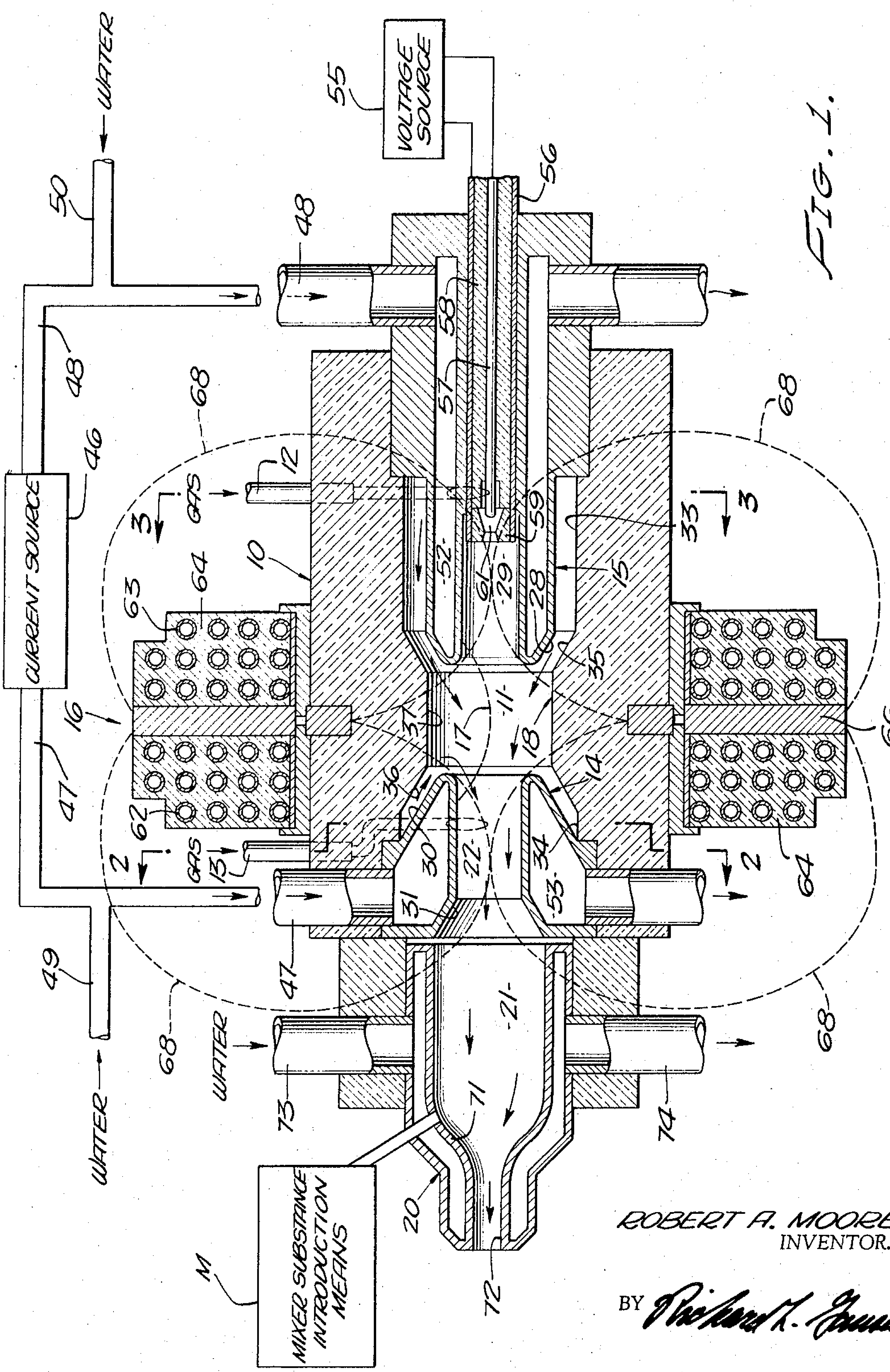

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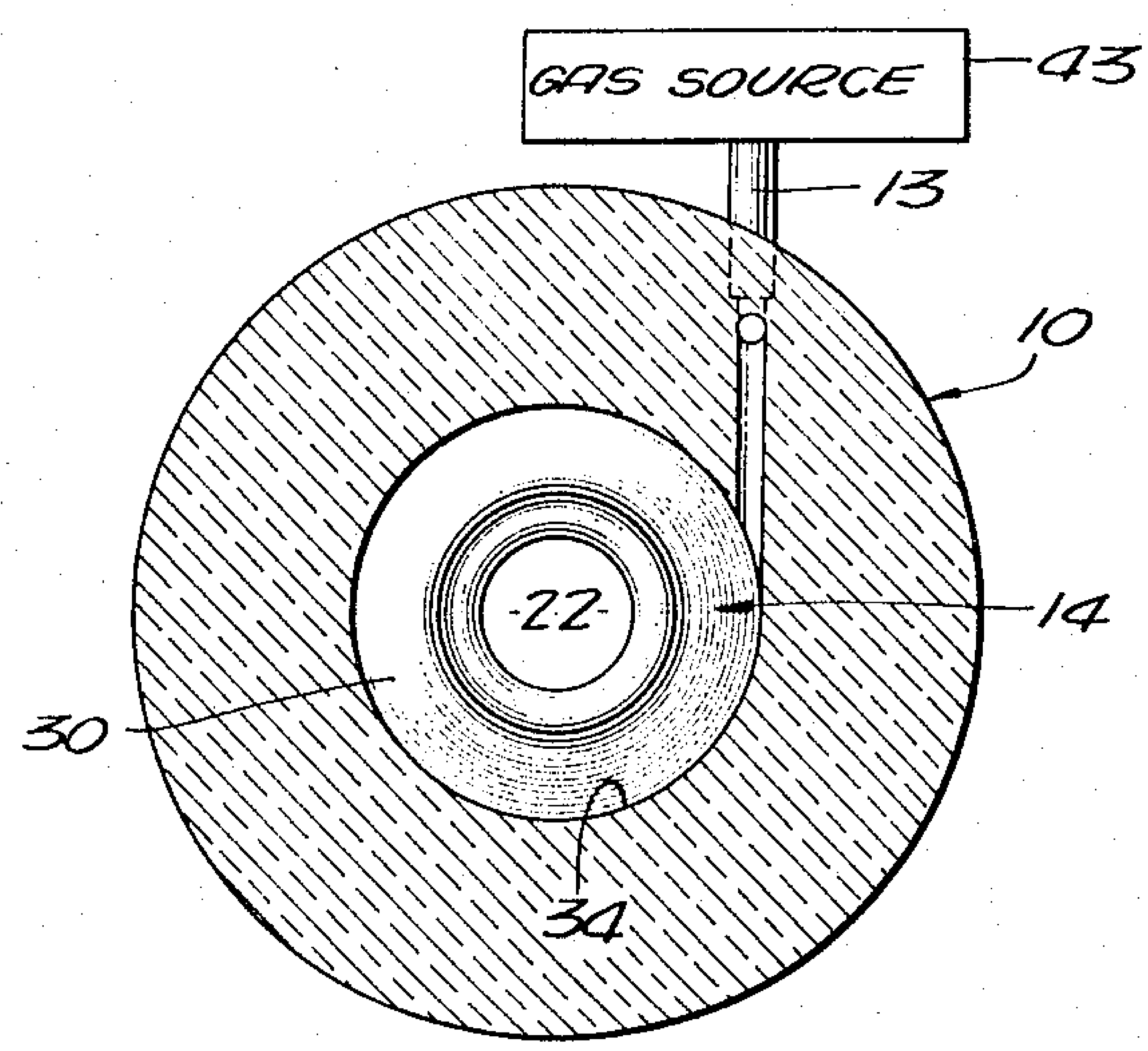

FIG. 2.

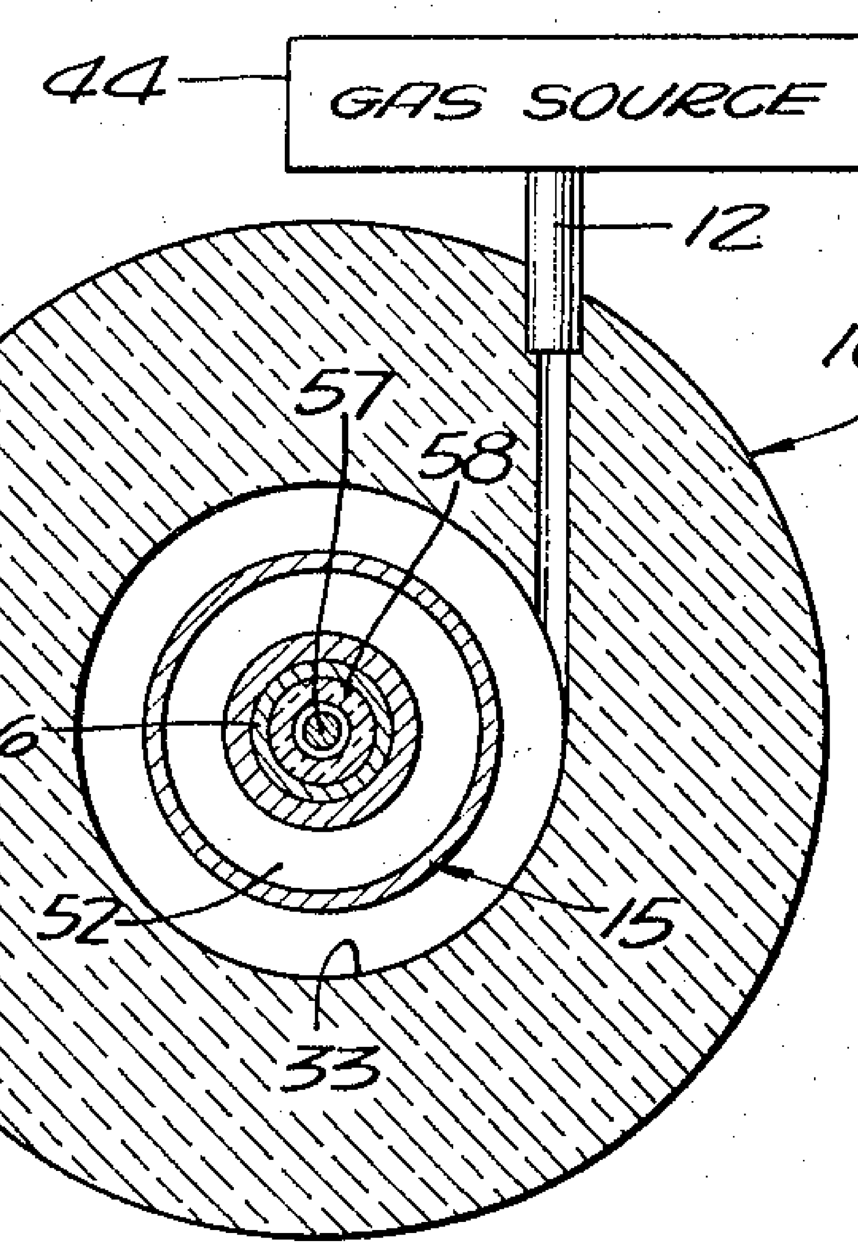

FIG. 3.

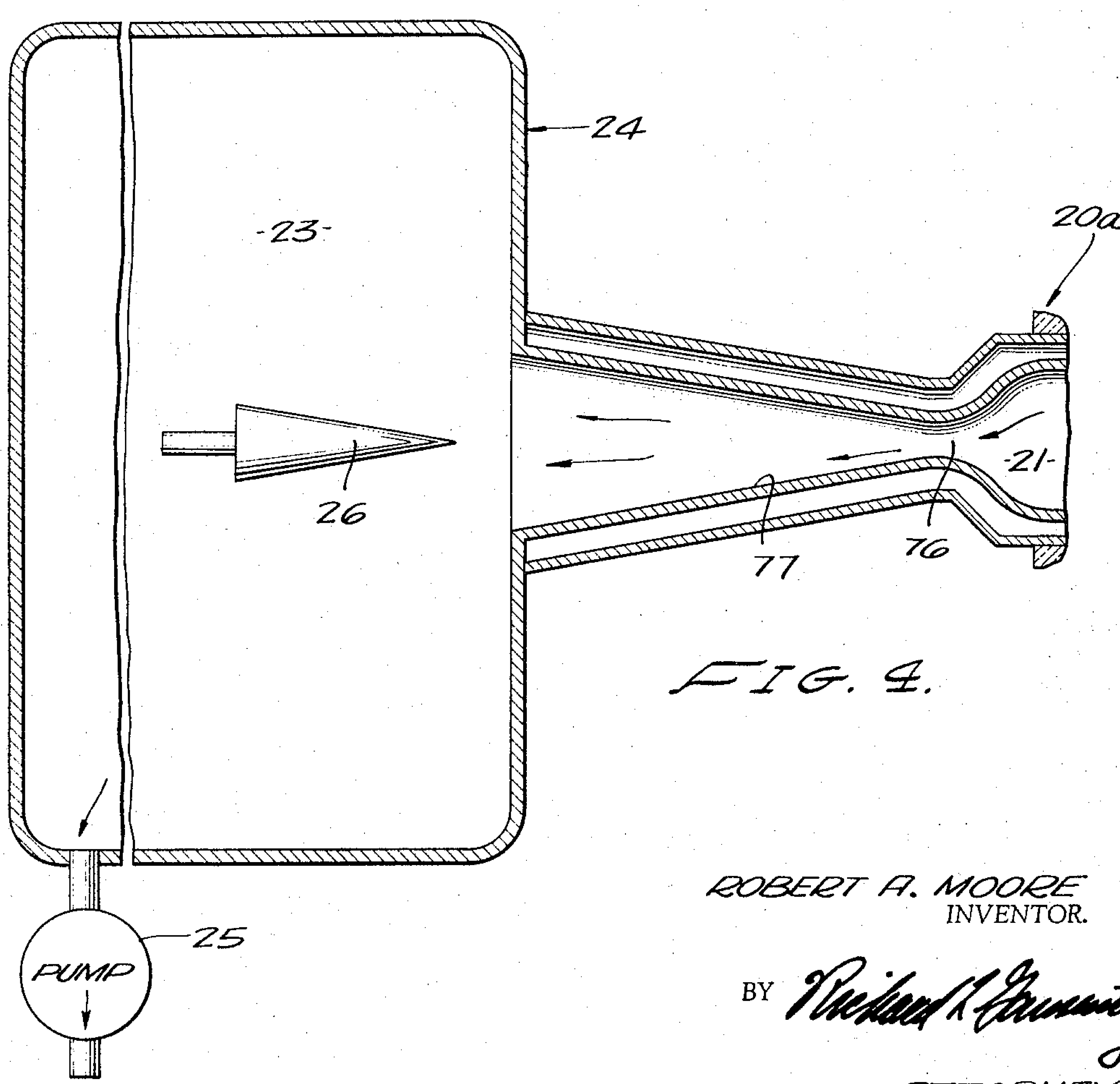

FIG. 4.

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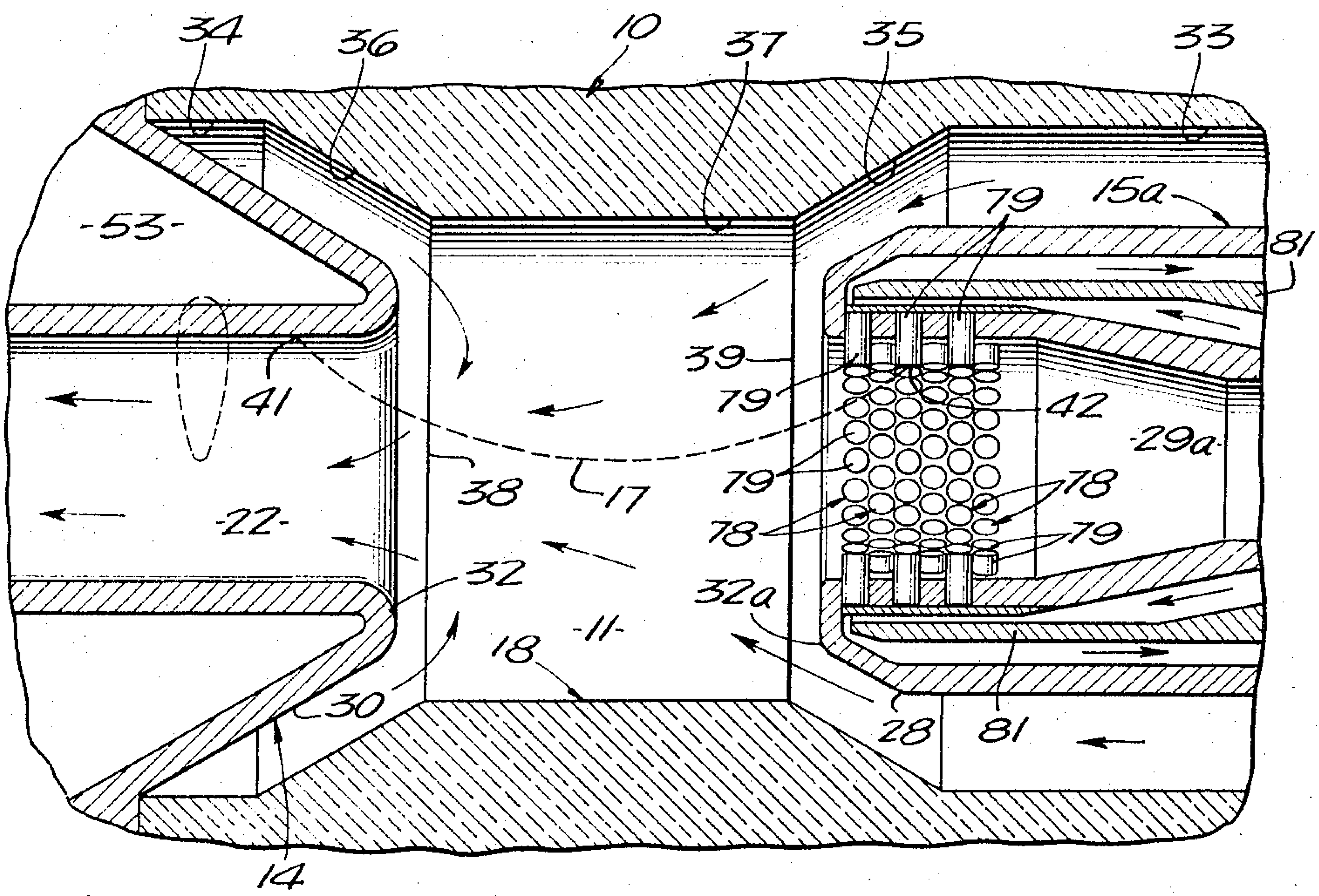

FIG. 6.

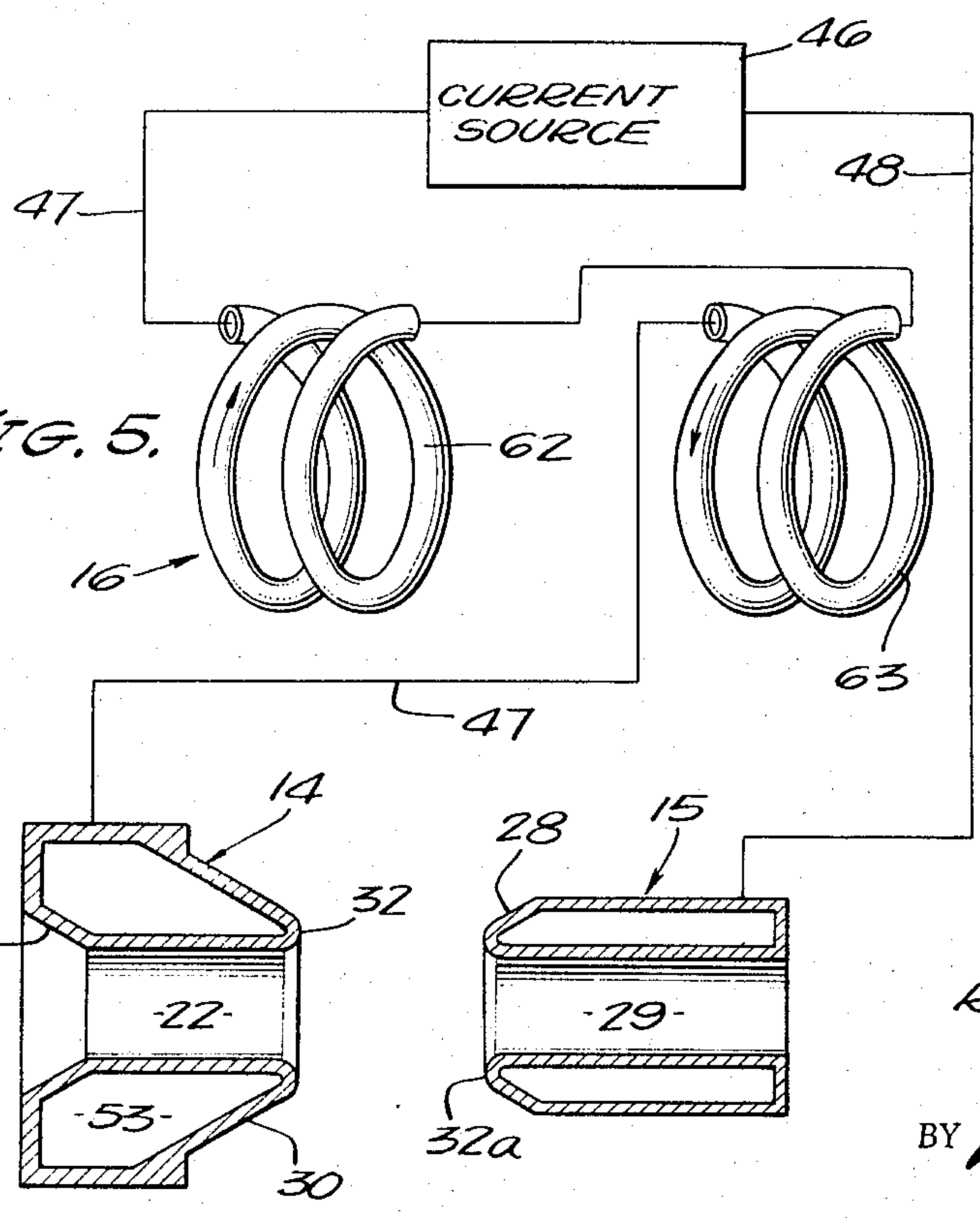

FIG. 5.

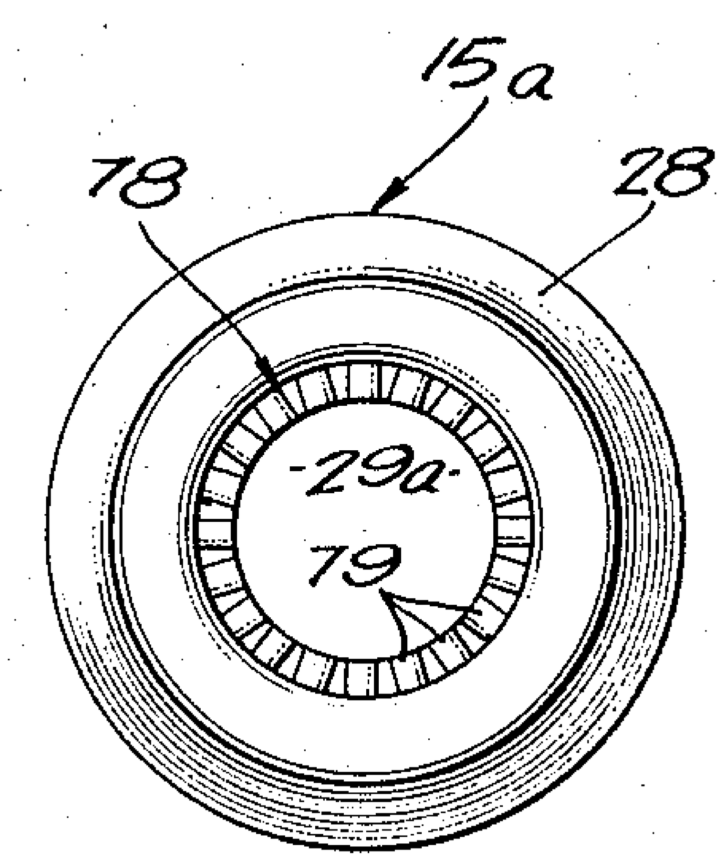

FIG. 7.

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3,360,682
APPARATUS AND METHOD FOR GENERATING HIGH-ENTHALPY PLASMA UNDER HIGH-PRESSURE CONDITIONS

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Continuation of application Ser. No. 183,832, Mar. 30, 1962. This application Oct. 15, 1965, Ser. No. 502,818
13 Claims. (Cl. 315—111)

The present application is a continuation of my copending patent application Ser. No. 183,832, filed Mar. 30, 1962 now abandoned, for Apparatus and Method for Generating High-Enthalpy Plasma Under High-Pressure Conditions.

This invention relates to plasma-generating apparatus and methods, being particularly directed to the problem of generating high-enthalpy plasma under high-pressure conditions. The invention additionally relates to a rocket exhaust simulator, a hyperthermal tunnel apparatus, and a chemical synthesis apparatus. Furthermore, the invention relates to novel electrode configurations and constructions.

It has long been desired to provide a method and apparatus which will generate plasma efficiently under conditions of both high enthalpy and high pressure. For example, to simulate the conditions encountered by a nose cone re-entering the earth's atmosphere, the temperature must be high in order to simulate the temperature generated by air friction, and the pressure must be high since the pressure adjacent the nose cone is great due to the extreme velocity thereof. However, such generation of high-enthalpy plasma under high-pressure conditions is very difficult for a variety of reasons. In the first place, the current density of the arc increases so that it becomes much more difficult to mix the gas with the arc and achieve an efficient transfer of arc heat to the gas. Such a current density increases greatly the tendency of the terminal portions of the arc to burn into the electrodes and melt the same, so that the electrodes are damaged and the plasma is contaminated by electrode material. Furthermore, the high pressure renders the arc much less stable than at lower pressures, makes starting of the arc extremely difficult, and increases the convective and radiation heat losses from the arc to the walls of the chamber and thus to the cooling water.

In view of the above objects characteristic of the field of plasma generators, a principal object of the present invention is to provide a plasma-generating apparatus and method capable of effecting efficient generation of plasma under conditions of high enthalpy and high gas pressures.

Another object of the invention is to provide a plasma-generating apparatus and method adapted to be employed for numerous purposes including rocket exhaust simulation, materials testing, and chemical synthesis.

An additional object is to provide an apparatus and method for simulating in a relatively realistic manner the re-entry thermal conditions encountered by a space vehicle traveling at very high velocities.

A further object is to provide a plasma-generating method and apparatus which operate at very high pressure and power levels, for example on the order of one million watts at six hundred p.s.i.a.

An additional object is to provide a plasma-generating apparatus and method characterized by a relatively short arc, with consequent minimum loss of power due to convection and radiation.

A further object is to provide a plasma generator wherein the arc is constricted in a novel manner which minimizes danger of melting the walls of the arc chamber.

A further object is to provide a plasma generator and

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method wherein magnetic fields and gas are both employed in a highly efficient manner to effect movement of the arc terminals, thereby preventing melting of the electrodes and contamination of the plasma with electrode material.

An additional object is to provide a plasma generator wherein the gas is maintained in the arc region for a relatively long period of time in order to result in an efficient and uniform heating of the gas.

A further object is to provide an electrode construction making use of a large number of small elements of refractory and emissive metal, in combination with means to cool such elements whereby the power level may be increased substantially.

These and other objects and advantages of the invention will be more fully set forth in the following specification and claims, considered in connection with the attached drawings to which they relate.

In the drawings:

FIGURE 1 is a schematic longitudinal central sectional view illustrating a plasma-generating apparatus constructed in accordance with the present invention;

FIGURES 2 and 3 are transverse section taken respectively on lines 2—2 and 3—3 of FIGURE 1;

FIGURE 4 is a view schematically illustrating the combination of the plasma-generating apparatus of FIGURE 1 with a hyperthermal tunnel chamber adapted to contain a test object;

FIGURE 5 is a schematic view illustrating the electric circuit means through which power is supplied to the electrodes, the circuit means being illustrated to include the coils which generate the magnetic fields producing or augmenting rotation of the arc terminals;

FIGURE 6 is an enlarged fragmentary longitudinal central sectional view corresponding generally to the center portion of FIGURE 1, but illustrating a modification wherein a large number of small electrode elements are incorporated in one of the electrodes; and

FIGURE 7 is an end view of the electrode shown at the right in FIGURE 6, illustrating the radial positioning of the small electrode elements.

Stated generally, the plasma-generating apparatus comprises wall means **10** to define an elongated gas-pressure chamber **11**, and conduit means **12** and **13** to introduce gas tangentially into opposite end portions of the chamber **11** for helical or vortical flow about the longitudinal axis thereof. The plasma generator further comprises front and rear electrodes **14** and **15**, respectively, mounted axially of the chamber **11** in opposed relationship relative to each other. Magnetic means **16** are provided and cooperate with the gas in effecting rapid rotation of the footpoints (the term "footpoints" is hereby defined to mean terminal portions) of an electric arc **17** which is maintained between the electrodes.

It is a feature of the invention that the wall portion of gas-pressure chamber **11**, between the opposed ends of electrodes **14** and **15**, is shaped to direct the gas inwardly in a manner effecting constriction of the arc **17** and also in a manner preventing (as will be described subsequently) the terminals of the arc from engaging the adjacent lip portions of the electrodes. Such wall portion is indicated at **18** and may be termed the constrictor wall, although it is to be understood that constriction is effected not by the wall directly but by the gas which is crowded radially-inwardly toward the central portion of the chamber.

The apparatus of the invention additionally comprises means **20** to define a mixing or plenum chamber **21** into which the plasma is introduced through a central passage or opening **22** in front electrode **14**, such electrode also serving as a nozzle means. The mixing chamber may discharge into the ambient atmosphere or space, as illustrated in FIGURE 1, or into a test or environmental chamber such as is indicated at **23** in FIGURE 4. A typical environmental chamber, and the wall means **24** which define the same, are normally very large. The chamber is evacuated by means of a pumping apparatus such as is schematically represented at **25**. Means are provided to support in the test section of chamber **23** an object, such as the illustrated conical element **26**, which it is desired to subject to a testing operation.

It is to be understood that the apparatus of FIGURE 1 may also discharge directly into a water-cooled test chamber, in the absence of an elongated nozzle such as is shown at the right in FIGURE 4. Such an arrangement would be employed for rocket exhaust simulation, for example, whereas FIGURE 4 illustrates a hyperthermal or wind tunnel arrangement.

Throughout the present specification and claims, the term "arc" will be employed to denote not only the central thin filament, a representative one of which is indicated by a dashed line at **17** in FIGURE 1, but also the extremely high-temperature gas or plasma which immediately surrounds such filament.

Detailed description of the plasma generator

The wall means **10**, including the constrictor wall portion **18**, comprises a mass of highly refractory insulating material such as boron nitride. The upstream or rear electrode **15** (or **15***a*, FIGURE 6) is cylindrical, having a beveled or conical end **28**. The beveled end **28** merges through a smooth curve with the wall of a stagnation chamber or sub-chamber **29** which is defined within the electrode **15** or **15***a*, such electrode being hollow. The exterior and interior walls of electrode **15** are shown in FIGURES 1 and 5 as being co-cylindrical, the cylinders being coaxial with chamber **11**.

The front or nozzle electrode **14** has a conical exterior surface which is designated **30** in FIGURE 6. Such surface converges in an upstream direction, that is to say toward the rear electrode **15** or **15***a*, this being in contrast with the conical end **28** which converges in a downstream direction. Surface **30** merges through a smooth curve with the wall of nozzle passage **22**, such wall being illustrated as cylindrical throughout the portion thereof which is relatively adjacent rear electrode **15**. The cylindrical portion of the nozzle passage merges with a divergent conical portion **31** which communicates at its wide end with mixing or plenum chamber **21**.

From the above it will be understood that opposed and generally corresponding lips **32** and **32***a* (see FIGURE 6), having a space or gap therebetween, are formed at the adjacent ends of the electrodes. Such lips are important relative to the gas flow pattern, the locations of the arc footpoints or terminals, etc., as will be set forth hereinafter.

The wall of gas-pressure chamber **11** has first and second cylindrical sections which are designated **33** and **34** in FIGURE 6. The first such section (number **33**) is disposed radially outward from and is generally coextensive with the cylindrical exterior surface of rear electrode **15** or **15***a*, whereas the second cylindrical section **34** is disposed adjacent the outermost region of conical surface **30** of the front electrode. The cylindrical sections **33** and **34** merge with frustoconical wall sections **35** and **36** which are disposed, respectively, radially-outwardly from the conical surface **28** of the rear electrode and the smaller portion of conical surface **30** of the front electrode. The cone angles of the electrode surfaces and of the wall sections **35** and **36** are shown as being substantially the same, the arrangement being one which may be termed co-conical in each instance. It is pointed out that the resulting gas-flow channels converge towards each other, that is to say towards the central region between lips **32** and **32***a*.

The remaining wall portion of the gas-pressure chamber **11** comprises a cylindrical section designated **37**, being of substantially smaller diameter than the first and second cylindrical sections **33** and **34**. In the illustrated embodiment, the diameter of the third-mentioned cylindrical wall section **37** is on the order of the external diameter of rear electrode **15** or **15***a*, being substantially greater than the internal diameter of either the front or rear electrode. The ends of cylindrical section **37** merge with the respective frustoconical sections **35** and **36** at lines **38** and **39** (FIGURE 6) which lie in planes intermediate the planes of the lips or rims **32** and **32***a*.

From the above it will be understood that the constriction wall **18**, comprising the frustoconical surfaces **35** and **36** and also the smaller diameter cylindrical surface **37**, effects inward crowding of the gas which is introduced around the electrodes as will next be described. The gas is thus forced to flow radially-inwardly to gas-constrict the arc **17** at regions thereof intermediate the electrodes, and to effect relatively efficient and uniform heating of the gas by the arc.

In the case of the gas which is introduced around the front or nozzle electrode **14**, and as indicated by the arrows in FIGURE 6, the gas flow reverses direction and is therefore in contact with the arc region for a substantial period of time resulting in highly efficient transfer of heat from the arc to the gas. The relationship is such that the gas, in passing adjacent lip **32**, changes direction through substantially more than a right angle, the illustrated angle of flow reversal being on the order of 140 degrees. Thus, the gas adjacent lip **32** has a substantial component which is upstream relative to the flow direction through nozzle passage **22**.

The gas flow pattern, electrode configurations, etc., are also such that the footpoints or terminal portions of the arc, indicated at **41** and **42** in FIGURE 6, are not located on the electrode rims **32** and **32***a* but instead at points spaced from such rims on the internal cylindrical surfaces of the respective electrodes. Such positioning of the footpoints is highly important in preventing melting of portions of the electrodes, and contamination of the plasma with electrode material.

Proceeding next to a description of the gas-introduction means, the conduits **12** and **13** are, as shown in FIGURES 2 and 3, tangentially related to the gas-pressure chamber and more specifically to the cylindrical sections **33** and **34** thereof. Particularly in the case of the rear electrode **15** or **15***a*, the tangential inlet is located relatively remote from the region between the electrode rims or lips **32** and **32***a*. The conduits may be connected to one or more sources of gas, two separate sources being indicated schematically at **43** and **44** in FIGURES 2 and 3. Such gas sources are adapted to effect high-velocity gas flow, the flow being preferably sonic at the inlets where the conduits **12** and **13** enter gas-pressure chamber **11**. It is to be understood that the sources **43** and **44**, and/or other sources, may contain the same or different gases, depending upon the desired application.

The gas which is introduced tangentially into the rear end portion of chamber **11**, through conduit **12**, flows helically or vortically around the rear electrode **15** or **15***a* and is then forced inwardly by constrictor **18** to the central region between electrode rims **32** and **32***a*. The gas which is introduced tangentially through conduit **13** flows vortically through the space between electrode surface **30** (FIGURE 6) and wall section **36**, and then flows around the lip **32** into and out the nozzle passage **22**.

The gases from both conduits **12** and **13** mix with each other in (and also downstream of) the region between lips **32** and **32***a*. Since the arc **17** is gas-constricted in this region, there is a very efficient transfer of arc energy to the gas from both conduits. The heat-transfer efficiency is further increased (as previously indicated) because of the flow reversal adjacent lip **32**, and also because the vortically-moving gas remains in the chamber longer than does gas which moves merely axially. Another of several other important factors relative to efficiency is that lip

32 is spaced so far from arc **17** that such lip is effectively cooled by the vertically-flowing gas (the coldest part of which is adjacent surface **37**) and need not be excessively water cooled. There is accordingly a relatively small heat loss from the arc to the cooling water.

The means to supply current to the electrodes **14** and **15** (or **15a**) is illustrated schematically to comprise a current source **46** and associated conductors or leads **47** and **48**. The conductors or leads **47** and **48**, which connect respectively to the electrodes **14** and **15**, are associated with water conduits **49** and **50** adapted to supply water for cooling of the conductors and also for cooling of the electrodes. The water conduits communicate with coolant chambers **52** and **53** formed in the electrodes, the chambers being only schematically represented in FIGURES 1 and 5. In the actual apparatus, the chambers are provided with suitable baffles which direct the flow of water in a desired manner effecting a highly efficient cooling of the electrodes. One such baffle or deflector will be described subsequently in connection with back electrode **15a** shown in FIGURE 6.

Means are provided to initiate the electric arc **17**, and comprise a voltage source **55** (for example of the capacitor discharge type) having one terminal connected to a copper tube or sleeve **56** which is inserted into the hollow rear electrode **15** or **15a** in close-fitting relationship. The remaining terminal of source **55** is connected to an elongated conductor **57** disposed axially of sleeve **56**, being insulated therefrom by a ceramic insulating tube **58**. A metal nozzle and chamber-defining element **59** is mounted in the extreme inner end of copper sleeve **56**, adjacent the end of tube **58**, to define a gas chamber **61** into which the central conductor **57** protrudes.

To initiate the arc **17**, the gas sources **43** and **44** are utilized to fill the chamber **11** and thus chamber **61** with gas under relatively low pressure, following which the voltage source **55** is applied to generate a spark or arc between the tip of central conductor **57** and the inner wall of nozzle element **59**. Ionized gas or plasma is thus generated in chamber **61** and is ejected therefrom into the portion of chamber **11** between lips **32** and **32a**. The gas in chamber **11** is thus sufficiently ionized that upon application of current source **46** the main arc **17** will be initiated. The gas sources **43** and **44** are then adjusted in a manner increasing the gas flow until the full operating pressure is present in chamber **11**.

The described arc-starting system is in accordance with the basic principles set forth in Patent 3,007,030, issued Oct. 31, 1961, to Adriano C. Ducati, for Apparatus and Method for Initiating an Electrical Discharge, such patent being assigned to the assignee of the present invention.

There will next be described the magnet means **16** which cooperate with the whirling gas to stabilize the arc and effect rotation of arc terminals or footpoints **41** and **42**, thereby preventing such terminals from burning into the electrodes to erode the same and effect contamination of the gas with electrode material. Means **16** comprises first and second coils **62** and **63** mounted adjacent each other coaxially around the central portion of wall means **10**, radially-outwardly from the part of gas chamber **11** lying between electrodes **14** and **15** or **15a**. The coils are illustrated in FIGURE 1 as being hollow copper tubes embedded in ceramic **64** or the like, the ceramic being suitably mounted on the exterior surface of insulator wall means **10** on opposite sides of a ferrous metal ring **66**. Water is supplied to the coils **62** and **63** to prevent melting thereof despite the passage of extremely large currents therethrough.

The coils **62** and **63** may be supplied with large currents from one or more current sources, not shown, or may be incorporated in a single electrical circuit. In FIGURE 5, the coils **62** and **63** are shown as incorporated in the leads **47** and **48** which supply power from current source **46** to electrodes **14** and **15**.

As indicated in FIGURE 5, the coils **62** and **63** are so wound and connected that the current flows in opposite directions therein, so that the coils are in bucking relationship. The resulting magnetic fields are represented schematically and in distorted relationship in FIGURE 1, comprising lines of force or flux **68** which pass through the ferrous metal ring **66** and through the gas-pressure chamber **11**. The lines of force intersect arc **17** generally at right angles, so that Lorentz forces are created effecting rotation of the terminal portions of the arc about the common axis of electrodes **14** and **15** or **15a**.

The terminal portions or footpoints **41** and **42** (FIGURE 6) of arc **17** are thus caused to rotate in the same direction about the electrode axis, such direction being the same as that in which the gas whirls in arc chamber **11** after being introduced therein through the conduits **12** and **13**. Stated otherwise, and referring to FIGURES 2 and 3, the direction of rotation of the arc footpoints, and the direction of rotation of gas from surces **43** and **44**, are both clockwise. Thus, the gas and the magnetic fields cooperate to effect highly efficient rotation of the arc terminals, preventing the same from burning into the electrodes and melting various portions thereof. Because of this rapid shifting of the arc terminals, and because the arc terminals are maintained away from lips **32** and **32a**, an enormous amount of power may be introduced into the arc **17** without destroying the electrodes or effecting substantial contamination of the plasma with electrode material.

Detailed description of the mixing chamber and associated apparatus

The mixing chamber **21** is illustrated in FIGURE 1 as having a cylindrical wall the diameter of which is approximately equal to the diameter of the downstream end of conical wall portion **31** of the nozzle electrode. The cylindrical wall merges with a nozzle portion **71** which, in turn, merges with a generally cylindrical throat **72**. The wall means **20** which defines the chamber **21** is cooled by water or other coolant passed therethrough by suitable conduits **73** and **74**.

As previously indicated, the mixing or plenum chamber **21** receives the plasma in a relatively uniformly heated condition from the plasma-generating portion of the apparatus. The plasma circulates in the chmber **21** and becomes additionally mixed prior to discharge through the throat **72**.

It is to be understood that various gases, powders, liquids, etc., may be introduced into chamber **21** through one or more ports in order to achieve chemical synthesis and other effects, or to dilute the plasma which is discharged into the atmosphere or into a test chamber. One substance-introduction means is schematically represented at M in FIGURE 1. It is also to be understood that various types of aerodynamic and other nozzles may be provided to discharge the plasma from chamber **21**. Furthermore, it is pointed out that in certain forms of apparatus the wall means **20** and chamber **21** are not employed.

Referring to FIGURE 4, a modified wall means **20a** is employed to define a relatively short nozzle throat **76** which forms part of a supersonic nozzle having a divergent portion **77**. As previously indicated, the plasma from mixing chamber **21** flows through the supersonic nozzle **76–77** and impinges against a test object **26** in the evacuated chamber **23**.

Description of electrode 15a, FIGURES 6 and 7

The electrodes **14** and **15** or **15a** are formed of highly conductive metal such as copper. In the case of electrode **15a** shown in FIGURES 6 and 7, the arcing portion comprises bundles or rows **78** of refractory metal elements **79**. More specifically, the elements **79** may comprise small cylinders of thoriated tungsten adapted to increase electron emission, the polarity of the source **46** in the illustrated embodiment being such that electrode **15a** is the cathode and electrode **14** is the anode. It is to be understood that the cylindrical elements may instead be incorporated in the nozzle **14** (particularly in situations where the polarity is reversed). They may also be incorporated in both electrodes.

In the illustrated embodiment, there are six circular rows **78** of refractory metal elements **79**. The inner portions of such elements are inserted into correspondingly-sized openings in the interior portion of electrode **15***a* and brazed therein by braze metal having a high melting point, for example a nickel-gold alloy. The inner portions of the tungsten elements **79** protrude radially into stagnation chamber **29***a*, the amount of inward protrusion or projection being such that the extreme inner ends of the tungsten elements closely approach (but preferably do not touch) each other, as shown in FIGURE 7. Alternate rows **78** are offset and substantially nested, each row or circle lying in a plane perpendicular to the axis of the apparatus. As previously indicated, it is preferred that the tungsten elements be close together but out of actual contact.

The means to effect water cooling of the tungsten elements **79** includes a generally tubular baffle **81** which is mounted concentrically in the coolant chamber defined within electrode **15***a*. The construction and mounting of baffle **81** are such that there is only a narrow annular gap between it and the inner ends of the tungsten elements **79**. The coolant inlet is so located that the water flows, as indicated by the arrows in FIGURE 6, into the indicated annular gap and thence around the inner end of baffle **81** for discharge to a suitable drain. Because of the small dimension of the annular gap, the water flows at extremely high velocity when it is adjacent the tungsten elements **79**. Accordingly, the cooling of such elements is highly effective and efficient. Such cooling action, in combination with the arc rotation caused by the gas and the magnetic field, permit application of extremely high powers to cathode **15***a*.

Summary of the method, and operation

In performing the method of the invention, the arc **17** is initiated (while the pressure in chamber **11** is relatively low) through use of the starting electrodes **57** and **59** as described in detail previously. The gas pressure is then increased until it is very high, for example on the order of six hundred p.s.i.a. Current source **46** may then be employed to deliver on the order of one million watts, for example one thousand amperes at one thousand volts.

The gas is caused to enter the end portions of chamber **11** tangentially and at sonic velocity, flowing vortically helically in the chamber and around the lip portions **32** and **32***a* of the electrodes. As indicated by the arrows in FIGURES 1 and 6, the gas follows flow paths (created by the vortical flow and by the constrictor wall portion **18**) which effect gas-constriction of the arc **17**. Furthermore, and very importantly, the vortically-flowing gas and the magnetic field generated by means **16** cooperate to stabilize the arc **17** and effect rotation of the footpoints or terminals **41** and **42** (FIGURE 6) thereof about the axis of the apparatus. The resulting efficient and rapid rotation of footpoints **41** and **42** prevents damaging or destroying the electrodes, as previously stated.

It is to be noted that the arc **17** is generally bowed or arcuate, having a major portion which extends along the axial region of chamber **11**. The described bowing of the arc, which results primarily from the gas flow pattern, further increases the efficiency of footpoint rotation since it causes the arc and magnetic field to be substantially perpendicular to each other (for increased Lorentz force effect) at locations adjacent the footpoints.

The electrodes are further protected from damage by the arc due to the fact that the footpoints are spaced away from the electrode lips or rims **32** and **32***a*, contacting instead the cylindrical walls of stagnation chamber **29** and nozzle passage **22**. It is pointed out that movement of each terminal is not only rotational but to some extent longitudinal or axial, so that the arc terminals travel over much larger areas than would be the case if the arc merely extended between the adjacent lips **32** and **32***a*. Accordingly,

the present method and apparatus result in efficient cooling of the arcing portions, permitting application of very large currents.

The above-described action may be referred to as vortical sweeping since the vortically-flowing high-velocity gas creates gas flow patterns which prevent arcing at the electrode rims or lips. It is an important feature of the invention that the gas not only achieves the desired results relative to prevention of electrode deterioration, but also thoroughly mixes with and passes through the arc in a manner resulting in efficient high-energy heat transfer (as previously described) from arc to gas. There is, therefore, a novel and important cooperation between the electrodes, the gas, the magnetic field and the arc to achieve arc stability, minimized electrode deterioration, and extremely efficient heat transfer.

Although the gas operates as described above to lengthen the arc **17** somewhat, so that it does not follow the shortest path between the electrode rims, it is a feature of the invention that the arc is not made excessively long. A long arc is not desired since it generates excessive radiation and convective heat losses, a very large portion of the arc heat then being transferred to the cooling water and not to the gas. In the present apparatus, the downstream footpoint or terminal **41** of arc **17** normally remains in the vicinity of the point indicated in FIGURE 6, spaced varying distances from the electrode rim **32** but not excessively far downstream therefrom. In no event can there be arcing to the wall of mixing chamber **21** since such wall is spaced and insulated from the nozzle electrode **14**, there being a short gap therebetweeen as shown in FIGURE 1.

It has been found that the above-indicated desirable results are achieved when there is a proper balance between the amount of gas introduced through conduit **12** and that introduced through conduit **13**. As one example of the desired gas flow, substantially equal quantities of gas are introduced through the conduits **12** and **13**.

A substantial number of types of gas may be passed through the apparatus without resulting in excessive deterioration of the electrodes. Not only may nitrogen, hydrogen, argon and helium be employed, but oxygen-containing gases such as carbon monoxide may be utilized. Thus, the gas composition may be varied through a wide range to achieve various results including simulation of the exhaust from a solid-propellant rocket engine.

The plasma which emanates from nozzle passage **22** may be diluted or varied in any desired manner through use of one or more of the means M (FIGURE 1) for introducing gas, powder, etc., into mixing chamber **21**. In this way, as well as by controlling the composition of gas passed into the gas-pressure chamber **11**, many conditions may be simulated and chemical synthesis effects may be achieved.

As previously described relative to FIGURE 4, aerodynamic testing may be carried out relative to a test object **26** disposed in a test chamber **23** which is substantially evacuated by means of pump means **25**. Also, as previously indicated, the aerodynamic nozzle which discharges gas from mixing chamber **21** may be directed into a suitable test chamber, which may be similar to the one shown in FIGURE 4 and may be water cooled. Materials and objects to be tested may then be disposed in such chamber by means of suitable remote-operated mounting and manipulation devices, not shown. For chemical synthesis effects, one or more chemicals are introduced into the chamber **21** and react therein to produce various effects and reactions.

It is to be understood that more than one tangential gas inlet may be employed relative to each of conduits **12** and **13**. Thus, for example, two tangential inlets may be provided at each end portion of chamber **11**.

The chamber (or sub-chamber) **29** formed within rear electrode **15** or **15***a* may be referred to as the stagnation chamber since it is not necessary to pass gas therethrough. Stated otherwise, it is a feature of the invention that it is not necessary to pass gas (such as along the path occupied by electrode 57) into and through chamber 29.

There will next be given a specific example of the apparatus and method, relative to the embodiment of FIGURES 6 and 7. The rate of gas flow through each of conduits 12 and 13 may be 0.05 pound per second, the gas being nitrogen. The gas pressure in chamber 11 may be six hundred p.s.i.a. The arc current may be one thousand one hundred amperes, and the arc voltage six hundred fifty.

The diameter of each of the lips 32 and 32*a* may be on the order of 1.5 inches. The gap between the opposed lips may be on the order of 1.25 inches. The distance between opposed faces of tungsten elements 79, diametrically of chamber 29*a*, may be on the order of 0.75 inch. The inner diameter of the cylindrical part of nozzle passage 22 may be 1.1 inch. The diameter of throat 72 may be 0.4 inch.

In summary, the present apparatus and method have a substantial number of important uses which have long been desired in various fields including re-entry simulation, rocket exhaust simulation, and chemical synthesis. The results are achieved in a highly efficient manner, and despite the obstacles stated at the beginning of the specification relative to pressure and power requirements.

Various embodiments of the present invention, in addition to what has been illustrated and described in detail, may be employed without departing from the scope of the accompanying claims.

I claim:

1. Apparatus for generating plasma, which comprises wall means to define a gas-pressure chamber the wall of which is a surface of revolution about a central axis, nozzle and back electrodes mounted in said chamber and having annular portions disposed in opposed relationship coaxially of said chamber, the nozzle passage in said nozzle electrode communicating with the exterior of said chamber, means to maintain a high-current electric arc between said electrodes, means to introduce gas tangentially into said chamber for vortical flow about said axis to thereby stabilize said arc and rotate both footpoints thereof about said axis, said gas being heated by said arc and discharging through said nozzle passage, means to generate in said chamber a magnetic field adapted to cooperate with said vortically-flowing gas in stabilizing said arc and effecting said rotation of said footpoints, and constrictor means provided in said chamber radially outwardly from the gap between said opposed annular portions of said electrodes, said constrictor means being coaxial with said axis and serving to effect radial-inward crowding of said gas into said gap to thereby constrict at least a substantial portion of said arc.

2. A plasma generating apparatus, comprising wall means to define an elongated chamber the wall of which is a surface of revolution about a central axis, elongated nozzle and back electrodes mounted coaxially in said chamber and having opposed annular lips, said nozzle electrode having a nozzle passage coaxially therethrough, said back electrode having a generally cylindrical recess therein coaxial with said nozzle passage, means to introduce gas tangentially into said chamber radially outwardly from said back electrode for flow generally longitudinally of said chamber and thence through the gap between said lips and out said nozzle passage, means to introduce gas tangentially into said chamber radially outwardly from said nozzle electrode for flow generally longitudinally of said chamber toward said back electrode and then around said nozzle electrode lip and through said nozzle passage, and means to maintain a high-current electric arc between said nozzle and back electrodes, the downstream and upstream footpoints of said arc being located respectively in said nozzle passage and back electrode recess and spaced from said lips, said arc serving to heat said gas efficiently whereby hot gas is discharged through said nozzle passage.

3. The invention as claimed in claim 2, in which first and second magnetic coils are provided coaxially around said wall means radially outwardly from the gap between said lips, and in which current is passed through said coils to generate magnetic fields in bucking relationship, said fields cooperating with said gas in effecting rotation of said upstream and downstream arc footpoints about the axis of said chamber.

4. The invention as claimed in claim 2, in which a mixing chamber apparatus is mounted in communication with the downstream end of said nozzle passage.

5. A plasma generator, comprising a nozzle, a back electrode having a recess therein opposite the opening in said nozzle, said back electrode having incorporated in the side wall of said recess a large number of radially-disposed refractory metal elements, said elements being adjacent each other and forming the arcing portion of said back electrode, means to maintain a high-current electric arc from said arcing portion of said back electrode through at least part of said nozzle opening, and means to pass gas between said back electrode and said nozzle and through said nozzle opening, said gas being heated by said arc.

6. A plasma generator, comprising a nozzle element having a nozzle passage or opening therethrough, said nozzle element also having an annular lip at the upstream end of said nozzle passage and coaxially thereof, a back electrode having an arcing portion disposed generally opposite said lip, means to define a gas-pressure chamber in which said lip and said arcing portion are disposed, means to maintain continuously a high-current electric arc from said arcing portion through at least a part of said nozzle passage, means to introduce gas continuously into said chamber and around said lip whereby said gas is heated efficiently by said arc prior to discharge through said nozzle passage, and magnetic means to effect rotation of at least one footpoint of said arc about the axis of said chamber.

7. Plasma generating apparatus, comprising a nozzle electrode having a relatively large-diameter annular lip at the upstream end thereof, a back electrode disposed opposite and spaced from said lip, means to define a gas pressure chamber the wall of which is a surface of revolution about the axis of said nozzle electrode, said wall encompassing said lip and having a constrictor portion coaxial with said nozzle electrode and located adjacent the gap between said lip and said back electrode, the diameter of said constrictor being on the order of the diameter of said lip, means to introduce gas into said chamber for flow into said gap and thence through said nozzle electrode, said gas-introduction means including means to introduce gas into said chamber on opposite sides of said constrictor, and means to maintain a high-current electric arc between said back electrode and said nozzle electrode to thereby effect heating of said gas.

8. Plasma generating apparatus, comprising a nozzle electrode having a relatively large-diameter annular lip at the upstream end thereof, a back electrode disposed opposite and spaced from said lip, means to define a gas pressure chamber the wall of which is a surface of revolution about the axis of said nozzle electrode, said wall encompassing said lip and having a constrictor portion coaxial with said nozzle electrode and located adjacent the gap between said lip and said back electrode, the diameter of said constrictor being on the order of the diameter of said lip, means to introduce gas into said chamber for flow into said gap and thence through said nozzle electrode, and means to maintain a high-current electric arc between said back electrode and said nozzle electrode to thereby effect heating of said gas, said gas-introduction means including means to introduce gas tangentially and at high velocity into said chamber for vortical flow about the axis of said nozzle electrode, said

gas being introduced at at least two points and on opposite sides of said constrictor to thereby achieve efficient heating of said gas and also effect maintenance of the downstream footpoint of said arc at a predetermined region in said nozzle electrode and downstream from said lip.

9. Plasma generating apparatus, comprising a nozzle electrode having a relatively large-diameter annular lip at the upstream end thereof, a back electrode disposed opposite and spaced from said lip, said back electrode also having an annular lip disposed opposite and coaxial with said lip of said nozzle electrode, means to define a gas pressure chamber the wall of which is a surface of revolution about the axis of said nozzle electrode, said wall encompassing said first-mentioned lip and having a constrictor portion coaxial with said nozzle electrode and located adjacent the gap between said first-mentioned lip and said back electrode, the diameter of said constrictor being on the order of the diameter of said first-mentioned lip, means to introduce gas into said chamber for flow into said gap and thence through said nozzle electrode, and means to maintain a high-current electric arc between said back electrode and said nozzle electrode to thereby effect heating of said gas, said gas being adapted to maintain the upstream and downstream footpoints of said arc respectively within said back and nozzle electrodes and spaced away from said lips, whereby said electrodes are prevented from deteriorating excessively and contaminating said gas with electrode material.

10. A plasma generator, which comprises first and second annular electrode surfaces disposed in spaced coaxial relationship, said surfaces being respectively defined by nozzle and back electrode elements, said nozzle electrode element having a nozzle passage coaxially therethrough, said back electrode element having a recess therein generally coaxial with said nozzle passage, means to maintain a high-current electric arc between said electrode elements, and means to pass gas radially inwardly through the gap between said surfaces to maintain the upstream and downstream footpoints of said arc respectively in said recess and in said nozzle passage and spaced away from said surfaces, said gas being heated by said arc and discharging through said nozzle passage, said last-named means including means to introduce gas at sonic velocity into a chamber in which said surfaces are disposed.

11. A plasma generator, which comprises first and second annular electrode surfaces disposed in spaced coaxial relationship, said surfaces being respectively defined by nozzle and back electrode elements, said nozzle electrode element having a nozzle passage coaxially therethrough, said back electrode element having a recess therein generally coaxial with said nozzle passage, said recess in said back electrode being a stagnation chamber adapted to receive gas only from the space between said surfaces, means to maintain a high-current electric arc between said electrode elements, means to pass gas radially inwardly through the gap between said surfaces to maintain the upstream and downstream footpoints of said arc respectively in said recess and in said nozzle passage and spaced away from said surfaces, and starting means to introduce ionized gas into said stagnation chamber and thus into said gap or space to thereby effect initiation of the arc between said nozzle and back electrode elements, said gas being heated by said arc and discharging through said nozzle passage.

12. A plasma generator, which comprises first and second annular electrode surfaces disposed in spaced coaxial relationship, said surfaces being respectively defined by nozzle and back electrode elements, said nozzle electrode element having a nozzle passage coaxially therethrough, said back electrode element having a recess therein generally coaxial with said nozzle passage, means to maintain a high-current electric arc between said electrode elements, said arcing means including a large number of short electrode elements provided in the side wall of said recess in said back electrode element and forming the arcing portion thereof, means to pass gas radially inwardly through the gap between said surfaces to maintain the upstream and downstream footpoints of said arc respectively in said recess and in said nozzle passage and spaced away from said surfaces, said gas being heated by said arc and discharging through said nozzle passage, and means to effect water cooling of said back electrode element and of said short electrode elements.

13. A plasma generator, which comprises first and second annular electrode surfaces disposed in spaced coaxial relationship, said surfaces being respectively defined by nozzle and back electrode elements, said nozzle electrode element having a nozzle passage coaxially therethrough, said back electrode element having a recess therein generally coaxial with said nozzle passage, means to maintain a high-current electric arc between said electrode elements, means to pass gas radially inwardly through the gap between said surfaces to maintain the upstream and downstream footpoints of said arc respectively in said recess and in said nozzle passage and spaced away from said surfaces, said gas being heated by said arc and discharging through said nozzle passage, and magnet means to create a Lorentz force effecting rotation of said footpoints of said arc about the axis of said electrode elements.

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