219-121. SR

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Dundas et al.

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

[54] **LOW FREQUENCY INDUCTION PLASMA SYSTEM**

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[73] Assignee: **Humphreys Corporation,** Bow, N.H.

[22] Filed: **Jan. 26, 1973**

[21] Appl. No.: **327,082**

Related U.S. Application Data

[63] Continuation of Ser. No. 173,500, Aug. 20, 1971, abandoned.

[52] **U.S. Cl.** .... **219/121 P**
[51] **Int. Cl.** **B23k 9/00**
[58] **Field of Search** .... 219/121 R, 121 P, 383, 219/74, 75; 336/212, 234, 84

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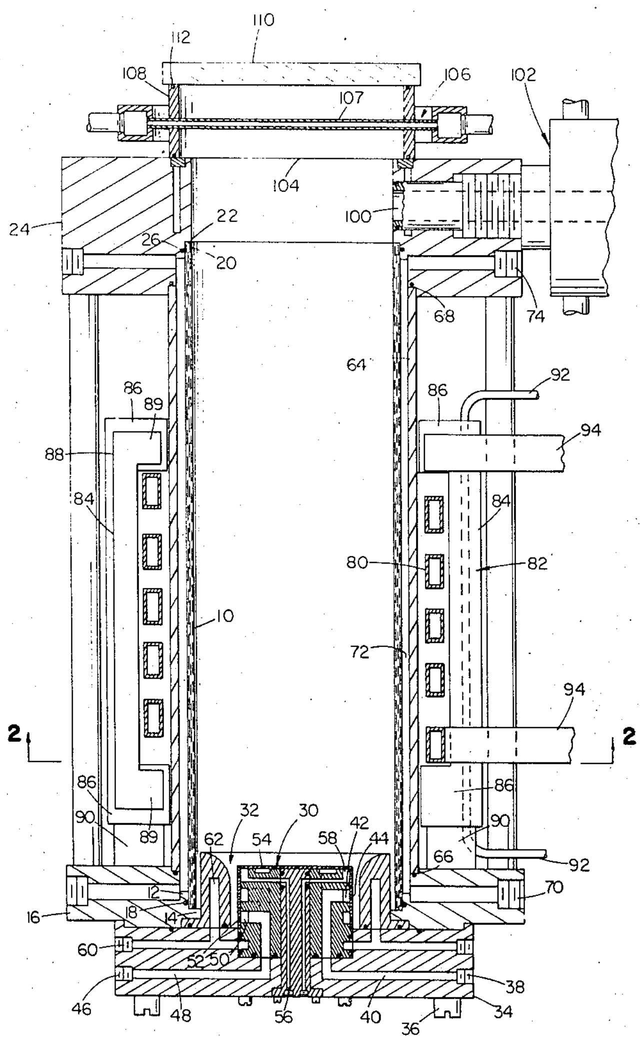
Primary Examiner—J. V. Truhe
Assistant Examiner—Gale R. Peterson

[57] **ABSTRACT**

A low frequency induction plasma system includes a plasma chamber and energizing coil dimensioned as a function of frequency. Structure for lowering the reluctance of the magnetic path surrounds the coil and the chamber so as to enhance the flux in the chamber produced by the energized coil. A thermal plasma in a flowing system is established by initiating a glow discharge with an auxiliary high frequency power supply and then creating a thermal plasma assisted by the enhanced flux in the chamber.

12 Claims, 3 Drawing Figures



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2 Sheets-Sheet 1

FIG 1

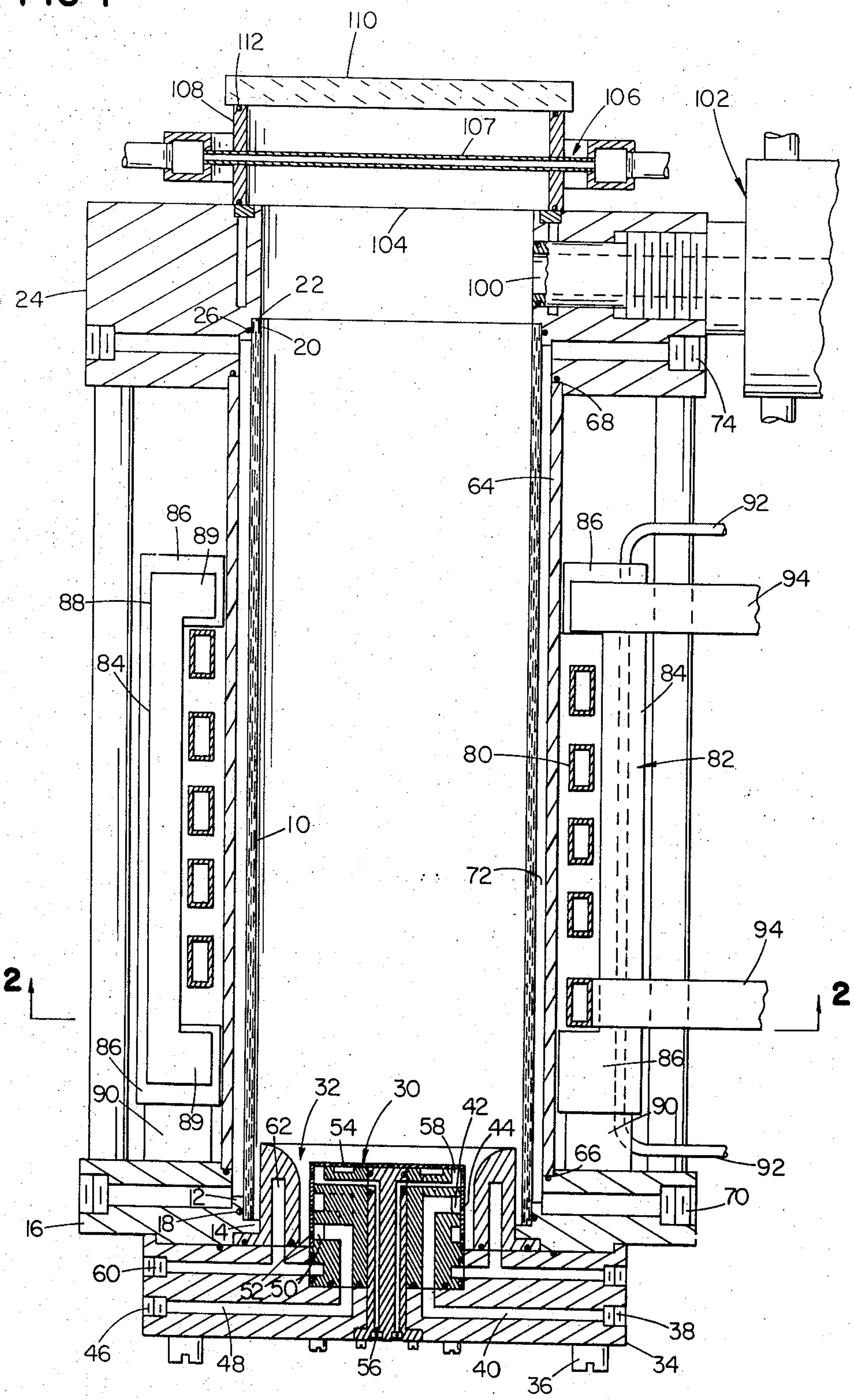
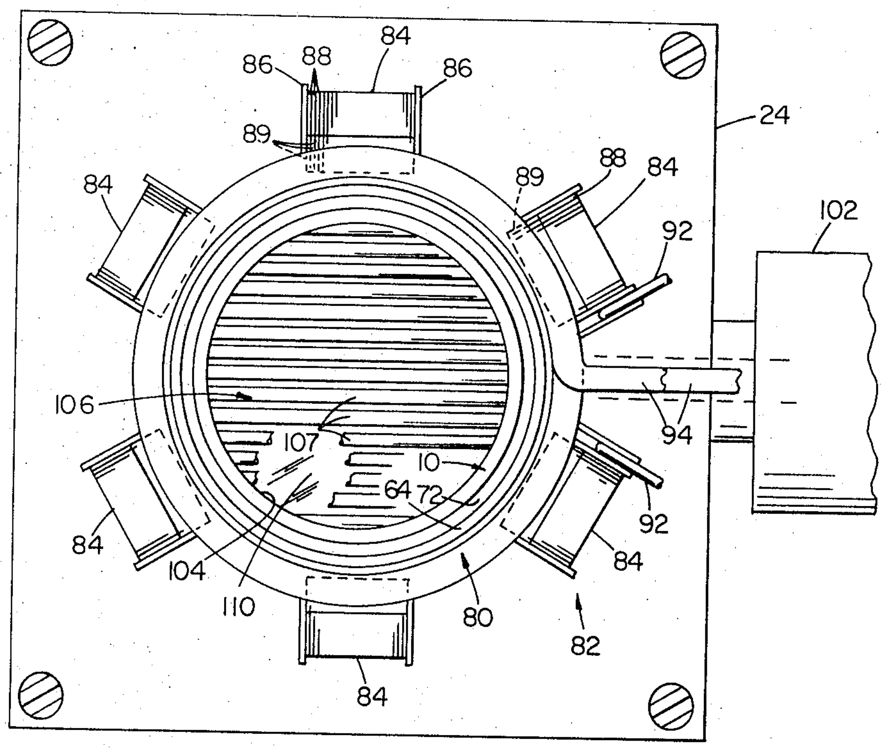


FIG 2


84
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24
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104
110
80
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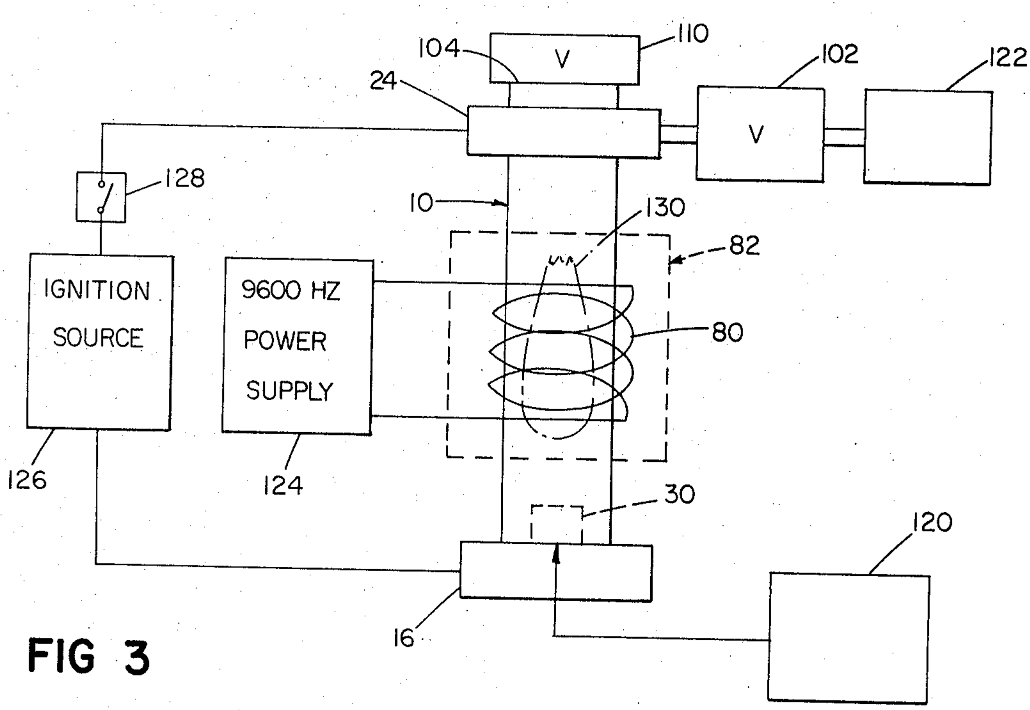
104
V
110
24
102
V
122
128
10
130
82
IGNITION
SOURCE
9600 HZ
POWER
SUPPLY
80
126
124
30
120
16

FIG 3

LOW FREQUENCY INDUCTION PLASMA SYSTEM

This application is a continuation of Ser. No. 173,500, filed Aug. 20, 1971, now abandoned, entitled "Low Frequency Induction Plasma System".

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568 (72 Stat. 435; 42 U.S.C. 2457).

SUMMARY OF INVENTION

This invention relates to induction plasma systems and to methods of operating such systems.

A thermal plasma is created and maintained in a system of the induction type by providing an intense electromagnetic field which produces an electrodeless discharge (thermal plasma) in an ionized medium. Such a thermal plasma has a temperature in the range of 8,000°–11,000°K and is useful for a variety of purposes including the performance of chemical reactions, the working of metallic and/or refractory materials, heaters for hypersonic tunnels and simulator devices that utilize the high temperatures produced by such systems. A number of arrangements have been proposed for generating such thermal plasmas, including both closed and flowing systems in which the plasma has been stably maintained both in reduced pressure environments and in atmospheric pressure environments. In general, such devices have the electromagnetic field produced by power sources operating in the megahertz and near megahertz frequency range, and as such require expensive electronic circuitry of relatively low efficiency.

It is an object of this invention to provide a novel and improved induction plasma system operable at frequencies well below the megahertz range.

Another object of the invention is to provide novel and improved induction plasma systems of the flowing type. A flowing type of system facilitates the performance of useful work, either by the plasma within the plasma chamber or by the effluent from the plasma chamber. In such flowing systems, the stabilization of the plasma, both spacially and electrically, becomes more critical, as that plasma must be stabilized under the dynamic flow conditions against drift which would damage the integrity of the apparatus and also to maintain the necessary electrical characteristics of the system so that the thermal plasma is not extinguished. The extinction of the thermal plasma is a function of the energizing frequency and the characteristic decay time of the plasma.

According to theory, the maintenance of an induction plasma is dependent on a circulating current which should circulate near the wall of the plasma chamber. The depth of penetration of such current may be termed "skin depth" and is represented by the formula:

$\delta = [4\ \pi^2 \tau \mu f\ ]^{-1/2}$ where

δ = skin depth

τ = conductivity of load

μ = magnetic permeability of load

f = frequency of applied energy

For coupling efficiency the skin depth should be less than the radius of the plasma and therefore the plasma diameter should be larger at lower frequencies of energization. A minimum voltage gradient around the plasma is required to sustain the plasma, this gradient being 2 volts/cm in a high current argon arc, and higher for air. Thus the requisite voltage increases with larger diameter plasmas. These additional considerations have lead experimenters in induction plasma systems to employ high frequency energizing sources. Through our invention involving particular ignition and magnetic enhancement techniques, we have successfully operated stable flowing induction plasma systems at frequencies far below the frequencies conventionally employed.

In accordance with our invention, there is provided a plasma generation system that includes an elongated plasma defining chamber having exhaust port structure at one end and injector structure at the one end for introducing material plasma forming material at one end of the chamber for flow through the chamber and exit through the exhaust port structure. An electrical coil surrounds the chamber and is connected to a relatively low frequency power supply (that is 20 kilohertz or below) for creating an intense electromagnetic field within the chamber. Magnetic enhancement structure that at least doubles the flux density in the chamber surrounds the electrical coil. In a particular embodiment this magnetic enhancement structure is formed of a series of discrete, spaced groups of clamped, axially extending electrical steel laminations, with cooling structures on the sides of the groups adjacent the leads of the electrical coil.

Plasma initiation in this low frequency system is preferably accomplished by initially reducing the pressure in the chamber and applying a high frequency (e.g., 20 megahertz) signal across the chamber to establish a glow discharge that substantially fills the chamber and then coupling the low frequency power supply to the electrical coil to convert the glow discharge to a thermal plasma. In a particular embodiment this glow discharge condition is established by short duration pulsed application of high frequency energy.

The methods and apparatus in accordance with the invention provide a simple, reliable, and relatively easy to operate induction plasma system of the flowing type operable to provide a stable thermal plasma energized at low frequencies of less than 20 kilohertz in a system.

Other objects, features and advantages of the invention will be seen as the following description of a particular embodiment progresses in conjunction with the drawings, in which:

FIG. 1 is a diagrammatic view of an induction plasma system constructed in accordance with the invention;

FIG. 2 is a sectional view showing details of the induction plasma apparatus shown in FIG. **1** taken along the line **2—2** of FIG. **1**; and

FIG. 3 is a diagram of an induction plasma system employing the apparatus as shown in FIG. **1.**

DESCRIPTION OF PARTICULAR EMBODIMENT

The induction plasma generator apparatus shown in FIG. 1 is designed for operation at 9600Hz and includes an opaque fused quartz tube **10** having an inner diameter of five and one-half inches and a length of twenty and one-half inches. In a system designed for operation at 960Hz a tube **10** that has a diameter of twelve inches and a length of sixty inches is employed. The upstream end **12** of tube **10** is seated on flange **14** of end plate structure **16** and sealed by O-ring **18,** and the downstream end **20** of tube **10** is similarly seated within recess **22** of end plate **24** and sealed by O-ring **26.**

Injector structure **30** and flow stabilizer structure **32** are positioned in end plate **16** and clamped plate **34** and bolts **36.** A first inlet port **38** supplies gas through channel **40** to annular chamber **42** for distribution through radially directed ports **44.** A second inlet port **46** supplies gas through passage **48** to annular chamber **50** for distribution through swirl ports **52.** Axial ports **54** are supplied through a third passage (not shown) that is angularly offset from passages **40** and **48.** The upper end of injector structure **30** is cooled by water flowing through passages **56** and chamber **58** which flow stabilizer structure **32** is cooled by water flowing through passages **60** and chamber **62.**

A cast acrylic cylinder **64** surrounds tube **10** with its upstream end seated in recess **66** in end plate **16** and its downstream end seated in recess **68** in end plate **24.** Pressurized coolant is supplied through passage **70** for flow through space **72** and exhaust through passage **74.** An induction coil **80** is formed of rectangular (one inch by one-half inch) one sixteenth inch wall copper tubing in a coil having an inner diameter of seven and one-quarter inches and a length of seven inches. Surrounding coil **80** is a magnetic enhancement structure **82** in the form of a series of six electrical steel lamination assemblies **84,** as indicated in FIG. **2.** Each such assembly includes two clamp plates **86** between which are disposed a stack of Armco Tran-cor T electrical steel laminations **88,** each lamination being 0.007 inch thick, seven-eighths inch wide and ten and one-half inches long, with inwardly extending ear portions **89** at either end. Each stack has a depth of two and one-half inches. Each lamination assembly **84** is mounted on support **90.** Cooling tubes **92** are secured to the clamp plates **86** on either side of coil terminals **94** by silver brazing and cooling water is flowed through tubes **94** during operation of the apparatus. This magnetic enhancement structure more than trebles the flux density in chamber **10.**

End plate **24** has an evacuation port **100** which is arranged for connection via valve **102** to a vacuum system and an exit port **104** across which is disposed a grid **106** of cooling pipes **107** supported on ring **108.** Glass plate **110** functions as a valve and as a sight port when the system is operating under reduced pressure conditions is seated on ring **108** and is sealed by O-rings **112.**

A diagram of the operating system is shown in FIG. **3.** The injector assembly **30** is connected to a suitable source **120** of gas. Top flange **24** is connected to vacuum system **122** as controlled by valve **102.** Exit port **104** is controlled by valve **110.** A 450 kilowatt 9600 Hertz motor generator power supply **124** and 9200 KVAR capacity is connected to coil **80** and high frequency (20 MHz) auxiliary ignition supply **126** connected through switch **128** across end plates **16** and **24.**

To form a thermal plasma **130** in chamber **10,** valve **110** is closed and the pressure in the chamber **10** is reduced to a pressure of one Torr., the RF power supply ignition source **126** is energized and a glow discharge is produced which fills chamber **10.** With the main (LF) power supply **124** energized, the glow discharge provides a sufficient load for coupling by the low frequency power and a thermal plasma **130** is established as signified by a dramatic change in brightness. Before establishment of the plasma **130** the power supply **124** was operating at full voltage, 60 percent current and 6 percent lead power factor. After establishment of plasma, voltage dropped to 40–50 percent current increased to 100 percent and the power factor shifted to 10 percent lag. With initiation of the thermal plasma, argon gas flow is increased, increasing the pressure in the chamber **10.** Plasma **130** is stably maintained as the pressure is increased to atmospheric pressure in a flowing mode of operation. With an argon flow rate of approximately 700 SCFH at one atmosphere pressure, the minimum sustaining power was 145 KW.

In a 960 Hz system, a 1250 KW motor generator power supply **124′** was employed with a capacitor bank of 22,000 KVAR capacity connected to coil **80′**. The high frequency ignition supply was a 25 KW 4 MHZ supply. Glow discharge at 0.35 Torr was produced by energizing coil **80′** and then applying a pulse (**172** millisecond in duration in one sequence) of ignition energy across end plates **16′**, **24′** to create a glow discharge that fills chamber **10′** and the low frequency enhanced electromagnetic field couples to the discharge and a plasma **130′** is established.

While a particular embodiment of the invention has been shown and described, various modifications thereof will be apparent to those skilled in the art and therefore it is not intended that the invention be limited to the disclosed embodiment or to details thereof and departures may be made therefrom within the spirit and scope of the invention as defined in the claims.

What is claimed is:

1. An induction plasma system for use with an ignition source comprising:

structure defining an elongated plasma chamber,

an electrical coil surrounding said chamber,

means for supplying a plasma forming material for flow into said chamber and conversion to plasma condition under the influence of an electromagnetic field produced by said electrical coil, and exhaust port structure at one end of said chamber defining a port for flow of said material from said chamber, wherein the improvement comprises a low frequency power supply connected to said coil for creating an intense electromagnetic field within said chamber, and

magnetic enhancement structure disposed adjacent said coil, said magnetic enhancement structure providing magnetic flux density in said chamber that is at least twice the flux density that exists in said chamber in the absence of said magnetic enhancement structure.

2. The system as claimed in claim **1** wherein said magnetic enhancement structure comprises a series of spaced groups of axially extending laminations of electrical steel that surround said coil.

3. The system as claimed in claim **2** and further including cooling means disposed between the leads of said coil and each immediately adjacent group of laminations.

4. The system as claimed in claim **1** and further including an auxiliary high frequency power supply and means to connect said auxiliary power supply across the ends of said plasma chamber and establish a glow discharge in said plasma chamber.

5. The system as claimed in claim **1** and further including means for sealing said exhaust port structure and further including auxiliary exhaust port structure of substantially smaller dimension than the dimension of said main exhaust port structure.

6. The system as claimed in claim **5** wherein said plasma chamber defining structure is a tubular member of uniform cross-sectional configuration throughout its axial length and said exhaust port sealing means includes a removable plate member disposed across the downstream end of said plasma chamber defining structure.

7. Ths system as claimed in claim **5** wherein said magnetic enhancement structure comprises a series of spaced groups of axially extending laminations of electrical steel that surround said coil and further including cooling means disposed between the lead of said coil and each immediately adjacent group of laminations.

8. The system as claimed in claim **7** and further including means to reduce the pressure in said plasma chamber, an auxiliary high frequency power supply and means to connect said auxiliary power supply across the ends of said plasma chamber and establish a glow discharge in a reduced pressure environment is said plasma chamber.

9. A method for initiating operation of a low frequency induction flowing plasma system having a plasma defining chamber having a gas inlet port at one end and a plasma outlet port at the opposite end, and an electrical coil surrounding said chamber and adapted to be connected to a suitable low frequency power supply for creating an intense electromagnetic field within said chamber comprising the steps of

continuously applying said low frequency energy to said coil,

reducing the pressure in said chamber,

establishing a glow discharge in said chamber by applying a discharge pulse of high frequency energy across the ends of said plasma chamber to create a conductive condition in the reduced pressure environment in said chamber, said conductive condition enabling a thermal plasma to be established in said chamber under the influence of the electromagnetic field created by the low frequency energy applied to said electrical coil, and after said thermal plasma is established, increasing the pressure in said chamber to atmospheric pressure while continuously flowing gas through said inlet port into said chamber so that plasma flows through said outlet port.

10. The system as claimed in claim **1** wherein said power supply has an operating frequency of less than 20 kilohertz for creating an electromagnetic field within said plasma chamber inside said electrical coil.

11. An induction plasma system for use with an ignition source comprising:

structure defining an elongated plasma chamber,

an electrical coil surrounding and extending along an axial length of said plasma chamber,

inlet port structure for supplying a plasma forming material for flow into said chamber and conversion to plasma condition under the influence of an electromagnetic field produced by said electrical coil, and exhaust port structure at one end of said chamber defining a port for flow of said material in plasma condition from said chamber, wherein the improvement comprises a low frequency power supply connected to said coil for creating an intense electromagnetic field within said chamber, and

magnetic enhancement structure disposed adjacent and outside of and extending around said coil and said chamber, said magnetic enhancement structure including a main portion extending the length of said coil and portions at either end of said main portion that overlie the ends of said coil and extend inwardly from said main portion towards said plasma chamber.

12. The system as claimed in claim **11** wherein said magnetic enhancement structure comprises a series of spaced axially extending members of magnetic material, said series of members surrounding said coil and each said member including an inwardly extending end portion that overlies the adjacent end of said coil, said magnetic enhancement structure being isolated from the high voltage that appears across the ends of said coil.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 3,862,393

DATED : January 21, 1975

INVENTOR(S) : Peter H. Dundas et al.

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 6, lines 5-6, delete "for creating an electromagnetic field within said plasma chamber inside said electrical coil".

Signed and sealed this 6th day of May 1975.

(SEAL)
Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents
and Trademarks