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[54] **PULSED PLASMA THRUSTER HAVING AN ELECTRICALLY INSULATING NOZZLE AND UTILIZING PROPELLANT BARS**

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Related U.S. Application Data

[51] **Int. Cl.**[6] **F03H 1/00**

[52] **U.S. Cl.** **60/203.1**; 219/121.48

[58] **Field of Search** 60/203.1, 202, 60/204; 313/231.31, 231.41; 219/121.48

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[57] **ABSTRACT**

A thruster includes a body having a cavity with a discharge end, an apparatus for generating an electric arc having a current path through the cavity between first and second locations, and a non-gaseous, non-liquid propellant material **(26)** that forms an ionized gas as an incident of being heated. The propellant material **(26)** is heated by the electric arc to produce an ionized gas in the cavity. The cavity is configured to cause the ionized gas to be expelled from the cavity through the discharge end of the cavity in a flow path that is substantially parallel to the electric arc and current path within the cavity. A thruster includes a body having a cavity with a discharge end, a substantially non-ablating, electrically insulating nozzle **(30)** having an inlet disposed adjacent to the discharge end and an outlet, a first electrode **(32)** disposed within the cavity, a second electrode **(34)** disposed adjacent to the outlet of the nozzle, an electric power supply connected to the first and second electrodes to generate an electric arc having a current path therebetween, and a non-gaseous, non-liquid propellant material that forms an ionized gas as an incident of being heated. The propellant material is heated by the electric arc to produce an ionized gas in the cavity. A method of producing plasma to be used to propel a mass includes the steps of providing a cavity with a discharge end, providing a non-gaseous, non-liquid propellant material that forms an ionized gas as an incident of being heated, generating an electric arc having a current path through the cavity between first and second locations, heating the propellant material to produce an ionized gas in the cavity; and expelling the ionized gas from the cavity through the discharge end of the cavity in a flow path that is substantially parallel to the electric arc and current path within the cavity.

24 Claims, 5 Drawing Sheets

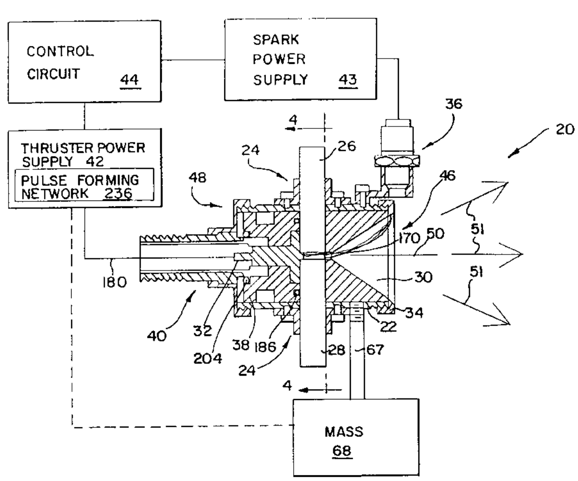

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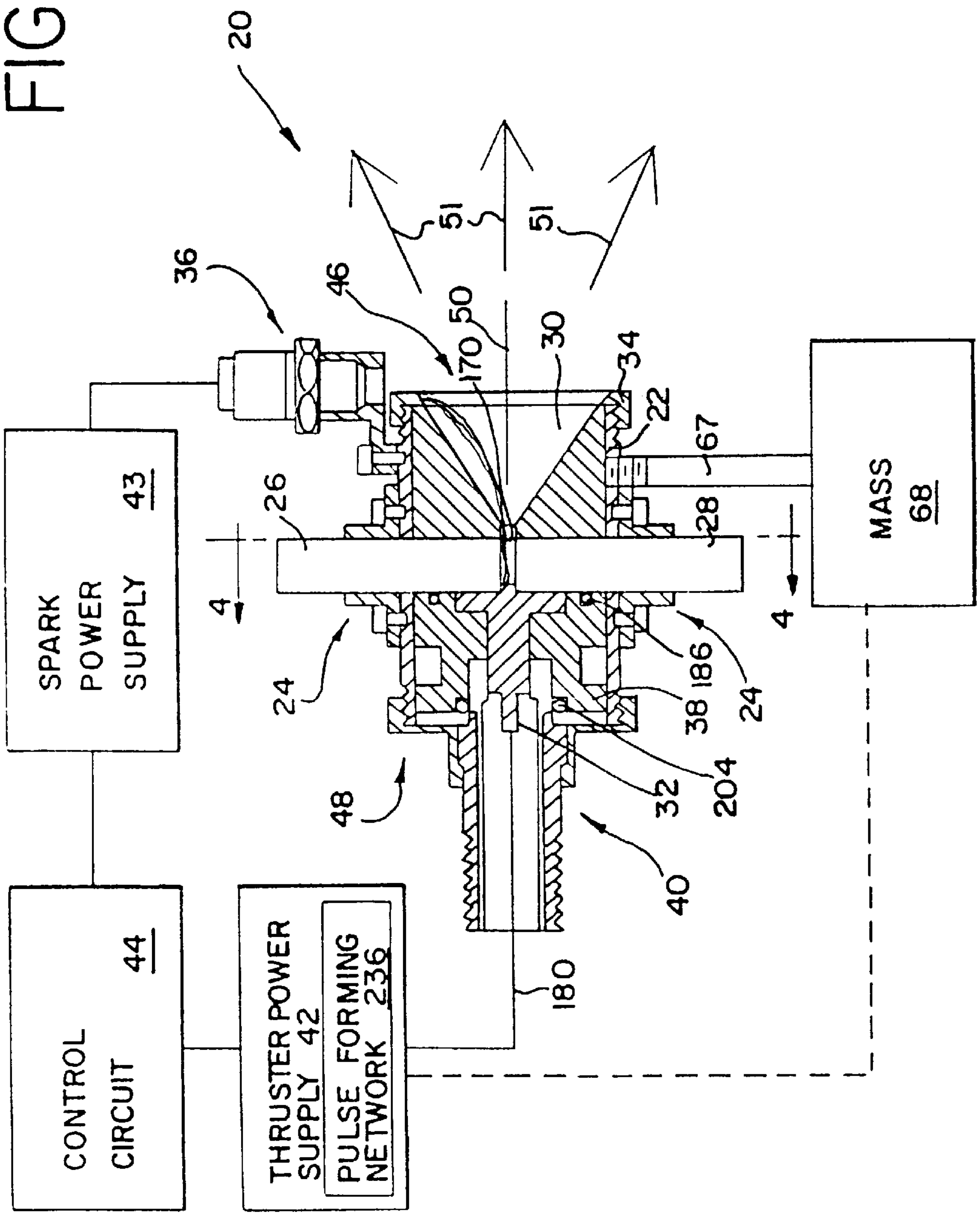
FIG. 1



SPARK POWER SUPPLY 43
CONTROL CIRCUIT 44
THRUSTER POWER SUPPLY 42
PULSE FORMING NETWORK 236
MASS 68
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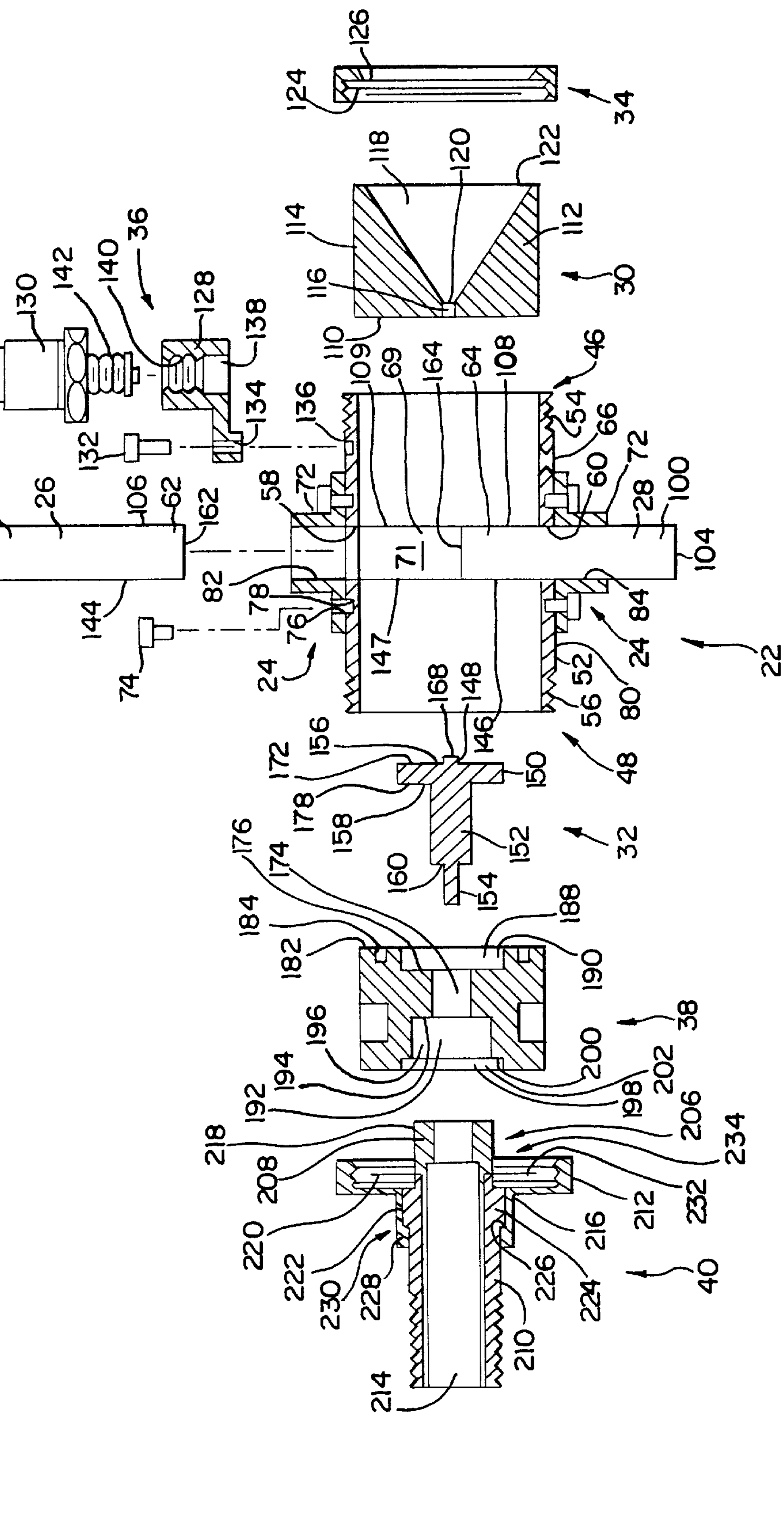


FIG. 2

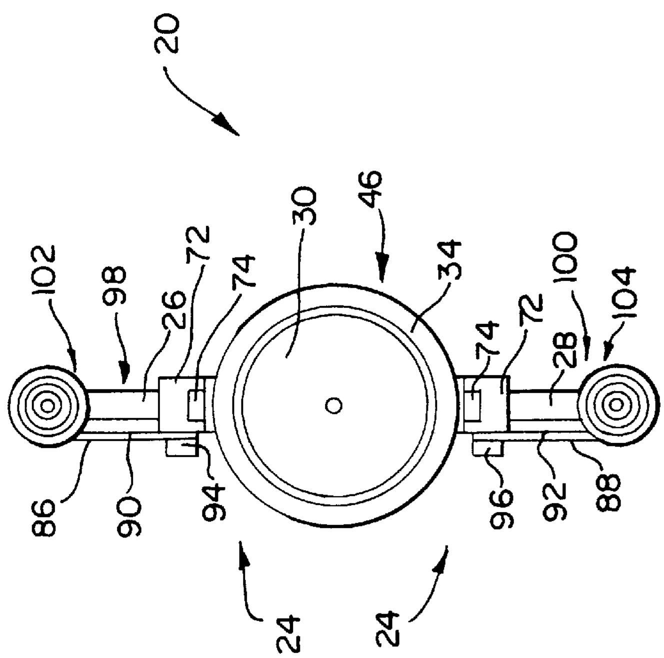


FIG. 3

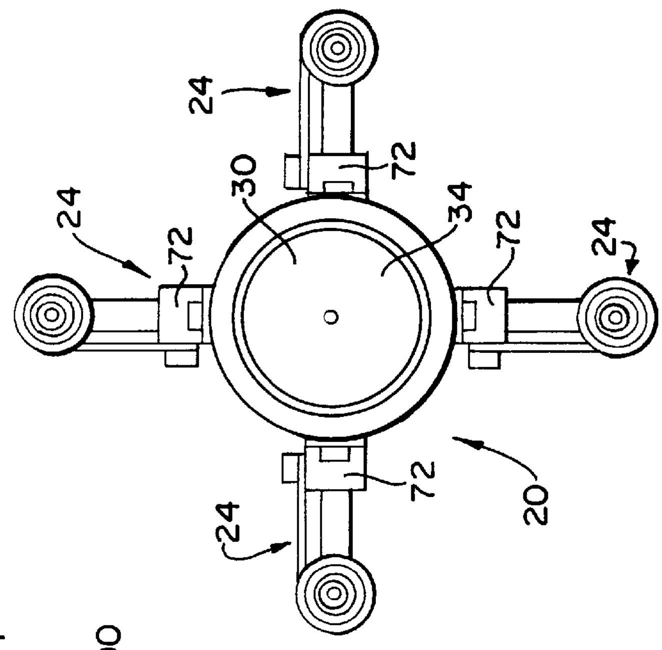


FIG. 7

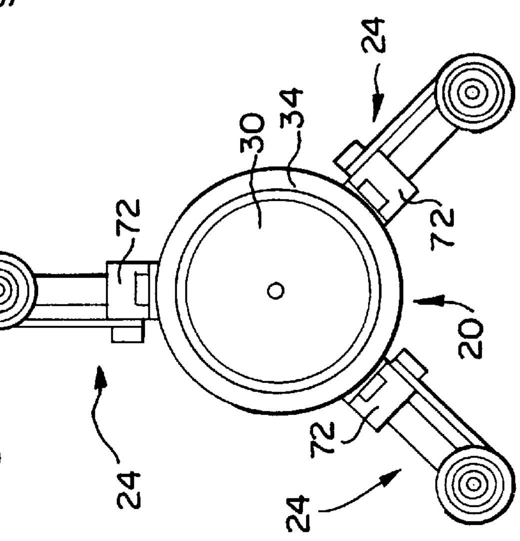


FIG. 5

FIG. 4

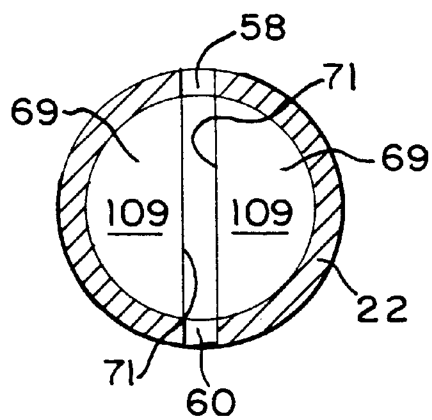


FIG. 4A

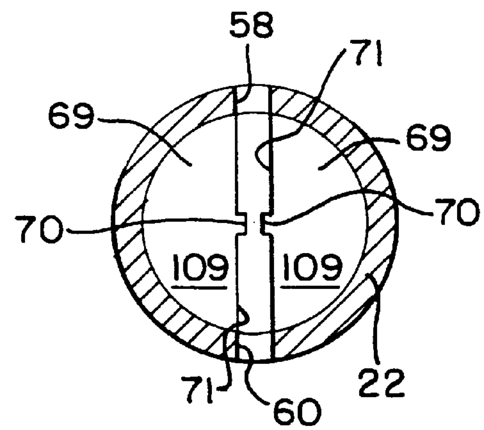


FIG. 6

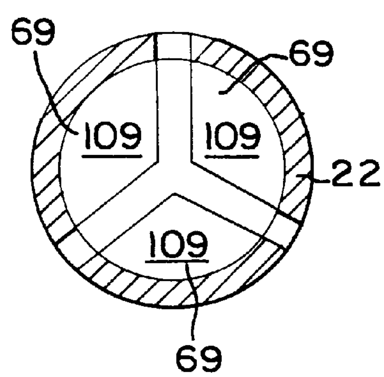
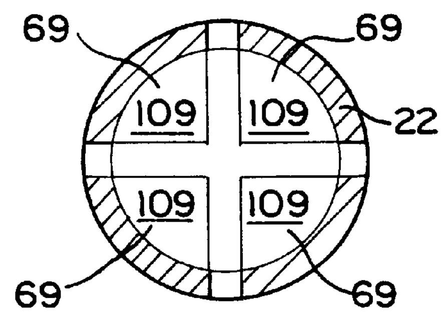


FIG. 8



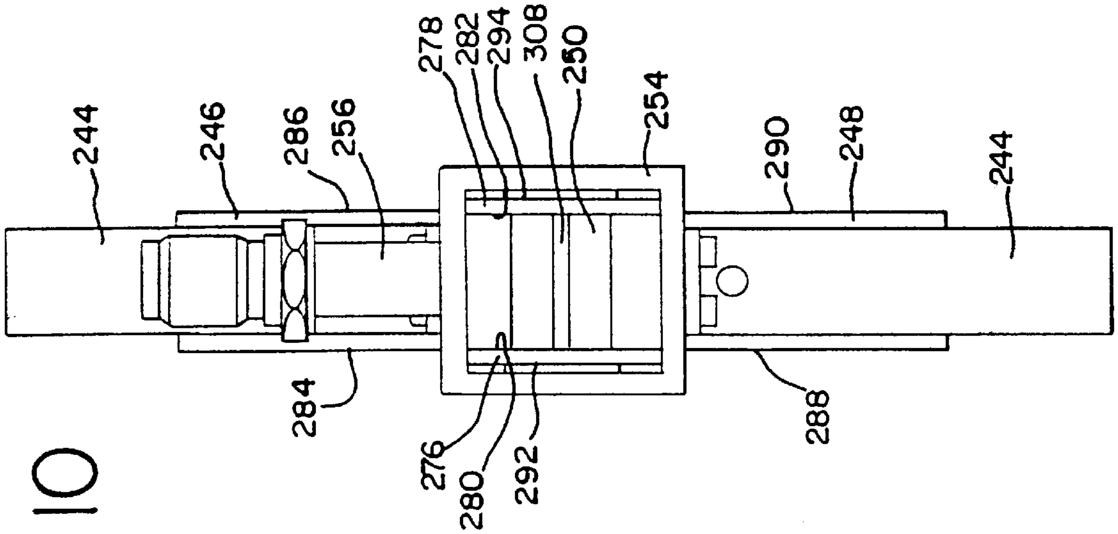

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FIG. 10

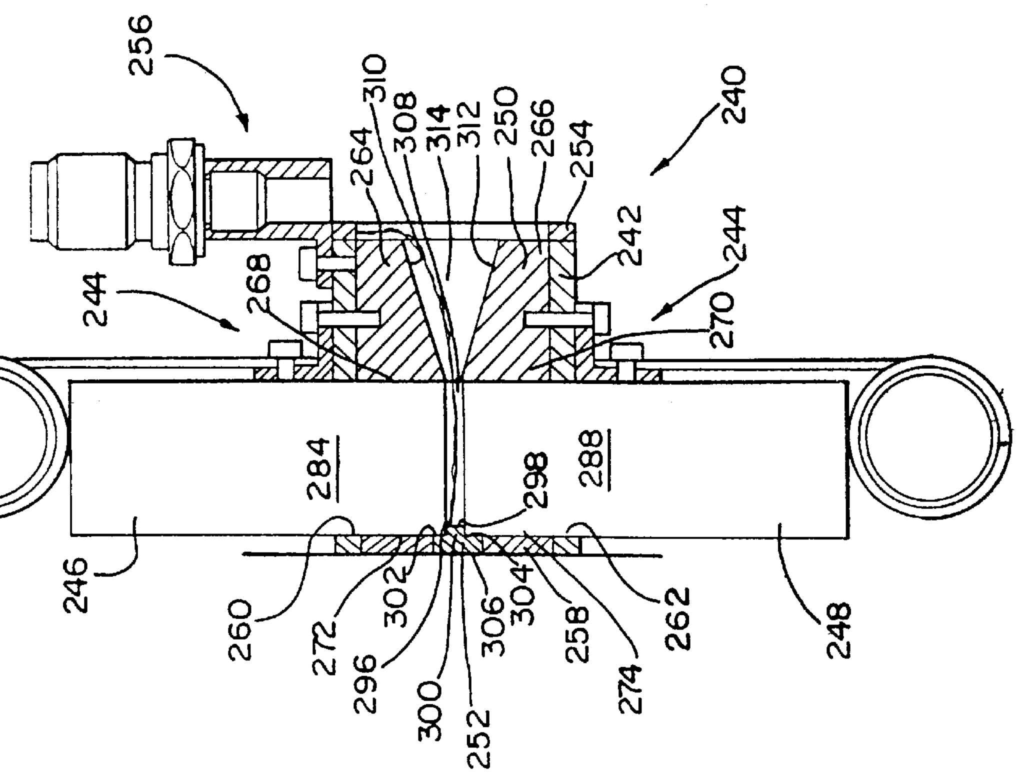
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FIG. 9

PULSED PLASMA THRUSTER HAVING AN ELECTRICALLY INSULATING NOZZLE AND UTILIZING PROPELLANT BARS

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH/DEVELOPMENT

This invention was made with Government support under Naval Research Laboratory Grant No. N00014-95-1-G041 awarded by the Department of the Navy. The Government has certain rights in the invention.

CROSS-REFERENCE TO RELATED APPLICATIONS

Not applicable.

BACKGROUND OF THE INVENTION

1. Technical Field

The present invention is directed to a thruster for propulsion of a mass, and in particular to a pulsed plasma thruster for propulsion of a mass.

2. Background Art

Pulsed plasma thrusters used to propel spacecraft and satellites in outer space are old in the art. In a plasma thruster, a stream of partially or fully ionized gas particles, called a plasma, is used to produce thrust. In a pulsed plasma thruster, an electric arc generated by a pulsed electric discharge applied between two electrodes is used to heat a propellant material to produce the ionized gas particles or plasma.

The propellant material is conventionally either in a gaseous state or a solid state prior to heating. In a gas-type plasma thruster, an electric arc is conventionally passed through the gas to ionize the gas and produce plasma. See U.S. Pat. Nos. 5,425,231; 4,821,508 and 3,425,223. In a solid-type plasma thruster, the electric arc is passed over the surface of the solid material to increase the temperature of the material, thereby ablating the material to form an ionized gas. See U.S. Pat. No. 3,447,322; G. Paccani, Anode-Nozzle Experimental Analysis in a Coaxial Non-Steady Solid Propellant Thruster, Deutsche Gesellschaft fuer Luft-und-Raumfahrt (1988); and D. Palumbo and W. Guman, Effects of Propellant and Electrode Geometry on Pulsed Ablative Plasma Thruster Performance, AIAA 11th Electric Propulsion Conference, AIAA Paper 75–409 (1975).

It is desirable to exhaust the plasma from the thruster to produce thrust and to perform useful work, such as to change the orientation or speed of a spacecraft mass to which the thruster is attached. The plasma may be exhausted from a chamber under the pressure caused by the heating and/or ablation process (electrothermal effect). Alternatively, the flow of electric current between the first and second electrodes may cause the ionized particles to be exhausted under the influence of the electric and magnetic fields caused therebetween (electromagnetic effect).

The production of plasma in conventional pulsed plasma thrusters, however, has come at a significant cost. Typically, conventional pulsed plasma thrusters have had an efficiency of less than 10%. See R. Vondra et al., Analysis of Solid Teflon Pulsed Plasma Thruster, Journal of Spacecraft (1970). That is, less than 10% of the total energy consumed by the thruster is converted to a form (thrust) which can be used to perform work. The low efficiency of these plasma thrusters has been a significant disadvantage, considering that energy consumption has always been a critical consideration in spacecraft design.

Palumbo and Guman describe a number of pulsed plasma thrusters which are claimed to have improved efficiency. In these thrusters, an electric arc is generated between two oppositely charged plate electrodes to heat two solid propellant bars disposed therebetween. With heating, the surfaces of the solid propellant rods are ablated, and an ionized gas is formed in a cavity or space defined by the surfaces of the electrodes and the bars. In all of the thrusters shown, the current path of the electric arc between the oppositely charged plates is perpendicular to the flow path of the gas generated by ablation of the solid propellant. Furthermore, in all of the thrusters shown, the space or cavity between the propellant bar surfaces is on the order of 1.7 cubic inches (28 cubic centimeters).

Paccani also describes a pulsed plasma thruster claimed to have improved efficiency. This thruster uses a coaxial arrangement of electrodes to heat and ablate a propellant material disposed therebetween to produce plasma. In all of the thrusters shown, the current path of the electric arc between the oppositely charged electrodes is substantially perpendicular to the flow path of the plasma produced from the solid propellant. Furthermore, after the plasma has passed through the space between the two electrodes, the plasma is exhausted out of a nozzle which is made of conductive material and formed integrally with one of the coaxial electrodes.

U.S. Pat. No. 3,447,322 describes a pulsed plasma thruster having first and second electrodes disposed at alternate ends of a cavity formed of a propellant material. The propellant material is heated in the cavity by an electric arc generated between the electrodes to produce plasma. The plasma is exhausted out of a nozzle which is made of conductive material and formed integrally with one of the electrodes. It is believed that the electric discharge is pulsed such that the gas is exhausted through the nozzle during the periods when no electric discharge occurs between the electrodes.

BRIEF SUMMARY OF THE INVENTION

In an embodiment of the present invention, a thruster includes a body having a cavity with a discharge end, an apparatus for generating an electric arc having a current path through the cavity between first and second locations, and a non-gaseous, non-liquid propellant material that forms an ionized gas as an incident of being heated. The propellant material is heated by the electric arc to produce an ionized gas in the cavity. The cavity is configured to cause the ionized gas to be expelled from the cavity through the discharge end of the cavity in a flow path that is substantially parallel to the electric arc and current path within the cavity.

Moreover, the non-gaseous, non-liquid propellant material may define at least a portion of the cavity.

Moreover, the thruster may include a nozzle made of a substantially non-ablating electrically insulating material with an inlet disposed adjacent to the discharge end of the cavity and an outlet. The electric arc and the current path may pass through the cavity and the nozzle, the ionized gas being expelled through the nozzle in a flow path that is substantially parallel to the electric arc and the current path within the nozzle. Furthermore, the nozzle may be made of boron nitride. Additionally, the apparatus for generating an electric arc may include a first electrode disposed within the cavity and adjacent to the propellant material, a second electrode disposed adjacent to the outlet of the nozzle, and an electric power supply connected to the first and second electrodes. Moreover, the electric power supply may have incorporated therein a pulse forming network to generate an electric discharge for a predetermined pulse width and at a predetermined repetition rate between the first and second electrodes to generate the electric arc having the current path through the cavity, the predetermined pulse width being between approximately 1 and 100 microseconds and the repetition rate being between approximately 0.1 and 10 Hz.

In another embodiment of the invention, a thruster includes a body having a cavity with a discharge end, a substantially non-ablating, electrically insulating nozzle having an inlet disposed adjacent to the discharge end and an outlet, a first electrode disposed within the cavity, a second electrode disposed adjacent to the outlet of the nozzle, an electric power supply connected to the first and second electrodes to generate an electric arc having a current path therebetween, and a non-gaseous, non-liquid propellant material that forms an ionized gas as an incident of being heated. The propellant material is heated by the electric arc to produce an ionized gas in the cavity.

Moreover, the non-gaseous, non-liquid propellant material may define at least a portion of the cavity.

Moreover, the nozzle may be made of boron nitride.

Moreover, the electric power supply may have incorporated therein a pulse forming network to generate an electric discharge for a predetermined pulse width and at a predetermined repetition rate between the first and second electrodes to generate the electric arc having the current path through the cavity, the predetermined pulse width being between approximately 1 and 100 microseconds and the repetition rate being between approximately 0.1 and 10 Hz.

Moreover, the body may have a first passage formed therein, the first passage in communication with the cavity, and the propellant material may have a bar form, the bar disposed in the first passage with a first surface of the bar defining at least a portion of the cavity. Furthermore, the thruster may include an apparatus for feeding the bar of propellant material through the passage towards the cavity as the propellant material is heated to produce an ionized gas. Additionally, the apparatus for feeding the bar of propellant material into the passage may include a spring with spaced ends, with one end of the spring attached to the body and the other end of the spring abutting a surface of the bar of propellant material.

Moreover, the body may have a plurality of passages formed therein, the plurality of passages in communication with the cavity, and the propellant material includes a plurality of bars, the plurality of bars disposed in the plurality of passages, each bar having a surface which defines at least a portion of the cavity. Furthermore, the first electrode may extend at least partially into the cavity and is disposed between the surfaces of at least two of the bars which define at least a portion of the cavity, and the surfaces of at least two bars and a surface of the first electrode at least partially define the cavity. Additionally, the thruster may include an apparatus for feeding the plurality of bars of propellant material through the plurality of passages towards he cavity as the propellant material is heated to produce ionized gas.

Moreover, the thruster may include an apparatus for generating an electric spark adjacent to the outlet of the nozzle, the spark initiating the generation of the electric arc between the first and second electrodes.

Moreover, the thruster may include a pair of D-shaped pieces disposed within the body, the D-shaped pieces defining a part of the cavity.

In a further embodiment of the invention, a method of producing plasma to be used to propel a mass includes the steps of providing a cavity with a discharge end, providing a non-gaseous, non-liquid propellant material that forms an ionized gas as an incident of being heated, generating an electric arc having a current path through the cavity between first and second locations, heating the propellant material to produce an ionized gas in the cavity; and expelling the ionized gas from the cavity through the discharge end of the cavity in a flow path that is substantially parallel to the electric arc and current path within the cavity.

Moreover, the step of providing a non-gaseous, non-liquid propellant material may include the step of providing a non-gaseous, non-liquid propellant material that defines at least a portion of the cavity.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

FIG. **1** is a cross-sectional view of a pulsed plasma thruster according to an embodiment of the present invention;

FIG. **2** is an enlarged, exploded cross-sectional view of the thruster shown in FIG. **1**;

FIG. **3** is a front elevation view of the thruster shown in FIG. **1**, with a spark generating apparatus removed to show the details of a bar feeding apparatus;

FIG. **4** is a cross-sectional view of the thruster shown in FIG. **1** taken about line **4—4**;

FIG. **4**A is a cross-sectional view of a pulsed plasma thruster according to a further embodiment of the present invention;

FIG. **5** is a front elevation view of a pulsed plasma thruster according to another embodiment of the present invention with three propellant bars and guides;

FIG. **6** is a cross-sectional view of the thruster shown in FIG. **5**;

FIG. **7** is a front elevation view of a pulsed plasma thruster according to a further embodiment of the present invention with four propellant bars and guides;

FIG. **8** is a cross-sectional view of the thruster shown in FIG. **7**;

FIG. **9** is a partial cross-sectional view of a pulsed plasma thruster according to still another embodiment of the present invention; and

FIG. **10** is a front elevation view of the pulsed plasma thruster shown in FIG. **9**.

DETAILED DESCRIPTION OF THE INVENTION

One embodiment of the present invention is shown in FIGS. **1–4**. Referring first to FIG. **1**, a pulsed plasma thruster **20** includes a body or housing **22** to which is attached a propellant bar feeding apparatus **24**, propellant bars **26**, **28**, a nozzle **30**, inner and outer electrodes **32**, **34**, a spark generating apparatus **36**, a spacer **38**, and an electrical connecting apparatus **40**. A thruster power supply **42** is connected to first and second electrodes **32**, **34** by a cable connected to the electrical connecting apparatus **40**. Similarly, a spark power supply **43** is attached to the spark generating apparatus **36** by a cable. The thruster power supply **42** and the spark power supply **43** are, in turn, connected to a control circuit **44**, which may be connectable to a user input/output device (not shown) so as to be programmable. Alternatively, the control circuit may be preprogrammed to control the electric discharge between the electrodes **32**, **34** and the firing of the spark generating apparatus **36**.

The thruster **20** is assembled by securing the bar feeding apparatus **24** to the body **22**. Bars **26, 28** are then disposed within the bar feeding apparatus **24**, and into the body **22**. The nozzle **30** is disposed into one end **46** of the body **22** so as to abut the bars **26, 28**. The electrode **34** is secured to the body **22** to maintain the nozzle **30** in its axial position. The electrode **32** is disposed into the other end **48** of the body **22** so as to abut and space the ends of the bars **26, 28**. The spacer **38** is disposed in the body **22** abutting the electrode **32** and bars **26, 28**. The electric connecting apparatus **40** is then secured to the body **22** to maintain the spacer **38** and the electrode **32** in their axial positions within the body **22**. Lastly, the spark generating apparatus **36** is secured to the body **22** at the end **46**.

In operation, a voltage on the order of 1500 volts is applied across the electrodes **32, 34** by the thruster power supply **42** under the control of the control circuit **44**. The control circuit **44** then signals the spark power supply **43** to fire the spark generating apparatus **36**, thereby causing a breakdown arc to form between the electrodes **32, 34** preferably with an amplitude of approximately 200 to 50,000 amperes, a pulse width of approximately 1 to 100 microseconds, and a repetition rate of 0.1 to 10 pulses per second (Hz). The arc heats the bars **26, 28** so that ionized gas forms, exiting outwardly under electrothermal and electromagnetic forces along an axis **50** in the direction indicated by arrows **51**.

Turning now to the elements of the thruster **20** in greater detail the cylindrically-shaped body **22** has a wall **52**, preferably made of aluminum. The body **22** also has external threads **54, 56** formed at the ends **46, 48**. The body **22** also has two equally-sized, facing, rectangularly-shaped openings **58, 60** formed in the wall **52**. These openings **58, 60** allow bars **26, 28** to be disposed with an end **62, 64** within the body **22**. A threaded mounting hole **66** is also formed in the body **22** so that the body **22** can be mounted by a mount **67** to a mass **68**, such as a spacecraft or satellite.

The bars **26, 28** are of a non-gaseous, non-liquid propellant material. Preferably, the bars **26, 28** are have a uniform rectangular cross-section and are made of a solid TEFLON material. Alternatively, the propellant material may take on any shape and be made of any suitable non-gaseous, non-liquid material, including, for example, those materials typically classified as viscoelastic materials, i.e. material which are elastic and viscous. See W. Findley, et al., Creep and Relaxation of Nonlinear Viscoelastic Materials 2–3 (1976), which is herein incorporated by reference. The viscoelastic materials may be in the form of a gel or a paste. Suitable changes would be made to the feeding apparatus **24** as are known to one of ordinary skill in the art to allow incorporation of such various shapes and materials.

Disposed within the body **22** are two D-shaped pieces **69**. The pieces **69** are formed of a high-temperature, electrically insulating material such as boron nitride. The D-shaped pieces **69** have a radius of curvature to form an effective diameter slightly smaller that of wall **52**, and are disposed approximately equidistantly from the ends **46, 48** of the body **22**. The pieces **69** abut the bars **26, 28** on either side to space and align the bars **26, 28** within the body **22**, and to perform other functions as explained in greater detail below. The pieces **69** may be urged against the bars **26, 28** through the use of washer springs (not shown) disposed between the pieces **69** and the wall **52** of the body **22**.

Alternatively, the pieces **69** may be formed with extensions **70** as shown in FIG. **4**A. The extension **70** depend from the surface **71** of the plates **69** in a radially inward direction.

As a further alternative, if more than two bars of propellant material are used, the shape of the pieces **69** may be varied accordingly to space and align the bars, as shown in FIGS. **5–8**. FIGS. **5** and **6** show an alternative embodiment in which three bars of propellant material are used, while FIGS. **7** and **8** show an alternative embodiment in which four bars of propellant material are used. As shown, the bars are equally spaced about the body **22**.

The bar feeding apparatus **24** includes guide blocks or guides **72** attached to the body **22** using screws **74**, which are passed through holes **76** formed in the guides **72** and then screwed into internally threaded holes **78** formed in the wall **52** of the body **22**, and in particular in an outer surface **80** of the body **22**. The guides **72** are preferably formed from nylon. The guides **72** have rectangularly-shaped passages **82, 84** formed therethrough, which rectangularly-shaped passages **82, 84** are substantially equally-sized to the openings **58, 60** formed in the wall **52** of body **22**. With the guides **72** attached to the body **22**, the passages **82, 84** are substantially aligned with the openings **58, 60** and help to align bars **26, 28** which are disposed therethrough.

The bar feeding apparatus **24** also includes spiral coiled springs **86, 88** attached to the guides **72** at first ends **90, 92** of the springs **86, 88**. Preferably, screws **94, 96** are used to secured the first ends **90, 92** of the springs **86, 88** to the guides **72**. As shown, the springs **86, 88** contact ends **98, 100** of the bars **26, 28** along surfaces **102, 104** of the springs **86, 88**. The springs **86, 88** urge the bars **26, 28** radially inward relative to the axis **50**.

As shown in FIG. **2**, the bar feeding apparatus includes two guides **72** and two springs **86, 88**. Alternatively, in the embodiments wherein more than two bars of propellant material are used, more than two guides **72** and springs may be used. For example, FIGS. **5** and **6** show an embodiment of the present invention wherein three guides **72** and springs are used, and FIGS. **7** and **8** show an embodiment of the present invention wherein four guides **72** and springs are used.

The nozzle **30** abuts a first side **106, 108** of the ends **62, 64** of the bars **26, 28** and outwardly axially facing ends **109** of the D-shaped pieces **69** along an inner nozzle end **110**. The nozzle **30** is preferably formed of a high-temperature, electrically insulating material, such as boron nitride. The nozzle **30** includes a nozzle body **112** having a first surface **114**, a second surface **116**, and a third surface **118**. The first surface **114** is cylindrically-shaped and has an effective diameter slightly smaller than the internal diameter of the wall **52** of body **22**. The second surface **116** is also cylindrically-shaped with a circular cross-section of substantially uniform area. The third surface **118** is conically-shaped with a circular cross-section of substantially increasing area from an interface **120** between the second and third surfaces **116, 118** to an outer end **122** of the nozzle **30**. In this manner, the nozzle **30** defines a diverging-type nozzle, although other types of nozzles may be used.

Abutting the outer end **122** of the nozzle **30** is the outer electrode **34**. The outer electrode **34** is made of an electrically conducting material, preferably brass, and is formed as a ring-shaped collar. The outer electrode **34** has an internal thread **124** that mates with the external thread **54** formed in the outer surface **80** of the body **22**. The outer electrode **34** is secured to the body **22** by screwing the electrode **34** onto the body **22** at end **46**. The outer electrode **34** also has an axially inwardly facing rim **126** which abuts the outer end **122** of the nozzle **30**, thereby substantially fixing the axial position of the nozzle **30** within the body **22**.

Disposed adjacent to the outer electrode **34** is the spark-generating apparatus **36**. The spark-generating apparatus **36** includes a mounting guide **128** and a spark plug **130**, preferably of the semiconductor-type. The mounting guide **128** is secured to the body **22** of the thruster **20** by means of a fastener **132**, such as a screw, which is passed through an opening **134** formed in the guide **128** and into a threaded hole **136** formed in the outer surface **80** of the body **22**. The mounting guide **128** has a passage **138** formed therethrough, with an internal thread **140** formed therein. The spark plug **130**, having an external thread **142**, is secured to the mounting guide **128** by screwing the spark plug **130** into the internally-threaded passage **138**. With the spark plug **130** secured in the mounting guide **128**, and the mounting guide **128** attached to the body **22**, the spark plug **130** is disposed adjacent to the outer electrode **34**.

The inner electrode **32** is disposed along a second side **144**, **146** of the ends **62**, **64** of the bars **26**, **28** and inwardly axially facing ends **147** of the D-shaped pieces **69**. The inner electrode **32** is made of an electrically conducting material, preferably brass. The inner electrode **32** has a stepped-shape formed of a series of cylindrical sections **148**, **150**, **152** and **154** set off by shoulders **156**, **158**, and **160**.

The first cylindrical section **148** is typically 0.125 inches (0.318 cm) in diameter, and may be disposed between facing surfaces **162**, **164** of the bars **26**, **28** so as to space the bars **26**, **28**. Alternatively, the radially inwardly depending extensions **70** of the D-shaped pieces **69** (FIG. 4A) may be used to space the facing surfaces **162**, **164** of the bars **26**, **28**. The spaced facing surfaces **162**, **164**, the D-shaped pieces **69**, and an axially outwardly facing surface **168** of the cylindrical section **148** cooperatively define a cavity **170**.

The cavity **170** defined therebetween is roughly rectangular in shape, having an effective width of 0.25 inches (0.635 cm), height of 0.125 inches (0.318 cm) and a length of approximately 0.5 inches (1.27 cm). The cavity thus has a volume of approximately 0.016 cubic inches (0.25 cubic centimeters).

The second cylindrical section **150**, and in particular an axially outwardly facing surface **172** thereon, abuts the second sides **144**, **146** of the bars **26**, **28** to help align the bars **26**, **28** within the body **22**, and also abuts the ends **147** of the D-shaped pieces **69**. The third cylindrical section **152** is disposed in a throughpassage **174** formed in the spacer **38**, preferably with an axially outwardly facing surface **176** of the spacer **38** abutting an axially inwardly facing surface **178** of the second cylindrical section **150** so as to align and position the electrode **32** within the body **22** and relative to the bars **26**, **28**. The fourth cylindrical section **154** forms a connective pin for attachment to the power supply **42** via a cable **180**, such as a coaxial cable.

The spacer **38** also abuts the second side **144**, **146** of the ends **62**, **64** of the bars **26**, **28** and the ends **147** of the D-shaped pieces **69** along an axially outwardly facing surface **182**. The spacer **38** is preferably made of an electrically insulating material, such as boron nitride. An annular groove **184** is formed in the axially outwardly facing surface **182**, and an O-ring **186** is disposed therein. The O-ring **186** is intended to limit or prevent gas generated in the cavity **170** from leaking out between the axially outwardly facing surface **182** of the spacer **38** and the axially inwardly facing surfaces **144**, **146** of the bars **26**, **28**.

The spacer **38** also has the stepped throughpassage **174** previously discussed. The stepped passage **174** has a number of different diameter sections. In particular, a first section **188** of the passage **174** is defined in part by the axially outwardly facing surface **176** and also by a radially inwardly facing surface **190**. The second cylindrical section **150** of the electrode **32** is disposed within the first section **188** with the axially inwardly facing surface **178** of the second cylindrical section **150** abutting the axially outwardly facing surface **176** of the spacer **38**. A second section **192** is defined by an axially inwardly facing surface **194** and a radially inwardly facing surface **196**. A third section **198** is contiguous with the second section **192**, and is defined by an axially inwardly facing surface **200** and a radially inwardly facing surface **202**. As shown, an O-ring **204** is disposed in the third section **198** to provide additional sealing to prevent leakage of the gas from the cavity **170** into the electrical connecting apparatus **40**.

The spacer **38** is maintained in its axial position in the body **22** of the thruster **20** abutting the bars **26**, **28** and pieces **69** through the cooperation of the axially inwardly facing surface **194** and/or radially inwardly facing surface **196** of the second section **192** of the spacer **38** and the axially outwardly extending end **206** of the electrical connecting apparatus **40**. The electrical connecting apparatus **40** includes a stepped, electrically insulating insert **208**, a threaded, electrically conducting tube **210**, and a stepped, electrically conducting locking collar **212**.

The insert **208** is generally cylindrical in shape, with a passage **214** formed therethrough. As explained above, the first end **206** fits within the second section **192** formed in the spacer **38** and cooperates with the spacer **38** to maintain the spacer **38** consistently axially and radially positioned. The first end **206** also has a inwardly facing, stepped shoulder **216** formed on a surface **218** at the first end **206**.

The treaded conducting tube **210** surrounds a part of the insert **208**. Similar to the insert **208**, the conducting tube **210** is a stepped cylinder, having axially inwardly and outwardly facing surfaces **220**, **222** disposed about a stepped region **224**. The axially inwardly facing surface **220** abuts an axially outwardly facing surface **226** formed on a rim **228** of the locking collar **212**.

The locking collar **212** is disposed about the conducting tube **210** and insert **208**, and cooperates with the threaded end **56** of the body **22** to maintain the electrode **32**, spacer **38**, and electrical connecting apparatus **40** in an operative position relative to the bars **26**, **28** and the D-shaped pieces **69**. In addition to the rim **228** formed in an inward end **230** of the locking collar **212**, the locking collar **212** has an internal thread **232** formed in an outward end **234**. The locking collar **212** is secured to the body **22** by screwing the external thread **56** of the body **22** into the internal thread **232** of the locking collar **212**.

Alternatively, a steel spring (not shown) may be located in the body **22** between the locking collar **212** and the spacer **38** to maintain the electrode **32** and spacer **38** in an operative position relative to the bars **26**, **28** and D-shaped pieces **69**.

In operation, the control circuit **44**, of technology known to those of skill in the art, signals the power supply **42** to charge an internal storage capacitor to a first voltage. When or after the first voltage is reached, the control circuit signals the power supply **43** to fire the spark plug **130**. The firing of the spark plug **130** adjacent to the electrode **34** causes a breakdown arc, driven by the current from the storage capacitor (not shown) and an associated pulse forming network **236**, to form between the electrode **34** and the electrode **32**. The arc passes through the nozzle **30** and the cavity **170**, close to the facing surfaces **162**, **164** on the bars **26**, **28**. As the arc passes over the surfaces **162**, **164**, the propellant material at the surfaces **162**, **164** is heated past the temperature at which the solid TEFLON propellant material forms an ionized gas, typically 10,000–20,000 degrees Kelvin. The arc may be of a single pulse, or may be of a series of pulses, each pulse having, for example, a pulse width of approximately 1 to 100 microseconds and a repetition rate of approximately 0.1–10 pulses per second (Hz).

It is theorized that the positioning of the electrodes **32, 34** at opposite ends of the nozzle **30**, rather than at opposite ends of the cavity **170** provides for an electric current path through the cavity **170** and nozzle **30** that is substantially parallel to the flow of the plasma out of the cavity **170** in the direction of the arrow **50**, except in the region immediately adjacent to the electrode **34**. It is further theorized that by having the electric current path running parallel to the direction of the plasma flow in the cavity **170** and nozzle **30**, greater efficiencies are achievable. This parallel path theory is contrary to the conventional solid thruster design, which emphasizes current flow perpendicular to the plasma flow.

As the gas forms in the cavity **170**, the gas pressure within the cavity **170** builds, typically to a level of 10–100 atmospheres, forcing the ionized gas or plasma outward from the cavity **170** in the direction of the arrow **50**. Because of the considerable small cavity in which the gas is being formed, the pressures in the cavity **170** are in excess of 50 times the conventional pressures. It is theorized that the high pressures suppress multiple ionization of the propellant, promote radiation heat transfer to the propellant surface to abet heating, and provide adequate numbers of molecular collisions to permit recovery of the propellant gas energy in the nozzle **30**. Additionally, electric and magnetic fields produced by the electrodes **32, 34** cause the ionized gas to accelerate further as it exits the thruster **20**.

With the cavity **170** as described above, the electrothermal effects may provide approximately 80% kinetic energy to the plasma stream, while electromagnetic effects may provide approximately 20%. With an embodiment constructed as shown in FIGS. **1–4**, an efficiency in excess of 20% of the energy put in to the thruster **20** can be had.

A further embodiment of the present invention is shown in FIGS. **9** and **10**. A thruster **240** includes a body **242** to which is attached a bar feeding apparatus **244**, bars **246, 248**, a nozzle **250**, electrodes **252, 254**, a spark generating apparatus **256**, and a spacer **258**. The thruster **240** would also include an electrical connecting apparatus, thruster and spark power supplies and a control circuit. These elements are not shown in FIGS. **9** and **10**, but would be substantially similar in structure and function to the electrical connecting apparatus **40**, thruster power supply **42**, spark power supply **43**, and control circuit **44** shown above for the thruster **20** in FIGS. **1** and **2**.

The body **242** is formed of a conduit having a rectangular cross-section, and preferably of a conducting material, such as aluminum. The body **242** has openings **260, 262** through which bars **246, 248** are disposed. The nozzle **250**, preferably of boron nitride, having upper and lower nozzle sections **264, 266**, is secured within the body **250** and abuts the bars **246, 248** along a first side **268, 270** thereof. The electrode **252** and the spacer **258** are also disposed within the body **242**, and abut a second side **272, 274** of the bars **246, 248**. Additionally, side plates **276, 278** are disposed within the body **242** and have facing surfaces **280, 282** which abut the bars **246, 248** along third and fourth sides **284, 286, 288, 290**. The plates **276, 278** may be forced tightly against the bars **246, 248** through the use of washer springs **292, 294**.

The bars **246, 248** also have facing surfaces **296, 298**, which are separated by the end **300** of the electrode **252**. In particular, surface **296** abuts a shoulder **302** of the electrode **252**, while the surface **298** abuts a shoulder **304**. Thus separated, the facing surfaces **296, 298** of the bars **246, 248**, the facing surfaces **280, 282** of the plates **276, 278** and an axially outwardly facing surface **306** of the electrode **252** define a cavity **308**. Similarly, the upper and lower sections **264, 266** of the nozzle **250** have surfaces **310, 312**, which with facing surfaces **280, 282**, define a diverging rectangular nozzle cavity **314**.

In operation, the thruster **240** is thought to perform much like the thruster **20**. An arc, initiated by a spark from the spark generating apparatus **256**, passes through the cavity **308** and the nozzle cavity **314** between the electrodes **252, 254**. As the arc passes over the facing surfaces **296, 298** of the bars **246, 248**, the arc heats the propellant material to form a ionized gas or plasma. As described above, it is theorized that the plasma moves through the cavity **308** and the nozzle cavity **314** in a direction parallel to the current path between electrodes **252, 254**. It is also thought that the plasma is accelerated primarily by electrothermal effects, but also experiences significant acceleration through electromagnetic effects.

Still other aspects, objects, and advantages of the present invention can be obtained from a study of the specification, the drawings, and the appended claims.

We claim:

1. A thruster comprising:

a body having a cavity with a discharge end;

a diverging nozzle which is at least in part non-ablating and substantially electrically insulating and which has an inlet disposed adjacent to the discharge end and an outlet;

a first electrode disposed within the cavity;

a second electrode disposed adjacent to the outlet of the nozzle;

an electric power supply connected to the first and second electrodes to generate an electric arc having a current path therebetween,

a non-gaseous, non-liquid propellant material that forms an ionized gas as an incident of being heated,

the propellant material being heated by the electric arc to produce an ionized gas in the cavity,

the electric power supply including a pulse forming network circuit coupled to the first and second electrodes so that in a first operational mode an electric arc is generated between the first and second electrodes having a current path through the cavity and the nozzle while the ionized gas is passing through the nozzle.

2. The thruster according to claim **1**, wherein the non-gaseous, non-liquid propellant material defines at least a portion of the cavity.

3. The thruster according to claim **1**, wherein the nozzle is made of boron nitride.

4. The thruster according to claim **1**, wherein the electric power supply has incorporated therein a pulse forming network to generate an electric discharge for a predetermined pulse width and at a predetermined repetition rate between the first and second electrodes to generate the electric arc having the current path through the cavity, the predetermined pulse width being between approximately 1 and 100 microseconds and the repetition rate being between approximately 0.1 and 10 Hz.

5. The thruster according to claim **1**, wherein the cavity comprises a cylindrical cavity of substantially constant diameter.

6. A thruster comprising:

a body having a cavity with a discharge end and a first passage formed therein in communication with the cavity;

a diverging nozzle which is at least partially non-ablating and substantially electrically insulating and which has an inlet disposed adjacent to the discharge end and an outlet;

a first electrode disposed within the cavity;

a second electrode disposed adjacent to the outlet of the nozzle;

an electric power supply connected to the first and second electrodes to generate an electric arc having a current path therebetween; and

a non-gaseous, non-liquid propellant material that forms an ionized gas as an incident of being heated,

the propellant material being heated by the electric arc to produce a pressurized, ionized gas in the cavity,

the propellant material having a bar form, the bar disposed in the first passage with a first surface of the bar defining at least a portion of the cavity.

7. The thruster according to claim 6, further comprising means for feeding the bar of propellant material through the passage towards the cavity as the propellant material is heated to produce an ionized gas.

8. The thruster according to claim 7, wherein the means for feeding the bar of propellant material into the passage comprises a spring with spaced ends, with one end of the spring attached to the body and the other end of the spring abutting a surface of the bar of propellant material.

9. The thruster according to claim 6, wherein:

the body has a plurality of passages formed therein, the plurality of passages in communication with the cavity; and

the propellant material comprises a plurality of bars, the plurality of bars disposed in the plurality of passages, each bar having a surface which defines at least a portion of the cavity.

10. The thruster according to claim 9, wherein:

the first electrode extends at least partially into the cavity and is disposed between the surfaces of at least two of the bars which define at least a portion of the cavity;

the surfaces of at least two bars and a surface of the first electrode at least partially define the cavity.

11. The thruster according to claim 9, further comprising means for feeding the plurality of bars of propellant material through the plurality of passages towards the cavity as the propellant material is heated to produce ionized gas.

12. A thruster comprising:

a body having a cavity with a discharge end;

a diverging nozzle which is at least partially non-ablating and substantially electrically insulating and which has an inlet disposed adjacent to the discharge end and an outlet;

a first electrode disposed within the cavity;

a second electrode disposed adjacent to the outlet of the nozzle;

an electric power supply connected to the first and second electrodes to generate an electric arc having a current path therebetween;

a non-gaseous, non-liquid propellant material that forms an ionized gas as an incident of being heated, the propellant material being heated by the electric arc to produce a pressurized, ionized gas in the cavity; and

means for generating an electric spark adjacent to the outlet of the nozzle, the spark initiating the generation of the electric arc between the first and second electrodes.

13. The thruster according to claim 12, wherein the cavity comprises a cylindrical cavity of substantially constant diameter.

14. The thruster according to claim 6, further comprising a pair of D-shaped pieces disposed within the body, the D-shaped pieces defining a part of the cavity.

15. The thruster according to claim 6, wherein the cavity comprises a cylindrical cavity of substantially constant diameter.

16. A method of producing plasma to be used to propel a mass comprising the steps of:

providing a cavity with a discharge end;

providing a diverging nozzle which is at least partially non-ablating and substantially electrically insulating and has an inlet disposed adjacent to the discharge end and an outlet;

providing a non-gaseous, non-liquid propellant material that forms an ionized gas as an incident of being heated;

generating an electric arc having a current path through the cavity and the nozzle between a first electrode disposed in the cavity and a second electrode adjacent the nozzle outlet; and

heating the propellant material to produce an ionized gas in the cavity; and

expelling the ionized gas from the cavity through the nozzle while generating the electric arc having a current path between the electrodes and through the cavity and the nozzle.

17. The method according to claim 16, wherein the step of providing a non-gaseous, non-liquid propellant material includes the step of providing a non-gaseous, non-liquid propellant material that defines at least a portion of the cavity.

18. The thruster according to claim 16, wherein the cavity comprises a cylindrical cavity of substantially constant diameter.

19. A thruster comprising:

first, upstream and second, downstream spaced electrodes defining a space;

a non-gaseous, non-liquid propellant disposed in the space with a surface which defines at least in part an ionized propellant generation region within the space which the first electrode is disposed in and which has an outlet;

a first non-ablating, electrically insulating diverging wall disposed in the space with a surface which defines an acceleration region within the space having an inlet adjacent to the outlet of the ionized propellant generation region and an outlet adjacent to the second electrode; and

an electric power supply coupled to the first and second electrodes to generate an electric arc having a current path therebetween to ablate the propellant to produce an ionized propellant,

the electrical energy supply including a pulse forming network circuit having an operational mode wherein an electric arc is generated between the first and second electrodes having a current path through the space while the ionized propellant accelerates in the acceleration region.

20. The thruster according to claim 19, wherein the non-ablating insulating wall is made of boron nitride.

21. The thruster according to claim 19, wherein the pulse forming network generates an electric discharge for a predetermined pulse width and at a predetermined repetition rate between the first and second electrodes to generate the electric arc having the current path through the space, the predetermined pulse width being between approximately 1 and 100 microseconds and the repetition rate being between approximately 0.1 and 10 Hz.

22. The thruster according to claim 19, wherein the surface of the non-gaseous, non-liquid propellant defines a cylindrical cavity of substantially constant diameter.

23. The thruster according to claim 19, further including:

a second non-ablating, electrically insulating wall which with the non-gaseous, non-liquid propellant defines the ionized propellant generation region, the wall having an opening therethrough,

the non-gaseous, non-liquid propellant having a bar form, the bar disposed through the opening with a first surface of the bar at least in part defining the ionized propellant generation region.

24. The thruster according to claim 23, wherein:

the opening in the second non-ablating, electrically insulating wall has spaced upstream and downstream ends,

the bar disposed through the opening such that the first surface also has spaced upstream and downstream ends exposed to the electric arc generated in the operational mode of the pulse forming network circuit.

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