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Muehlberger

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[45] **Oct. 21, 1975**

[54] **COATING HEAT SOFTENED PARTICLES BY PROJECTION IN A PLASMA STREAM OF MACH 1 TO MACH 3 VELOCITY**

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[73] Assignee: **Geotel, Inc.,** Amityville, N.Y.

[22] Filed: **Aug. 6, 1973**

[21] Appl. No.: **386,036**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 143,956, May 17, 1971, abandoned, and a continuation-in-part of Ser. No. 372,260, June 21, 1973, Pat. No. 3,823,302, which is a continuation of Ser. No. 214,584, Jan. 3, 1972, abandoned.

[52] **U.S. Cl.** .... **219/76;** 219/121 P

[51] **Int. Cl.** **B23k 9/04**

[58] **Field of Search** .... 219/121 P, 74, 75, 76; 13/9, 31; 239/3, 15, 434; 313/231

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Primary Examiner—J. V. Truhe
Assistant Examiner—G. R. Peterson
Attorney, Agent, or Firm—Gausewitz, Carr & Rothenberg

[57] **ABSTRACT**

An electric arc plasma spray gun provides optimum coating of substrates by projecting a stream of plasma at a velocity at or about Mach two, at ambient pressure, and entraining therein particles of material to be coated upon said substrate. Power, pressures and temperatures are employed together with a unique set of interchangeable supersonic nozzles to achieve particle exit velocities of from one to ten thousand feet per second, heating said particles to a temperature below their melting point but sufficient to soften the particles for enhanced coating. Unique parameters of particle size, particle injection angle and particle injection positions are identified for different materials to be entrained in the supersonic plasma stream.

6 Claims, 12 Drawing Figures

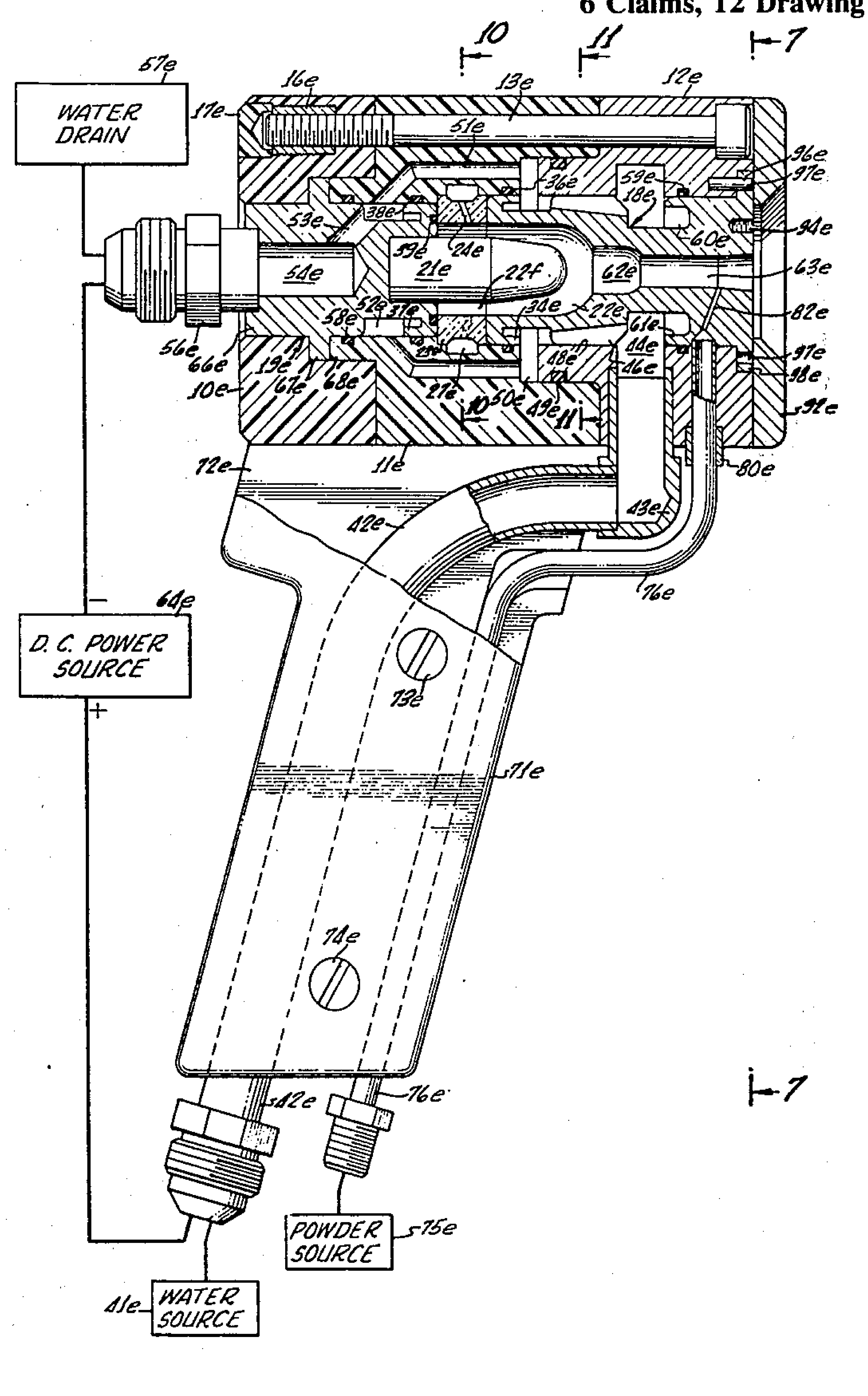
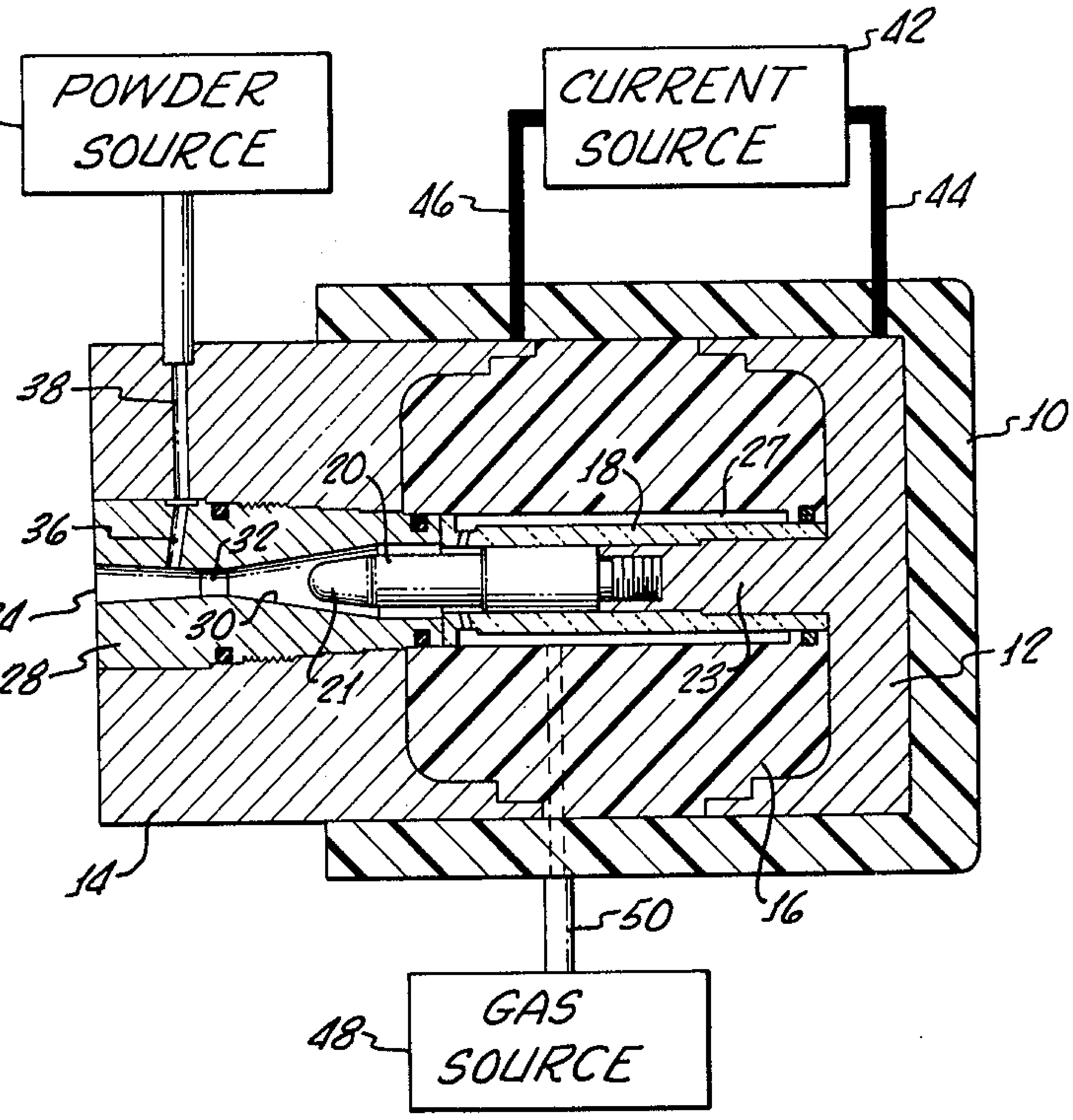


FIG. 1.



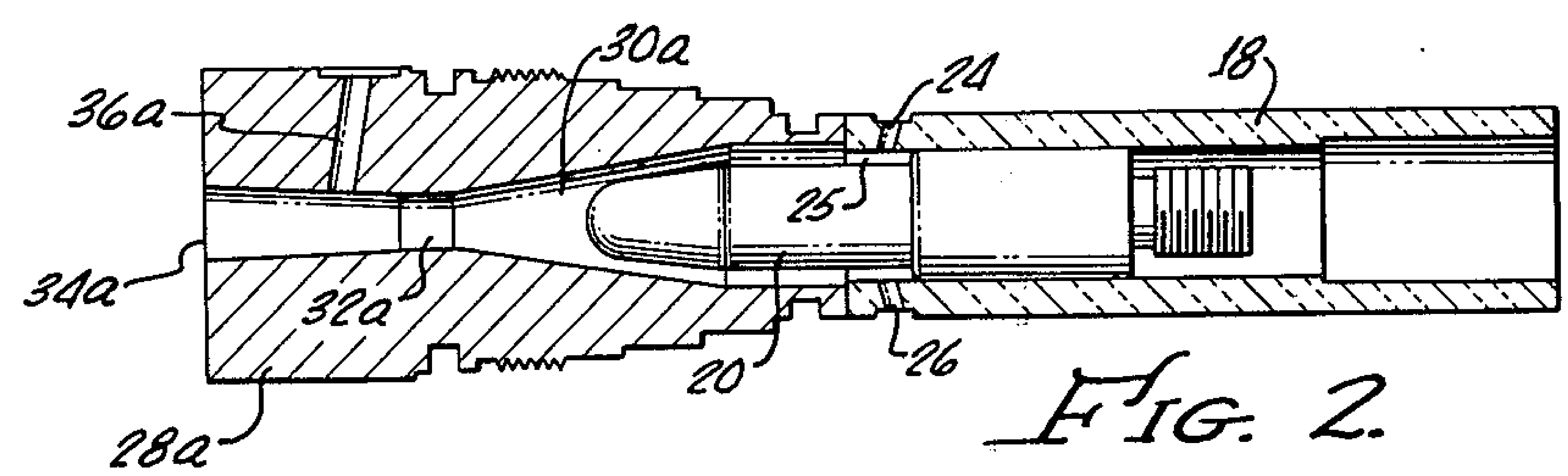


FIG. 2.

FIG. 3.

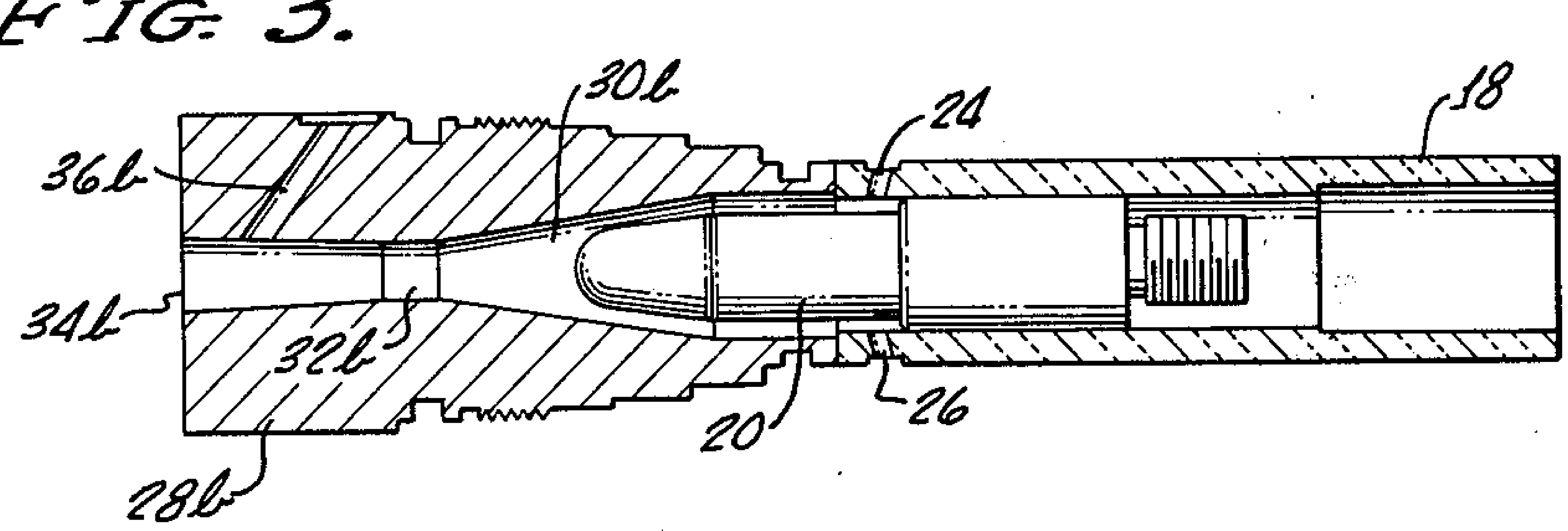
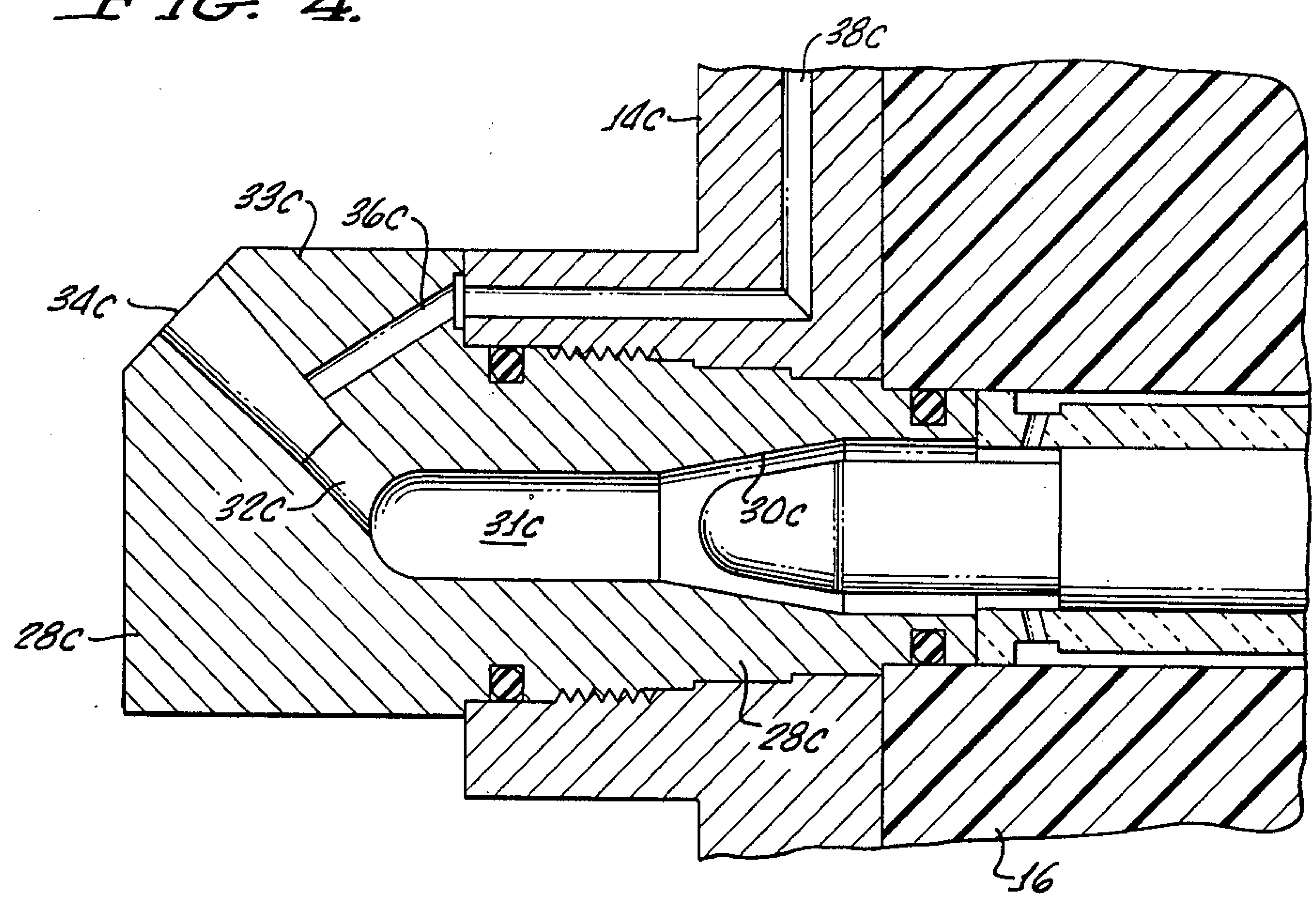


FIG. 4.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32c
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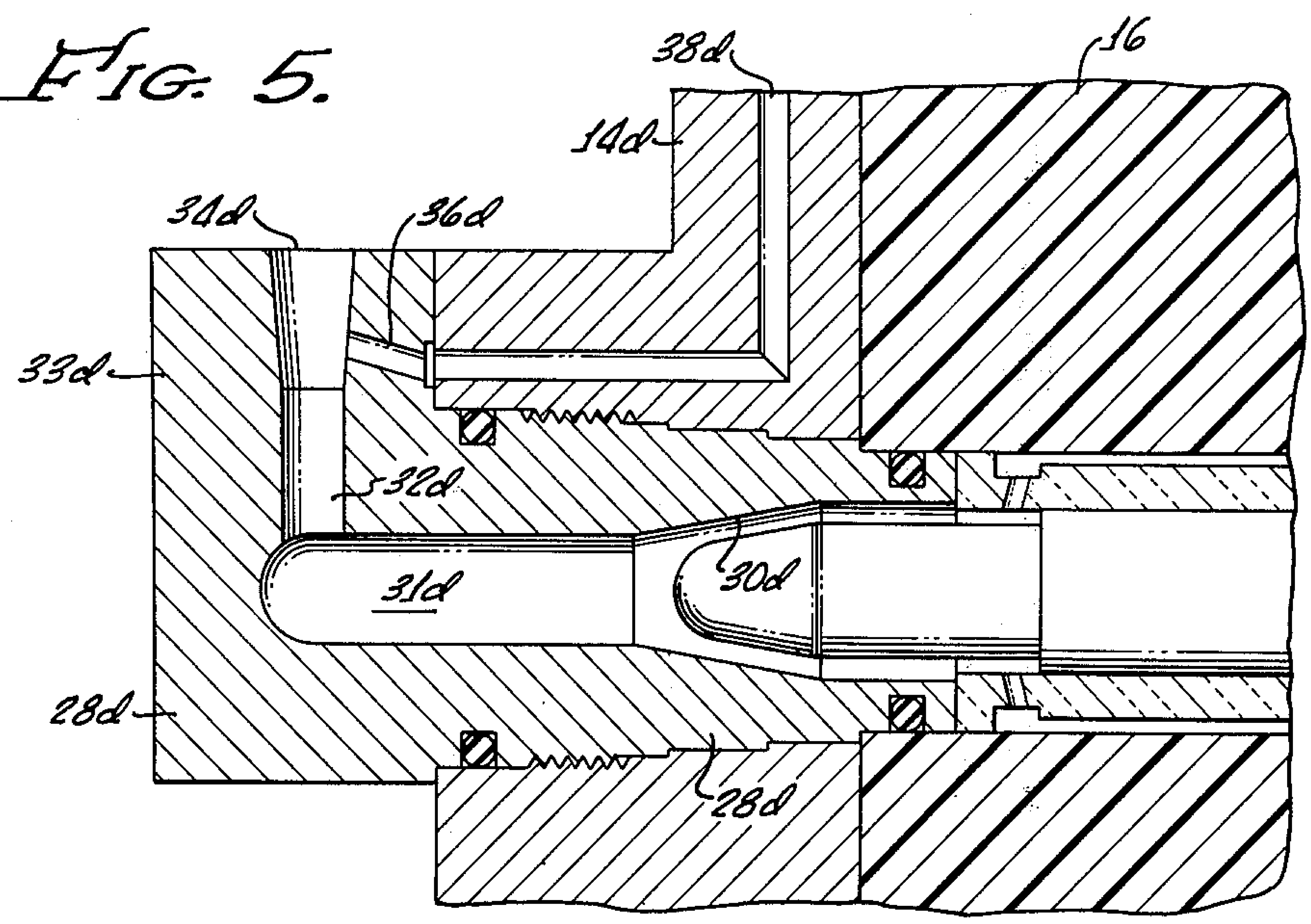
30c
28c
28c
16

FIG. 5.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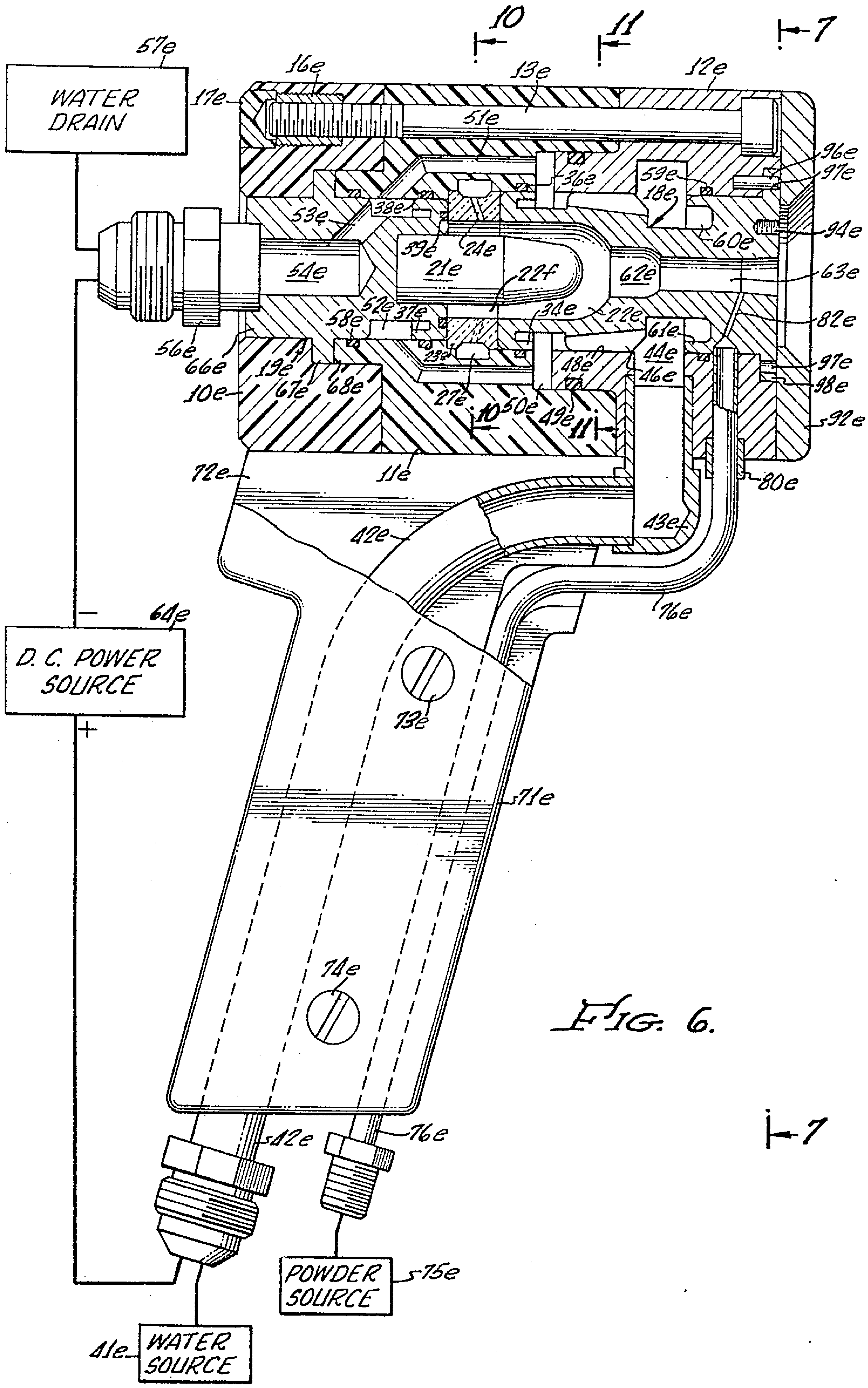
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D. C. POWER SOURCE
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WATER SOURCE
41e
POWDER SOURCE
75e
10
11
7
12e
13e
16e
17e
51e
96e
97e
59e
18e
36e
38e
53e
39e
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21e
22f
62e
63e
94e
60e
54e
52e
37e
34e
22e
82e
58e
61e
44e
46e
48e
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50e
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28e
10e
19e
67e
68e
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74e

FIG. 6.

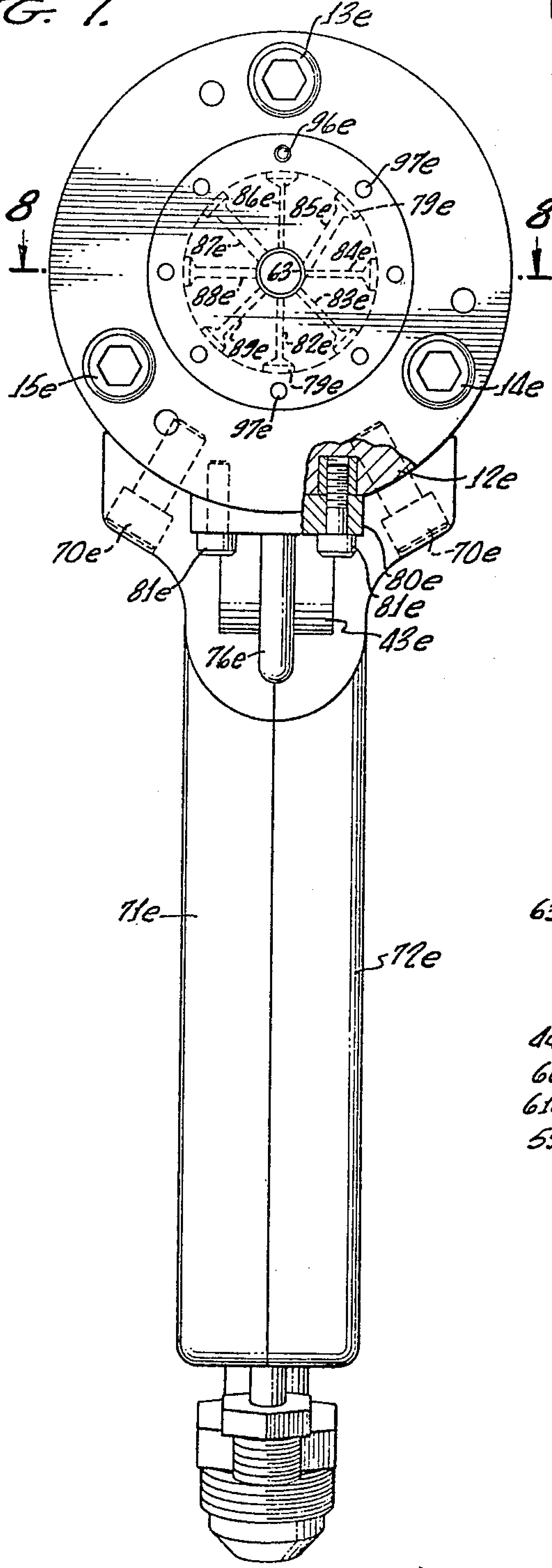

FIG. 7.

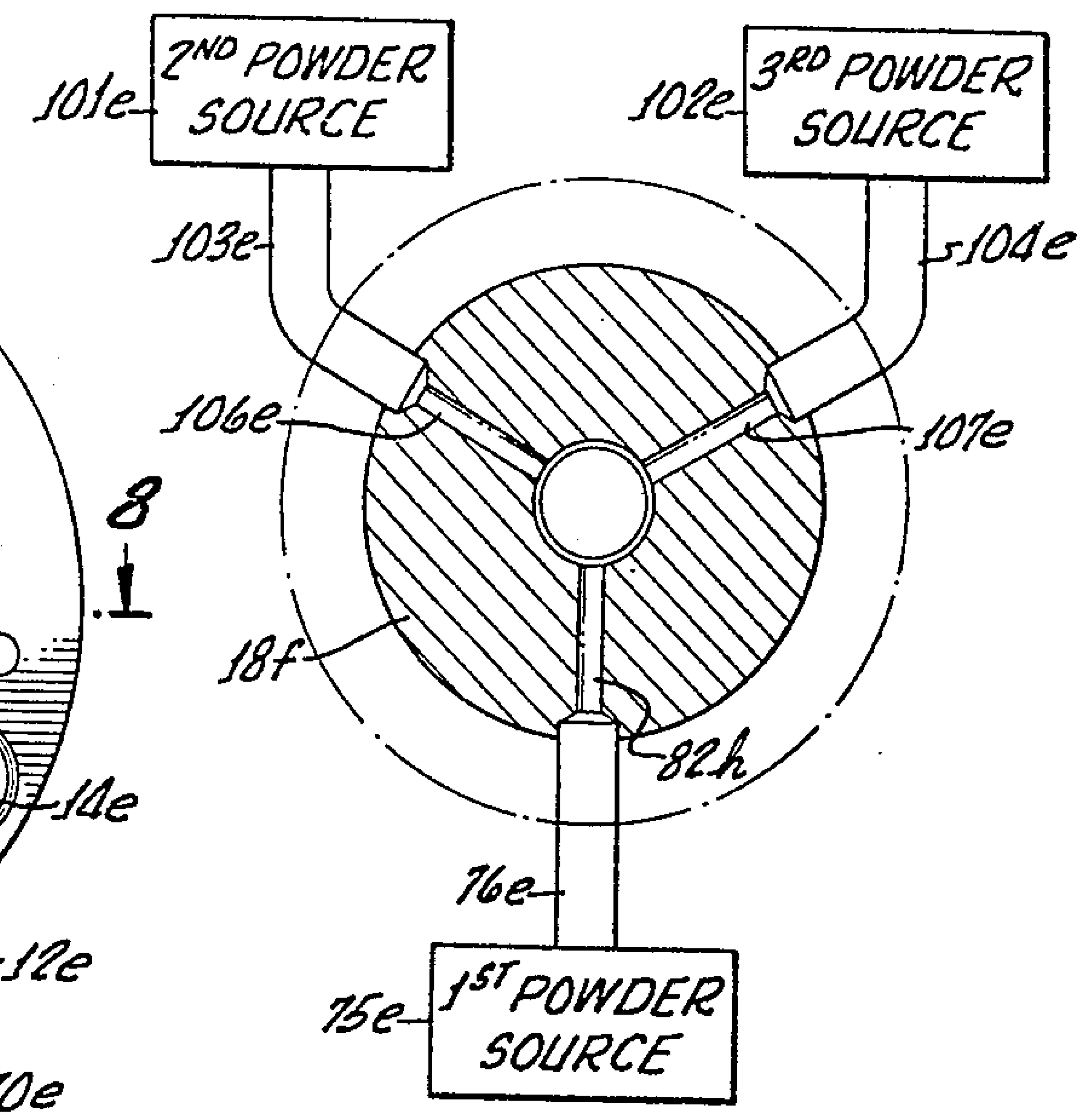

FIG. 12.

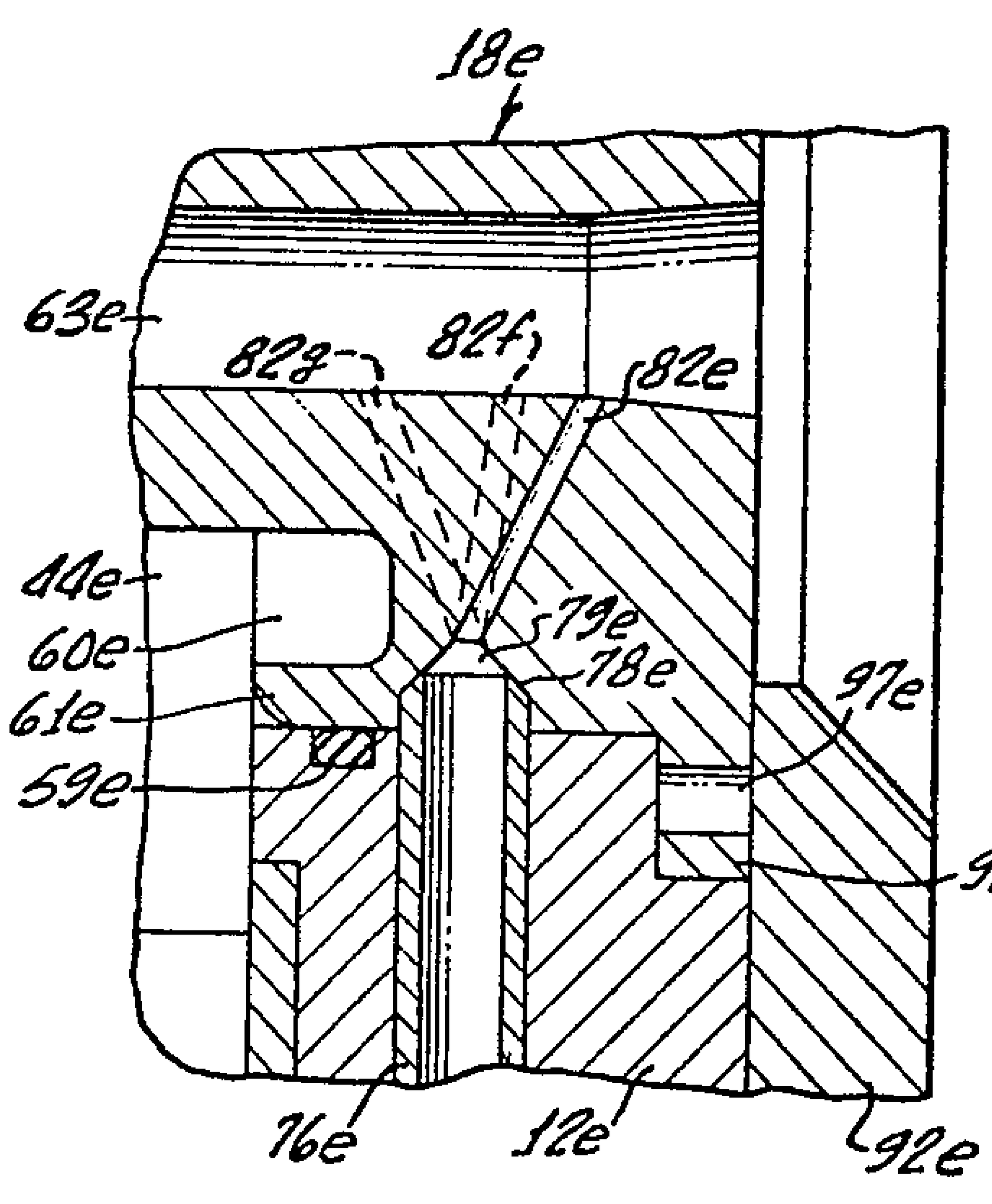

FIG. 9.

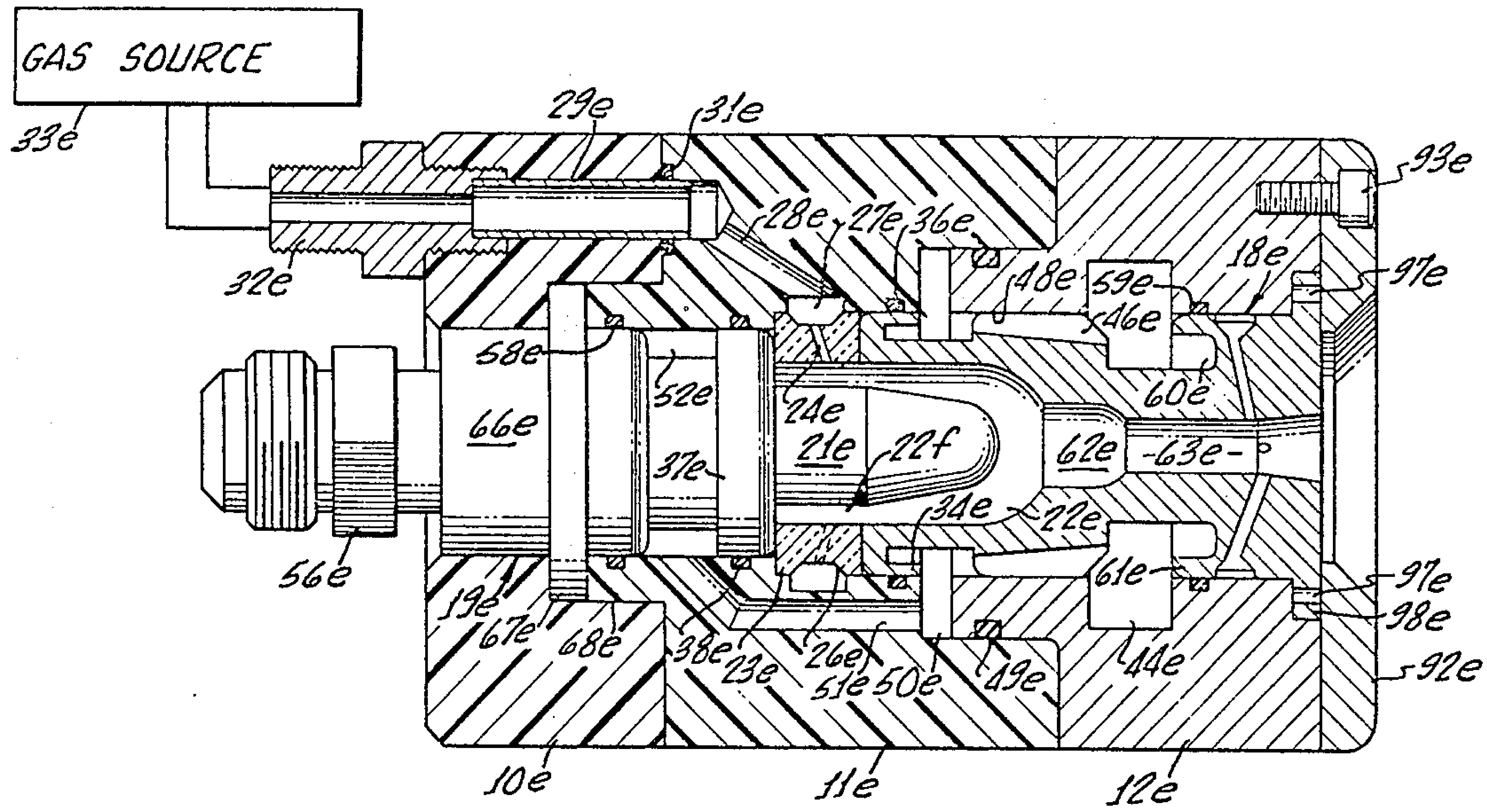

FIG. 8.

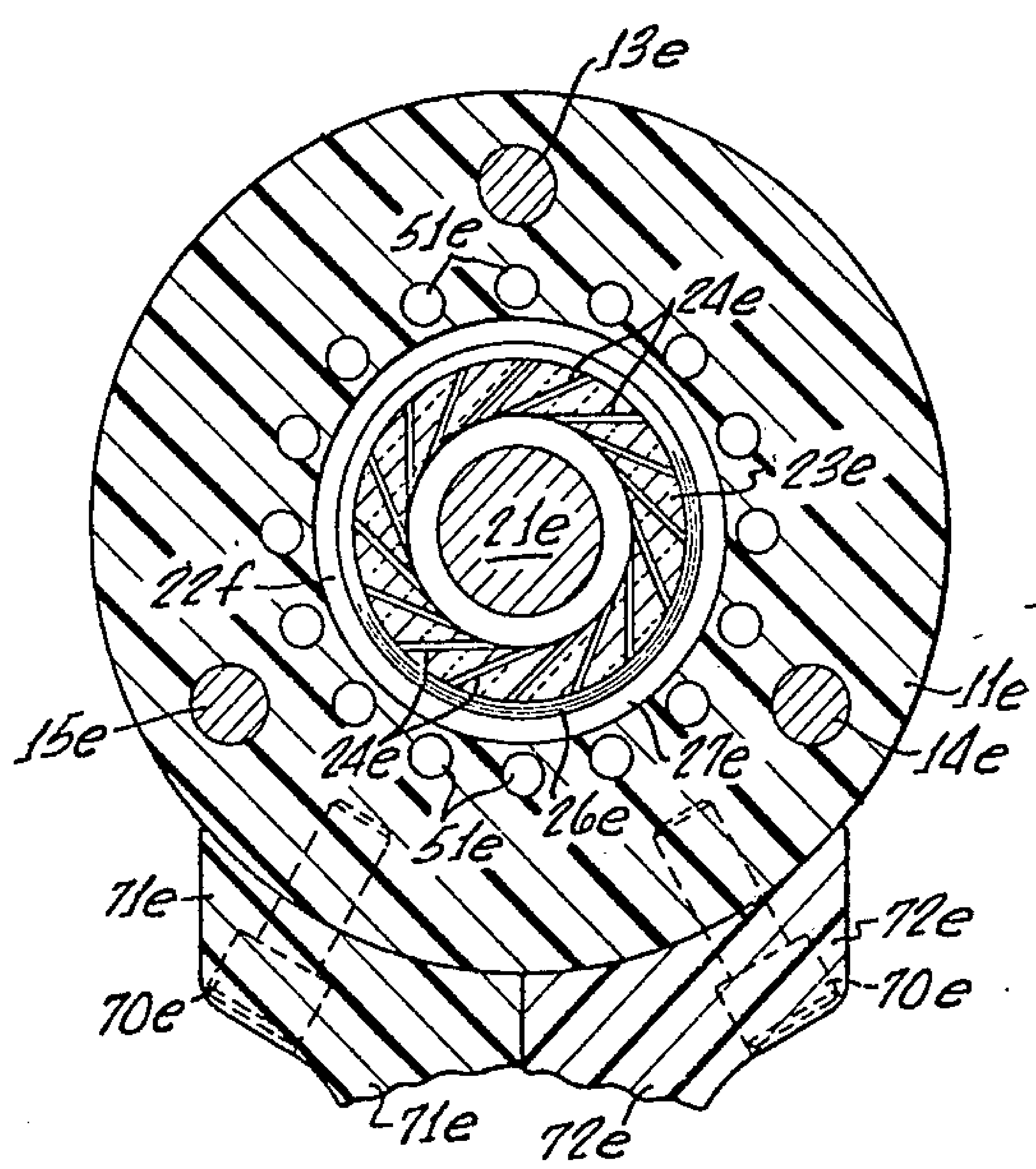

FIG. 10.

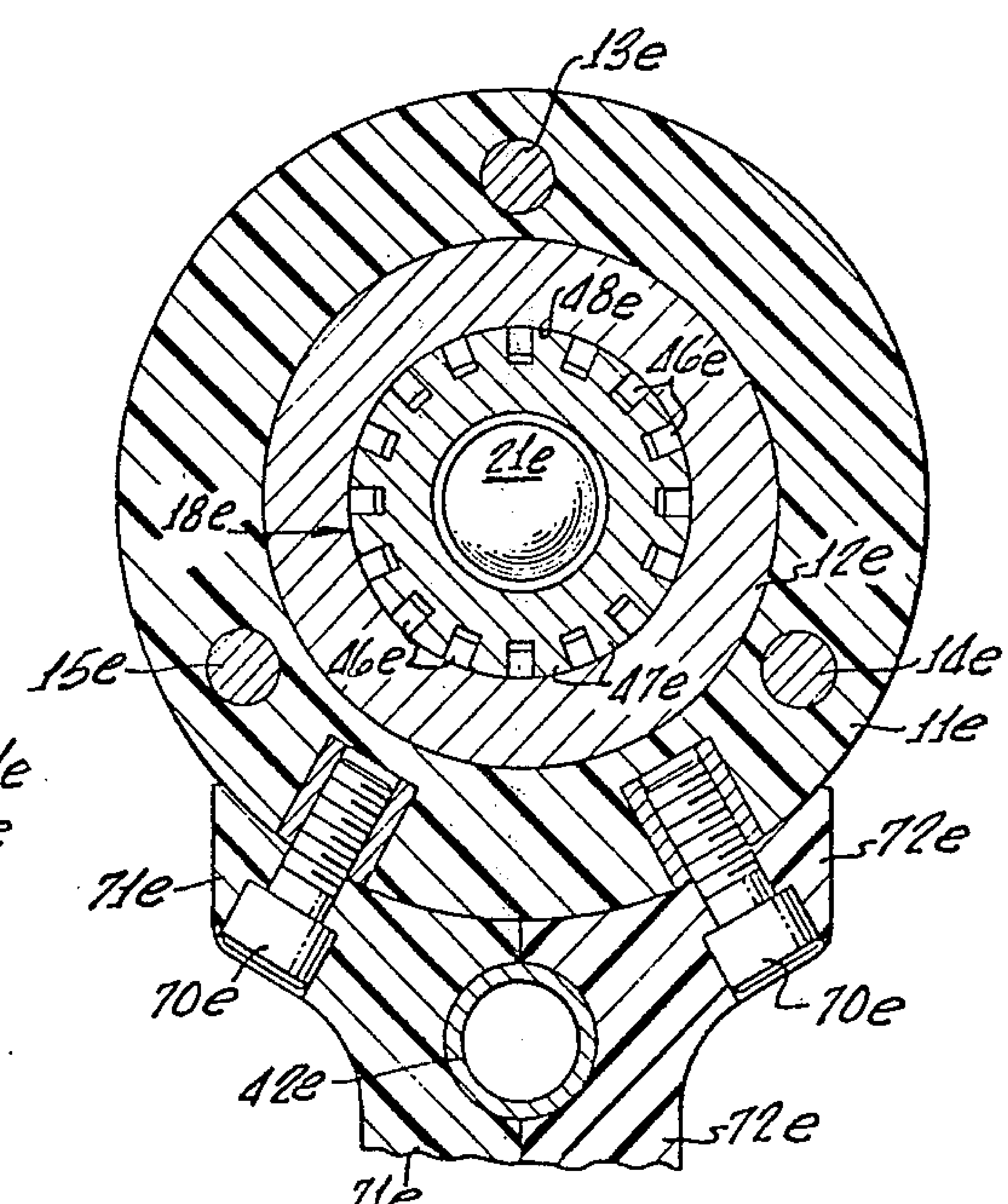

FIG. 11.

COATING HEAT SOFTENED PARTICLES BY PROJECTION IN A PLASMA STREAM OF MACH 1 TO MACH 3 VELOCITY

CROSS-REFERENCE TO RELATED APPLICATIONS:

This application is a continuation-in-part of Ser. No. 143,956, filed May 17, 1971 now abandoned, for Coating Heat Softened Particles by Projection in a Plasma Stream of Mach 1 to Mach 3 Velocity, and is also a continuation-in-part of application Ser. No. 372,260, now Pat. No. 3,823,302 filed June 21, 1973, for Apparatus and Method for Plasma Spraying. Said last-mentioned application Ser. No. 372,260 is a continuation of Ser. No. 214,584, filed Jan. 3, 1972, now abandoned, for Apparatus and Method for Plasma Spraying. This application is related to application Ser. No. 351,814 filed Apr. 17, 1973 now Pat. No. 3,839,618 which is a continuation-in-part of application Ser. No. 214,584, now abandoned.

BACKGROUND OF THE INVENTION

1. Field of the Invention:

The present invention relates to electric plasma arc apparatus and methods, and more particularly concerns such apparatus and methods for coating substrates with high-velocity heat-softened particles entrained in a supersonic plasma stream.

2. Description of Prior Art:

Arc torch devices comprising electrically powered generation of high-temperature high-velocity plasma streams have been used for many years as heat sources, as cutting torches, for plating or for coating processes, and many other similar uses. High-temperature high-velocity plasma streams projected into a vacuum test chamber have been used throughout the industry to obtain environmental conditions for research and laboratory testing. Many of these devices employ convergent-divergent or supersonic nozzle to provide the desired supersonic plasma velocity. Typical of such environmental test apparatus are devices shown in U.S. Pat. Nos. 3,149,222, 3,075,065, 3,233,147, 3,304,774, 3,106,631, 3,301,995, 3,418,445, 3,106,632.

The high temperature of the plasma stream has enabled these devices to be widely adapted for cutting of various types of materials. Examples of such plasma cutting torches are shown in U.S. Pat. Nos. 3,370,148, 2,874,265, 3,366,772 and 3,106,633. In these cutting torch arrangements, the velocity of the plasma stream is of secondary significance as compared with the stream temperature and density. Accordingly, high electrical input powers and high pressures are employed to achieve the desired temperature.

Apparatus for generating plasma streams generally comprises an arrangement for striking an electric arc between a pair of electrodes, means for passing gas under pressure into an arc chamber adjacent the arc and a nozzle for confining the exiting plasma stream.

In plasma arc generators of the transferred arc type, which are generally used as torches for cutting, welding and the like, the arc normally is struck from a rear electrode, such as a cathode, to the workpiece that is to be cut. The nozzle is often water cooled. Concomitantly, a stream of gas under pressure is passed through the nozzle with the arc.

In plasma arc torches of the nontransfer type, the arc is struck between a rear electrode, commonly a cathode, and a forward electrode that forms the exit nozzle for the plasma stream.

Another well-known use of the electric arc plasma stream comprises the coating of various materials upon a substrate. For spraying particles, as in coating, the electric arc plasma torch is provided with means for injecting suitable particles or powder into the exiting plasma stream, to be softened or melted and accelerated to high velocity. Typical of such electric arc plasma spray guns are U.S. Pat. Nos. 3,179,782 to Matvay, 3,145,287 to Siebein et al., 3,308,623 to Ferrie et al., and 3,313,908 to R. Unger et al.

It has long been known that coating qualities, including characteristics of bonding strengths, coating density and coating uniformity, show marked improvement with increasing velocity of the impinging particles. Recognizing this desideratum, much time and effort has been expended in attempts to achieve apparatus and methods that provide supersonic velocities in a plasma spray gun. In fact, several of the arrangements of the prior patents are described by the patentees, optimistically but erroneously, as capable of providing supersonic exit velocity. For example, the above-identified patent to Matvay states that an object of his invention is to propel particles at supersonic velocity and further states that the particles which are changed to molten gaseous vapor or atomic particles are conveyed at sonic or supersonic velocity.

Similarly, in the description of the patent to Unger et al., such high velocities are suggested. Nevertheless, it is a well known fact that supersonic velocity of a gas cannot be achieved without the use of the commonly known converging-diverging supersonic nozzle. As a practical matter particles injected into the plasma stream will not attain a velocity equal to that of the stream itself. Particle velocity cannot exceed gas velocity as long as the gas velocity is in a state of acceleration, as in the divergent nozzle. Only when the gas stream is decelerating can the particles achieve the same velocity as the gas stream.

Thus, if devices such as shown in the Matvay and Unger et al. patents fail to show or suggest any equipment or configuration capable of achieving supersonic gas or plasma flow, no such supersonic particle velocity can be accomplished with such configuration. Attesting to this fact is the total absence of any plasma arc equipment today (excepting that employing principles of the present invention) that actually achieves supersonic spray coating.

Accordingly, it is an object of the present invention to provide an improved method of high velocity spray coating and an improved electrical plasma torch apparatus for accomplishing such coating.

SUMMARY OF THE INVENTION

In carrying out principles of the present invention in accordance with a preferred embodiment thereof, certain supersonic parameters of a plasma stream are matched to specified parameters of particle injection. There is provided a supersonic plasma spray gun for generating and projecting a stream of plasma comprising a converging-diverging nozzle having a ratio of exit area to throat area sufficient to achieve a plasma stream exit velocity between Mach 1 and Mach 3, the nozzle including means for injecting into the plasma stream at a point between the throat and exit of the nozzle a stream of particles to be entrained by the plasma stream, the particles having a size not greater than 44 microns (−325 mesh), and being injected into the plasma stream at such an angle with respect to the direction of the stream and at such a position between the throat and exit of the nozzle as to substantially maximize the velocity imparted to the particles by the plasma stream and to provide a dwell time of particles within the stream sufficient to achieve a temperature nearly at but below the particle melting point. Different types of materials having different melting temperatures and different heat characteristics may be employed in the coating process by employing a selected one of a group of nozzles each of which has a ratio of exit area to throat area sufficient to maintain the plasma stream exit velocity within the indicated range of Mach numbers, and each of which has a differently and uniquely oriented and/or positioned particle entry conduit so that the particle dwell time within the supersonic plasma stream will optimize velocity and temperature of different materials to be sprayed.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view of the working portions of a high-velocity plasma gun employed in the practice of the present invention;

FIG. 2 is an enlarged view of an anode and cathode arrangement together with arc gas injection ports and powder injection conduit employed for spraying relatively high melting temperature particles in the gun of FIG. 1 to achieve plasma stream exit velocity of Mach 2;

FIG. 3 is a view of the anode and cathode employed in the gun of FIG. 1 for use with particles of lower temperature melting points;

FIG. 4 is a sectional view of another nozzle embodiment for spraying at a 45° angle;

FIG. 5 is a sectional view of a nozzle arranged for spraying at a 90° angle;

FIG. 6 is a vertical sectional view illustrating an additional embodiment of an electrical plasma-jet spray torch;

FIG. 7 is a sectional view taken on line 7—7 of FIG. 6;

FIG. 8 is a section taken on line 8—8 of FIG. 7;

FIG. 9 is an enlarged fragmentary sectional view showing a lower-right portion of the torch of FIG. 6, and also illustrating in dashed lines various alternative positions for the powder port;

FIG. 10 is a transverse sectional view on line 10—10 of FIG. 6;

FIG. 11 is a transverse sectional view on line 11—11 of FIG. 6; and

FIG. 12 is a transverse sectional view illustrating schematically an embodiment wherein a plurality of powder sources are employed to inject powder into the torch.

DETAILED DESCRIPTION

The fundamental parts and the overall arrangement, configuration and mode of operation of the electric arc plasma torch illustrated in FIG. 1 are substantially the same as in several prior electric arc plasma spray guns made and sold by the assignee of the present invention, including, for example, the gun shown in the patent to Johnson 3,179,783, that shown in the patent to Winzeler et al., 3,378,391, and that shown in the patent to Unger et al., 3,313,908. The disclosures of these patents are incorporated herein by this reference, as though fully set forth herein.

Proceeding first to a general description of the entire apparatus, the electrical plasma torch is illustrated to comprise an insulating handle and casing **10**, of which only portions are shown, which comprises a cup-shaped insulating body mounting a rear housing member **12** and a front housing member **14** separated from each other by an insulating ring **16**. Forwardly projecting from the rear housing member **12** is an insulating and rear electrode support sleeve **18** that encompasses a forwardly projecting rear electrode **20**. Preferably, the rear electrode comprises a thoriated tungsten tip **21** and is mounted by means including a male threaded member that extends into the threaded end of a forwardly projecting portion **23** of rear housing **12**.

The forward portion of electrode **20** has a somewhat smaller diameter than its sleeve **18** to provide a gas entry or vortex chamber **25** (see FIG. **2**) between its outer periphery and the inner periphery of sleeve **18**. Formed in the wall of sleeve **18** and communicating with the gas vortex chamber **25** are a plurality of arc gas entry conduits of which only two, **24** and **26**, are illustrated (see FIGS. **2** and **3**).

Securely fixed to, but detachable from front housing member **14** is a front electrode **28**. The front electrode **28** forms a supersonic converging-diverging nozzle that provides exiting expansion of the plasma stream to achieve the desired supersonic exit velocity. The nozzle bore includes a converging portion **30** that extends from a straight portion co-operating with the sleeve **18** and cathode **20** to define the annular gas entry chamber **25**, and then converges, tapering inwardly in close proximity to and along the mating tapered tip **21** of electrode **20**, to a nozzle throat **32**. From the throat, the nozzle bore diverges at an angle substantially less than the angle of convergence of the rearward portion to its exit port indicated at **34**.

Formed in and extending from the exterior of the nozzle or front electrode **28**, for communication with the nozzle bore, is a powder entry conduit **36**. The enlarged outer end of conduit **36** is in communication with the inner end of a passage **38** formed in the forward housing member **14**. Passage **38** is connected to a positive-feed powder hopper **40**, preferably of the type described in detail in U.S. Pat. No. 3,517,861 to R. P. De La Vega, of which the description is incorporated herein by this reference, as though fully set forth herein.

Schematically illustrated in FIG. **1** is a source of electrical power **42** having electrical connections via leads **44** and **46** to the rear and forward housing members **12** and **14**, respectively, and, through these members, to the rear and forward electrodes. Preferably, lead **44** is connected to the negative side of the power source, wherefor the rear electrode **20** is the cathode and the forward electrode **28** is the anode.

A source **48** of arc gas, such as argon for example, is coupled by means of a feed conduit **50** to provide the arc gas under pressure to the group of arc gas entry conduits **24**, **26** et cetera, via an annular space **27** formed between insulating ring **16** and sleeve **18**. In a preferred embodiment, 16 arc gas entry conduits are provided equi-spaced around the periphery of the forward end of sleeve **18**. Each of these conduits extends through the sleeve 18 in a direction that is nearly tangent to the outer periphery of rear electrode 20. In addition to this tangential inclination, each of the conduits is forwardly inclined, by an angle such as 15° with respect to a plane normal to the longitudinal axis of the apparatus. The substantially full tangential inclination of the arc gas entry conduits creates a maximum vortex pattern within the arc gas chamber. This produces a highly stable arc and minimized electrode wear to thus promote longer life of the apparatus. The forward rake of the entry conduits enhances the flow of the arc gas to and through the nozzle.

In its broad aspects, operation of the described electric arc plasma spray gun is substantially the same as that of previous guns although, as will be described in detail below, the present invention provides for selection and control of a number of essential and variable parameters which interact and must be collectively considered and controlled for a particular material in order to achieve the improved apparatus and methods of the present invention. Fundamentally, however, when power is applied from source 42 by means of a controlling switch (not shown), an electric arc is produced from the forward tip 21 of the rear electrode 20 to the forward electrode 28, impinging upon the converging internal surface 30 of the nozzle bore. Gas is fed under pressure from gas source 48 via entry conduits 24, 26 and others (not shown) where it proceeds in a helical vortex forwardly around the rear electrode 20. The gas is ionized and heated in the electric arc as it flows from the converging section of the nozzle to the throat section 32. The heated ionized gas is now a body of plasma which flows to the exit of the nozzle as an expanding and accelerating high-temperature stream of plasma. Powder hopper 40 supplies a fine powder, entrained in a powder gas, via conduits 38 and 36 to be injected into the outflowing plasma stream. The powder particles are entrained in the plasma and carried thereby to impinge upon a substrate (not shown) that is to be coated by the particles.

It is known from studies by numerous investigators that an optimum particle temperature range exists for specific materials. If this temperature range is exceeded, the particle may melt, its fluidity becomes too great, and spattering occurs when it impacts the workpiece. On the other hand, if the temperature is too low, insufficient deformation of the particle occurs upon impact, wherefor poor bonding and coating quality result. Thus, it will be seen that the only way by which individual particle energy can be increased is by increasing the kinetic energy of the particle. By increasing the velocity of the individual particles, kinetic energy, which varies as the square of the velocity, can be significantly increased. Increased total energy of the particle results in greater deformation upon impact and results in coatings having improved bonding, higher densities and greater uniformity.

To achieve this higher kinetic energy, the above-described apparatus attains a particularly specified range of plasma velocities by employing a converging-diverging supersonic nozzle together with an improved arc gas injection arrangement and matches certain critical particle parameters to these supersonic plasma stream parameters. These critical particle parameters include those relating to particle size, material, heat characteristics and angle and position of particle injection.

Many different and interacting factors must be considered, identified and controlled if the optimum particle temperature is to be obtained concomitantly with maximized particle velocity. Furthermore, these factors will vary with different particle materials. In the past, plasma spray guns have attempted to solve problems involved in spraying of different materials by varying the power input and arc gas flow rate. The above-described patent to Unger et al. suggests increase of residence time by increasing nozzle bore diameter to thereby decrease gas velocity. The above-mentioned patent to Siebein et al. suggests a forward or rearward inclination of the powder injection inlet for the spraying of different materials. However, there is no previous suggestion of either recognition or solution of the problems involved in attaining supersonic plasma flow or the requirement for varying both injection position and inclination in accordance with materials to be injected in such a supersonic flow.

In accordance with illustrative embodiments of the present invention, optimum conditions of temperature and maximized particle velocity are achieved with a variety of different materials, without varying electrical input power, temperature, arc chamber pressure or arc gas flow rate, by providing a group of nozzles each of which has an area ratio that produces a plasma stream exit velocity between Mach 1 and Mach 3, preferably, at or about Mach 2. Different nozzles are provided with powder injection passages all communicating with the nozzle bore between the nozzle throat and exit and each inclined at uniquely different angles and/or intersecting the nozzle bore at uniquely different points thereof.

Illustrated in an enlarged view in FIG. 2 is one nozzle 28*a* (also showing the rear electrode and sleeve 18 of a set of nozzles modified to enable use of the gun with different types of powder materials. The front electrode of FIG. 2 includes a nozzle particularly designed for materials of intermediate temperature melting points (between 2000° and 3000°F.). Typical of such materials are stainless steels, nickel, chromium and hard-facing alloys such as nickel-chromium-tungsten-boron, cobalt-chromium-molybdenum-boron and iron-nickel-chromium-boron. This nozzle is designed to achieve exit velocity of Mach 2 into ambient atmospheric pressure and has a throat diameter of 0.140 inches and an exit diameter of 0.190 inches for a specified power of 50 kilowatts. This provides a required area ratio that establishes the specified Mach number and a given ratio of ambient pressure to pressure at the throat of the nozzle. The length of the nozzle exit cone from the forward edge of the throat to the exit is 0.477 inches. In the specified example, the area ratio is 1.813 and the pressure ratio is 0.1314. Where ambient pressure is 1 atmosphere this entails a pressure of 7.6 atmospheres in the arc chamber and provides a gas exit speed of approximately 10,000 feet per second.

These plasma stream conditions are achieved by a power input of approximately 50 kilowatts, employing 900 amperes at 55 volts and an arc gas flow from source 48 of 225 standard cubic feet per hour.

As shown in FIG. 2, the particle injection conduit for these conditions and for the above-identified group of materials of intermediate melting temperatures is inclined downstream at an angle of 10° with respect to a normal to the direction of plasma flow (axially of the nozzle bore). The axis of the particle injection conduit

36*a* intersects the outer surface of nozzle **28***a* at a point that is spaced 0.375 inches rearwardly of the nozzle exit. This positions the particle injection conduit at a point on the nozzle bore substantially midway between the nozzle exit and throat but somewhat closer to the throat.

The same gun, having the same power and gas inputs, may be employed for spraying of materials having substantially higher temperature melting points (3000°F. and higher), such as tungsten carbide-cobalt, chromium carbide-nickel chromium blends, tungsten, and molybdenum. For such application, the nozzle **28***a* of FIG. **2** is replaced by the nozzle **28** (of FIG. **1**) that is identical to the nozzle **28***a* in all respects except for the angle and location of the particle injection conduit. The nozzle **28** of FIG. **1** is the "high temperature" nozzle of the exemplary set of three interchangeable nozzle described herein. For such high-temperature materials, the angle of inclination of the injection passage axis with respect to a normal to the bore axis is decreased and is 5°. The point of entry of the injection conduit **26** into the nozzle bore is moved slightly rearwardly. This may be achieved, for example, by retaining the same location for the intersection of the particle conduit axis and the external surface of the nozzle, whereby the decreased angle will move the entry port closer to the nozzle throat. By decreasing the angle of inclination of the particle injection conduit, dwell time of the particles in the plasma stream is increased at least in part because the particles have a smaller initial component of velocity parallel to the direction of plasma flow. Further, the relatively rearward positioning of the particle injection conduit also increases the dwell time.

This positioning of particle entry achieves other more significant results in the transfer of kinetic energy from the plasma stream to the particles. In particular, since in this converging-diverging supersonic nozzle the plasma stream has its highest density at or near the nozzle throat, the closer the particle injection is to such point of maximum plasma density, the greater is the heating effect of the plasma upon the particles. With greater density of plasma, there is a much greater frequency of collision between powder particles and plasma, this collision frequency being the essential mechanism by which kinetic energy is imparted to the powder particles. Thus, the rearward positioning of the particle entry port achieves increased acceleration of the particles and increased rate of heating, whereby for materials of the indicated high-temperature melting point the projected particles will have maximized velocity and, at the same time, will be sufficiently heated.

For another group of materials having a lower temperature melting point (2000°F. and less), such as bronze, copper and aluminum, it is necessary to provide a shortened dwell time and to provide injection at a much increased angle and at a point closer to the nozzle exit if optimum velocity is to be achieved without premature melting of these particles. For such low-temperature melting point materials, there is provided a third type of nozzle **28***b*, as illustrated in FIG. **3**. This nozzle is interchangeable with each of the others and also is identical to each of the others in all respects except for the angle and position of the particle entry port **36***b*. Thus this nozzle assumes the same physical and operative position with respect to the rear electrode **20** and sleeve **18**, which are also shown in FIG. **3**. As illustrated in FIG. **3**, particle entry conduit **36***b* is inclined at an angle of 36° with respect to a normal to the axis of the nozzle bore. This increased inclination, of course, will move the intersection of the entry end of the injection conduit with the nozzle bore much closer to the nozzle exit. Nevertheless, it is found that if still greater forward displacement of the point of particle entry is desired the point of intersection of the injection conduit with the exterior of the nozzle insert may also be moved somewhat forwardly with respect to the similar point of the other nozzles. The short dwell time and injection of particles adjacent the nozzle exit with this low-temperature nozzle prevents premature melting of the particles and plating buildup in the nozzle bore.

From the above description, it will be seen that the exemplary set of nozzles enables a unique co-operative action between the elongated and smoothly diverging bore of the converging-diverging supersonic nozzle and the particle injection passage of selectively variable inclination and position along the bore. Although but three nozzles are included in the described set it will be readily understood that more nozzles may be employed and formed with still other choices of angle and position of particle entry conduit as determined for optimum operation with particular powders.

Illustrated in FIG. **4** is a nozzle employing principles of the invention as described herein and formed with the specific parameters, dimensions and shapes described above. This nozzle has certain modifications that enable the plasma spray stream to be projected at an169 angle of substantially 45° with respect to the axis of the rear electrode. The 45° spray nozzle **28***c* of FIG. **4** is substantially similar in size and nozzle dimensions to the nozzle described above, and includes a converging nozzle portion **30***c*. The nozzle also includes a throat section **32***c* and a diverging portion that terminates in a nozzle exit **34***c*, all of which are identical in dimensions and operation with the corresponding parts described in connection with FIGS. **1** through **3**. In this arrangement the nozzle is formed with an intermediate nozzle portion **31***c* that is interposed between converging nozzle section **30***c* and throat section **32***c*. This facilitates the angular transition of the plasma flow and enables the axis of the projected plasma stream to extend at the indicated 45° angle.

A powder conduit **36***c* is positioned at an angle and at a location between nozzle exit and nozzle throat exactly as specified in connection with the above described nozzles of FIGS. **1** through **3** for high, low or intermediate temperature powders, as desired. Since the axis of the diverging nozzle portion is at 45° with respect to the axis of the converging nozzle portion, the nozzle is formed with a projecting shoulder **33***c* in which the powder conduit **36***c* is formed. It will be readily appreciated that the other portions of the spray gun are suitably modified so that the powder conduit **38***c* will properly deliver powder to the passage **36***c*. Therefore, a slightly different configuration of the spray gun front housing member **14** is required for the angulated spray nozzles.

For ejecting a plasma stream and entrained particles at a 90° angle, the nozzle **28***d* of FIG. **5** is employed. This has a configuration quite similar to that of FIG. **4** and includes a converging nozzle portion **30***d*, an intermediate nozzle passage portion **31***d*, a nozzle throat **32***d* and a nozzle diverging portion that terminates in nozzle exit **34***d*. This nozzle, like the nozzle of FIG. **4**, includes a powder entry conduit **36***d* that is positioned to intersect the diverging nozzle portion at a particularly chosen point between the throat and exit and is directed at an angle with respect to the direction of the motion of the plasma stream in accordance with the particular critical parameters described herein. Again, as in FIG. 4, the nozzle throat and diverging nozzle portion are formed within a projecting shoulder **33***d*, in which shoulder is also formed the powder entry conduit **36***d*. The angulated nozzle of FIG. **5** like the angulated nozzle of FIG. **4**, requires modification of the spray gun itself in order to provide flow of powder through the gun passage **38***d* and thence into the powder entry conduit **36***d*.

Except for the described variations in angulation of the nozzle, the nozzles of FIGS. **4** and **5** both employ all of the critical dimensions and operating parameters described in connection with the nozzles of FIGS. **1** through **3** and either of the nozzles of FIG. **4** or FIG. **5** may be employed with any one of the described powder entry conduit angles and locations for spraying of low, intermediate or high temperature melting point particles.

For each of the described nozzles, typical dimensions and angles in addition to those identified above are as follows: The converging portion of the nozzle surface **30** makes an angle of 10° with respect to the gun axis. The diverging portion of the nozzle, between its throat and exit, has a considerably smaller degree of angulation, such as 3°. The distance between the forward tip of the rear electrode **20** and the nozzle exit (FIGS. **1–3**) is 1.0 inches. The length of the nozzle throat of unvarying diameter is 0.15 inches, and the diameter of the particle entry passage is 0.062 inches. Further, all particle sizes are less than 44 microns.

Shown in Table I are typical materials, particle sizes, powder entry velocities and powder entraining gas flow rates that exemplify, but in no way limit, the practice of this invention.

Each of the materials of Table I has been sprayed in the described apparatus at plasma exit velocities of Mach 2, all employing 900 amperes of current at 55 volts, with an arc gas flow rate of 225 standard cubic feet per hour. The aluminum, bronze and copper have been sprayed with the above-described low-temperature nozzle as illustrated in FIG. **3**. The stainless steel, nickel-chromium, and chromium carbide-nickel chromium were projected with the intermediate temperature nozzle of FIG. **2**, and the other materials of Table I were projected with the high-temperature (5° inclination) nozzle shown in FIG. **1**. It will be seen that all of the particles were injected in sizes considerably smaller than 44 microns. The aluminum and copper particles were analyzed as having an average size of 9 microns.

TABLE I

Material	Composition	Particle Size Microns	Anode	Power Flow Rate (lb/hr)	Power Gas scfh
Aluminum	99.5% Al	44	Low Temp.	0.5	20
Aluminum Bronze	10% Al, 90% Cu	44	Low Temp.	1.7	20
Copper	99.3% Cu	44	Low Temp.	1.5	20
Nickel-Chromium	80% Ni – 20% Cr	10 – 25	Int. Temp.	1.8	25
Chromium Carbide-Nickel Chromium	75% Cr_3C_2 25% NiCr	15 – 25	Int. Temp.	1.3	20
Molybdenum	99.5% Mo	10 – 44	High Temp.	2.9	25
Stainless Steel (304)	18% Cr, 8% Ni, balance Fe	44	Int. Temp.	1.4	20
Tungsten	99.5%	10 – 44	High Temp.	2.6	25
Tungsten Carbide-Cobalt	88% WC, 12% Co	10 – 25	High Temp.	1.6	25

In Table I where but a single size (not a range) of particle size is given, this identifies a maximum, with average size in all cases being considerably less than 44 microns.

As described above, the choice of powder entry conduit location, together with choice of powder entry conduit angle, are critical parameters that must be matched with the particular material being sprayed. Nevertheless, the values specified are the preferred values within a range of such locations and angles that may be employed in the practice of the invention. The following ranges of angles and locations are given by way of examples for the illustrated gun. In these ranges, the outer end of the powder entry conduit is retained at the same position and the entry angles are varied. Therefore, the entry locations are also caused to vary. Although this is a most convenient way to manufacture a group of nozzles with different entry angles and positions within the diverging exit cone of the supersonic nozzle, it will be readily appreciated that either the angle only may be changed while retaining the same position of entry of the powder entry conduit or, alternatively, the angle of entry may remain the same and the position of the entry of the powder conduit into the nozzle exit cone may be varied. Within such ranges of variations of angle and location of powder entry conduit for the respective low, intermediate and high temperature melting point particles, the desired end conditions will be optimized, these conditions being maximized heating of the particles without melting and minimized velocity differential between the plasma and the particles.

The ranges are as follows. For anode **28**, designed for high (3000°F. and higher) melting point materials, the powder is normally injected at a forwardly inclined (downstream) angle of 5° and enters the exit cone of the nozzle 0.129 inches from the forward edge of the nozzle throat. To optimize the injection of specific high melting point materials, the injection angle can vary from -13° upstream (inclined rearwardly), entering the nozzle exit cone 0.032 inches from the nozzle throat, to 7.5° downstream (forwardly inclined), entering the nozzle exit cone 0.142 inches from the nozzle throat.

For anode **28***a*, designed for intermediate (2000° to 3000°F.) melting point materials, the powder is normally injected at an angle of 10° downstream and enters the exit cone of the nozzle at 0.156 inches from the nozzle throat. To optimize injection of specific intermediate melting point materials, the injection angle can vary from 7.5° downstream, entering the nozzle exit cone at 0.142 inches from the nozzle throat, to 25° downstream, entering the nozzle exit cone 0.244 inches from the nozzle throat.

For the anode **28***b*, designed for low (2000°F. and less) melting point materials, the powder is normally injected at an angle of 36° downstream and enters the nozzle exit cone 0.324 inches from the nozzle throat. To optimize the injection of specific low melting point materials, the injection angle can vary from 25° downstream, entering the nozzle exit cone at 0.244 inches from the nozzle exit, to 49° downstream, entering the nozzle exit cone 0.453 inches from the nozzle throat.

The above-specified preferred values for Mach number, power, gas flow and related nozzle dimensions have been chosen for practical purposes, and it will be readily appreciated that these may be varied without departing from the principles of the described invention. Nevertheless, there are certain critical limits for the several parameters as described above without which optimization of the specified temperature and velocity of ejected particles cannot be accomplished. Thus, with a plasma exit velocity of less than Mach 1, desirable density, bonding and uniformity of particle coatings cannot be achieved. On the other hand, to attain an exit velocity of Mach 3 or greater requires too much power. Further, at plasma velocities of Mach 3 and greater, the energy of the stream is much too high.

It will be readily understood that pressure of the powder gas, that is pressure in the powder hopper from which the injected particles are drawn, is established at a value greater than the static pressure within the supersonic nozzle at the point of powder injection. In the supersonic nozzle, the gas stream pressure, and also the static gas pressure at the periphery of the nozzle bore, varies (in a non-linear fashion) from a maximum at the entrance to the nozzle throat, to its lowest value at the nozzle exit. For the exemplary guns described herein, the arc chamber pressure, which is the gas pressure at the entrance to the nozzle throat, is 7.6 atmospheres, whereas the pressure at the nozzle exit is ambient pressure, or 1 atmosphere. These nozzle pressures are higher than those in the subsonic spray guns and, accordingly, require higher powder gas hopper pressures.

Various factors are involved in optimizing particle and gas entrance velocity and hopper pressure. In general, entrance velocity of the powder gas need not be supersonic, nor even sonic. High subsonic entrance velocities of the powder gas have been found to be adequate. A primary constraint is that the momentum of the particles entrained in the powder gas must be sufficient to allow the particles to penetrate the boundary layer of the outflowing plasma stream and enter into the stream toward the center thereof. In addition to the static pressure of the outflowing plasma stream at the point of entry of the particles, the angular velocity of the plasma stream is also a factor. It will be recalled that the arc gas enters the arc chamber tangentially, whereby the outflowing gas follows a helical, or spiraling path, having its greatest angular velocity at the nozzle throat. As the nozzle and gas expand, the angular velocity component of the exiting plasma decreases. Note that the relatively greater angular velocity component of the plasma at or near the throat is yet another factor (in addition to the above-described greater plasma density) that enhances transfer of kinetic energy to particles injected closer to the throat.

For a given entry point within the nozzle bore, injected particles of greater mass will have greater momentum for the same velocity, as compared with particles of lesser mass so that comparatively lower entrance velocities of powder gas may be employed for such higher mass particles. In any event, entrance velocities of the powder gas at, or approaching sonic velocity, (Mach one) are preferred. It will be understood that supersonic entrance velocities of the powder gas may be useful under certain conditions and can be achieved by employing appropriate area ratios and pressure ratios of a converging-diverging powder entry conduit.

With the exemplary high temperature particle nozzle, illustrated in FIG. **1**, wherein powder conduit entry angle is 5°, entering the nozzle exit cone 0.129 inches downstream of the nozzle throat, powder gas entry velocity at, or nearly at Mach 1, is achieved with a hopper pressure of some 40 to 50 pounds per square inch. At this particular point of entry within the illustrated nozzle, static pressure of the plasma has decreased from its maximum, at the throat, to a value of approximately 25 pounds per square inch. This achieves a pressure ratio of approximately the required 1.8 to 2.0 for sonic or near sonic entry velocity of the powder gas. The increased powder gas pressures within the powder hopper that are required for the greatly increased plasma pressures through a major portion of the nozzle bore are readily available with the above-described hopper by increasing the pressure of the powder gas that is fed to the hopper. In general, the pressure of such input powder gas to the hopper is maintained at least equal to, but preferably above, the pressure required to ensure the desired entrance of the particles into the plasma stream.

As described in detail herein, a number of critical dimensions and operating parameters are required for the practice of the present invention. Nevertheless, the sizes and powers described for the exemplary guns may be scaled to provide spray guns of different sizes and powers, still achieving the improved results of the present invention. These varying sizes may be accomplished by suitable scaling of several of the parameters of the described guns. To vary the gun size and accordingly to vary the output of the gun, it is necessary to linearly scale certain of the gun parameters, although other essential parameters such as Mach number and temperature of the plasma stream will remain the same. Factors that are linearly scaled, either upwardly or downwardly from those described herein, are the area ratio, the nozzle volume (between throat and exit), the mass flow rate of gas, the feed through flow rate of powder and the power applied to the gun. For example, in order to upwardly scale the described gun by a factor of 10, assuming for this example that the power applied to the described gun is 50 kilowatts, one would apply 500 kilowatts to the gun, increase the area of both nozzle throat and nozzle exit by a factor of 10, increase the nozzle volume between throat and nozzle exit by a factor of 10, and also increase the mass flow rate both of the gas and of powder by a factor of 10. Even with such increases in this upward scaling, temperature and exit speed of the plasma and entrained particles remain substantially the same. The critical angles and locations of the particle entry passages also remain the same.

Scaling upwardly by a factor of 100 requires the use of 5 megawatts of power and results in the use of a nozzle having an exit diameter of 1.9 inches. Thus, the exiting collimated stream of coating particles would have a diameter of 1.9 inches in such upwardly scaled gun, as compared to a similar diameter of 0.19 inches in the gun illustrated in FIGS. **1–3.**

Similarly, the illustrated gun may be scaled downwardly by linearly changing the identified dimensions and parameters.

The desired Mach number and critical area ratio may be obtained with nozzle cone half angles (angle of divergence of the diverging nozzle portion) within the range of 3 to 18°. Nevertheless, the smallest cone half angle is preferred since this smaller angle enables use of a greater length of diverging nozzle portion (between exit and throat). The increased nozzle length provides for a greater dwell time which is particularly useful for high temperature melting point particles, and thus allows for a greater energy exchange between the plasma stream and the entrained particles.

With the above-identified nozzle parameters and Mach number there is provided what is termed a "matched nozzle" which results in a substantially collimated exit stream having a minimum of a divergence after it leaves the nozzle. Thus, upward scaling of the nozzle and spray gun and related parameters, as described above, will achieve a larger area of particle coating stream. Similarly, downward scaling will achieve a smaller area of particle stream whereby the gun may be designed in accordance with the principles of the present invention to provide the desired coating stream area.

There have been described an improved apparatus and method for supersonic spraying of fine particles employing a unique combination of electrical power and supersonic nozzle, having particularly selected and controlled particle size, entry angle and location. The described invention accomplishes the spray coating of particles of many different heat characteristics with the same spray gun operated under the same parameters merely by selecting one of a group of supersonic nozzles having individual and uniquely oriented and positioned powder entry passages. Thus, plasma exit velocities of from 5 to 50,000 feet per second are achieved entraining optimumly heated particles having velocities of 1 to 10,000 feet per second.

DESCRIPTION OF FIGS. 6-11, INCLUSIVE

Referring next to FIG. **6**, a torch body is illustrated to comprise three annular body members **10***e* **11***e* and **12***e* which are mounted in closely nested relationship relative to each other. The rear body member, numbered **10***e*, is formed of a suitable insulating plastic such as a phenolic. The intermediate body member **11***e* is also formed of insulating plastic but preferably one which is much stronger, such as a fiber glass-resin composition. Front body member **12***e* is formed of metal, such as brass.

Each of the annular body members defines an opening therethrough, and the three such openings combine to produce an opening or passage through the torch. Into such torch opening or passage are inserted the anode and cathode means, as described below.

The annular body members **10***e*–**12***e* are maintained in assembled relationship, despite the very high pressures contained therein, by means of three bolts **13***e*–**15***e* (FIGS. **6** and **7**) which are oriented longitudinally to the common axis of the body members and are circumferentially spaced 120° from each other. The bolts extend interiorly of the body members, instead of through external flanges or connectors, thereby greatly improving the compactness of the torch.

The head of each bolt **13***e*–**15***e* is recessed into a cylindrical cavity in the forward surface of front body member **12***e*. The threaded rear end of each bolt is threaded into a nut **16***e* (FIG. **6**) which is mounted in a recess in the rear member **10***e*. An insulating plug **17***e* is cemented into the recess in member **10***e* to conceal the rear end of each bolt and to prevent the operator from making electrical contact therewith.

It is emphasized that all portions of the torch rearwardly of the metallic front body member **12***e* are insulating, except for the connection to the cathode means described below. This relationship makes the present apparatus relatively safe to operate.

As shown in FIGS. **6** and **8**, the body members **10***e*–**12***e* receive in snug-fitting relationship an anode means **18***e* and a cathode means **19***e*, the latter having a stick (rod) electrode portion **21***e* which extends coaxially into an arc chamber **22***e* in the anode means.

A gas-injector ring **23***e*, formed of a heat-resistant insulating ceramic such as boron nitride, aluminum oxide, zirconium oxide, etc., is mounted between the adjacent or inner end portions of the anode means and the cathode means and in radially-outwardly spaced concentric relationship to the stick electrode portion **21***e*. More specifically, the cylindrical inner surface of gas-injector ring **23***e* is flush with the cylindrical surface of the side wall of arc chamber **22***e*, so that the gas-injector ring and the anode means cooperate to define a gas-vortex chamber **22***f* around the stick electrode portion.

Arc gas is introduced into such gas-vortex chamber **22***f* through a multiplicity of small-diameter gas-inlet passages **24***e* (FIGS. **6, 8** and **10**) which are drilled through the gas-injector ring **23***e*. The illustrated passages **24***e* are, in the illustrated embodiment, tangentially oriented relative to the gas-vortex chamber **22***f* and, furthermore, incline somewhat forwardly relative to a vertical plane which is perpendicular to the axis of the apparatus. In some instances, however, other types of gas injection may be employed, for example injection which is not adapted to effect vortical flow in the chamber around the stick electrode.

It is an important advantage of the present torch that the manner of arc gas injection may be readily changed, merely by substituting one ring **23***e* for another. The ring **23***e* also produces other important advantages, including (a) permitting the vortex chamber **22***f* to be small in diameter, and (b) effectively insulating the anode and cathode from each other.

Gas-injector ring **23***e* has a rectangular cross section except at the exterior surface thereof, which is provided with an annular groove **26***e* communicating with the various gas-inlet passages **24***e*. The ring **23***e* is seated in a recess or counterbore which is formed in the forward side of intermediate body member **11***e*. The wall of such recess or counterbore is undercut, at the region radiallyoutwardly of groove **26***e*, to provide an annular manifold chamber **27***e* into which arc gas is introduced through a passage **28***e* (FIG. **8**). Passage **28***e* communicates with a recess in intermediate body **11**e, and into which a tube **29***e* is sealingly inserted (there being an O-ring 31*e*). Tube 29*e* is soldered to a fitting 32*e* adapted to be connected to a gas source which is schematically represented at 33*e*.

It is emphasized that, in accordance with the present apparatus and method, a very large amount of power is "packaged" within a very small space, with consequent enormous generation of heat. For example, in a torch wherein the arc chamber 22*e* is only about two-thirds of an inch in diameter, the power input may be between 80 kilowatts and 100 kilowatts. The heat-resistant gas-injector ring 23*e*, particularly since it is spaced rearwardly from the arcing tip of the electrode 21*e*, is able to withstand the resulting extremely high temperatures. However, means are provided to cool the seals which prevent escape of gas from manifold chamber 27*e* except through the gas-inlet passages 24*e*.

The inner end of anode means 18*e* has a radial flange the rear radial surface of which is abutted against the radial forward surface of gas-injector ring 23*e*. The flange extends outwardly to a cylindrical element 34*e* the exterior surface of which abuts an O-ring 36*e* which is mounted in a groove formed in the interior wall of intermediate body 11*e*. Furthermore, an undercut is formed between the element 34*e* and the main body of the rear portion of anode means 18*e*, into which water flows to thereby maintain O-ring 36*e* sufficiently cool that it will not deteriorate.

In similar manner, the forward end of the stick-holder or slug-holder portion (described hereinafter) of cathode means 19*e* is provided with a radial flange and with a cylindrical element 37*e*, the latter contacting an O-ring 38*e* which is seated in the intermediate body. The resulting undercut receives water which maintains the O-ring 38*e* relatively cool. In addition, an O-ring 39*e* is mounted in the radial forward surface of the slug holder, in contact with the radial rear wall of the gas-injector ring 23*e*, being cooled by water present in the undercut in the cathode means.

There will next be described the remainder of the cooling means which maintain the anode and cathode means sufficiently cool that they will not melt or deteriorate excessively, despite the great heat which is generated by the electric arc. Water from a suitable source 41*e* (FIG. 6) is caused to flow rapidly through a large-diameter conduit 42*e* and thence into a right-angle fitting 43*e* the upper end of which is brazed into a recess in front body 12*e*. The fitting communicates with an annular groove 44*e* formed in the front body 12*e*. From such groove 44*e*, the water is forced rearwardly through a large number of saw cuts or notches 46*e* (FIG. 11) which are defined by teeth 47*e* extending outwardly from anode means 18*e* at the region around arc chamber 22*e*. The teeth 47*e* are in surface engagement with an interior cylindrical surface 48*e* of the front body 12*e*, so that the water is not merely caused to flow around the saw cuts or notches 46*e* but instead is forced rapidly therethrough in highly efficient cooling relationship to the anode means.

The interior surface 48*e* is formed on a neck portion of the front body 12*e*, such neck portion extending rearwardly into a large counterbore in intermediate body 11*e*. An O-ring 49*e* is provided to prevent leakage of water out of such counterbore.

The rear end of the neck portion of front body 12*e* is spaced forwardly from the opposed radial surface of intermediate body 11*e* at the indicated counterbore, whereby to form an annular chamber 50*e* into which the water flows after leaving the saw cuts or notches 46*e*. It is emphasized that the water upon entering the chamber 50*e* impinges against the above-described cylindrical element 34*e* to aid in cooling the O-ring 36*e* adjacent thereto.

From chamber 50*e*, the water flows rearwardly through a large number of circumferentially-spaced longitudinal bores or passages 51*e* in intermediate body 11*e* (FIG. 10), such bores having rear portions which incline inwardly and rearwardly to a chamber 52*e* which is defined in intermediate body 11*e* around cathode means 19*e*. The chamber 52*e* communicates with a plurality (for example, six) of passages 53*e* which are formed through the cathode means 19*e* and which communicate with a central passage 54*e* therein and thus with a fitting 56*e* leading to a suitable drain 57*e*.

An O-ring 58*e* is provided around the cathode means 19*e* to prevent leakage of water from chamber 52*e*. An additional O-ring, numbered 59*e*, is formed around the front portion of the anode means 18*e* between a cylindrical external surface thereof and an interior cylindrical surface of the front body 12*e*, forwardly of annular groove 44*e*. Heating of the last-mentioned O-ring 59*e* is prevented by water present in an undercut region 60*e* of the anode means, such region being located radially-inwardly of a cylindrical portion 61*e* of the anode means and which abuts the O-ring 59*e*.

Anode means 18*e* is a single element made of copper, and which is machined or otherwise formed to contain the various cooling portions described above. The anode means also contains the arc chamber 22*e* as described, which arc chamber 22*e* communicates coaxially with a smaller-sized arc chamber or counterbore 62*e* located forwardly of the rounded tip of the cathode stick or slug 21*e*. The forward regions of the arc chamber 22*e* and of the smaller arc chamber 62*e* are generally rounded or spherical.

The smaller arc chamber 62*e* communicates coaxially with a nozzle passage 63*e* having a cylindrical rear portion and a somewhat flared or conical forward portion. The illustrated nozzle passage is of the supersonic type. Nozzle passage 63*e* will not be described in detail since counterparts thereof are set forth previously in this specification.

The present spray torch is of the non-transferred arc variety, wherein the entire arc is contained within the torch. Thus, a D.C. power source 64*e* (FIG. 6) has the positive terminal thereof connected to conduit 42*e* (which is formed of copper) to thereby supply D.C. power of positive polarity to the fitting 43*e* and thus to the front body 12*e* and to the anode means 18*e* in contact therewith. The negative terminal of power source 64*e* is connected to fitting 56*e* and thus to the cathode means 19*e*. An electric arc is thus maintained between the tip of the cathode means and the wall of the arc chamber 62*e*.

Because gas is introduced at high pressure from source 33*e* (FIG. 8) through the passages described above, the gas pressure in chambers 22*e* and 62*e* is high (for example, 120 psi gauge when the electric arc is present). This high pressure cooperates with the high electric power contained in the torch, and with the characteristics of nozzle passage 63*e*, in such manner that the flow through the nozzle passage is caused to be supersonic, for example between Mach 1 and Mach 3 (preferably about Mach 2 when spraying is being effected in the atmosphere, as distinguished from being effected in a vacuum chamber).

As previously indicated, the cathode means **19***e* comprises (in addition to the thoriated tungsten slug, stick or rod **21***e*) a slug-holder or stick-holder **66***e* having a radial flange **67***e*. Such flange is seated between the bottom of a recess in rear body **10***e* and the rear end of a neck **68***e* on intermediate body **11***e*. The slug holder **66***e* is preferably formed of copper.

Referring next to FIGS. **6, 7** and **11** in particular, the torch further comprises handle means which are screwed directly to the torch body by means of the screws **70***e*. The screws project into inserts in the intermediate body **11***e*, which (being formed of fiber glass) is very strong. Screws **70***e* project respectively through the upper ends of first and second handle portions **71***e* and **72***e* which are mirror images of each other and abut at the central plane of the torch. Portions **71***e* and **72***e* are secured together by bolts **73**e and **74***e* shown in FIG. **6.**

The handle portions **71***e* and **72***e* have grooves therein which cooperate to form passages through which the above-described conduit **42***e* passes, as does an additional tube or conduit **76***e* adapted to supply spray powder to nozzle passage **63***e* as described below. Both the conduit **42***e* and the conduit **76***e* extend upwardly through the handle and then bend forwardly to a position in advance of the handle, whereupon they bend upwardly into forward body **12***e* as shown in FIG. **6.**

Powder tube **76***e* is supplied by a source **75***e* (FIG. 6) with spray powder entrained in gas. Such a source is shown in U.S. Pat. No. 3,517,861.

The upper end of powder conduit **76***e* projects slidably through a corresponding radial bore in the lower region of front body member **12***e*. Furthermore, as best shown in FIG. **9,** the extreme upper end of the powder conduit or tube **76***e* is beveled at **78***e* to abut the conical wall of a recess **79***e* formed in anode means **18***e*. A cross-member or fitting **80***e* (FIG. 7) is rigidly secured to the powder tube or conduit **76***e* (as by brazing), and is fastened by screws **81***e* (FIG. 7) to the front body **12***e*.

Loosening of the screws **81***e* permits the operator to shift the upper end of powder tube **76***e* downwardly and out of the recess **79***e* (FIG. 9), thereby permitting rotation of the anode means **18***e* as described below. Correspondingly, tightening of the screws **81***e* forces the beveled upper end of tube **76***e* into recess **79***e* and effects a seal with the wall of such recess, so that all gas and powder which flow upwardly through the tube **76***e* pass into the nozzle passage **63***e*.

Anode means **18***e* is provided with a plurality, for example eight in the illustration, of such recesses **79***e* (FIG. 9), in circumferentially-spaced relationship. Each recess **79***e* communicates with a port or passage which extends inwardly to the nozzle passage **63***e*. The various ports or passages are numbered **82***e*–**89***e* in FIG. 7, and each has at least one characteristic different from that of all the others. Thus, for example, the passages may have different diameters, different inclinations, etc.

As an example, the passage **85***e* (FIG. 7) is shown as being tangentially related to the nozzle passage, the relationship being such that the powder is introduced in a clockwise manner as viewed from the front of the torch. This is opposite to the direction of introduction of arc gas through injector ring **23***e*, this being counterclockwise as shown in FIG. **10.**

Referring to FIG. **9,** the passages **82***f* and **82***g* correspond to passage **82***e* except that they are inclined at different angles relative to a plane which is perpendicular to the nozzle passage **63***e* and contains the powder tube **76***e*. It is pointed out that the three passages **82***e*, **82***f* and **82***g* (FIG. **9**) are not present in the same torch (there preferably being only one port **82***e*, etc., which communicates with tube **76***e* at any one time). The passages **82***f* and **82***g*, each of which communicates with the throat of nozzle passage **63***e*, are illustrated herein as alternative angles of powder introduction. Various angles and types of powder introduction are described previously in this specification.

To cause a selected one of passages **82***e*–**89***e* to register with powder conduit **76***e*, the upper end of such conduit is lowered by loosening the screws **81***e* (FIG. 7) as described above. Thereafter, a front retainer ring **92***e* (which normally locks the anode means **18***e* in position) is removed from the front of the torch by removing mounting screws **93***e* (FIG. **8**) therefor. After the front ring is removed, a threaded tool is inserted into an internallythreaded bore **94***e* (FIG. 6) in the forward face of the anode means **18***e*.

The threaded relationship between the tool and the threads in bore **94***e* permits the operator to pull the entire anode means **18***e* forwardly for a fraction of an inch, until there is no longer any engagement with an indexing pin **96***e* (FIG. **6**) which is permanently and fixedly mounted in the forward face of front body **12***e* in parallel relationship to the axis of the torch. The pin **96***e* is selectively received in any one of eight circumferentially-spaced bores **97***e* which are provided in a flange **98***e* in anode means **18***e*. Each bore **97***e* corresponds in position to one of the conical recesses **79***e* described relative to FIG. **9.** The flange **98***e* seats in a counterbore in the face of front body **12***e*.

Since the indexing pin **96***e* is no longer inserted in one of the bores **97***e* after the anode means **18***e* is pulled forwardly as stated above, the operator may rotate the anode in order to cause the desired one of passages **82***e*–**89***e* to register with the upper end of powder conduit **76***e*. Thereafter, the anode **18***e* is pushed rearwardly until indexing pin **96***e* is again inserted in one of the bores **97***e*, following which the front ring **92***e* is mounted in position by means of screws **93***e*, and following which the screws **81***e* (FIG. **7**) are tightened to elevate the powder tube **76***e* and effect a seal at bevel **78***e* (FIG. **9**) as stated above.

The described rotation of the anode **18***e* permits a single anode to have a much greater utility than in the prior art, so that various types of powders, various settings of the torch, etc., may be employed with a single anode as necessary in order to achieve maximum spray rates.

DESCRIPTION OF FIG. 12

The method which will next be described, in connection with FIG. **12,** relates to the discovery that the combination of supersonic plasma flow, simultaneous plural-port injection of spray powder, and very high arc power produces spray rates which are surprisingly high. It is emphasized, however, that the arc power must be related to the size of the torch, since the larger torches normally generate arc powers much higher than do the smaller torches.

The preceding part of this specification discloses supersonic flow but does not disclose simultaneous plural-port powder injection. Such prior-art patents as 3,114,826; 3,183,337; and 3,197,605 teach plural-port powder injection, but only at subsonic flows and relatively low arc powers. Patents 3,179,782 and 3,246,114 purport to teach supersonic flow, and appear ambiguous relative to whether or not there are plural powder ports. It has now been ascertained that if the arc power is extremely high compared to the size of the torch, if plural-port powder injection is employed, and if supersonic flow is employed, then the spray rates increase extremely rapidly.

The method will be described in connection with the torch of FIGS. **6–11**, which has (as mentioned above) an arc chamber diameter of about two-thirds inch (chamber **22***e*). The torch has a nozzle passage diameter of 0.234 inch at the smallest portion thereof, and a nozzle passage length of 0.812 inch.

For a torch of the indicated size, the arc power is in excess of 50 kilowatts, and is preferably in the range of 80 kilowatts to 100 kilowatts. As one illustrative condition, the arc current is 900 amperes and the arc voltage 90 volts.

The pressure of the arc gas (for example, argon) introduced from source **33***e* (FIG. **8**) is in excess of 50 psi gauge, which produces in arc chamber **22***e* a gas pressure of 120 psi gauge after the arc is initiated. The combination of the high gas pressure and the high arc power combine with the characteristics of the supersonic nozzle passage **63***e* to create a supersonic flow through the nozzle and out the torch. The velocity of the plasma emanating from the torch may be about 10,000 feet per second when spraying occurs in the atmosphere. Stated otherwise, the plasma emanating from the torch is in the range of Mach 1 to Mach 3, being preferably about Mach 2 (when spraying is in the atmosphere as distinguished from in a vacuum chamber).

By plural-port powder injection it is meant that separate powder sources are employed simultaneously to feed powder and gas through separate conduits to the nozzle passage **63***e*, as described below relative to FIG. **12.** It is not preferred to use a single powder source which feeds powder and gas to a plurality of ports.

Referring to FIG. **12**, there is schematically represented a powder source **101***e* and a powder source **102***e* which are connected, respectively, to the torch by means of powder tubes **103***e* and **104***e*. Such sources **101***e* and **102***e* combine with powder from the first source **75***e* and which is connected through the tube **76***e* as described relative to FIGS. **6** and **9.**

The powder tubes **103***e*, 104*e* and **76***e* communicate, respectively, with powder ports **106***e*, 107*e* and **82***f* which are provided in the anode means **18***f*.

In the present example, all of the ports **106***e*, 107*e* and **82***h* correspond to each other in diameter, angle, etc., and all are constructed as shown in FIG. **9** relative to port **82***e*. It is to be understood, however, that different longitudinal or circumferential positionings may be employed, as well as different angular relationships, etc.

In the present example, and with the torch of the size described above, each port **106***e*, 107*e* and **82***h* has a diameter (for example) of one-sixteenth inch. The rate of gas flow from each source **101***e*, *102e* and **75***e* is 50 scfh. The spray coating is thus deposited on a substrate (not shown) at a rate of, for example, 40 pounds per hour.

Except as specifically stated above, the torch of FIG. **12** is identical to the one previously described in detail relative to FIGS. **6–11**, inclusive.

The foregoing detailed description is to be clearly understood as given by way of illustration and example only, the spirit and scope of this invention being limited solely by the appended claims.

I claim:

1. The method of projecting high velocity particles onto a substrate to coat the same, comprising the steps of:

establishing a plasma stream,

expanding said plasma stream from the throat to the exit of a supersonic nozzle having a ratio of exit area to throat area sufficient to achieve a plasma stream exit velocity greater than Mach 1 and less than Mach 3,

injecting into said plasma stream a stream of particles to be projected, said particles having a diameter not greater than about 44 microns,

heating said particles to a temperature near but less than their melting point, said last-mentioned step comprising controlling the time of dwell of said particles within said plasma stream by selectively controlling both the angle and position of injection of said particles into said stream substantially at the throat of said nozzle, whereby said particles will be softened, but not melted, and will obtain a velocity that is substantially maximized with respect to the velocity of said plasma stream, and

impinging said softened particles against a substrate to thereby coat said substrate.

2. A supersonic plasma spray gun for projecting particles of high velocity comprising:

means for producing a plasma arc at a pre-selected pressure and electrical power, and including nozzle means for expanding plasma produced in said arc to provide a plasma stream having an exit velocity of greater than Mach 1 and less than Mach 3,

means for injecting a stream of particles of a size not greater than 44 microns into said plasma stream to be entrained thereby, and

means for controlling time of dwell of said particles within said plasma stream so as to heat the particles to a temperature near to, but below, their melting point and to achieve substantially maximized velocity of said particles,

said means for controlling dwell time comprising a plurality of nozzles, each including means for selective and alternative attachment to said spray gun, and each having a bore having a ratio of exit area to throat area sufficient to produce the above-mentioned plasma stream exit velocity, and

each of said nozzles having a particle injection conduit providing communication between a source of particles exterior to said nozzles and the bore of said nozzle at a point thereof between said exit and throat for injection of said particles into the plasma stream,

a first one of said nozzles for use with particles of low melting points such as bronze, copper and aluminum, having its particle injection conduit extending at a large angle (between 25° and 49°) with respect to a normal to the direction of flow of said plasma stream, and communicating with the bore of said nozzle at a point closely adjacent the nozzle exit to thereby provide a short dwell time that prevents premature melting and plating of the nozzle bore,

a second one of said nozzles for use with materials of intermediate melting points (2000°F to 3000°F), such as stainless steel, nickel, chromium, and hard facing alloys having its particle injection conduit extending at an intermediate angle (between 7.5° and 25°) with respect to a normal to the direction of plasma stream flow and communicating with the bore of its associated nozzle at a point substantially midway between the throat and exit, but somewhat closer to the throat

whereby the dwell time of such intermediate temperature melting point particles is greater than the dwell time achieved by lower temperature particles in said first-mentioned nozzle, and

a third one of said nozzles for use with high temperature melting point particles such as tungsten carbide-cobalt, chromium carbide nickel chromium blends, tungsten and molybdenum, having its particle injection conduit extending at a considerably smaller angle (between −13° and 7.5°) with respect to a normal to the direction of the plasma stream and communicating with the bore of its associated nozzle at a point thereof substantially at its throat whereby dwell time of such high temperature particles is at least sufficient to ensure substantial heat softening of the particles without melting.

3. A method of projecting particles to be spray-coated upon a substrate wherein the particles are borne by a supersonic stream of plasma having a velocity greater than Mach 1 and less than Mach 3 and wherein the velocity of the particles is substantially maximized as the particles are heated, said method comprising:

providing an electrical plasma jet torch having a gas vortex chamber communicating with a nozzle passage having a throat, said torch also having a rear electrode extending adjacent said nozzle passage,

creating and maintaining an electric arc in said nozzle passage between said rear electrode and a forward electrode that defines said nozzle passage,

introducing plasma arc gas into said vortex chamber in a direction that is substantially tangential thereto but inclined forwardly through a relatively small angle and causing said gas to flow vortically and helically in said vortex chamber and toward said nozzle passage,

ionizing said plasma arc gas in said electric arc,

constricting said ionized gas as it flows from said rear electrode toward the throat of said nozzle passage, and continuously expanding said ionized gas as it flows from said throat to the exit of said nozzle passage to attain said supersonic velocity,

injecting into said nozzle, through the boundary layer of said ionized gas, a stream of particles having a size not greater than 44 microns and having melting temperatures above 3000°F, said last-mentioned step including injecting said particles into said nozzle at an angle within the range of −13° and 7.5° relative to said plasma flow and at a position within said nozzle between 0.032 and 0.142 inches downstream of the nozzle throat, so that the particles are heated to a temperature near but less than their melting point, and

projecting said heated particles against a substrate.

4. The method of high velocity spraying of particles comprising the steps of:

generating a stream of plasma,

flowing said plasma stream through a converging diverging supersonic nozzle having a throat and an exit,

causing said plasma stream to expand from the nozzle throat to the nozzle exit to provide a plasma stream exit velocity of between Mach 1 and Mach 3 at ambient exit pressure, and also causing the plasma stream to decrease in density from a high density at said throat to a lower density at said exit,

feeding to said nozzle a flow of particles having a maximum dimension of 44 microns,

injecting said particles through the boundary layer and toward the center of said plasma stream at a point within said nozzle where said plasma stream has substantially said high density so as to heat said particles to a temperature near but less than the melting point thereof, whereby greater kinetic energy is transferred from said plasma stream to the particles injected therein, and

impinging said heated particles against a substrate to thereby coat said substrate.

5. The method of claim **4**, wherein said step of injecting particles into said plasma stream comprises injecting said particles into said nozzle in a direction that is inclined rearwardly with respect to the direction of flow of said plasma stream whereby transfer of kinetic energy from said plasma stream to said particles is still further increased.

6. Particle spraying apparatus for generating and projecting a stream of plasma exiting therefrom at a Mach number exit velocity greater than 1 and less than 3, said apparatus comprising:

a gun having front and back electrodes and a vortex chamber extending about said back electrode,

means for feeding gas under pressure into said vortex chamber adjacent said back electrode,

means for energizing said electrodes to form an arc therebetween to ionize said gas and create a plasma stream flowing to and through said front electrode,

said front electrode comprising an exit nozzle communicating with said vortex chamber and having an exit, having a throat spaced downstream of said back electrode, and having a portion diverging from said throat to the exit of said nozzle to provide a ratio of area of said exit to area of said throat sufficient to provide an exit velocity greater than Mach 1 and less than Mach 3, said nozzle having an axis along which said plasma stream flows,

said means for feeding gas under pressure including means for effecting a pressure in said vortex chamber in the vicinity of said arc having a relation to ambient pressure sufficient to provide said Mach number exit velocity with said ratio of areas, and

means for entraining and heating in said plasma stream a flow of particles having a size of less than 44 microns to be coated upon a substrate against which said plasma stream impinges, said means for entraining and heating causing said particles to be heated to a temperature near but below their melting point,

said means for entraining comprising a particle injection conduit intersecting the nozzle at a point adjacent the nozzle throat wherein said plasma stream is of relatively higher density, and means for feeding said particles through said conduit and through the boundary layer of said plasma stream toward the center thereof whereby both transferred kinetic energy and dwell time of the particles in the plasma stream are increased.

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