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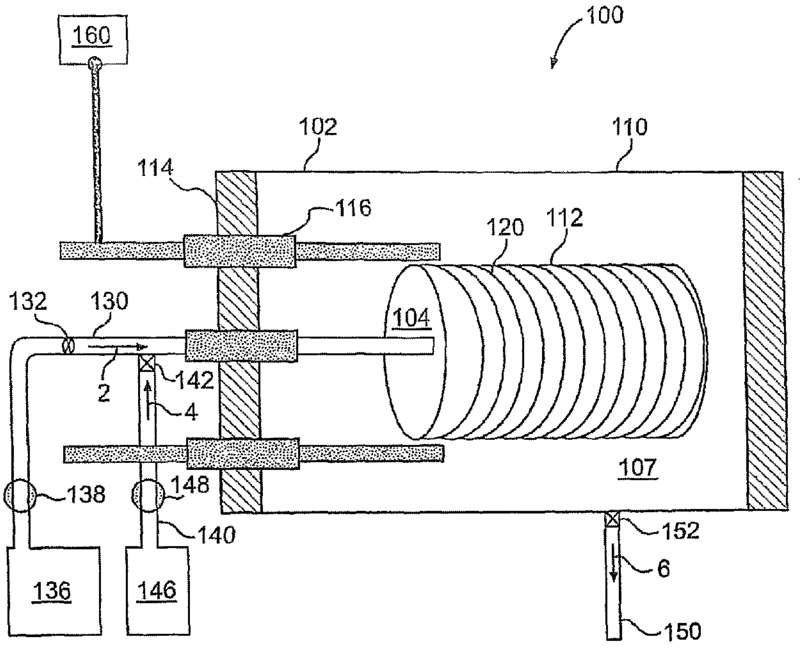
[Continued on next page]

(54) **Title:** HOLLOW CATHODE PLASMA SOURCE FOR BIO AND CHEMICAL DECONTAMINATION OF AIR AND SURFACES



(57) **Abstract:** Hollow cathode source pollution abatement systems for the remediation of chemical and microbiological pollutants are disclosed. The systems comprise a plasma generator having a hollow cathode source (HCS) for generating plasma to break down pollutant chemicals and microorganisms into simpler byproducts. The byproducts are trapped on an inner surface of the HCS. The systems allow for elimination of pollutant chemicals and microorganisms from air or gas streams as well as from the surfaces of articles. Methods of operating such systems are also disclosed.

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HOLLOW CATHODE PLASMA SOURCE FOR BIO AND CHEMICAL DECONTAMINATION OF AIR AND SURFACES

FIELD OF THE INVENTION

[0001] The disclosure relates to the abatement of airborne chemical or biological pollutants.

BACKGROUND OF THE INVENTION

[0002] It is known to use non-thermal plasma devices for elimination of chemical and biological agents. For example, *Prospects for Non-thermal Atmospheric Plasmas for Pollution Abatement* provides an overview of different non-thermal plasma technologies. See, *Prospects for Non-thermal Atmospheric Plasmas for Pollution Abatement*, R. McAdams, AEA Technology, Cutham Science Centre, Abingdon, Oxfordshire 0X14 3ED, UK 3. Phys. D: Appl. Phys. 34 (2001), pp. 2810-2821. In non-thermal plasmas, the electrons have a significantly higher temperature compared to the ions, atoms and molecules. The McAdams paper provides an overview of both the technologies involved and the diverse potential application areas. A general description of these atmospheric plasmas and the basic principles involved in the destruction or removal of gaseous phase pollutants, based on the nature of the processes taking placv within these plasmas, is given. Several examples of the different plasma technologies are described. The technologies described include pulsed corona, microwave and dielectric barrier plasma technologies. Their suitability and use in various application areas are also discussed, including incinerator off-gas treatment, industrial process off-gas treatment and diesel exhaust after-treatment.

[0003] H. W. Herrmann, I. Henins, J. Park and G. S. Selwyn have disclosed the use of an atmospheric pressure plasma jet for neutralizing chemical warfare agents. According to Herrmann et al., the atmospheric pressure plasma jet (APPJ) is a nonthermal, high pressure, uniform glow plasma discharge that produces a high velocity effluent stream of highly reactive chemical species. The discharge operates on a feedstock gas (e.g., $He/O_2/H_2O$!), which flows between an outer, grounded, cylindrical electrode and an inner, coaxial electrode powered at 13.56 MHz rf. While passing through the plasma, the feedstock gas becomes excited, dissociated or ionized by electron impact. Once the gas exits the discharge volume, ions and electrons are rapidly lost by recombination, but the fast-flowing effluent still contains neutral metastable species (e.g., O_2, He*) and radicals (e.g., O, OH). This reactive effluent has been shown to be an effective neutralizer of surrogates for anthrax spores and mustard blister agent. See, *Decontamination of Chemical and Biological Warfare (CBW) Agents Using an Atmospheric Pressure Plasma Jet (APPJ)*, H. W. Herrmann, I. Henins, J. Park, and G. S. Selwyn, Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, Physics of Plasmas, 6, 2284 (1999).

[0004] Additionally, a process using microwave plasmas for the destruction of perfluorocompounds has been experimentally investigated. The plasma device for this process was operated at atmospheric pressure and at a frequency of 2.45 GHz in synthetic gas mixtures containing N_2 and CF_4. It was found that the perfluorocompound destruction and removal efficiency of the process is highly dependent on the total gas flow and concentration of CF_4. Destruction and removal efficiencies of CF_4 up to 98% have been achieved using 1.9 kW of microwave power at 16 L/min total flow rate. See, *Studies of 2.45 GHz Microwave Induced Plasma Abatement of CF4*, Marilena Radoui, BOC Edwards, Exhaust Gas Management, Kenn Business Park, Kenn Road, BS21 6TH Clevedon, U.K., Environ. Sci. Technol. 2003, 37, 3985-3988.

[0005] Conventional plasma-based chemical and biological agent abatement devices, such as those disclosed in the literature discussed above, are relatively complex. Additionally, such devices often require high voltage power generators. It is therefore desirable to provide devices and methods for eliminating chemical and biological pollutants that are less complicated and less expensive than known plasma-based pollution abatement devices and methods. It is further desirable to provide a devices and processes for the elimination of chemical and biological agents that require lower power consumption than known devices and methods.

BRIEF SUMMARY OF THE INVENTION

[0006] The disclosure concerns systems and methods for eliminating chemical and biological pollutants. The systems and methods employ a hollow cathode plasma generator that breaks down chemicals and microorganisms into byproduct compositions and traps the byproduct compositions inside the plasma generator.

[0007] According to one embodiment, a pollution abatement system comprises:

a plasma generator, wherein said plasma generator comprises a hollow cathode source disposed in a housing and an anode spaced from said hollow cathode source;

a power supply connected to said plasma generator;

a feed gas supply comprising a feed gas suitable for generating plasma within an inner volume of the hollow cathode;

a feed gas tube extending from said feed gas supply into the inner volume of said hollow cathode source and arranged to carry a first gas stream comprising the feed gas;

a contaminated gas source comprising a contaminated gas;

a contaminated gas tube in communication with said contaminated gas source and connected to introduce a second gas stream comprising the contaminated gas to said first gas stream; and

a gas outlet in communication with an inner chamber of the housing and arranged to remove remediated gas from said plasma generator.

[0008] The feed gas tube and the contaminated gas tube may be separate gas tubes in selective communication with each other, wherein the contaminated gas is introduced from the contaminated gas tube into the feed gas tube as a second gas stream. Alternatively, the feed gas tube and the contaminated gas tube may be the same gas tube, wherein the feed gas includes the contaminated gas.

[0009] According to another embodiment, a pollution abatement system comprises:

a plasma generator, wherein said plasma generator comprises a hollow cathode source disposed in a housing and an anode spaced from said hollow cathode source;

a power supply connected to said plasma generator;

a feed gas supply comprising a feed gas suitable for generating plasma within an inner volume of the hollow cathode;

a feed gas tube extending from said feed gas supply into the inner volume of said hollow cathode source and arranged to carry a first gas stream comprising the feed gas;

a gas outlet in communication with an inner chamber of the housing and arranged to remove gas from said plasma generator; and

a contaminated article disposed inside the hollow cathode source and arranged to be decontaminated by exposure to the plasma, wherein the contaminated article is contaminated by at least one of the following agents: a chemical pollutant, a volatile organic compound and a microorganism.

[0010] Further embodiments are related to methods for decontaminating gases and surfaces. According to one embodiment, a method for decontaminating a gas comprises:

providing a plasma generator, wherein said plasma generator comprises a hollow cathode source disposed in a housing and an anode spaced from said hollow cathode source;

powering said plasma generator with a power source;

supplying a feed gas to an inner volume of the hollow cathode so as to generate plasma within said inner volume;

supplying a contaminated gas to said inner volume and passing said contaminated gas through said plasma so as to break down said contaminated gas into remediated gas and byproducts; and

removing said remediated gas from said plasma generator.

[0011] According to another embodiment, a method for decontaminating a gas comprises:

providing a plasma generator, wherein said plasma generator comprises a hollow cathode source disposed in a housing and an anode spaced from said hollow cathode source;

powering said plasma generator with a power source;

supplying a feed gas to an inner volume of the hollow cathode so as to generate plasma within said inner volume, wherein said feed gas includes at least one contaminant;

passing said at least one contaminant through said plasma so as to break down said at least one contaminant into byproducts, and thereby remediating said feed gas; and

removing remediated gas from said plasma generator.

[0012] According to yet another embodiment, a method for decontaminating an article comprises:

providing a plasma generator, wherein said plasma generator comprises a hollow cathode source disposed in a housing and an anode spaced from said hollow cathode source;

placing the article inside the hollow cathode source, wherein a surface of the article is contaminated by at least one of the following agents: a chemical pollutant, a volatile organic compound and a microorganism;

powering said plasma generator with a power source;

supplying a feed gas to an inner volume of the hollow cathode so as to generate plasma within said inner volume;

exposing said surface of said article to said plasma so as to break down said agent into byproducts; and

removing uncontaminated gas from said plasma generator.

[0013] Further features and advantages of the invention will become apparent from the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIG. 1 is a schematic illustration of a pollution abatement system according to one embodiment;

[0015] FIG. 2 is a schematic illustration of a pollution abatement system according to another embodiment;

[0016] FIG. 3 is a schematic illustration of a pollution abatement system for the decontaminating surfaces;

[0017] FIGS. 4-5 are schematic illustrations of experimental pollution abatement systems;

[0018] FIGS. 6A-6F are mass spectrometer chromatographs showing the remediation of benzene using the system of FIG. 4.

[0019] FIGS. 7A and 7B are multiple ion detection (MID) plots from a mass spectrometer demonstrating the remediation of benzene using the system of FIG. 4;

[0020] FIGS. 8A-8E are mass spectrometer chromatographs showing the remediation of benzene using the system of FIG. 5.

[0021] FIGS. 9A and 9B are MID plots from a mass spectrometer demonstrating the remediation of benzene using the system of FIG. 5; and

[0022] FIG. 10 is a comparison of the MID plots for the systems of FIGS. 4 and 5.

DETAILED DESCRIPTION OF THE INVENTION

[0023] FIG. 1 shows a pollution abatement system **100** which includes a hollow cathode source plasma generator **110**. The plasma generator **110** includes a hollow cathode source (HCS) **112** enclosed in a housing **102**, and an anode **114** axially spaced and insulated from the HCS **112** by an insulator **116**. The HCS **112** is connected to a power supply **160** and the anode **114** is electrically grounded. Cooling water tubes **120** are disposed around the HCS **112**. The housing **102** electrically isolates the HCS **112** from the atmosphere to avoid plasma formation on the surface rather than the inside of the HCS **112**.

[0024] A feed gas tube **130** extends from a feed gas supply **136** through the housing **102** and into an inner volume **104** of the HCS **112**. The feed gas supply tube **130** carries a feed gas stream **2** which may comprise air or another gas suitable for generating plasma within the generator **110**. The feed gas may be supplied through the feed gas supply tube **130** from the feed gas supply **136** by a pump **138** or other suitable device. The system further includes a contaminant source **146**. The contaminant source **146** may contain one or more gases including pollutant chemical compounds, volatile organic compounds (VOCs) or microorganisms. A contaminant supply tube **140** connects the contaminant source **146** to the feed gas supply tube **130** and carries a contaminated gas stream **4** from the contaminant source **146**. A pump or other delivery device **148** may be provided for feeding the contaminated gas stream **4** through the supply tube **140**. The system **100** further includes a gas outlet tube **150** extending from the interior chamber **107** of the housing **102** to an area outside of the plasma generator **110**. The gas outlet tube **150** allows harmless, remediated gas **6** to be removed from the inner chamber **107**. The feed gas tube **130**, contaminant supply tube **140** and gas outlet tube **150** may be provided with valves **132, 142, 152** and associated controls (not shown) in order to maintain a desired pressure within the cathode inner volume **104**.

[0025] In the operation of the system **100**, the plasma generator **110** is powered and feed gas stream **2** is fed through the feed gas tube **130** to the inner volume **104** of the HCS **112**, causing the generation of plasma in the inner volume **104** in a known manner. As the feed gas stream **2** flows through the feed gas tube **130**, the polluted gas stream **4** is introduced into the feed gas tube **130** through the supply tube **140**. The contaminated gas stream **4** mixes with the feed gas stream **2** in the feed gas tube **130**. Thereafter, the contaminated gas stream **4** is introduced inside the HCS **112** where it interacts with the plasma. The plasma generator can be operated with the inner volume **104** at pressures as low as 1 mTorr. Therefore, the pressure of the polluted gas stream **4** and the feed gas stream **2** can be as low as 1 mTorr.

[0026] As the polluted gas stream **4** passes through the plasma, the plasma breaks down pollutant chemical compounds, volatile organic compounds (VOCs) or microorganisms in the polluted gas stream **4**. Chemical compounds, VOCs or microorganisms are broken down into simpler byproduct waste molecules such as CO, O_2, CO_2 and H_2O. The byproduct waste molecules are removed from the gas phase and trapped on the inner surface of the HCS **112**. As plasma generation (i.e., the plasma "on" phase) continues and byproduct waste molecules collect on the inner surface of the HCS **112**, the pressure of the inner volume **104** of the HCS **112** falls. Once the pressure of the inner volume **104** falls below a certain level (typically below about 1 mTorr), the plasma becomes unstable and plasma generation ceases (i.e., the plasma "off" phase). Once plasma generation ceases, the pressure of the inner volume **104** rises until it reaches a level at which plasma generation begins again.

[0027] The inventive system and method goes beyond the chemical cleaving provided by prior art pollution remediation devices. As described above, the inventive system and method provides complete elimination of pollutants and trapping of waste molecules inside the HCS **112**. Waste can be removed from the plasma generator **110** by simply cleaning off the inner surface of the HCS **112**. Additionally, in contrast to more complex, conventional pollution abatement systems which use microwave or corona discharge-type plasma generation and usually require high voltage power generators, the inventive system **100** can be operated with a relatively low voltage power supply **160**.

[0028] The inventive system **100**, and the individual components thereof, can be scaled for use in various applications. Such applications include, but are not limited to, residential and industrial air cleaning systems and industrial waste gas cleaning systems. Where the system **100** is an air cleaning system, the pollutant source **146** would be a room or building and the polluted gas stream **4** would comprise room or building air that is to be remediated by exposure to the plasma. Where the system **100** is an industrial exhaust gas processing system, the pollutant source **146** would be equipment used in an industrial process and the polluted gas stream **4** would comprise waste gas generated by the industrial process, wherein the waste gas is to be remediated prior to release into the atmosphere.

[0029] FIG. 2 shows a system **200** according to another embodiment, in which the feed gas supply **136** contains polluted gas. Therefore, there is no need for a separate pollutant source and supply tube. Referring to FIG. 2, in which reference numbers repeated from FIG. 1 indicate similar components, the system **200** includes a hollow cathode source plasma generator **110** including HCS **112** enclosed in a housing **102**, and an anode **114** axially spaced and insulated from the HCS **112** by insulator **116**. The HCS **112** is connected to power supply **160** and the anode **114** is electrically grounded. Cooling water tubes **120** are disposed around the HCS **112**. The housing **102** electrically isolates the HCS **112** from the atmosphere to avoid plasma formation on the surface rather than the inside of the HCS **112**.

[0030] A feed gas tube **130** extends from a feed gas supply **136** through the housing **102** and into the inner volume **104** of the HCS **112**. The feed gas supply tube **130** carries a feed gas stream **20** which may comprise air or another gas suitable for generating plasma within the generator **110**. The feed gas stream **20** further comprises one or more pollutants, which may include gaseous chemicals and/or microorganisms. The feed gas stream **20** may be supplied through the feed gas supply tube **130** from the feed gas supply **136** by a pump **138** or other suitable device. The system **200** further includes a gas outlet tube **150** extending from the interior volume **104** of the HCS **112** to an area outside of the plasma generator **110**. The gas outlet tube **150** allows harmless, remediated gas **6** to be removed from the inner volume **104**. The feed gas tube **130** and gas outlet tube **150** may be provided with valves **132, 152** and associated controls (not shown) for maintaining a desired pressure within the cathode inner volume **104**.

[0031] In the operation of the system **200**, the plasma generator **110** is powered and feed gas stream **20** is fed through the feed gas tube **130** to the inner volume **104** of the HCS **112**, causing the generation of plasma in the cathode inner volume **104** in a known manner. As indicated with regard to the previous embodiment, the plasma generator can be operated with the inner volume **104** at pressures as low as 1 mTorr. Therefore, the pressure of the feed gas stream **20** can be as low as 1 mTorr.

[0032] As plasma is generated from the feed gas stream **20**, the plasma breaks down pollutant chemical compounds, volatile organic compounds (VOCs) and/or microorganisms in the feed gas stream **20**. As is the case in the previous embodiment, the chemical compounds, VOCs or toxic microorganisms are broken down into simpler byproduct waste molecules such as CO, O_2, CO_2 and H_2O, and the byproduct waste molecules are removed from the gas phase and trapped on the inner surface of the HCS **112**. As plasma generation (i.e., the plasma "on" phase) continues and byproduct waste molecules collect on the inner surface of the HCS **112**, the pressure of the inner volume **104** of the HCS **112** falls. Once the pressure of the inner volume **104** falls below a certain level (typically below about 1 mTorr), the plasma becomes unstable and plasma generation ceases (i.e., the plasma "off" phase). Once plasma generation ceases, the pressure of the inner volume **104** rises until it reaches a level at which plasma generation begins again.

[0033] Thus, the operation of systems **100** and **200** is similar, except that the system **200** does not include a separate pollutant source, since the pollutants originate from the feed gas supply **136.**

[0034] As is the case the with system **100,** the system **200** may be scaled for use in various applications, including residential and industrial air cleaning systems or industrial waste gas cleaning systems. In an air cleaning system, the feed gas supply **136** would be a room or building and the feed gas stream **20** would comprise polluted air in the room or building. Alternatively, in an industrial waste gas cleaning system, the feed gas supply **136** would be equipment used in an industrial process and the feed gas stream **20** would comprise polluted waste gas generated by the industrial process.

[0035] According to another embodiment, the system **200** may be an exhaust gas cleaning system for a motor vehicle. In such an embodiment, the plasma generator **110** may be a catalytic converter, in which case the feed gas supply **136** would be an engine and the feed gas stream **20** would comprise exhaust gases generated by the engine.

[0036] An embodiment of a pollution abatement system for cleaning surfaces is shown in FIG. 3. As shown in FIG. 3, system **300** is similar to system **200**, except that it comprises a feed gas stream **2**, which may comprise any suitable feed gas, and an article **50** having a surface **52** that is to be cleaned by the plasma generator **110**. The surface **52** is contaminated by chemicals or microbiological organisms.

[0037] In operation of the system **300**, the article **50** is first placed in the inner volume **104** of the HCS **112**. Plasma is generated as described with respect to the embodiment of FIG. 2. As plasma is generated from the feed gas stream **2**, the plasma breaks down chemical compounds, volatile organic compounds (VOCs) and/or microorganisms on the surface **52** of the article **50** into byproduct waste molecules such as CO, CO_2 and H_2O. The byproduct waste molecules are trapped on the inner surface of the HCS **112**. Uncontaminated gas **6** is removed via the gas outlet tube **150**. As plasma generation (i.e., the plasma "on" phase) continues and byproduct waste molecules collect on the inner surface of the HCS **112**, the pressure of the inner volume **104** of the HCS **112** falls. Once the pressure of the inner volume **104** falls below a certain level (again, typically below about 1 mTorr), the plasma becomes unstable and plasma generation ceases (i.e., the plasma "off" phase). Once plasma generation ceases, the pressure of the inner volume **104** rises until it reaches a level at which plasma generation begins again. This process may be repeated until the article **50** is substantially entirely decontaminated.

[0038] The following examples discuss the implementation of certain experimental embodiments of a device and method for the elimination of chemical and biological agents.

<u>Example 1</u>

[0039] An experimental hollow cathode source pollution abatement system **400**, illustrated in FIG. 4, was constructed. Reference numbers repeated from FIGS. 1-3 indicate similar components. The system **400** included a plasma generator **210** comprising a hollow HCS **112** disposed in the inner chamber **207** of a housing **202**, and an anode **114** axially spaced and insulated from the HCS **112** by an insulator **116**. The HCS, or target **112** was made of an aluminum tube having a length of 5 inches and a diameter of 2.5 inches. Copper cooling water tubes **120** were wrapped around HCS **112**. The anode **114** was made from aluminum disks. The hollow cathode/cooling water tube assembly was insulated with Kapton tape (not shown). The device **210** was connected to a 15 watt power supply **160a**. The housing **202** was constructed to electrically isolate the HCS **112** from the atmosphere to avoid plasma formation on the outer surface rather than the inside of the HCS **112**. The housing **202** was further constructed to maintain a vacuum inside the device **210** in order to allow for the performance of mass spectrometry without the complication of residual gases in the device **210**.

[0040] An aluminum feed gas tube **130** was provided at a first end of the system **400** for the introduction of feed gas stream **20** into the inner volume **104** of the hollow cathode. The feed gas tube **130** was arranged such that the gas inlet was placed one inch inside the HCS **112**. A feed gas reservoir **136** was connected to the feed gas tube **130** through a needle valve (not shown). Benzene was selected as the feed gas for the system, and was filled into the feed gas reservoir **136**.

[0041] The system **400** was further provided with a 120 L/s turbomolecular pump (TMP) **190** to create vacuum in the device **210** so that the benzene could be fed into the system. The TMP **190** was backed by a foreline pump **192**, which was provided to take away the gas pumped out by the TMP **190**. A gate valve **196** was provided to control the flow to the TMP **190**. The base internal pressure of the system (i.e., the lowest pressure obtained before the start of the experiment) was 4×10^{-7} Torr.

[0042] A differentially pumped quantum mass spectrometer (QMS) **180** was provided in a chamber **106** at a second end of the system **400** to enable the detection of byproduct molecules generated by the breakdown of benzene in the generator **210**. The chamber **106** for the QMS **180** was connected to the inner volume **104** through a 10μm orifice **108** and was connected to a TMP **182** backed by a foreline pump **184**. The TMP **182** was provided to supply molecules to the QMS **180** for mass spectrometery. The foreline pump **184** was provided to take away the gas pumped out by the TMP **182**. A gate valve **186** was provided to control the flow to the TMP **182**.

[0043] Once the plasma device was set up, the power supply **160a** was turned on and benzene was allowed to flow from the reservoir **136** into the inner volume **207** of the HCS **112**. The flow rate of the benzene was estimated by measuring the flow rate of argon required to maintain the same chamber pressure under similar conditions. QMS spectra and the chamber pressure were recorded as shown in the chromatographs of FIGS. 6A-6F and the multiple ion detection (MID) plots FIGS. 7A and 7B.

[0044] As shown in FIGS. 7A and 7B, benzene cracked to yield CO, O_2, CO_2 and H_2O when passed through the plasma. These byproducts of benzene cracking were trapped on the inner surface of the HCS **112**, which resulted in the fall of the QMS signal and the chamber pressure, as shown in FIGS. 6A-6D. The chamber pressure continued to fall due to the cracking of benzene until the plasma became unstable and shut off (see FIGS. 6E-6F). The MID plots in FIGS. 7A and 7B present consolidated data showing the removal of benzene byproducts from the gas phase during operation of the system **400**.

<u>Example 2</u>

[0045] A hollow cathode source plasma system **500**, shown in FIG. 5, was constructed and operated in similar fashion to the system **400** of Example 1, except that the device **210** was connected to a 50 watt power supply **160b**. QMS spectra and the chamber pressure were recorded as shown in Figures 8A-8E under both "plasma on" and "plasma off conditions."

[0046] As shown in FIGS. 9A-9B, benzene cracked to yield CO, CO_2 and H_2O when passed through the plasma. As in the previous example, these byproducts of benzene cracking were trapped on the inner surface of the HCS **112**, which lead to the fall of the QMS signal and the chamber pressure, as shown in FIGS. 8A-8C. The chamber pressure continued to fall due to the cracking of benzene until the plasma became unstable and shut off (see FIGS. 8D-8E). FIGS. 8A and 8B indicate the removal of benzene byproducts from the gas phase during operation of the system **500**.

[0047] FIG. 10 provides comparative MID plots for experimental systems **300** and **400**. Instead of partial pressure of the gases of interest shown in FIGS., 7A, 7B, 9A and 9B, FIG. 10 shows the total pressure of the cathode **112** in Examples 1 and 2.

[0048] In Examples 1 and 2, the successful cracking of benzene and trapping of benzene byproducts on the inner surface of the HCS demonstrate that HCS pollution abatement systems as disclosed herein can successfully eliminate chemical pollutants. The confined plasma in the hollow cathode is an energetic species. The break up of benzene shows that there is enough energy in the plasma to break the chemical bonds in benzene. Since the bonds in benzene are strong, the above examples illustrate that the disclosed HCS pollution abatement systems can successfully eliminate other chemical pollutants as well. Furthermore, microbiological species typically have less bonding energy than organic chemicals, and therefore the disclosed HCS pollution abatement systems are also capable of eliminating many microbiological organisms. Also, the confined plasma in a hollow cathode is even more energetic than the conventional plasma sources for decontaminating surfaces, and HCS systems will therefore also be effective in decontaminating surfaces.

[0049] The foregoing description illustrates and describes only selected embodiments, but it is to be understood that modifications within the scope of the inventive concept as expressed herein are possible, commensurate with the above teachings, and/or within the skill or knowledge of the relevant art. Accordingly, the description is not intended to limit the invention to the form disclosed herein. Also, it is intended that the appended claims be construed to include alternative embodiments, not explicitly defined in the detailed description.

CLAIMS

We claim:

1. A pollution abatement system comprising:

a plasma generator, wherein said plasma generator comprises a hollow cathode source disposed in a housing and an anode spaced from said hollow cathode source;

a power supply connected to said plasma generator;

a feed gas supply comprising a feed gas suitable for generating plasma within an inner volume of the hollow cathode;

a feed gas tube extending from said feed gas supply into the inner volume of said hollow cathode source and arranged to carry a first gas stream comprising the feed gas;

a contaminated gas source comprising a contaminated gas;

a contaminated gas tube in communication with said contaminated gas source and connected to introduce a second gas stream comprising the contaminated gas to said first gas stream; and

a gas outlet in communication with an inner chamber of the housing and arranged to remove remediated gas from said plasma generator.

2. The pollution abatement system of claim 1, wherein the contaminated gas comprises one or more of the following agents: at least one chemical pollutant, at least one volatile organic compound and at least one microorganism.

3. The pollution abatement system of claim 1, wherein the pollution abatement system is an air cleaning system, wherein the contaminated gas source is a building or room and wherein the contaminated gas is air from the building or room.

4. The pollution abatement system of claim 1, wherein the pollution abatement system is a waste gas cleaning system for an industrial process, wherein the contaminated gas source is equipment used in the industrial process and wherein the contaminated gas is waste gas generated by the industrial process.

5. The pollution abatement system of claim 1, wherein the feed gas tube and the contaminated gas tube are separate gas tubes in selective communication with each other, and the contaminated gas is introduced from the contaminated gas tube into the feed gas tube as a second gas stream.

6. The pollution abatement system of claim 1, wherein the feed gas tube and the contaminated gas tube are the same gas tube, and the feed gas includes the contaminated gas.

7. The pollution abatement system of claim 6, wherein the pollution abatement system is an exhaust system for a motor vehicle, wherein the plasma generator is a catalytic converter, wherein the feed gas supply is an engine in the motor vehicle and wherein the feed gas is exhaust gas from the engine.

8. The pollution abatement system of claim 1, comprising:

a mass spectrometry chamber in communication with the inner volume of the hollow cathode through an orifice and containing a quantum mass spectrometer; and

a turbomolecular pump arranged to supply molecules to the quantum mass spectrometer for mass spectrometery.

9. A pollution abatement system comprising:

a plasma generator, wherein said plasma generator comprises a hollow cathode source disposed in a housing and an anode spaced from said hollow cathode source;

a power supply connected to said plasma generator;

a feed gas supply comprising a feed gas suitable for generating plasma within an inner volume of the hollow cathode;

a feed gas tube extending from said feed gas supply into the inner volume of said hollow cathode source and arranged to carry a first gas stream comprising the feed gas;

a gas outlet in communication with an inner chamber of the housing and arranged to remove gas from said plasma generator; and

a contaminated article disposed inside the hollow cathode source and arranged to be decontaminated by exposure to the plasma, wherein the contaminated article is contaminated by at least one of the following agents: a chemical pollutant, a volatile organic compound and a microorganism.

10. A method for removing contaminants from a gas, comprising:

providing a plasma generator, wherein said plasma generator comprises a hollow cathode source disposed in a housing and an anode spaced from said hollow cathode source;

powering said plasma generator with a power source;

supplying a feed gas to an inner volume of the hollow cathode so as to generate plasma within said inner volume;

supplying a contaminated gas to said inner volume and passing said contaminated gas through said plasma so as to break down said contaminated gas into remediated gas and byproducts; and

removing said remediated gas from said plasma generator.

11. The method of claim 10, comprising trapping said byproducts on an inner surface of the hollow cathode.

12. The method of claim 11, comprising allowing said byproducts to accumulate on said inner surface until a pressure within said inner volume falls to a level low enough to cease generation of said plasma.

13. The method of claim 12, comprising, subsequent to cessation of generation of said plasma, allowing said pressure within said inner chamber to rise to a level high enough to initiate plasma generation.

14. The method of claim 10, wherein said contaminated gas comprises an agent from the group consisting of: a chemical pollutant, a volatile organic compound and a microorganism.

15. The method of claim 10, wherein the feed gas and the contaminated gas are fed from separate sources through a respective feed gas tube and a contaminated gas tube which are in selective communication with respect to each other.

16. The method of claim 10, wherein the feed gas is supplied from a source containing the contaminated gas, and the feed gas and the contaminated gas are supplied to the inner volume of the hollow cathode from the source through a common gas tube.

17. A method for decontaminating an article, comprising:

providing a plasma generator, wherein said plasma generator comprises a hollow cathode source disposed in a housing and an anode spaced from said hollow cathode source;

placing the article inside the hollow cathode source, wherein a surface of the article is contaminated by at least one of the following agents: a chemical pollutant, a volatile organic compound and a microorganism;

powering said plasma generator with a power source;

supplying a feed gas to an inner volume of the hollow cathode so as to generate plasma within said inner volume;

exposing said surface of said article to said plasma so as to break down said agent into byproducts; and

removing uncontaminated gas from said plasma generator.

18. The method of claim 17, comprising trapping said byproducts on an inner surface of the hollow cathode.

19. The method of claim 18, comprising allowing said byproducts to accumulate on said inner surface until a pressure within said inner volume falls to a level low enough to cease generation of said plasma.

20. The method of claim 19, comprising, subsequent to cessation of generation of said plasma, allowing said pressure within said inner chamber to rise to a level high enough to initiate plasma generation.

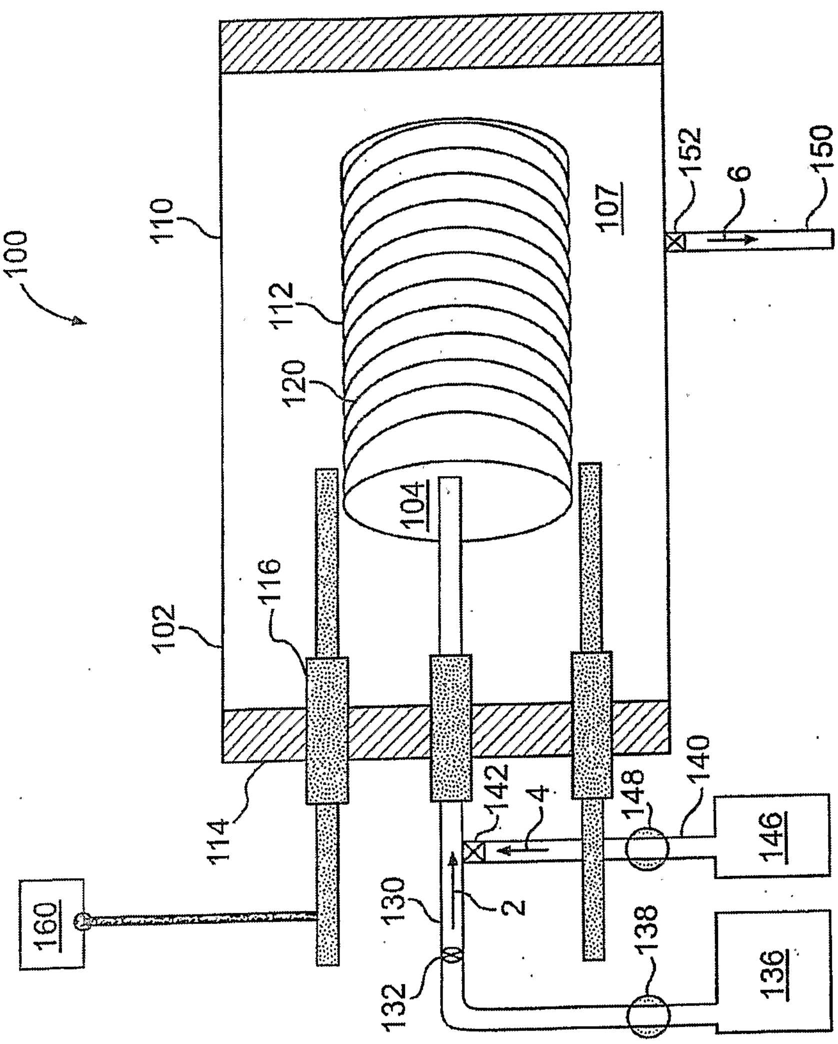

100
110
112
120
102
116
114
104
107
152
6
150
130
132
2
142
4
148
140
146
138
136
160

FIG. 1

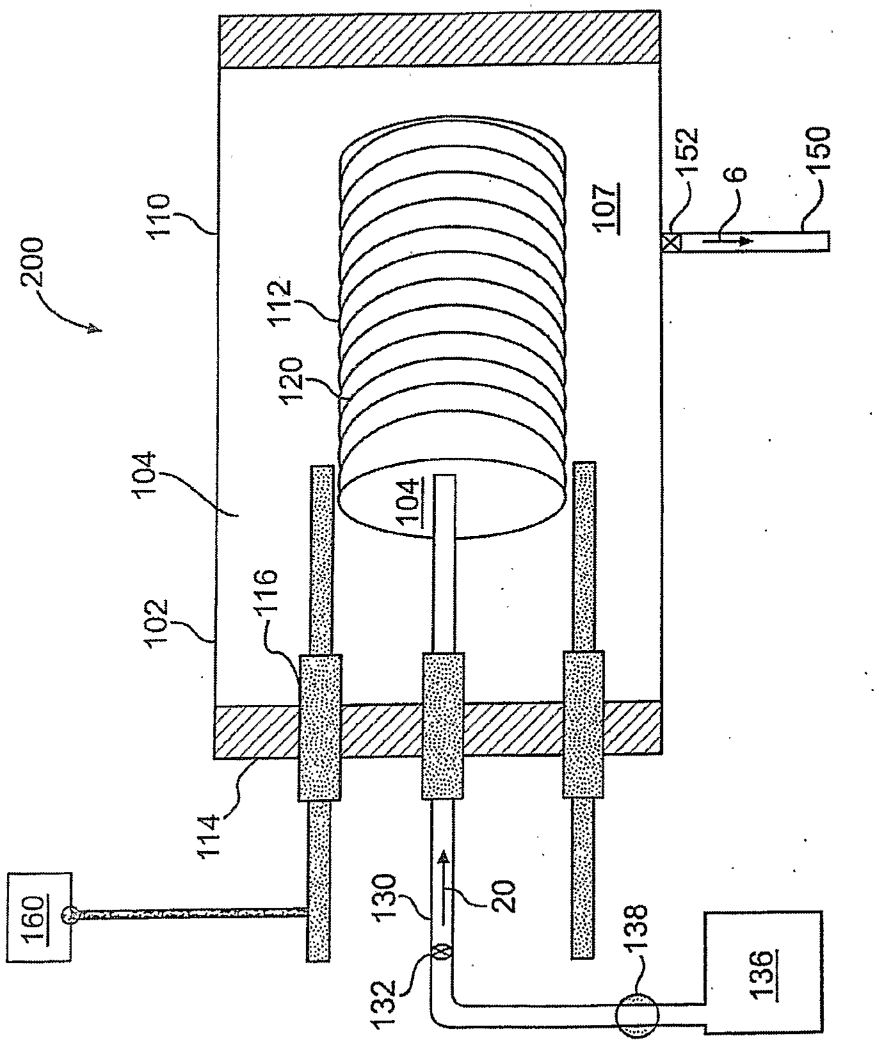

200
110
104
102
116
112
120
104
107
152
6
150
114
160
130
20
132
138
136

FIG. 2

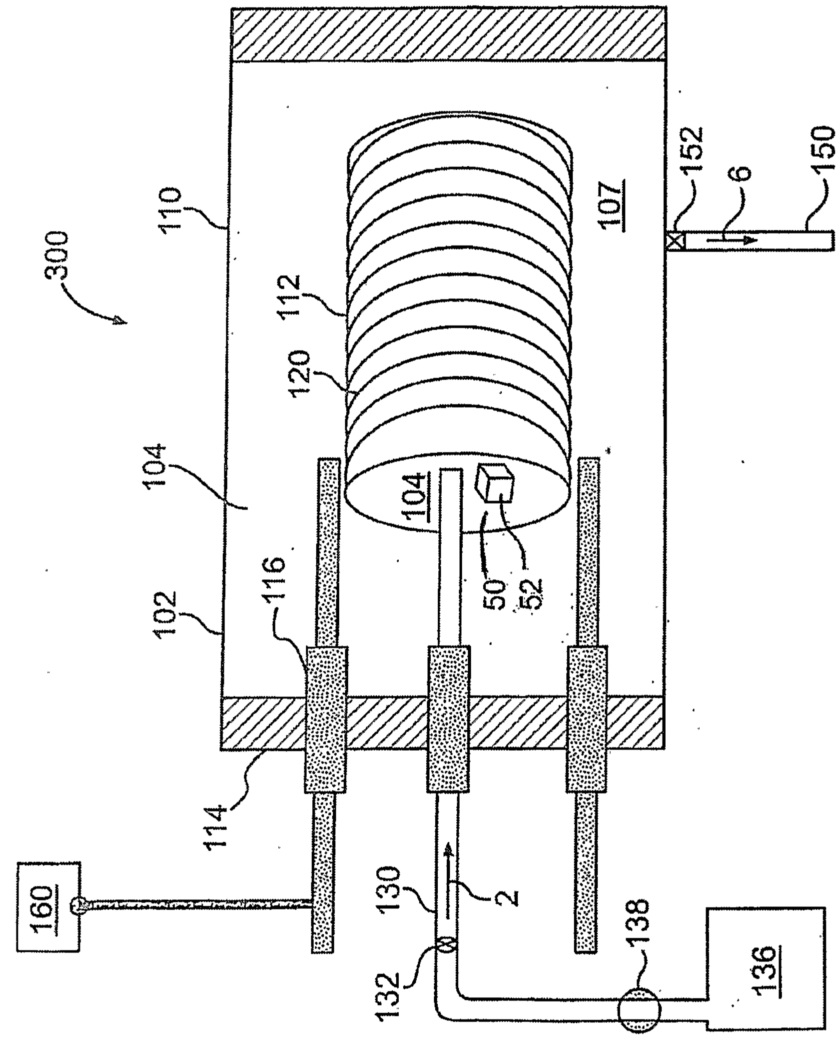
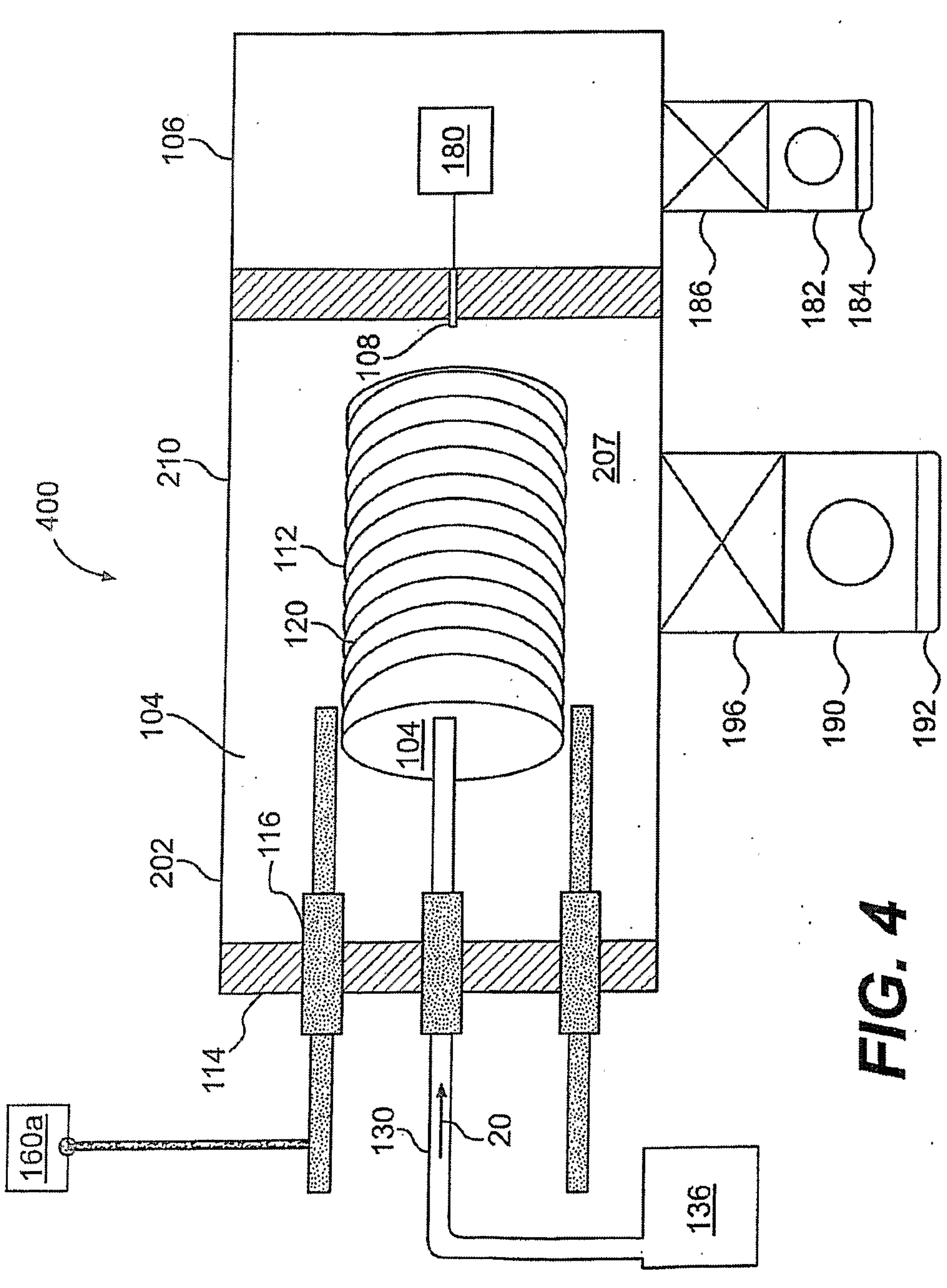

300
110
104
102
116
114
112
120
104
107
152
6
150
50
52
130
2
132
138
136
160

FIG. 3



400
106
180
108
210
112
120
104
207
104
202
116
114
130
20
160a
136
186
182
184
196
190
192

FIG. 4

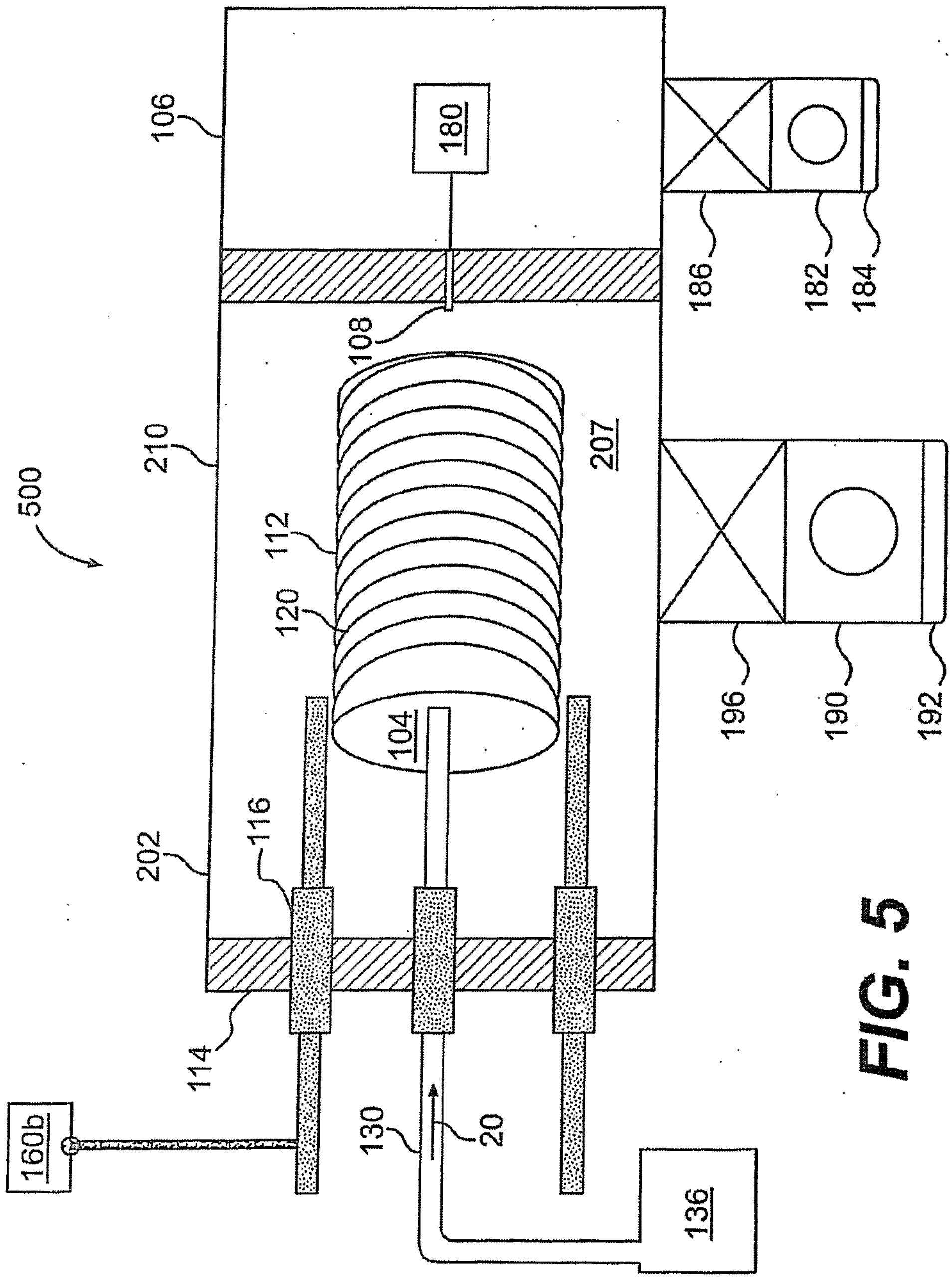

500
106
180
108
210
207
112
120
104
202
116
114
130
20
136
160b
186
182
184
196
190
192

FIG. 5

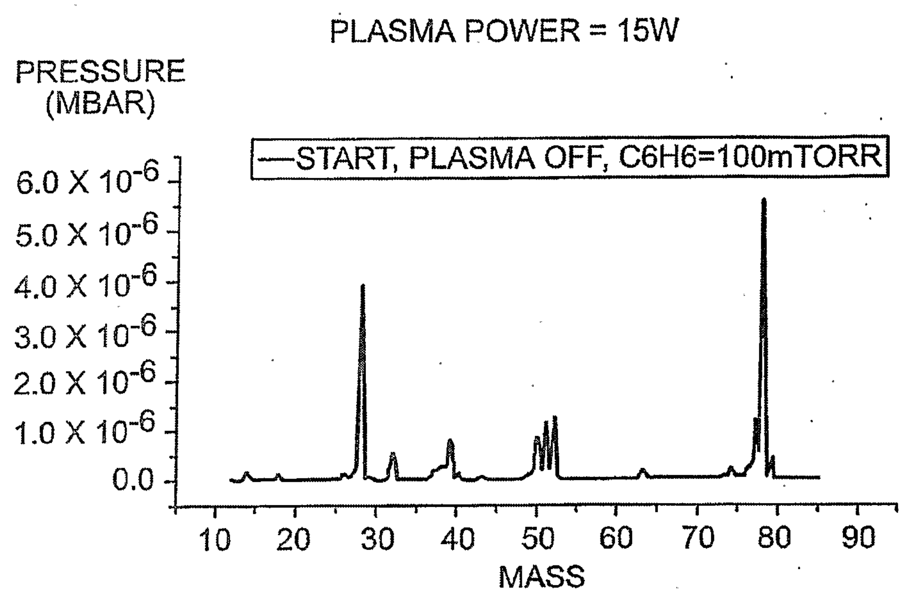

PLASMA POWER = 15W
PRESSURE (MBAR)
—START, PLASMA OFF, C6H6=100mTORR
6.0 X 10-6
5.0 X 10-6
4.0 X 10-6
3.0 X 10-6
2.0 X 10-6
1.0 X 10-6
0.0
10 20 30 40 50 60 70 80 90
MASS

FIG. 6A

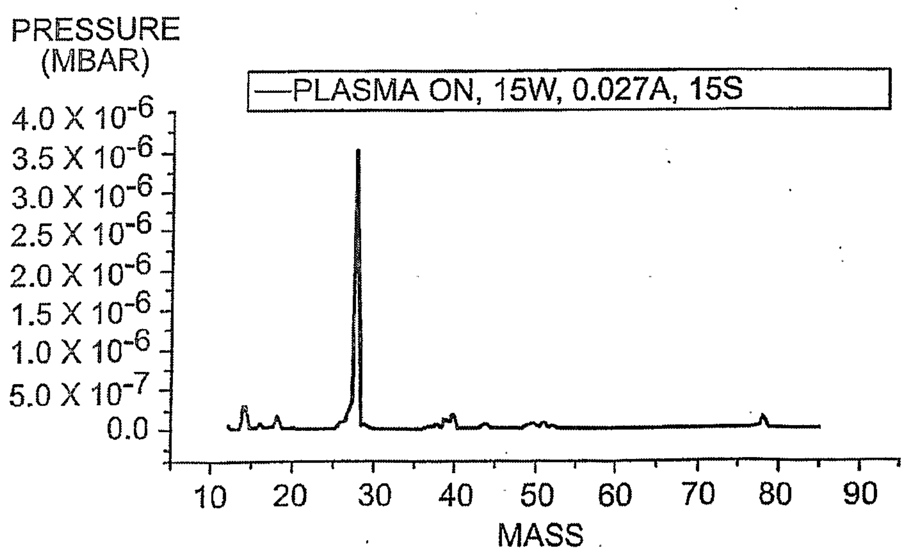

PRESSURE (MBAR)
—PLASMA ON, 15W, 0.027A, 15S
4.0 X 10-6
3.5 X 10-6
3.0 X 10-6
2.5 X 10-6
2.0 X 10-6
1.5 X 10-6
1.0 X 10-6
5.0 X 10-7
0.0
10 20 30 40 50 60 70 80 90
MASS

FIG. 6B

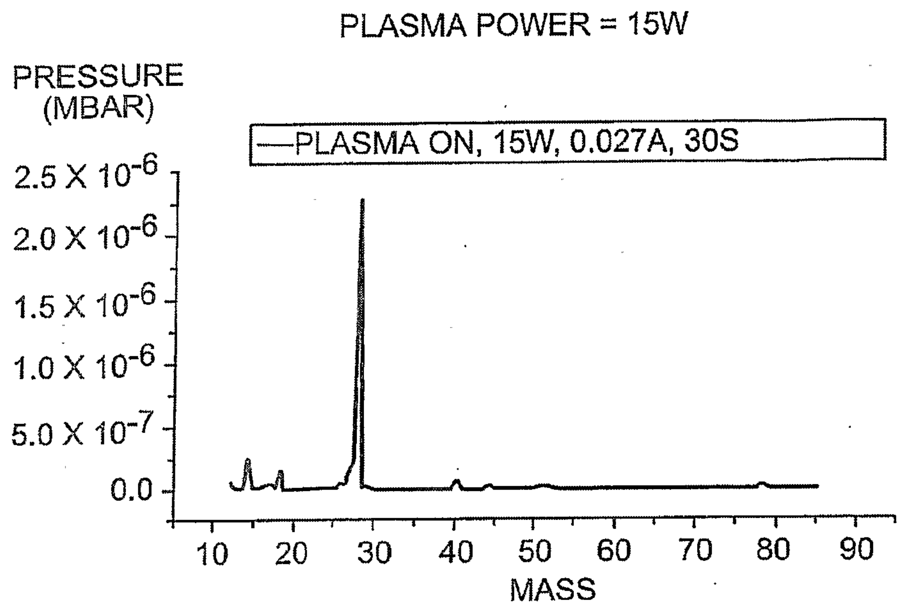

PLASMA POWER = 15W
PRESSURE (MBAR)
—PLASMA ON, 15W, 0.027A, 30S
2.5 X 10-6
2.0 X 10-6
1.5 X 10-6
1.0 X 10-6
5.0 X 10-7
0.0
10 20 30 40 50 60 70 80 90
MASS

FIG. 6C

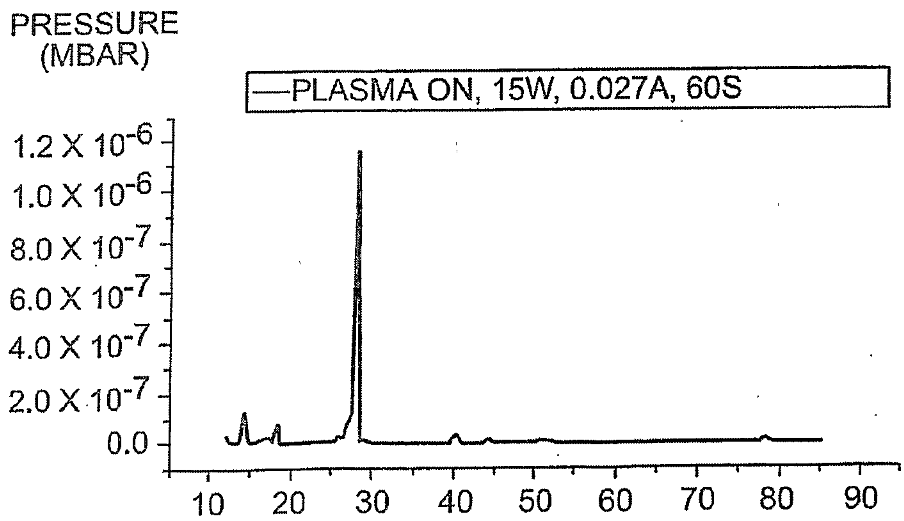

PRESSURE (MBAR)
—PLASMA ON, 15W, 0.027A, 60S
1.2 X 10-6
1.0 X 10-6
8.0 X 10-7
6.0 X 10-7
4.0 X 10-7
2.0 X 10-7
0.0
10 20 30 40 50 60 70 80 90

FIG. 6D

PLASMA POWER = 15W

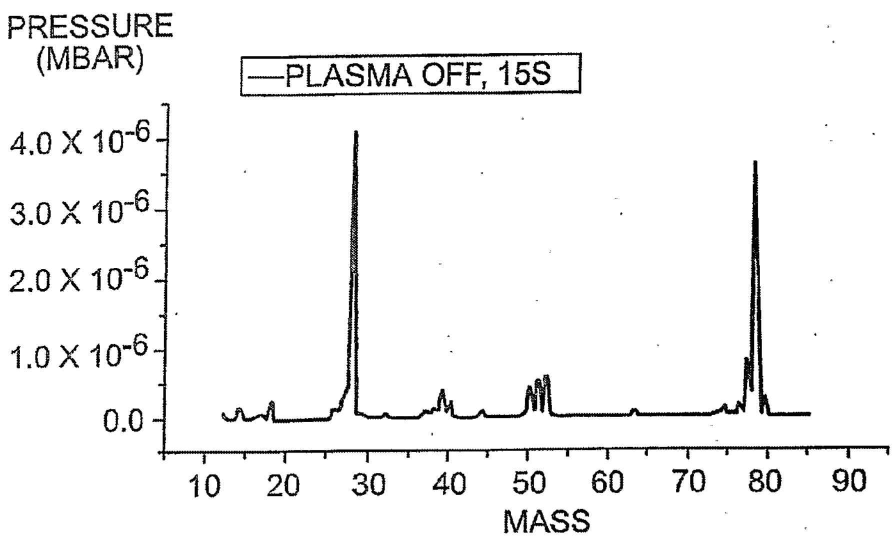


FIG. 6E

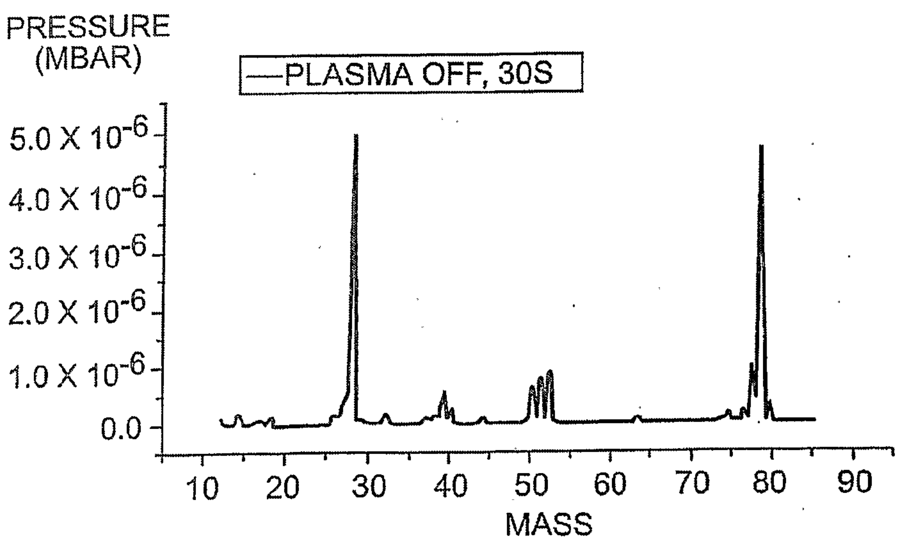


FIG. 6F

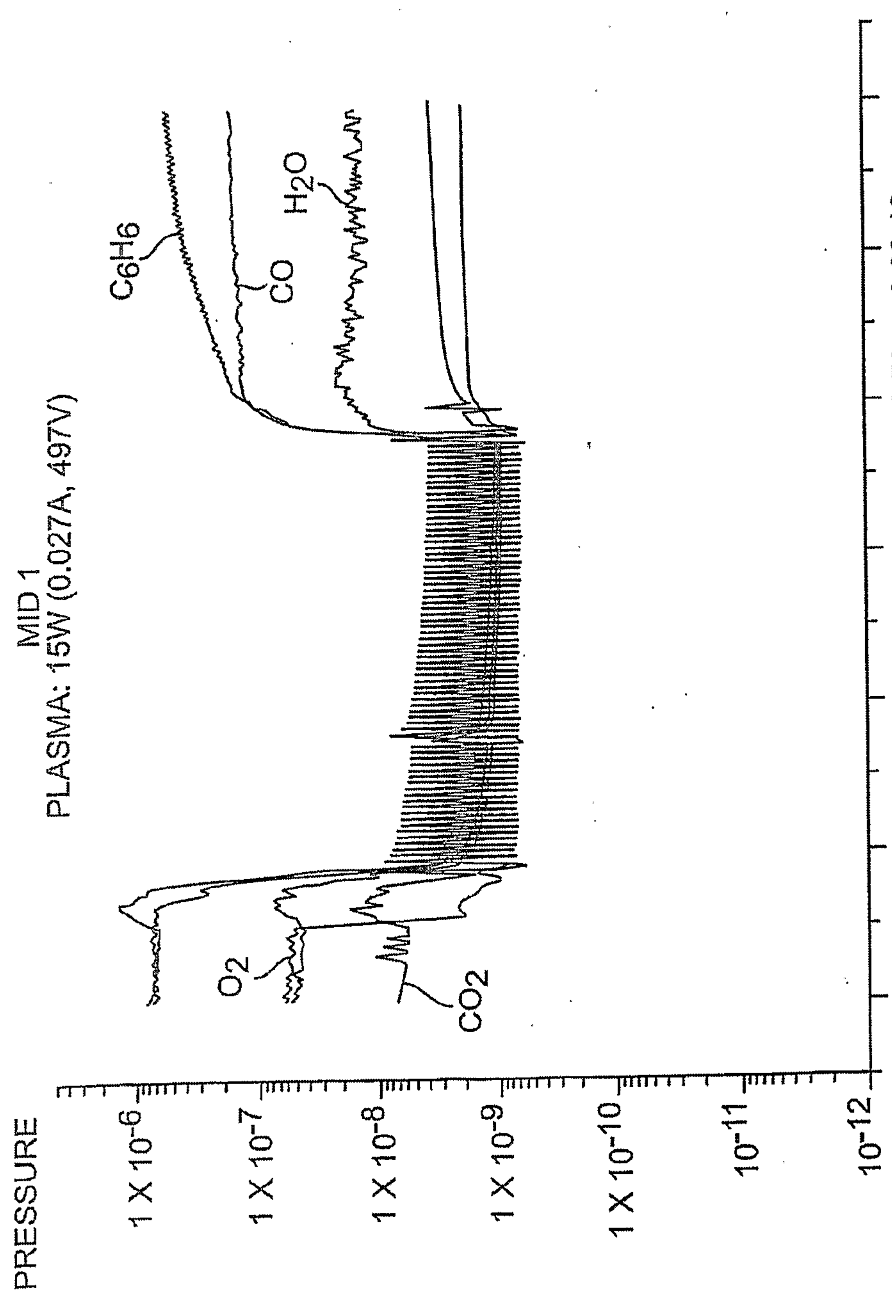

MID 1
PLASMA: 15W (0.027A, 497V)
PRESSURE
1 X 10^-6
1 X 10^-7
1 X 10^-8
1 X 10^-9
1 X 10^-10
10^-11
10^-12
TIME
0:01:38
0:03:19
0:05:02
0:06:50
0:09:10
C6H6
CO
H2O
O2
CO2

FIG. 7A

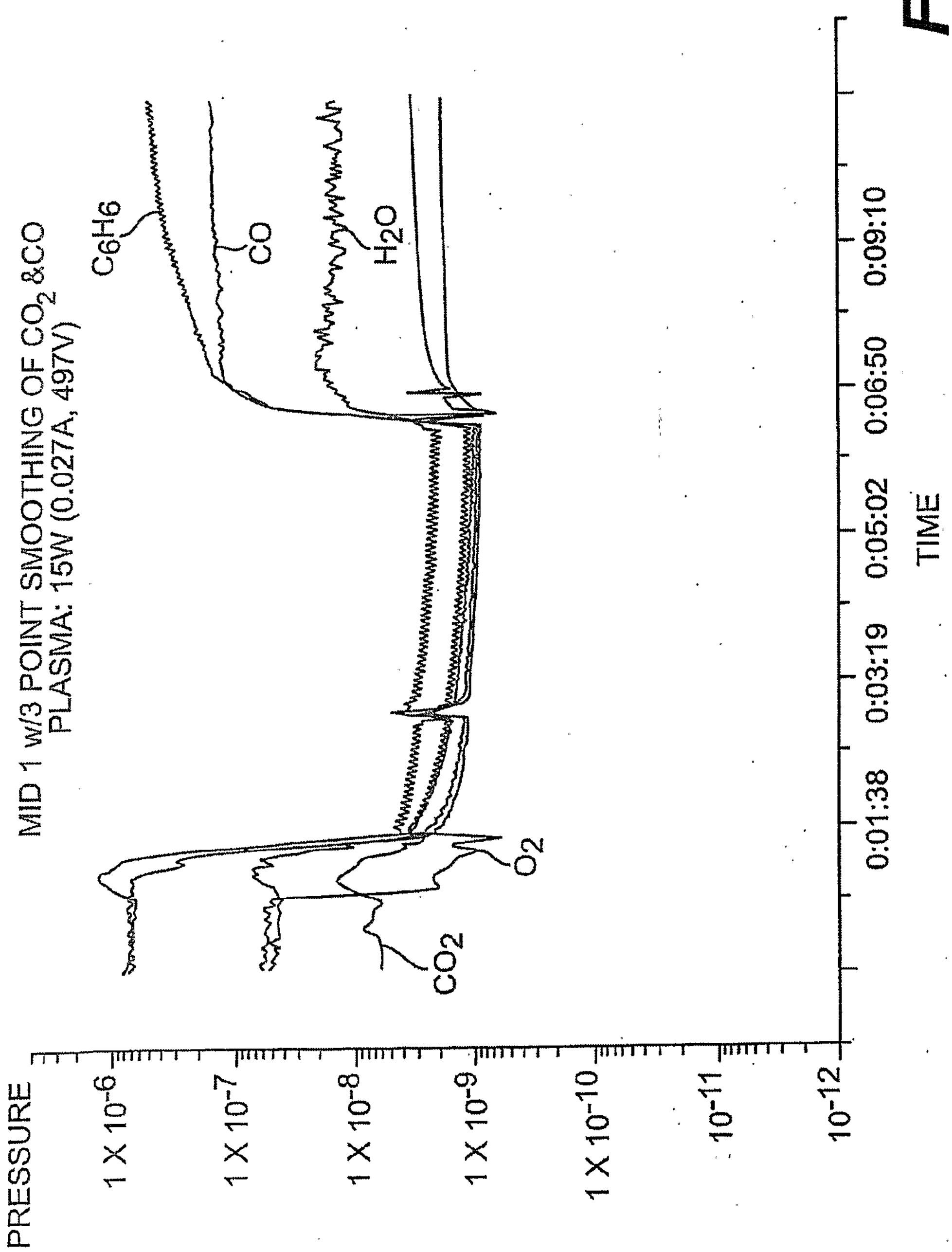

MID 1 w/3 POINT SMOOTHING OF CO_2 &CO
PLASMA: 15W (0.027A, 497V)
PRESSURE
1 X 10^{-6}
1 X 10^{-7}
1 X 10^{-8}
1 X 10^{-9}
1 X 10^{-10}
10^{-11}
10^{-12}
C_6H_6
CO
H_2O
CO_2
O_2
0:01:38
0:03:19
0:05:02
0:06:50
0:09:10
TIME

FIG. 7B

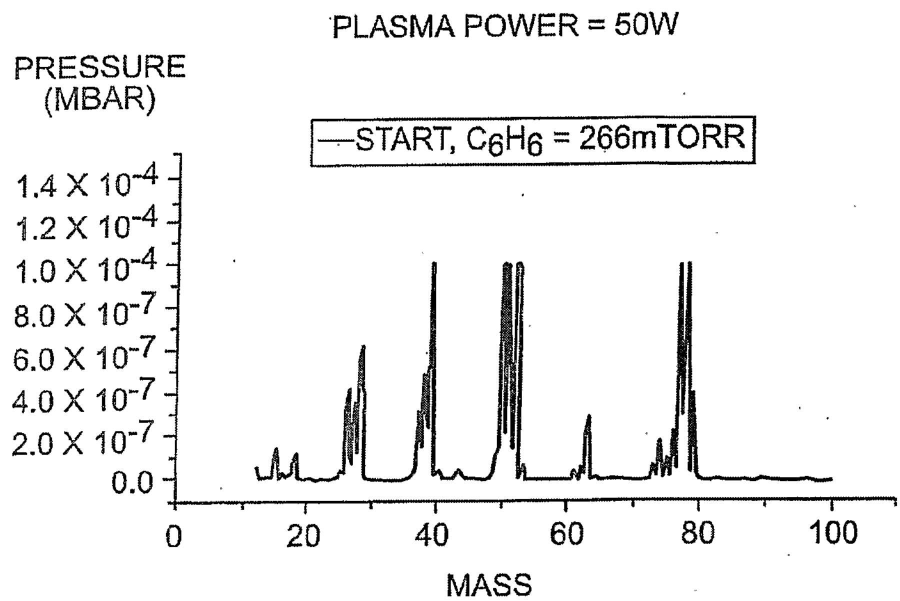

PLASMA POWER = 50W
PRESSURE (MBAR)
—START, C6H6 = 266mTORR
1.4 X 10-4
1.2 X 10-4
1.0 X 10-4
8.0 X 10-7
6.0 X 10-7
4.0 X 10-7
2.0 X 10-7
0.0
0
20
40
60
80
100
MASS

FIG. 8A

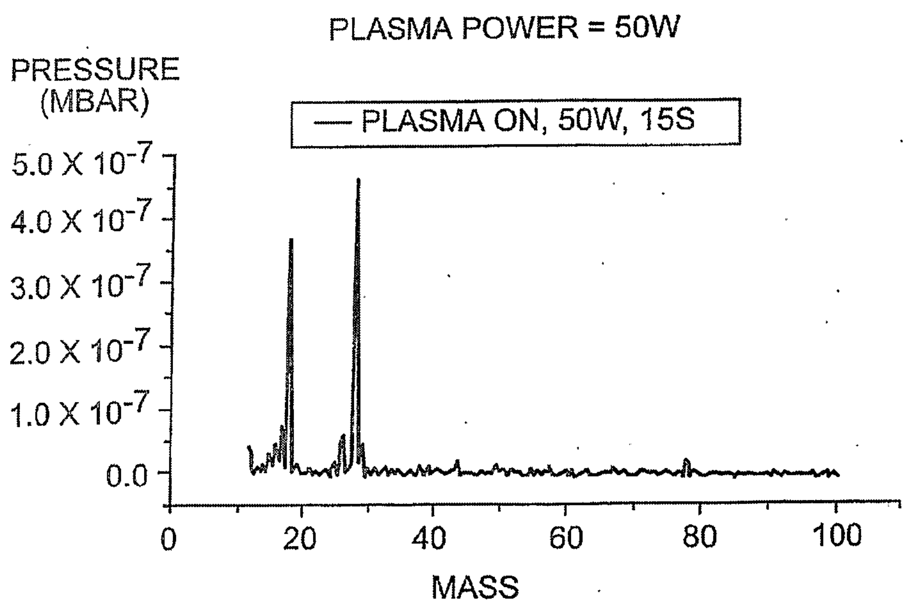

PLASMA POWER = 50W
PRESSURE (MBAR)
— PLASMA ON, 50W, 15S
5.0 X 10-7
4.0 X 10-7
3.0 X 10-7
2.0 X 10-7
1.0 X 10-7
0.0
0
20
40
60
80
100
MASS

FIG. 8B

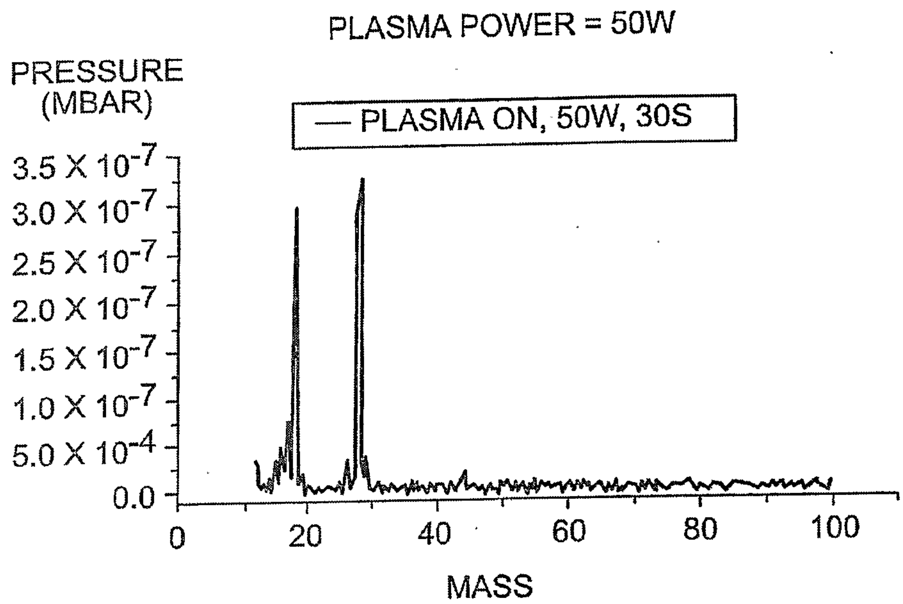

PLASMA POWER = 50W
PRESSURE (MBAR)
— PLASMA ON, 50W, 30S
3.5 X 10-7
3.0 X 10-7
2.5 X 10-7
2.0 X 10-7
1.5 X 10-7
1.0 X 10-7
5.0 X 10-4
0.0
0
20
40
60
80
100
MASS

FIG. 8C

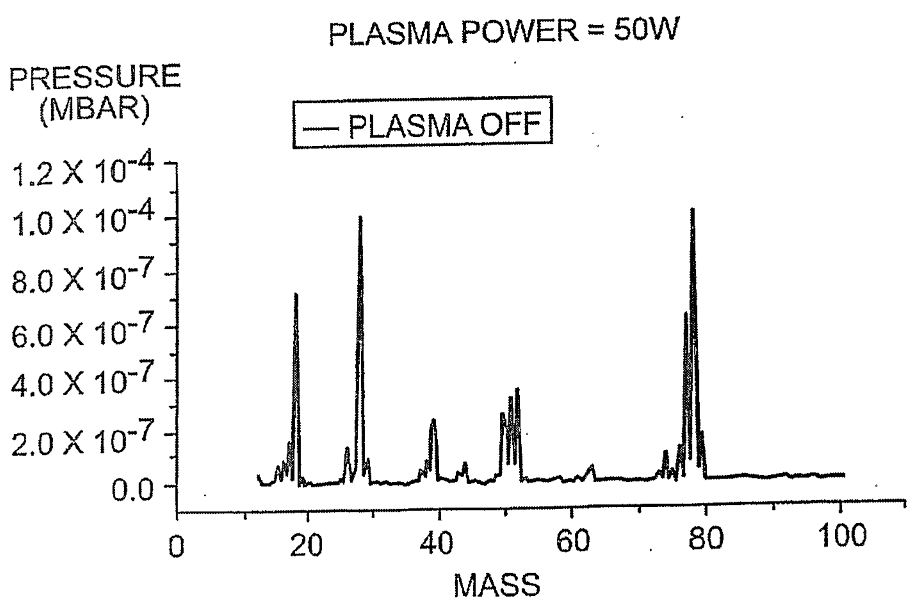

PLASMA POWER = 50W
PRESSURE (MBAR)
— PLASMA OFF
1.2 X 10-4
1.0 X 10-4
8.0 X 10-7
6.0 X 10-7
4.0 X 10-7
2.0 X 10-7
0.0
0
20
40
60
80
100
MASS

FIG. 8D

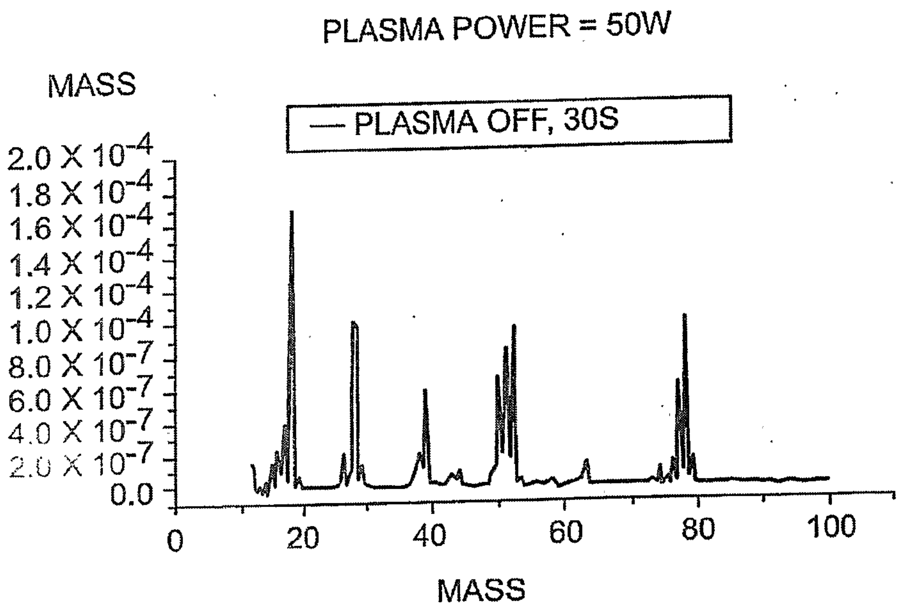

PLASMA POWER = 50W
MASS
— PLASMA OFF, 30S
2.0 X 10-4
1.8 X 10-4
1.6 X 10-4
1.4 X 10-4
1.2 X 10-4
1.0 X 10-4
8.0 X 10-7
6.0 X 10-7
4.0 X 10-7
2.0 X 10-7
0.0
0
20
40
60
80
100
MASS

FIG. 8E

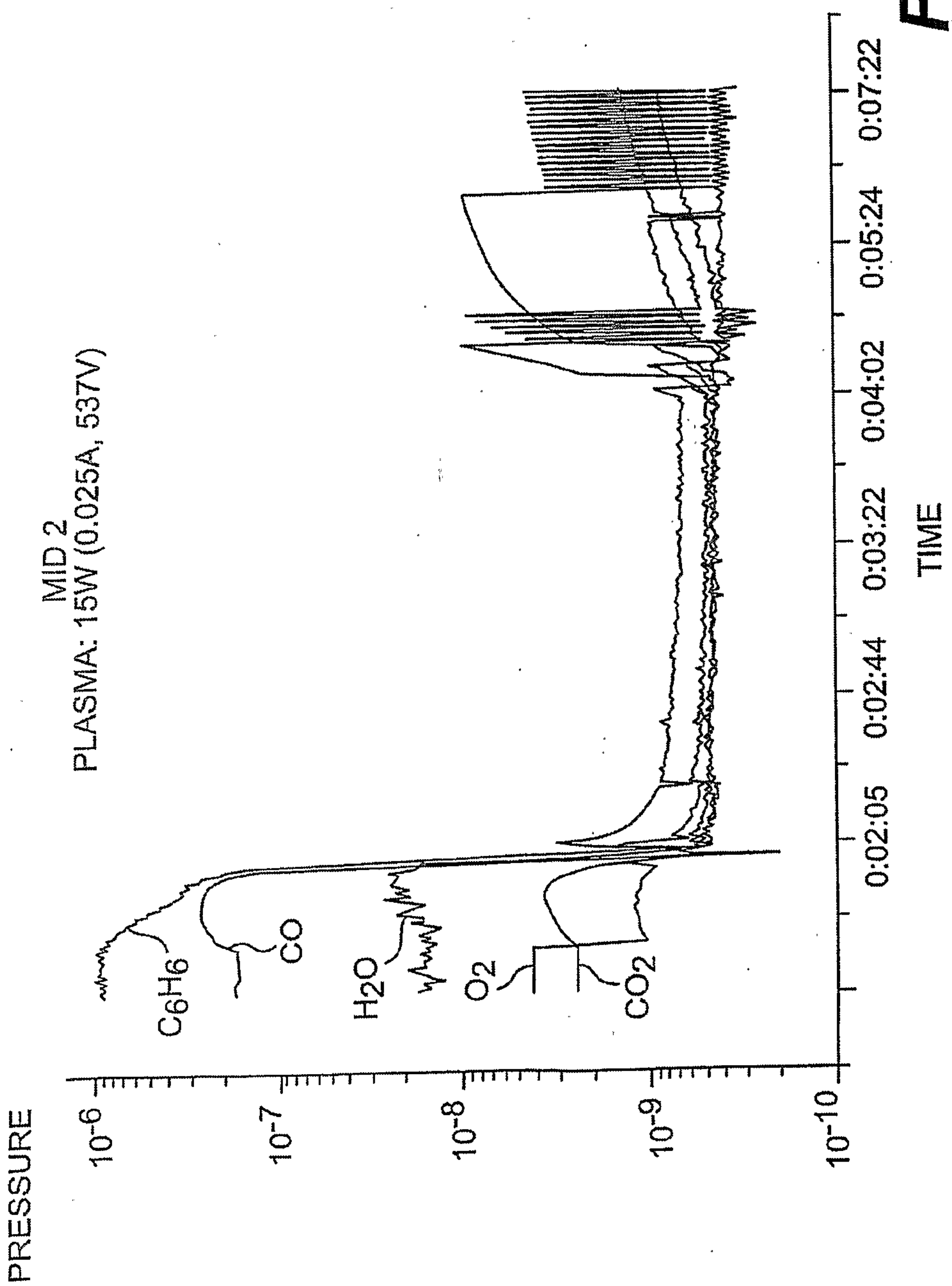

MID 2
PLASMA: 15W (0.025A, 537V)
PRESSURE
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
C_6H_6
CO
H_2O
O_2
CO_2
0:02:05
0:02:44
0:03:22
0:04:02
0:05:24
0:07:22
TIME

FIG. 9A

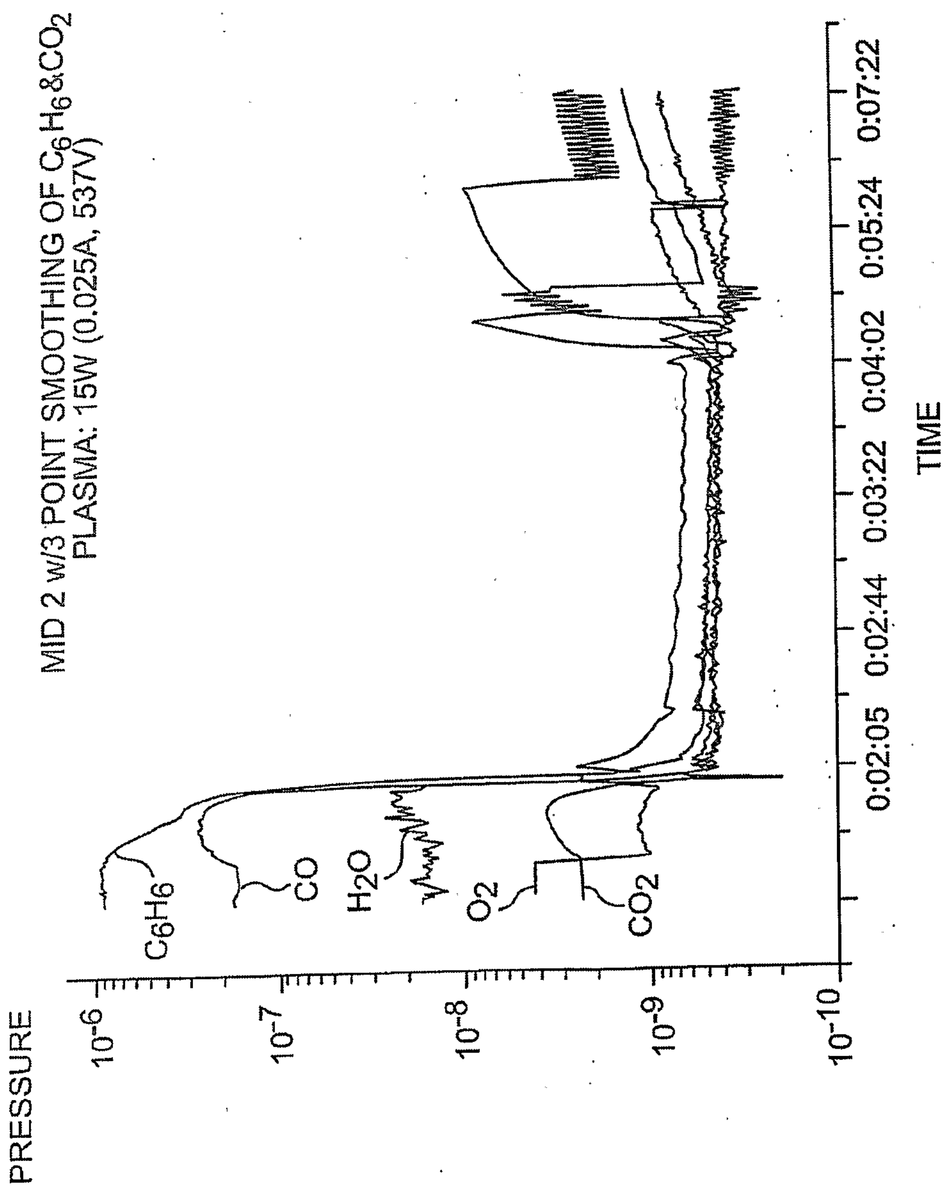

MID 2 w/3 POINT SMOOTHING OF C_6H_6&CO_2
PLASMA: 15W (0.025A, 537V)
PRESSURE
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
C_6H_6
CO
H_2O
O_2
CO_2
0:02:05
0:02:44
0:03:22
0:04:02
0:05:24
0:07:22
TIME

FIG. 9B

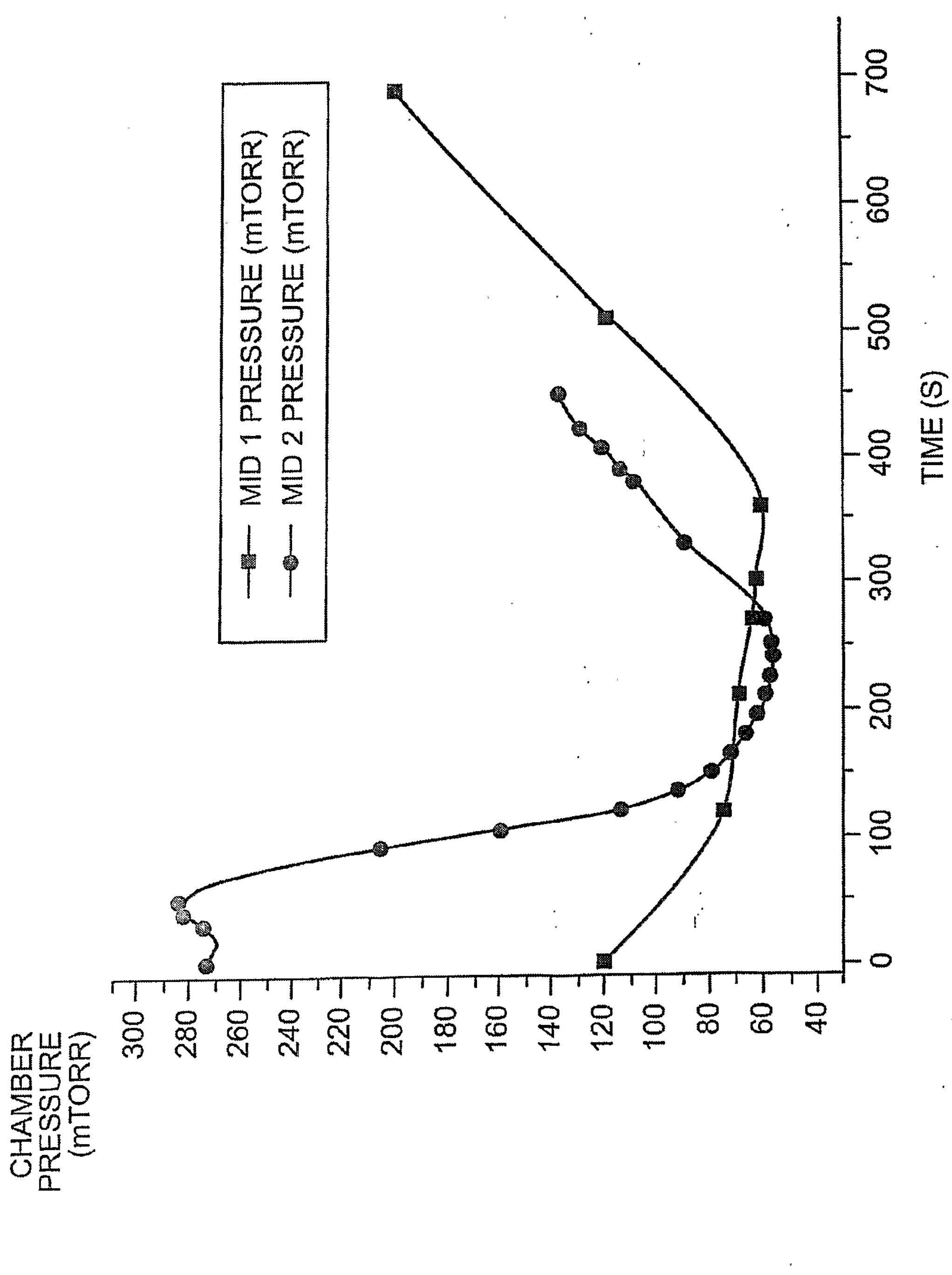

CHAMBER PRESSURE (mTORR)
300
280
260
240
220
200
180
160
140
120
100
80
60
40
0
100
200
300
400
500
600
700
TIME (S)
MID 1 PRESSURE (mTORR)
MID 2 PRESSURE (mTORR)

FIG. 10