

FIGURE 3 shows one type of electrical circuit useful with ablating probes; and

FIGURE 4 shows another type of electrical circuit especially suitable for use with non-ablating probes.

In the modification shown in FIGURE 1, the jet generator is assembled from a plurality of parts. They are held together as a unitary whole by some conventional clamping arrangement which may take any of a number of forms. Since it is conventional and forms no part of this invention, it has not been shown. Backing disc **1** is made of a refractory, electrical insulating material. Its inner surface **2** is in gas-tight contact with an open end of a cylinder **3**. The opposite end **4** of the cylinder **3** is closed to form an enclosed space **5**. Closed end **4** has a frustroconically shaped exterior surface **6** on the flat center portion of which is mounted a flat disc **7** of a refractory conductive material.

Cylinder **3** and end **4** are usually formed as a unitary machined casting from some good electrical conductor such as copper. It constitutes the "back" electrode and is connected through a conventional electrical lead (not shown) to one pole of a suitable source of electrical power. Enclosed space **5** is provided with conventional coolant inlet and outlet conduit means, which for simplification are not shown, liquid coolant is circulated therethrough in conventional manner to protect back electrode **3** from deterioration by the intense heat to which it is subjected during generator operation. Surrounding and in contact with the outer wall of cylinder **3** is a cylindrical, electrically-insulating sleeve **8**. One end **9** of cylinder **8** is in contact with flat backing surface **2**.

Surrounding, and in contact with, insulating ring **8** is cylindrical wall **10** of the "front" electrode. It also usually is formed in a single cast, machined piece from a good electrical conductor, such as copper. It too is connected by a conventional lead to a power source (not shown) and serves as the "front" electrode. The open "back" end electrode **10** is in contact with back wall surface **2**, its substantially closed opposite end **11** being pierced by a central discharge port **12**. Port **12** in turn is lined with an electrically conductive refractory cylinder **13**. Both the circular wall **10** and closed end **11** are hollow, forming an enclosed space **14** through which coolant liquid also is circulated by means of conventional inlet and outlet connections (not shown).

Thus, back plate **1**, back electrode **3** and front electrode **10** form an enclosed space **15**. A tangential inlet port **16** opens into space **15** and is connected through an outwardly extending passage through the cylindrical wall of electrode **10** with a gas inlet conduit **17**.

Inner space **15**, circumscribed by the walls of back electrode **3**, front electrode **10** and the inner end of insulating sleeve **8**, constitutes the arc chamber. Gas entering through tangential port **16** is forced into a circular spiral flow, is at least partially ionized by an electrical potential imposed across electrodes **3** and **10**. The resultant plasma stream is discharged through exit port **12**. This composite section of the apparatus will be referred to herein as the plasma "generator head." It has been given the general reference number **18**.

Plasma discharged through port **12** passes through a built-up composite " discharge section" **19**. In the direction of flow, this section is comprised of water-cooled an-

nular ring **20**, electrically insulating annular insert **21**, water-cooled annulus **22**, another electrically insulating annulus **23** and finally a water-cooled discharge nozzle **24**.

The central passage through annulus **20** has an inlet opening **25** of diameter equal to the inner diameter of sleeve **13** and is coaxially aligned with the latter. However, the central passage expands frustro-conically to an exit opening of several times that diameter. Annuli **21**, **22** and **23** have cylindrical central openings of substantially the same diameter as the exit opening from annulus **20** and also are coaxially aligned therewith and with central passage through elongated cylindrical discharge nozzle section **24**. This central passage has an inlet opening of the same diameter as annulus **23**. However, the cross section of the central passage decreases smoothly and rapidly and then expands more slowly to form a venturi throat **25**. As is also shown, each of sections **20**, **22** and **24** has a central open space to act as a passage or chamber for indirect circulation of liquid coolant in conventional manner.

Integrally mounted within annulus **22** is an annulus **26**, so-positioned that its largest diameter is normal to the direction of plasma flow. Its outer cylindrical surface is in thermal and electrical conducting contact with the inner surface of annulus **22**. Centrally in disc **26** is an opening or port **27**, axially aligned with those through ring sections **20**, **22** adn **24**. Port **27** should be of approximately equal diameter to the inner diameter of sleeve **13**. Annulus **26**, with its central passage or port **27**, in this modification constitutes the "probe." Provision and use of this probe is an essential feature of the present invention and will be designated as probe **26** in the following discussion. Its function and electrical contacts will be discussed below.

In FIGURE 2, another embodiment of this invention is shown. It employs the same plasma generator head **18**. For simplicity, only a part of electrode **10**, end **11** and sleeve **13** are shown. FIGURE 2 also employs a discharge section similar to **19** in FIGURE 1 differing only in that annular rings **22**, **23** and **26** are omitted.

A major distinction is in the location and construction of the probe assembly.

In this modification, a rod-shaped probe **28** is located in the plasma jet flow downstream from the exit end of nozzle section **24**. Probe **28** is constructed of some known electrically-conductive but heat refractory material such as graphite, tungsten or the equivalent. As shown in FIGURE 2, the long axis of probe **28** is in line with the direction of discharge flow from nozzle **24**. It is also so-located with respect to the discharge exit that at least a part of the plasma jet will impinge thereon when the generator is in operation. In this embodiment, probe **28**, having no provision for cooling, is illustrative of the use of ablating probes as discussed hereinbefore.

Plasma jet generators of FIGURES 1 and 2, insofar as the attainment of the hot plasma, operate along conventional lines. Thus, an electrical conduit leads from electrode **3** to one terminus of some conventional source. Preferably this should be a source of direct current. It should be capable of delivering a high current rate, ordinarily in the range of about 100–1000 amperes, at relatively low voltage, usually in the range of about 25–150 volts. When using direct current, back electrode **3** is preferably connected to the negative pole and becomes the arc cathode. Front electrode **10** is connected to the opposite terminus and in the illustrative case becomes the arc anode. Current thus flows into electrode **10** and annular ring **20**, from the inner surface of which it arcs back to plate **7** and then into arc cathode **3**. The conventional conduits and power source complete the circuit.

Plasma-forming gas which flows into arc chamber **15** through gas entry port **16** is forced into a high-velocity vortical flow pattern before passing out through port **12**. It flows around the arc which forms between cathode **3** and anode **10** to effect constriction of the arc. In operation, therefore, arc chamber **15** is filled with gas except for a vortex at the central axis of chamber. The arc is substantially confined within this vortex. Gas passes through the arc, becomes at least partially ionized and whirling gas made up of hot neutral gas, ions and electrons flows outwardly through discharge passage **12** and into discharge assembly **19**. The central passage of discharge assembly **19** can be termed the reaction chamber. It is in this space, that the hot plasma may be used as a high temperature source for the endothermic reactions and other uses as hereinbefore noted.

Flowing plasma naturally tends to become less ionized, and hence less conductive, as it passes along the passage through assembly **19** away from plasma generator head **18**. Since plasma temperature estimation according to the present invention depends upon the conductive capacity of the plasma, it is important that the probe, in whatever physical form it may be used, be positioned sufficiently near the generator head **18** to be impinged upon by plasma while still highly ionized. At the same time, in the case of an ablating probe such as probe **28** in FIGURE 2, the probe cannot be too close to the plasma generator head in the path of the plasma. Otherwise, it will deteriorate too rapidly.

This difficulty in the practical use of an ablating probe can be partially avoided by providing water cooling means for the probe and locating it so that only a small part of its cross-section is impinged upon by the plasma stream. The finding that this expedient is useful is the result of the discovery that the measured resistance of the plasma stream does not vary to any significant extent with the area of the probe which is directly impinged upon by the plasma jet. Once these principles are shown, balancing of these factors to find the proper location for an ablating probe is readily accomplished.

Operation of the present invention may be more readily discussed and illustrated with reference to FIGURES 3 and 4. In FIGURE 3, a plasma jet generator having an ablating probe of the type shown in FIGURE 2 is indicated generally by rectangle **29**. Electrical leads **30** and **31** connect the front electrode to a voltmeter **32** and then through leads **33** and **34** to the ablating probe. The latter is represented in FIGURE 3 by small rectangle **35**. A parallel circuit is formed by lead **36** connecting the junction of leads **30** and **31** with that of leads **33** and **34**. In series in this line is a variable resistance **36** and an ammeter **37**.

Probe **34** is in such location with respect to the generator **29** that highly ionized plasma from the latter impinges on a surface of the former.

The plasma generator is operated by passing a high amperage current at low voltage and at a known electrical power consumption rate through the arc electrodes. Water of known temperature is caused to flow at a known and controlled rate through all the cooling chambers. Plasma-forming gas is then passed at a known rate into arc chamber **15** through gas entry port **16**. Electrically conductive plasma passing in a continuous stream from the generator **29** past probe **35** puts the two in an ohmic relationship, thus completing the voltmeter-ammeter circuits.

In the circuit of FIGURE 3, current flows between the arc anode and the ablating probe when variable resistance **36** is made sufficiently small. The current flow is indicated by deflection of the ammeter. The current drawn does not appreciably alter the voltage and current flow between the arc electrodes. At the same time, readings are taken to determine the actual temperature of the plasma by the hereinbefore described heat balance method. The actual temperature is calculated and compared with the deflection reading of the ammeter.

This process is repeated for other conditions at both higher and lower arcing currents and therefore varied plasma temperatures. Each time the actual temperature of the plasma is determined by heat balance calculation and its conductivity at that temperature correlated with the ammeter reading, if so desired by direct marking on the scale. In either case, data is obtained for correlating or calibrating the actual meter deflection and plasma temperature over a wide range of temperatures. Once having accomplished this, a comparative chart or a direct reading scale can be prepared from which the plasma temperature at any time can be instantly determined by a reading of the ammeter deflection.

Another method of operation may be more readily described and illustrated by referring to FIGURE 4. Therein, a plasma jet generator of the type shown in FIGURE 1 is indicated by rectangle **38**. Lead **39** from the arc anode is connected into a conventional Wheatstone-bridge circuit. Probe **40** is connected thereto by lead **41** as is probe **42** by lead **43**. Leads **41** and **43** being connected to different points of a single pole double throw switch **44** shown in its "off" position. Moving the switch blade to either pole connects the circuit to the corresponding probe.

As is conventional, Wheatstone bridge circuit is equipped with a direct current source, herein battery **45**, the E.M.F. being variable by means of the single pole double throw switch **46**. Resistor **47** and variable resistor **48** and variable voltage source **49** form one leg of the bridge circuit. Resistor **50** and the plasma stream between probe **40**, or probe **42**, depending on the position of switch **44** forms the other leg of the bridge. Variable voltage source **49** in series with resistors **47** and **48** can be adjusted to partially compensate for perturbing potentials which may interfere with the milliammeter reading.

Probes **40** and **41** are of the non-ablating type shown in **26** in FIGURE 1. They are placed in such a manner that the cooler outer perimeter of the plasma stream barely contacts the walls of the central probe opening **27**.

This embodiment can be operated using either one or both of the probes. The practice of this invention using one non-ablating probe is practically the same as with one ablating probe. The primary difference is that a sufficiently high electromotive force as determined by separate experiment (i.e., above about 4.5 volts) as from a battery must be imposed on the probe to produce good ohmic contact between the probe and the plasma stream even if the former is not in the path of the latter.

The plasma jet generator is started as discussed above. Water is circulated through all the water cooling chambers. Gas is forced into a vortical flow in the arcing chamber. A direct current potential of the order of from about 8 to about 12 volts, as indicated on the voltmeter is imposed on the bridge circuit by switching in battery **45**. The actual temperature of the plasma is calculated as before by the heat balance method. As nearly simultaneously as practicable, readings for the calculations are taken, the bridge is balanced to the proper balance current flow by adjustment of variable resistance **48**. The balance condition is recognized when changing the voltage impressed on the bridge with switch **46** causes no change in milliammeter deflection. A reading of the setting of the variable resistance at the balance point is correlated to the actual temperature of the plasma as determined by the heat balance calculations.

As discussed above, a series of variations are run to obtain sufficient data for a temperature reading chart or scale for the variable resistance. Thereafter, the temperature of the plasma may be readily determined by adjustment of the resistance **48** to balance the bridge circuit and subsequent reference to the scale which correlates the temperature to that resistance value.

The practice of this invention using two non-ablating probes is essentially the same as when using only one non-ablating probe except that at a single temperature the bridge circuit is balanced first with one probe in circuit and then with the other in circuit. Resistance of the plasma between the two probes is obtained by subtracting the first value from the second.

Because the location of the arc node shifts, the length of the plasma jet, and thus the resistance between the probe and the head, is frequently in a minor state of flux. This factor affects somewhat the meter reading and adds a minor element of uncertainty in the correlation of the conductivity to plasma temperature. Use of two probes as discussed above has the advantage in that the resistance or conductivity of the plasma between the probes can be determined by difference and this difference calibrated to some direct reading scale. Since the length of the plasma stream between the two probes is constant, any change in resistivity can be attributed to a change in temperature and not the length of the plasma stream.

This invention may be variously otherwise embodied within the scope of the appended claims.

I claim:

1. In combination with a plasma jet generator having anode means, cathode means, means for striking an electrical arc therebetween, means for passing a fluid substance through said arc and means for discharging the arc effluent into a chamber means; electrical conducting means in proximity to the path formed by the discharge means and the chamber means, said electrical conducting means being in electrical circuit with a conductivity measuring device and an electrode of the plasma generator.

2. An apparatus according to claim 1, wherein the electrical conducting means is water cooled and is in said

path and is in electrical connection with means for determining voltage and means for determining amperage, the latter two means being in turn in electrical connection with the cathode means.

3. An apparatus according to claim 1, wherein the electrical conducting means is water cooled and partially overlaps said path.

4. An apparatus according to claim 3, wherein said electrical conducting means is connected through a Wheatstone bridge circuit to an electrode of said plasma jet generator.

5. An apparatus according to claim 4, wherein said circuit has a current source.

6. An apparatus according to claim 3, wherein the electrode is the anode.

7. An apparatus according to claim 3, wherein there are a plurality of electrical conducting means in a position such that there is only partial overlap between said means and said path, and means for alternatively switching in one of said plurality of electrical conducting means.

8. An apparatus according to claim 7 having at least two electrical conducting means.

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