US 20080003151A1

(19) **United States**

(12) **Patent Application Publication**

Raoux et al.

(10) **Pub. No.: US 2008/0003151 A1**

(43) **Pub. Date: Jan. 3, 2008**

(54) **METHODS AND APPARATUS FOR PFC ABATEMENT USING A CDO CHAMBER**

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(21) Appl. No.: **11/673,549**

(22) Filed: **Feb. 9, 2007**

Related U.S. Application Data

(60) Provisional application No. 60/772,317, filed on Feb. 11, 2006. Provisional application No. 60/865,347, filed on Nov. 10, 2006.

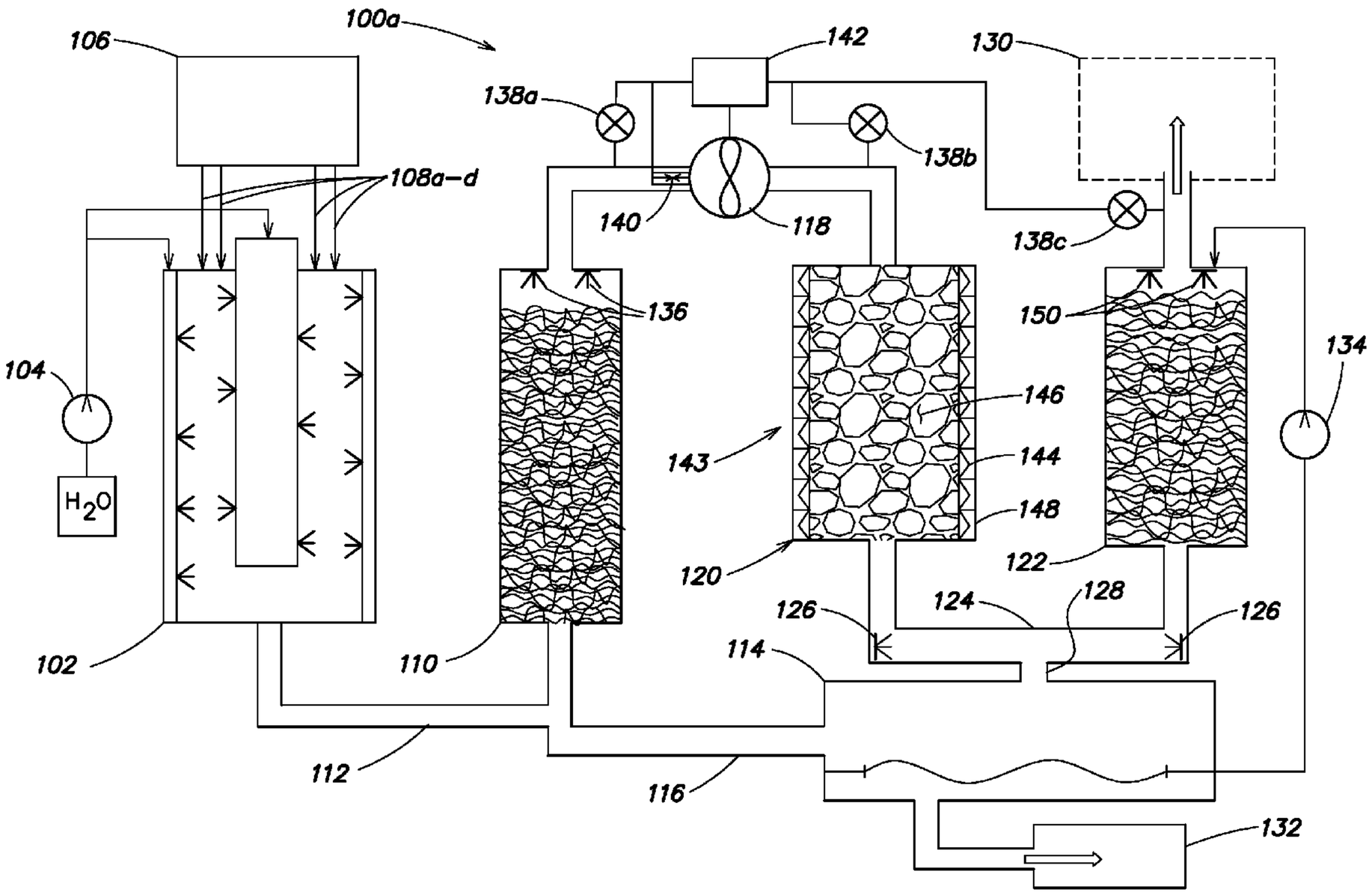
Publication Classification

(51) **Int. Cl.**
B01D 53/86 (2006.01)

(52) **U.S. Cl.** **422/173**; 422/168

(57) **ABSTRACT**

In some aspects, an apparatus is provided for abating perfluorocarbons (PFCs) in a controlled decomposition oxidation (CDO) thermal reaction chamber. The apparatus includes (1) a cartridge insertable into the thermal reaction chamber having gas-permeable first and second ends and including a catalyst material; and (2) thermally-conductive fixtures positioned within the cartridge. Numerous other aspects are provided.



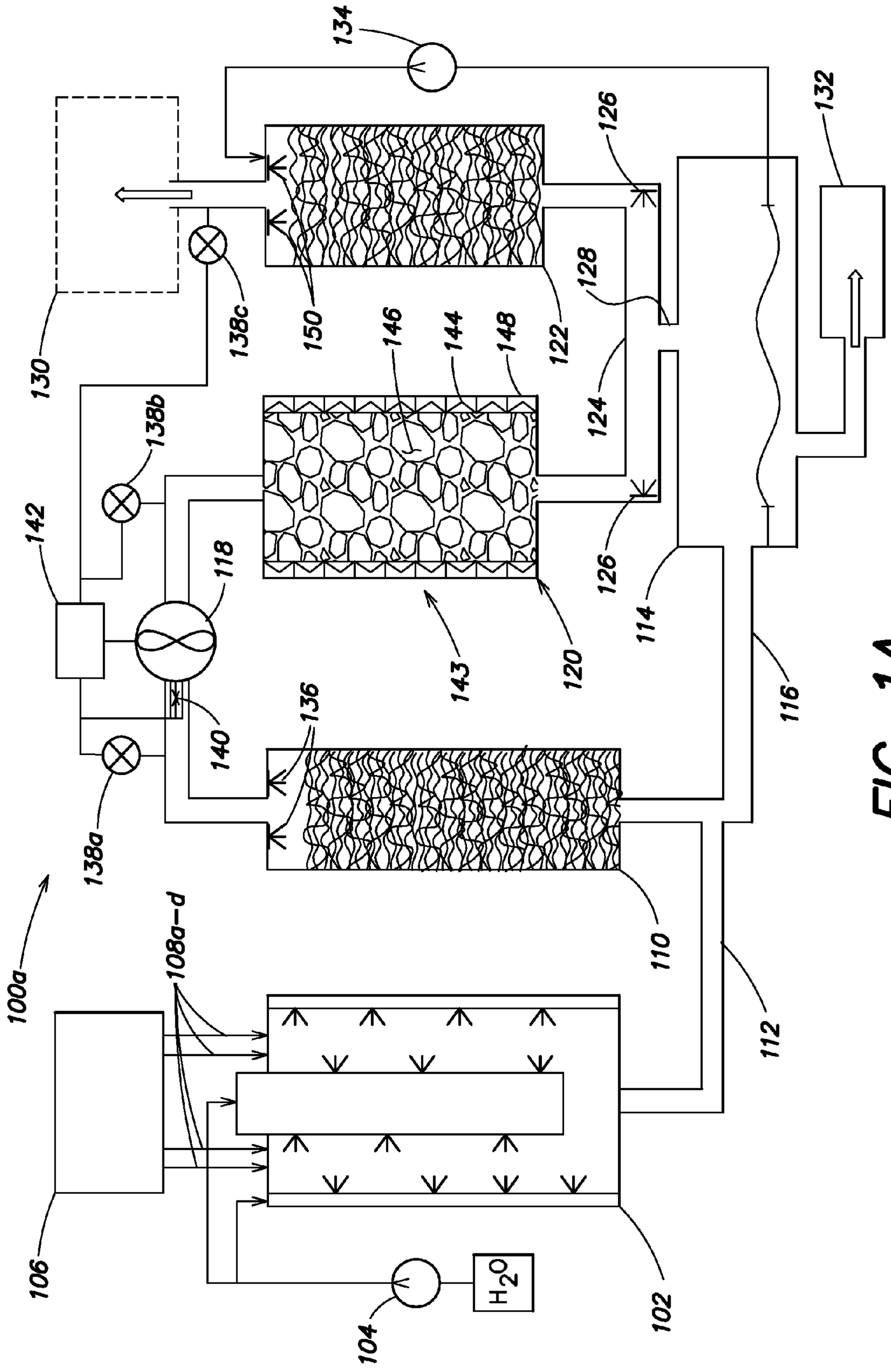

134
132
126
128
130
138c
150
146
144
148
122
124
138b
142
118
143
120
114
126
140
136
116
138a
100a
108a–d
110
112
106
104
H_2O
102

FIG. 1A

134
126
132
128
120
150
146
143
144
148
122
138c
130
162
138b
142
124
160
114
118
140
116
138a
136
110
108a–d
112
100b
106
102
104
H_2O

FIG. 1B

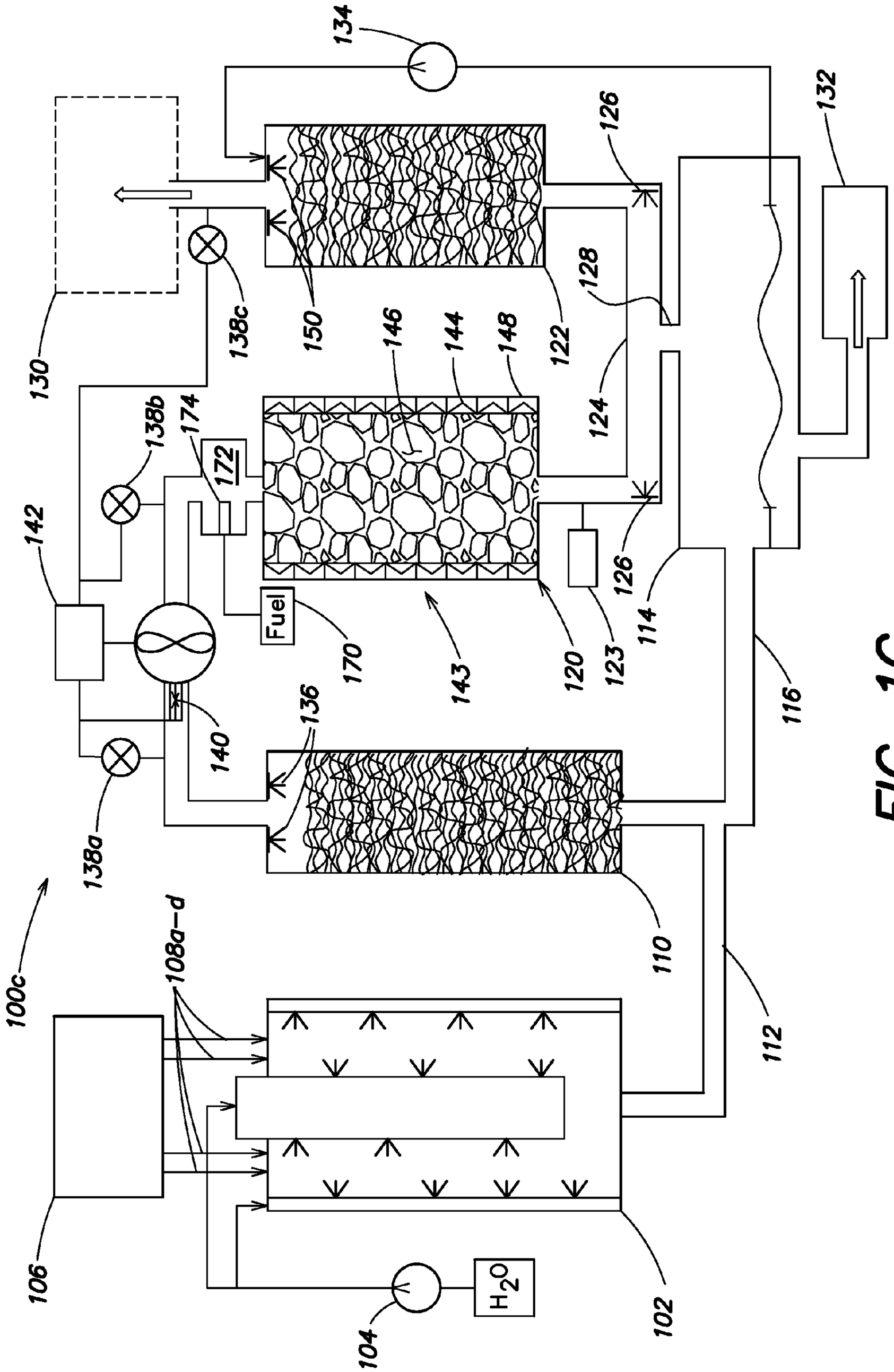

134
126
132
130
138c
150
146
144
148
122
128
124
138b
174
172
142
Fuel
170
143
120
123
126
114
136
140
138a
116
100c
108a–d
110
112
106
104
H_2O
102

FIG. 1C

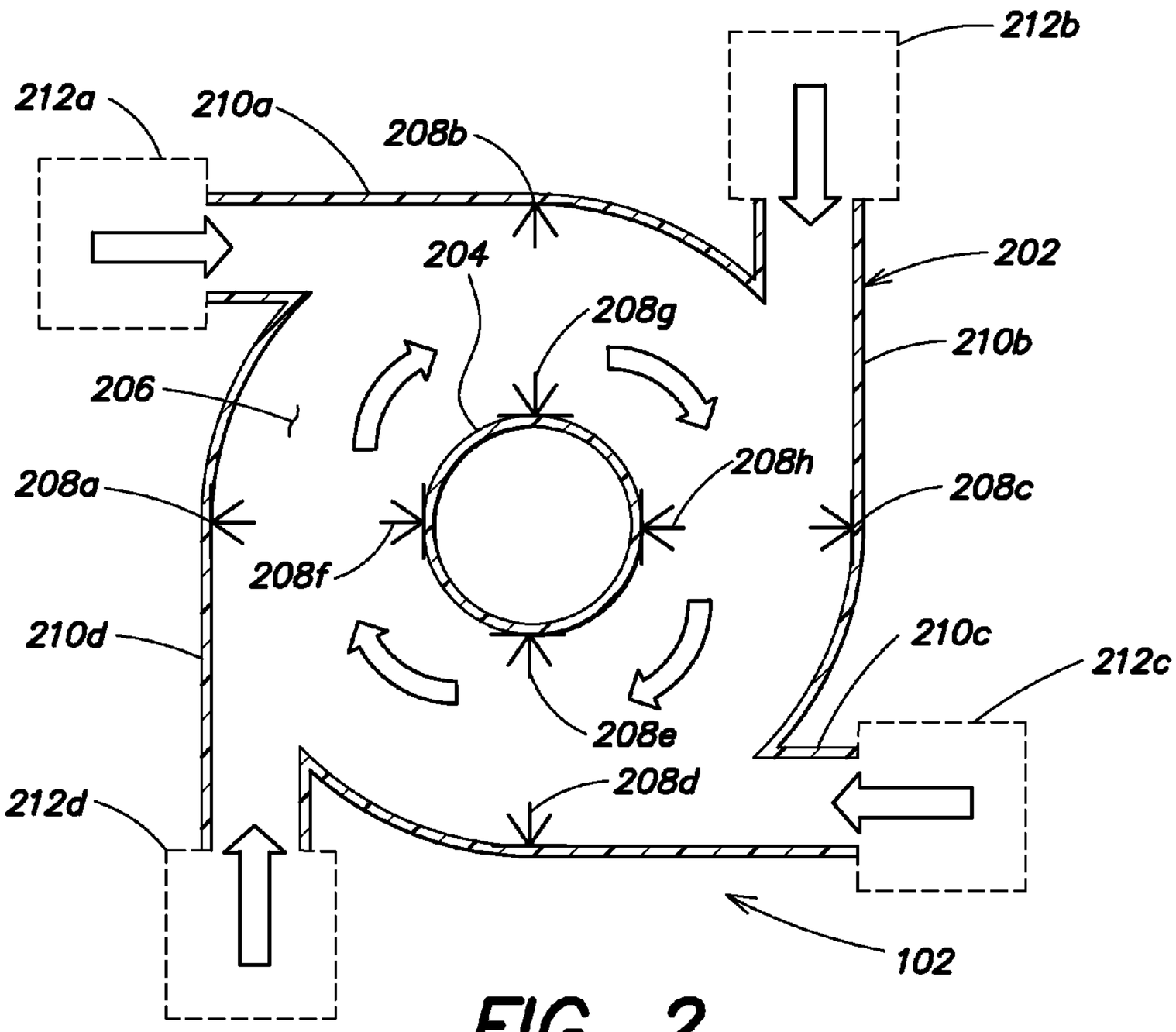

212b
212a
210a
208b
204
202
208g
210b
206
208a
208h
208c
208f
210d
210c
212c
208e
208d
212d
102

FIG. 2

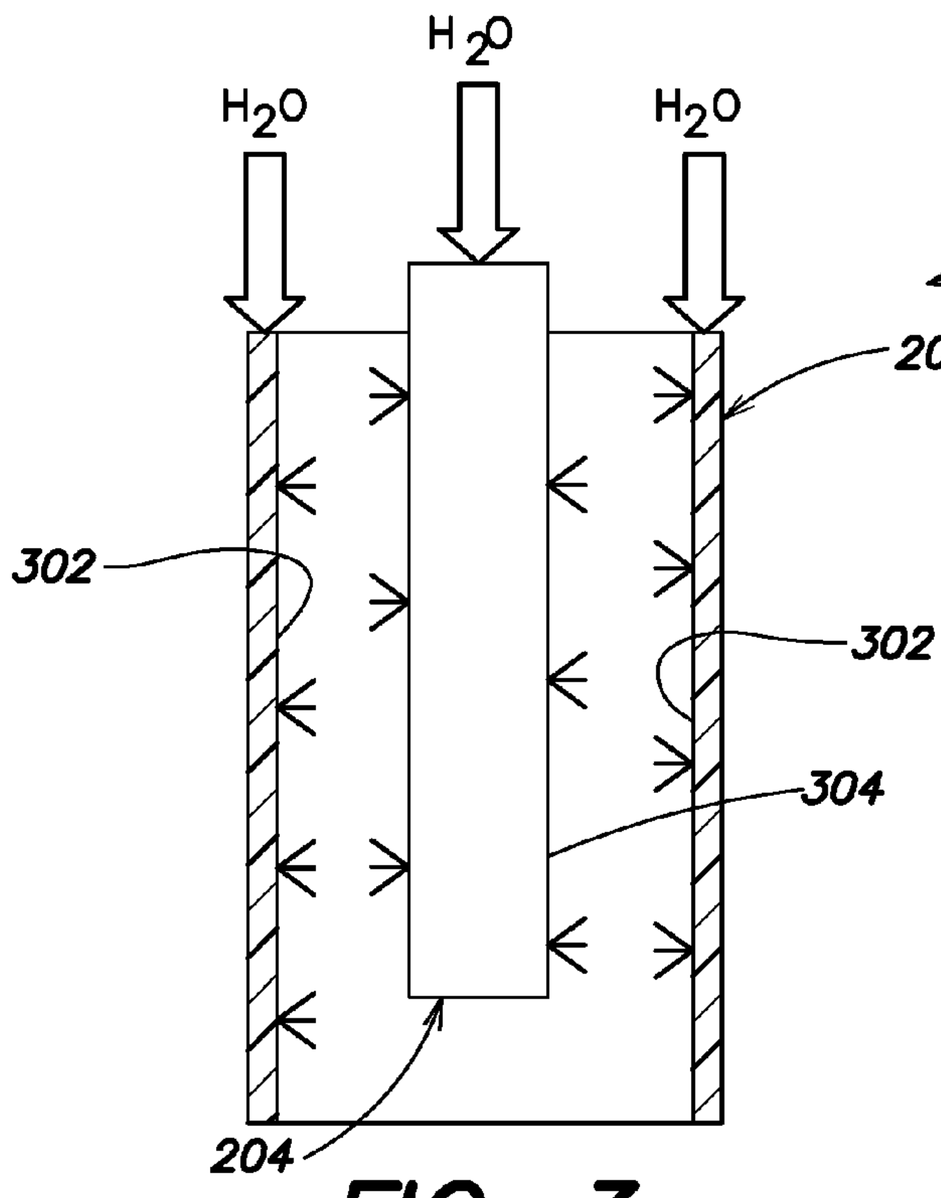

H2O
H2O
H2O
102
202
302
302
304
204

FIG. 3

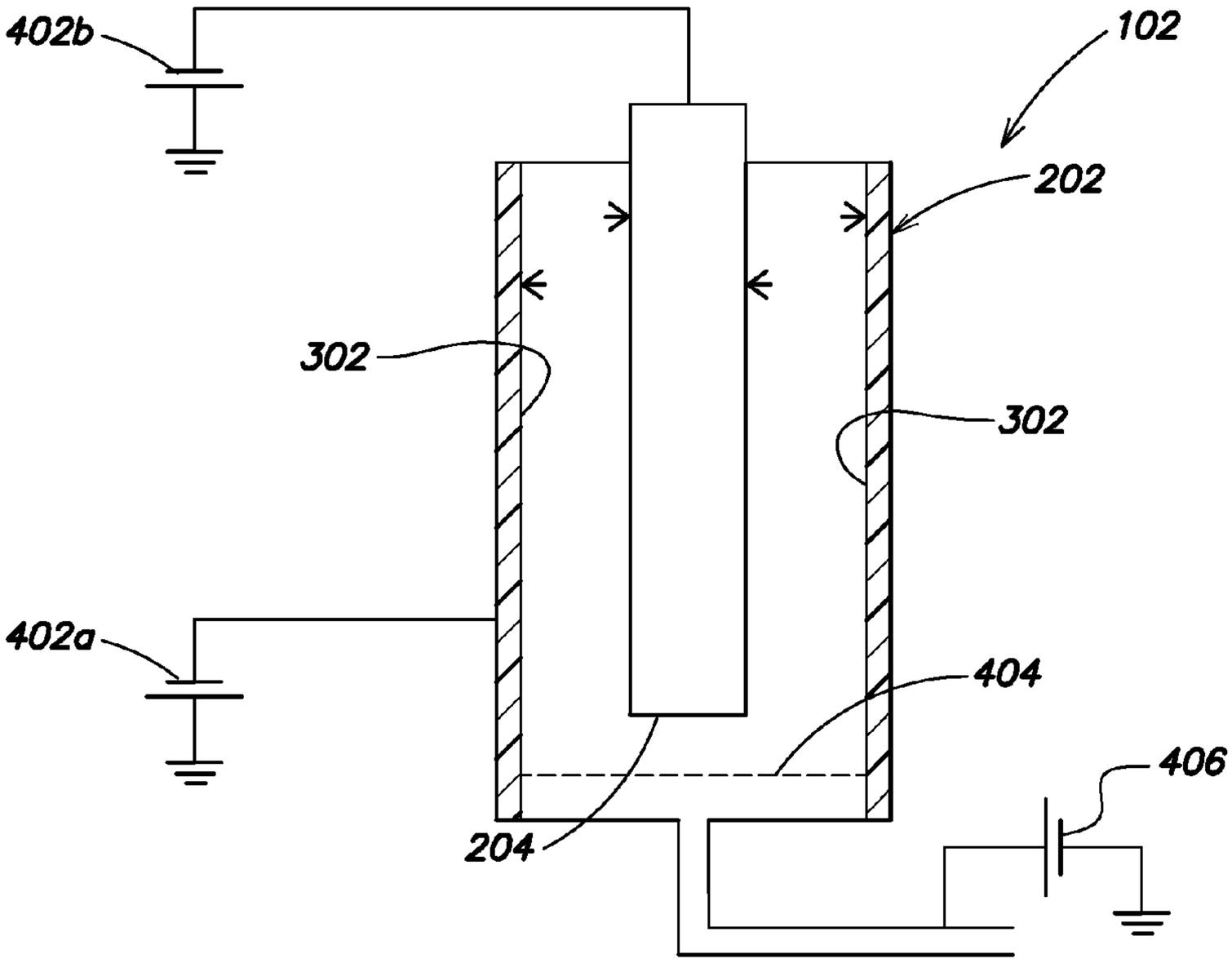


FIG. 4

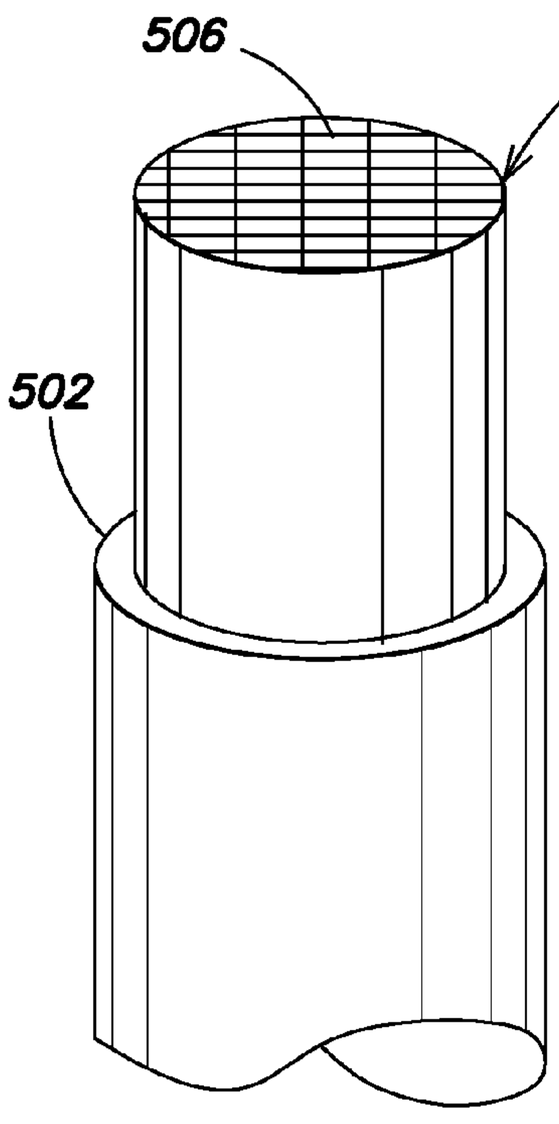


FIG. 5

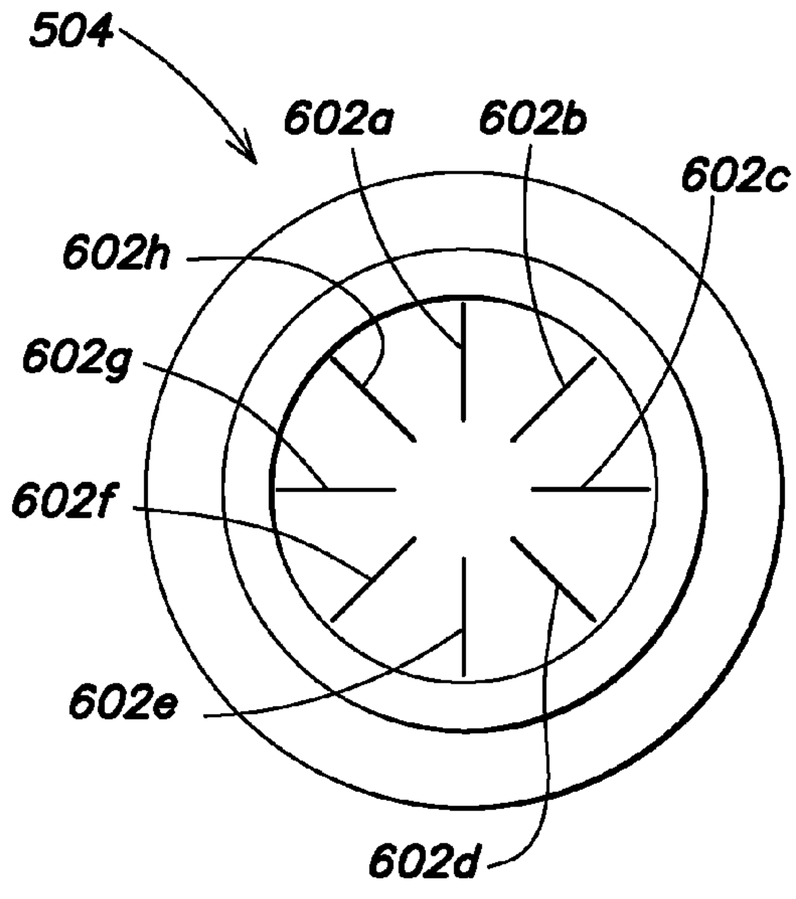


FIG. 6

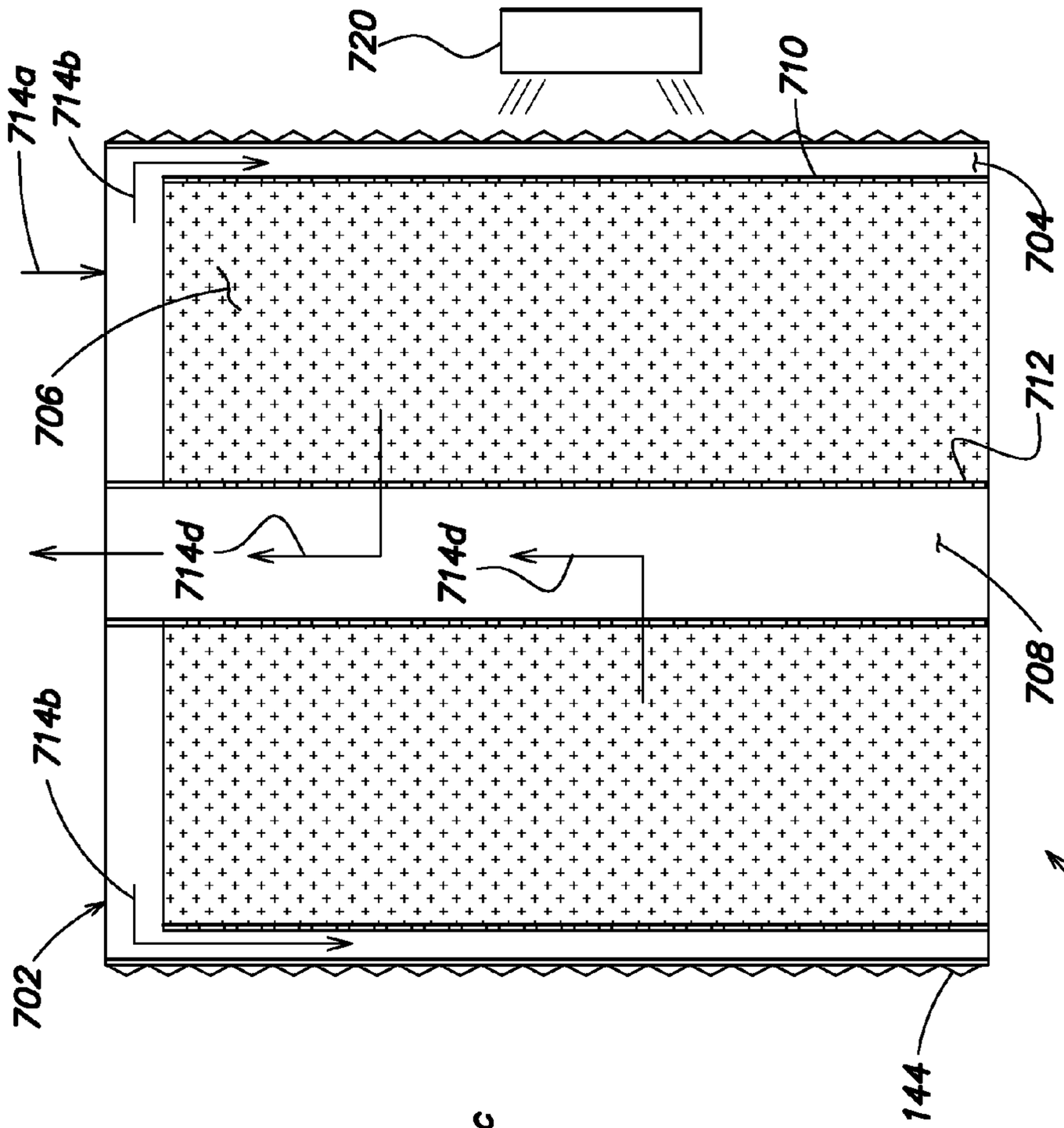

720
710
714a
714b
706
704
712
714d
714d
708
714b
702
700
144

FIG. 7B

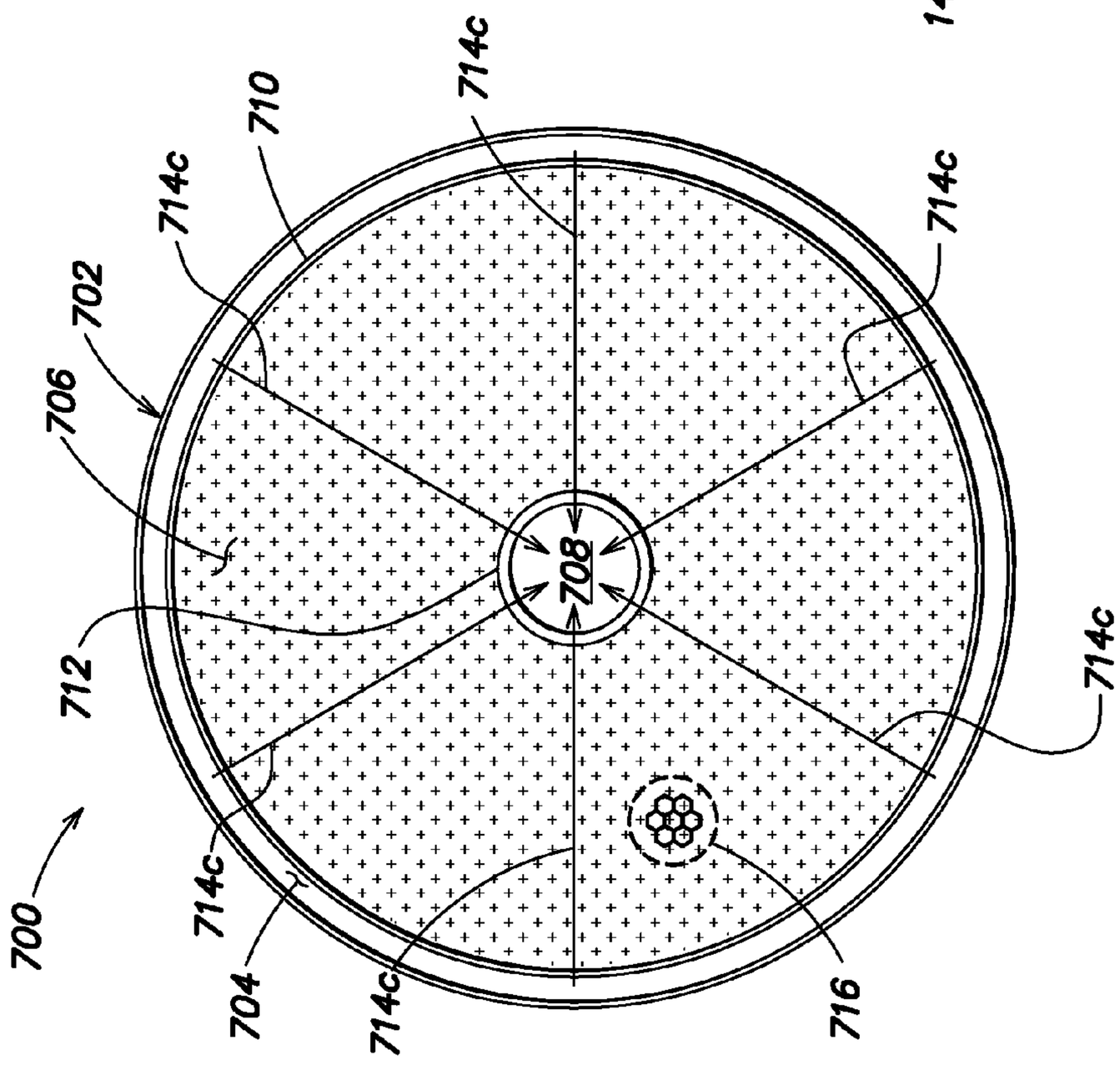

714c
710
714c
714c
702
706
708
712
714c
700
714c
704
714c
716

FIG. 7A

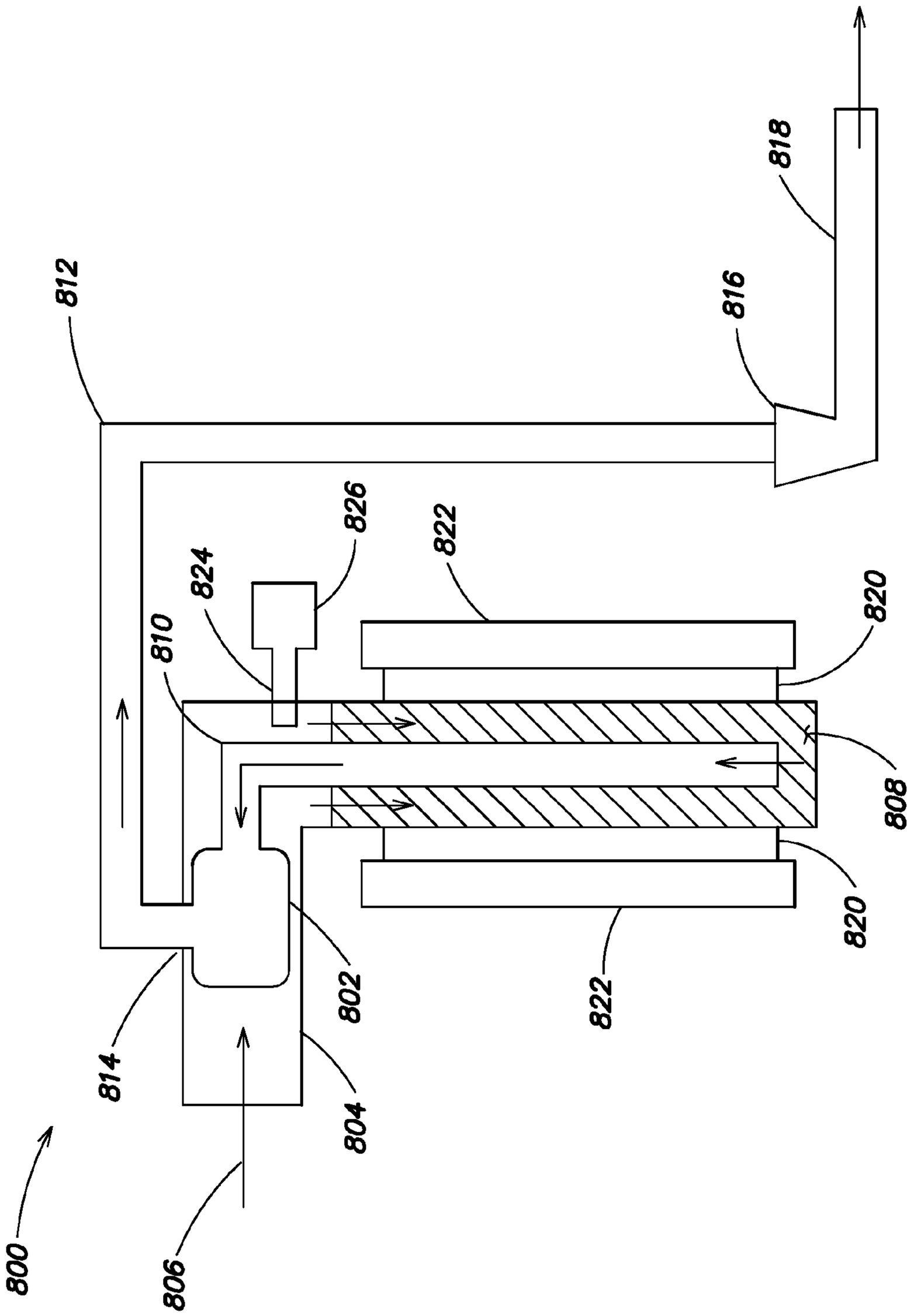


FIG. 8

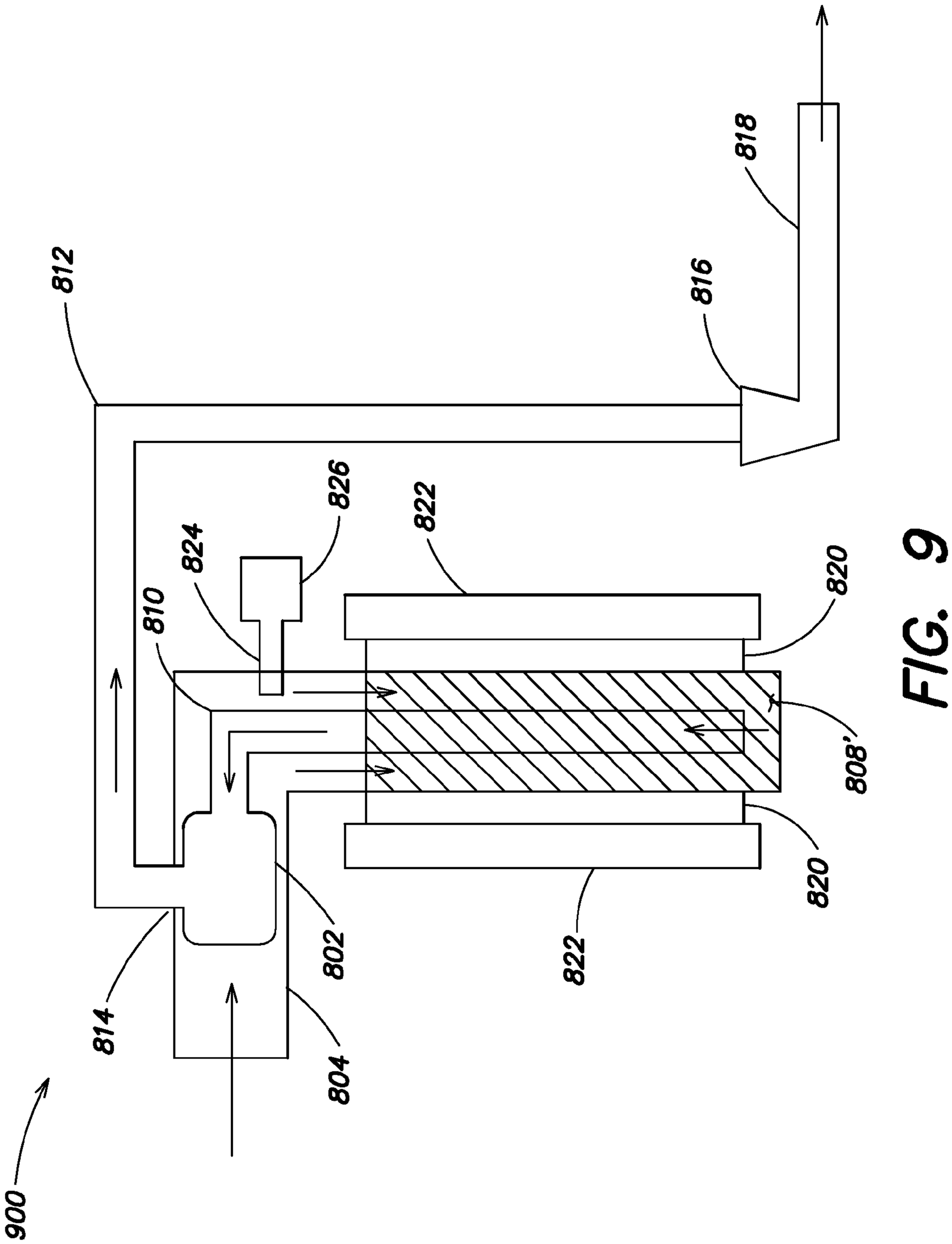


FIG. 9

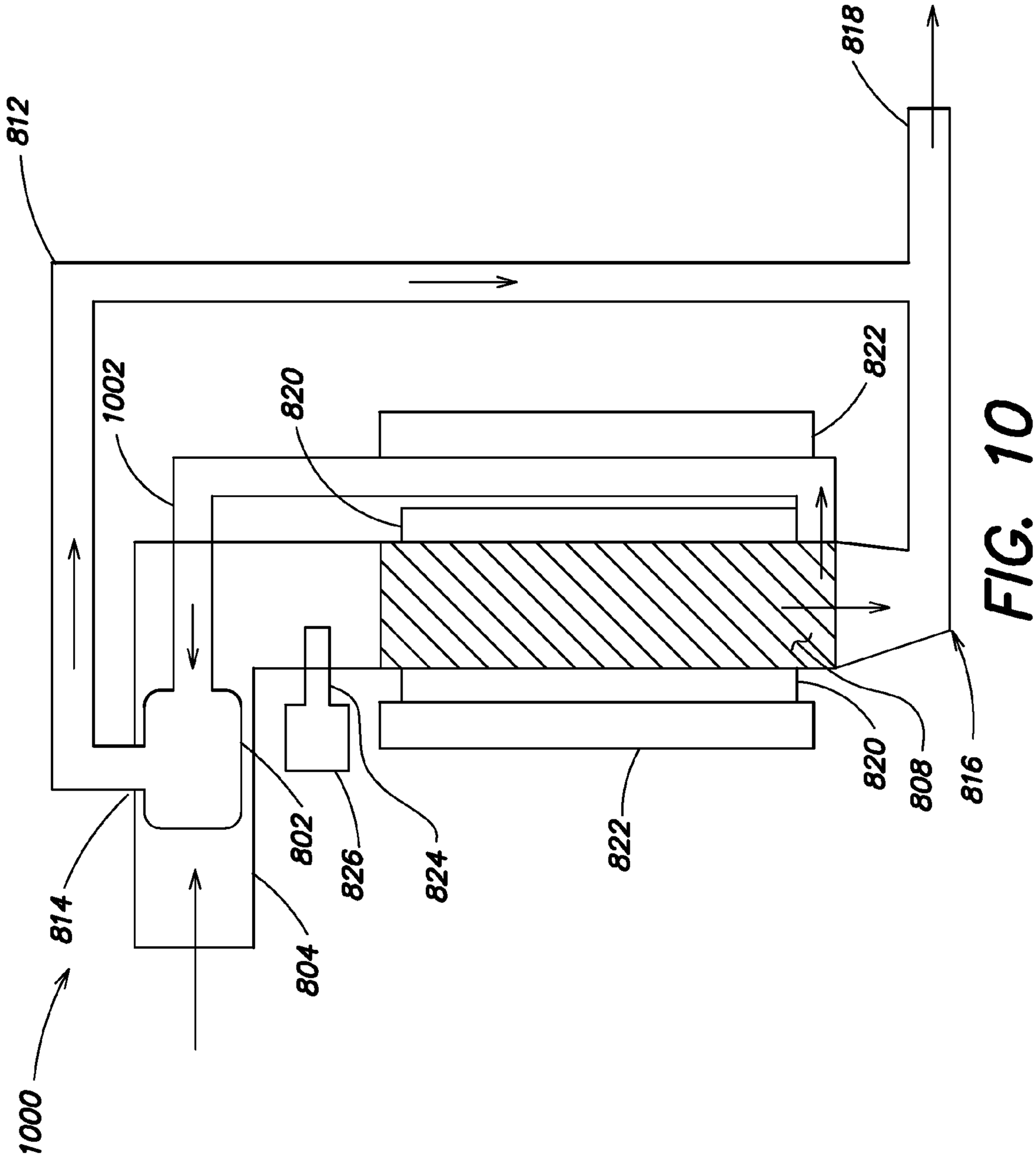


FIG. 10

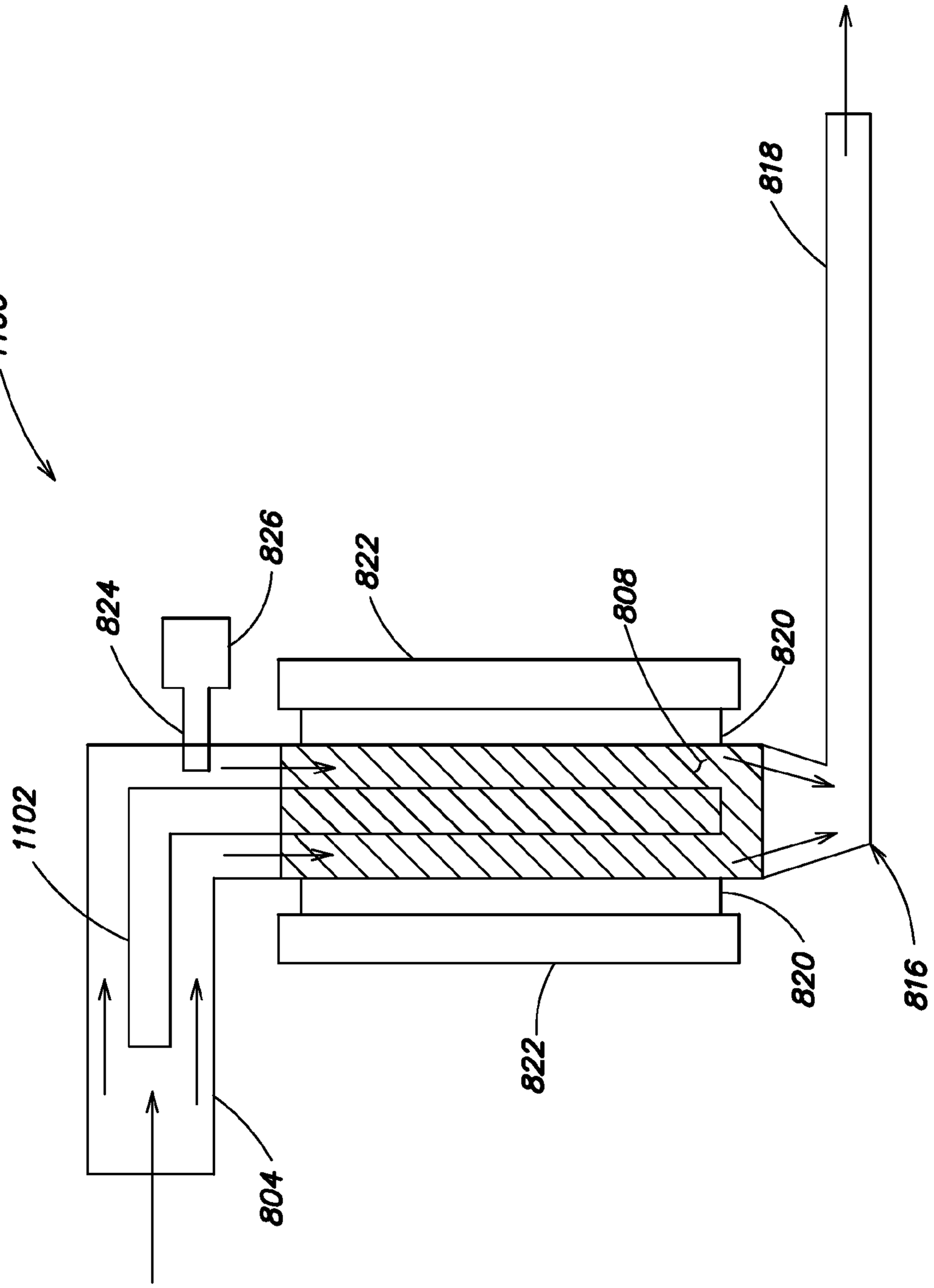


FIG. 11

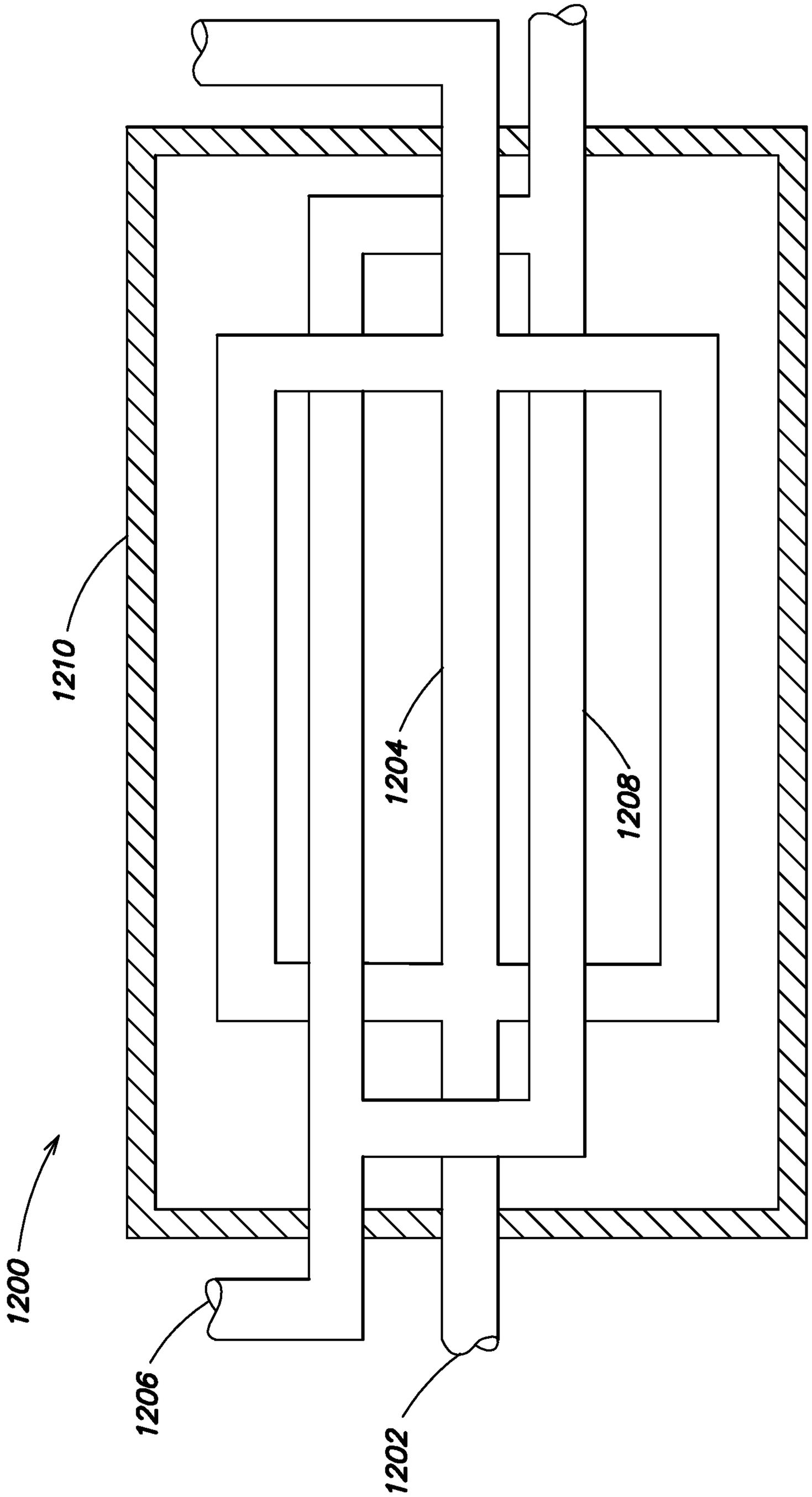


FIG. 12

METHODS AND APPARATUS FOR PFC ABATEMENT USING A CDO CHAMBER

[0001] The present application claims priority to U.S. Provisional Patent Application Ser. No. 60/772,317, filed Feb. 11, 2006 and entitled "METHODS AND APPARATUS FOR PFC ABATEMENT USING A CDO CHAMBER", (Attorney Docket No. 10910/L) and U.S. Provisional Patent Application Ser. No. 60/865,347, filed Nov. 10, 2006 entitled "METHODS AND APPARATUS FOR PFC ABATEMENT USING A CDO CHAMBER", (Attorney Docket No. 10910/L2), each of which is hereby incorporated herein by reference in its entirety for all purposes.

FIELD OF THE INVENTION

[0002] The present invention relates to semiconductor device manufacturing, and more specifically to methods and apparatus for PFC abatement using a CDO chamber.

BACKGROUND OF THE INVENTION

[0003] Many of the processes used during semiconductor device manufacturing, such as metal and dielectric etch processes, produce undesirable by-products including perfluorocompounds (PFCs) or by-products that may decompose to form PFCs. Cleaning processes used to remove materials accumulated on chamber components of deposition chambers, such as chemical or physical vapor deposition chambers, also may produce PFCs. Methods and apparatus for abating such PFCs are desirable.

SUMMARY OF THE INVENTION

[0004] In some aspects, a method is provided for abating perfluorocarbons (PFCs) in a gaseous waste abatement system having a pre-installed controlled decomposition oxidation (CDO) thermal reaction chamber that includes (1) providing a catalyst bed within the CDO thermal reaction chamber; and (2) introducing a gaseous waste stream into the CDO thermal reaction chamber so as to expose the gaseous waste stream to the catalyst bed.

[0005] In certain aspects, a system is provided for abating perfluorocarbons (PFCs) from a gaseous waste stream that includes (1) a wet scrubber adapted to scrub a gaseous waste stream and having an outlet adapted to discharge a scrubbed gaseous waste stream; and (2) a controlled decomposition oxidation (CDO) system. The CDO system includes a CDO thermal reaction chamber that includes (a) an inlet coupled to the outlet of the wet scrubber; (b) a catalyst bed adapted to abate PFCs within the CDO thermal reaction chamber; and (c) an outlet.

[0006] In some other aspects, a method is provided for abating perfluorocarbons (PFCs) in a gaseous waste abatement system having a controlled decomposition oxidation (CDO) thermal reaction chamber that includes (1) providing a catalyst bed within the CDO thermal reaction chamber; (2) conveying a gaseous waste stream past a heat exchanger into an inlet of the CDO thermal reaction chamber and to the catalyst bed; (3) filtering the gaseous waste stream through the catalyst bed, the filtered gaseous waste stream being heated in the catalyst bed; and (4) recirculating the heated gaseous waste stream from the catalyst bed to the heat exchanger.

[0007] In at least one aspect, a controlled decomposition oxidation (CDO) system is provided for abating perfluorocarbons (PFCs) that includes (1) an upstream portion including a first conduit adapted to convey a gaseous waste stream; (2) a thermal reaction chamber having an inlet coupled to the first conduit, a catalyst bed adapted to abate PFCs, and an outlet; and (3) a downstream portion including a second conduit having a first end coupled to the outlet of the thermal reaction chamber and having a portion, downstream from the first end, positioned proximate to the first conduit. The second conduit is adapted to convey a gaseous waste stream heated within the thermal reaction chamber to enable a transfer of heat energy from the second conduit to the first conduit so as to pre-heat the gaseous waste stream in the first conduit.

[0008] In some other aspects, a system is provided for abating perfluorocarbons (PFCs) that includes (1) an upstream portion including a first conduit adapted to convey a gaseous waste stream and a heating device coupled to the first conduit and adapted to pre-heat the gaseous waste stream; and (2) a thermal reaction chamber including an inlet coupled to the first conduit and a catalyst bed adapted to abate PFCs in the gaseous waste stream entering the thermal reaction chamber from the first conduit.

[0009] In certain other aspects, a system is provided for abating perfluorocarbons (PFCs) within a gaseous waste stream that includes (1) a first conduit adapted to convey the gaseous waste stream and having an outlet; (2) a heat exchanger positioned in the first conduit proximate to the outlet; (3) a thermal reaction chamber including an inlet coupled to the outlet of the first conduit, a catalyst bed having a catalyst material positioned within the thermal reaction chamber adapted to abate PFCs within the gaseous waste stream; and (4) a second conduit having a first end coupled to the catalyst bed and a second end coupled to the heat exchanger.

[0010] In yet other aspects, a system is provided for abating perfluorocarbons (PFCs) within a gaseous waste stream that includes (1) a first conduit adapted to convey the gaseous waste stream and having an outlet; (2) a thermal reaction chamber including an inlet coupled to the outlet of the first conduit, a catalyst bed having a catalyst material positioned within the chamber and adapted to abate PFCs within the gaseous waste stream, and an outlet positioned opposite the inlet; and (3) a second conduit having a first end coupled to the catalyst bed and a second end that extends into the first conduit.

[0011] In still other aspects, an apparatus is provided for abating perfluorocarbons (PFCs) in a controlled decomposition oxidation (CDO) thermal reaction chamber. The apparatus includes (1) a cartridge insertable into the thermal reaction chamber having gas-permeable first and second ends and including a catalyst material; and (2) thermally-conductive fixtures positioned within the cartridge.

[0012] In yet other aspects, an apparatus is provided for abating perfluorocarbons (PFCs) in a controlled decomposition oxidation thermal reaction chamber. The apparatus includes a cartridge insertable into the thermal reaction chamber having gas-permeable first and second ends and including a catalyst material.

[0013] In at least another aspect, an apparatus is provided for abating perfluorocarbons (PFCs) in a controlled decomposition oxidation (CDO) thermal reaction chamber that

includes an annular catalyst bed embedded in the thermal reaction chamber having an outer porous liner and an inner porous liner, the inner porous liner positioned within a central region of the thermal reaction chamber so as to define an inner plenum. A gaseous waste stream introduced into the thermal reaction chamber may flow through the outer porous liner through the catalyst bed and into the inner plenum.

[0014] In additional aspects, an apparatus is provided for abating perfluorocarbons (PFCs) in a gaseous waste stream that includes (1) a controlled decomposition oxidation (CDO) thermal reaction chamber having an inlet adapted to receive the gaseous waste stream; and (2) a catalyst bed including a catalyst material positioned within the CDO thermal reaction chamber so as to expose the gaseous waste stream to the catalyst material. Numerous other aspects are provided.

[0015] Other features and aspects of the present invention will become more fully apparent from the following detailed description, the appended claims and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. **1**A is a schematic diagram of a PFC abatement system according to at least one embodiment of the invention.

[0017] FIG. **1**B is a schematic diagram of a first alternative embodiment of the PFC abatement system of FIG. **1**A provided in accordance with the present invention.

[0018] FIG. **1**C is a schematic diagram of a second alternative embodiment of the PFC abatement system of FIG. **1**A provided in accordance with the present invention.

[0019] FIG. **2** is a top schematic view of an exemplary embodiment of the wet scrubber depicted in FIG. **1**A.

[0020] FIG. **3** is a cross-sectional view of the wet scrubber of FIG. **2**.

[0021] FIG. **4** is a cross-sectional view of an alternative embodiment of the wet scrubber of FIG. **3**.

[0022] FIG. **5** is a partial perspective view of a CDO chamber that may be used as a catalyst bed in accordance with the present invention.

[0023] FIG. **6** is a top view of an exemplary embodiment of the catalyst cartridge of FIG. **5**.

[0024] FIGS. **7**A and **7**B are a top view and a side view, respectively, of an exemplary reduced-pressure-drop catalyst bed provided in accordance with the present invention.

[0025] FIG. **8** illustrates a schematic view of a first apparatus for heating a catalyst bed provided in accordance with the present invention.

[0026] FIG. **9** illustrates a schematic view of a second apparatus for heating a catalyst bed provided in accordance with the present invention.

[0027] FIG. **10** illustrates a schematic view of a third apparatus for heating a catalyst bed provided in accordance with the present invention.

[0028] FIG. **11** illustrates a schematic view of a fourth apparatus for heating a catalyst bed provided in accordance with the present invention.

[0029] FIG. **12** is a schematic diagram of an exemplary cross heat exchanger that may be used in accordance with the present invention.

DETAILED DESCRIPTION

[0030] The present invention provides methods and apparatus for PFC abatement. In one or more embodiments of the invention, an existing controlled decomposition oxidation (CDO) chamber used to oxidize toxic materials such as acids, acid gases, hydrides, flammable gasses, etc., may be modified and/or retrofitted to abate PFCs. Use of existing, on-site abatement equipment such as a CDO chamber to abate PFCs can result in a significant cost savings when compared to the expense of installing a new, conventional PFC abatement system.

[0031] Exemplary processes that may be abated in accordance with the invention include metal and dielectric etch processes, cleaning processes for chemical vapor deposition, physical vapor deposition or other deposition processes, or the like. Exemplary PFCs that may be abated include CF_4, C_2F_6, C_4F_8, C_3F_8, CHF_3, CH_3F, CH_2F_2, SF_6, by-products of NF_3 cleaning, etc. Other processes may be abated, as may other PFCs.

System Overview

[0032] FIG. **1**A is a schematic diagram of a first exemplary PFC abatement system **100***a* according to at least one embodiment of the invention. The abatement system **100***a* includes a wet scrubber **102**, which is fed water (e.g., from house water, a pump, a high pressure pump **104**, etc.). Gaseous waste streams from one or more process chambers are directed (e.g., exhausted) into wet scrubber **102**. In FIG. **1**A, a single process tool **106** is shown that includes four process chambers (as indicated by exhaust lines **108***a-d*), each being exhausted into the water scrubber **102**. It is understood that water scrubber **102** may receive gaseous waste streams from any number of process tools and/or process chambers (e.g., 1, 2, 3, 4, 5, 6, etc.).

[0033] Wet scrubber **102** employs a water mist to remove or diminish the presence of one or more contaminants (e.g., SiF_4) from the gaseous waste streams. Preferably, SiF_4 may be reduced to a concentration of approximately less than one part per million. Greater or lesser concentrations of SiF_4 may be achieved.

[0034] The processed gaseous waste streams are then directed from wet scrubber **102** to a first packed bed chamber **110** via conduit **112**. Contaminants and/or particulates separated from the gaseous waste streams (e.g., HCl, HF, SiO_2 suspended in water, etc.) at the wet scrubber **102** may be directed to a sump **114** via a branch or extension **116** of conduit **112**. These separated contaminants may be removed by any other appropriate means. Additionally, some amount of the processed gaseous waste stream may be directed to the sump **114** without detriment to the abatement system **100***a*.

[0035] The first packed bed chamber **110** may remove water, contaminants, and/or particulates from the gaseous waste streams. The separated water, contaminants, and/or particulates may be directed to the sump **114** as described above. After passing through the first packed bed chamber **110**, the gaseous waste streams may be directed through a blower **118** into a catalyst bed **120**. As will be described further below, the catalyst bed **120** interacts with the gaseous waste streams to abate PFCs.

[0036] PFC abated gaseous waste streams are directed from the catalyst bed **120** to a second packed bed chamber **122** via conduit **124**. While in transit from catalyst bed **120** to second packed bed chamber **122**, the abated gaseous waste streams may be cooled by water spray nozzles **126** and/or other means in conduit **124**. Water, contaminants, and/or particulates separated from the abated gaseous waste stream in the catalyst bed **120**, the conduit **124**, and/or the second packed bed chamber **122** are directed to the sump **114** via a branch or extension **128** of conduit **124**. After passing through second packed bed chamber **122** the abated gaseous waste streams may be fed to a house exhaust system **130** (shown in phantom) and/or further abatement chambers (not shown).

[0037] Water, contaminants, and/or particulates separated from the gaseous waste stream and directed into sump **114** via extensions **116** and **128** may pass, along with any other fluid in sump **114** to an acid waste neutralization system **132**. In at least one embodiment, water from the sump **114** may be filtered and recirculated via a recirculation pump **134** to the second packed bed chamber **122** and/or to any other suitable location within the abatement system **100***a*.

[0038] FIG. **1**B is a schematic diagram of a first alternative embodiment of the PFC abatement system **100***a* of FIG. **1**A, referred to as PFC abatement system **100***b*. The PFC abatement system **100***b* is similar to the PFC abatement system **100***a* of FIG. **1**A, but includes a cross heat exchanger **160** or other recuperator for preheating a gas stream before entry into the catalyst bed **120**. Such pre-heating of the gas stream may assist in heating the catalyst used in the catalyst bed **120**. The cross heat exchanger **160** employs the gas stream output from the catalyst bed **120**, which is heated by the heaters **144** and/or exothermic abatement processes performed within the catalyst bed **120**, to pre-heat a gas stream before it enters the catalyst bed **120**. Any suitable heat exchanger or recuperator may be used. Exemplary cross heat exchangers are described below with reference to FIGS. **8-12**.

[0039] Additionally or alternatively, the PFC abatement system **100***b* may include a pre-heater **162**, such as an electric or other suitable heater, for pre-heating a gas stream before it enters the catalyst bed **120**. If both a heat exchanger and a pre-heater are employed, a smaller pre-heater may be used.

[0040] FIG. **1**C is a schematic diagram of a second alternative embodiment of the PFC abatement system **100***a* of FIG. **1**A, referred to as PFC abatement system **100***c*. The PFC abatement system **100***c* is similar to the PFC abatement system **100***a* of FIG. **1**A, but may employ a fuel source to pre-heat gas before entry into the catalyst bed **120**. A cross heat exchanger, recuperator and/or pre-heater also may be used.

[0041] The byproducts of hydrocarbon combustion are water vapor and CO_2. Using a fuel source such as natural gas, LPG, methane or the like to heat the gas stream before the gas stream contacts the catalyst in the catalyst bed **120** may add hydrogen in the form of water vapor, and provide a lower cost of operation than the use of electricity for heating. The heating of the gas stream with the fuel also destroys some PFCs that are easier to abate by temperature alone, and/or leaves PFCs with lower numbers of carbon atoms (rendering the PFCs easier to destroy by catalysts).

[0042] With reference to FIG. **1**C, the system **100***c* includes a fuel source **170** for adding a fuel such as natural gas to the gas stream to be abated, along with excess air (e.g., in a combustion region or chamber **172**). The fuel/air mixture is ignited either with an electric spark, a hot surface ignitor such as a hot metal surface, or a standing pilot **174**. Alternatively excess air may be added, and then fuel, possibly with a premix of some air, to insure a stable flame without the formation of soot.

Exemplary System Components

Wet Scrubber

[0043] As stated above, the wet scrubber **102** is adapted to use a water mist to remove contaminants, such as SiF_4, from the gaseous waste stream(s) output by the process tool **106**. For example, a plurality of high pressure nozzles may be used to create a mist within the wet scrubber **102**. Exemplary embodiments of the wet scrubber **102** are described below with reference to FIGS. **2-4**.

[0044] FIG. **2** is a top perspective view of an exemplary embodiment of the wet scrubber **102** depicted in FIGS. **1**A-C; and FIG. **3** is a cross-sectional view of the wet scrubber of FIG. **2**. In the embodiment of FIGS. **2-3**, wet scrubber **102** includes a set of concentrically nested tubes (e.g., an outer tube **202** and an inner tube **204**). The outer tube **202** and inner tube **204** define an inner cavity **206** through which gaseous waste streams from one or more process tools and/or process chambers may pass. Water and/or other gases and/or fluids may be directed through outer tube **202** and inner tube **204** and dispensed radially into the inner cavity **206** via spray nozzles **208***a-h*. Though depicted in FIG. **2** as four columns of nozzles spaced equally apart on both outer tube **202** and inner tube **204**, it is understood that any number and/or arrangement of spray nozzles **208***a-h* may be utilized.

[0045] With reference to FIG. **2**, the wet scrubber **102** includes four inlets/conduits **210***a-d*, each adapted to receive a gaseous waste stream from a process chamber **212***a-d* (shown in phantom). In general, the wet scrubber **102** may include any number of inlets/conduits, and each inlet/conduit may be coupled to one or more process chambers and/or process tools. Also, a single process chamber may be coupled to more than one of the inlets/conduits **210***a-d*.

[0046] In the embodiment of FIGS. **2-3**, the inlet/conduits **210***a-d* are arranged so that each inlet/conduit **210***a-d* directs a gaseous waste stream approximately tangentially along a first inner surface **302** (and/or a second inner surface **304**) of the water scrubber **102**. Such an arrangement increases the residence time of gaseous waste streams within the wet scrubber **102** thereby increasing the effectiveness of any water scrubbing process performed therein. Other inlet/conduit configurations may be used.

[0047] Outer tube **202** and inner tube **204** may be constructed of plastic or other materials and may be lined with plastic and/or other materials to prevent deposition of particles in the gaseous waste streams. Inner cavity **206** may be sealable such that inlets to the inner cavity **206** are confined to spray nozzles **208***a-h* and inlet/conduits **210***a-d* and outlets from the inner cavity **206** are confined to one or more conduits **112** (FIGS. **1**A-C). In at least one embodiment, outer tube **202** may be of a conical shape having a smaller

diameter at its bottom. This shaping may promote efficient run-off of water and prevent particulates and other unwanted debris from accumulating within inner cavity **206**. In an exemplary embodiment, the inner cavity **206** of wet scrubber **102** may have a volume of approximately 5-10 liters, although any larger or smaller sizes may be used.

[**0048**] Water and/or other gases and/or fluids may be directed through outer tube **202** and inner tube **204** and dispensed radially into the inner cavity **206** via spray nozzles **208***a-h*. Spray nozzles **208***a-h* may be atomizer type spray nozzles and may dispense a high pressure mist of water droplets. In some embodiments, spray nozzles **208***a-h* may dispense water droplets of a diameter of about 10 to 100 microns, and more preferably about 50 microns or less. Larger and/or smaller water droplet sizes may be dispensed. In at least one embodiment of the wet scrubber **102**, atomizing water nozzles are employed to produce drops of about a 10 to 100 micron diameter so as to create an approximately 0.1 to 5 second, and preferably about 2.5 to 5 second, contact time between water particles and the gaseous waste stream(s). Spray nozzles **208***a-h* and/or other water dispensers may also direct a water curtain along the first and second inner surfaces **302** and **304** of the inner cavity **206** to prevent deposition of particulates on these surfaces.

[**0049**] FIG. **4** is a cross-sectional view of an alternative embodiment of the wet scrubber **102** of FIG. **3**. In the embodiment of FIG. **4**, water droplets dispensed by spray nozzles **208***a-h* may be electrostatically enhanced. For example, biasing electrodes may charge water droplets dispensed by spray nozzles **208***a-h* to prevent the water droplets from coalescing. A positive or negative charge may be applied to water droplets by coupling a first charger **402***a* (e.g., a DC voltage supply) to the outer tube **202** and the same or a second charger **402***b* to the inner tube **204** of the wet scrubber **102**. As all water droplets have the same charge, the droplets repel each other, preventing and/or minimizing coalescence. The voltage applied to the inner/outer tubes may range from about 100 to 5000 volts, although larger or smaller voltages may be used.

[**0050**] A metal or otherwise conducting grid **404** may be positioned near the bottom of wet scrubber **102** to collect the charged water droplets. For example, as water droplets fall onto the grid **404**, the droplets will be collected by the grid and lose their charge, allowing the droplets to coalesce and fall through conduit **112** into sump **114**. The grid **404** may be grounded, floating or charged to an opposite polarity relative to the droplets. The grid **404** may be constructed of wire mesh or any other suitable material. In some embodiments, the grid **404** may be additionally and/or alternatively positioned before and/or after first packed bed chamber **110**. Other systems and/or methods to control water droplet size, direction of travel, and/or formation may be employed in wet scrubber **102**. For example, in addition to or in place of the grid **404**, a bottom or outlet of the wet scrubber **102** may be grounded, floating or charged (as indicated by reference numeral **406**) to an opposite polarity relative to the droplets.

First Packed Bed Chamber

[**0051**] Referring again to FIGS. **1**A-C, the first packed bed chamber **110** or "demister" removes any "fog" in gaseous waste streams received from the wet scrubber **102**. In some embodiments, the first packed bed chamber **110** may include a packed bed of beads, barrels, or other shapes formed from ceramic, metal alloy, polypropylene, and/or any other suitable material. A plurality of nozzles **136** near an outlet of the first packed bed chamber **110** create a stream or rainfall of water that flows (via gravity) down the packed bed to the sump **114**. In this manner, mist introduced to the gaseous waste stream(s) by the wet scrubber **102** is removed. The nozzles **136** may operate continuously or intermittently.

[**0052**] In some embodiments, the first packed bed chamber **110** may be a sealable tube arranged such that gaseous waste streams are directed via conduit **112** into a lower end of the packed bed chamber. As stated, the first packed bed chamber **110** may be packed (e.g., filled or partially filled) with material for trapping, removing, and/or abating liquid water, water vapor, chemicals, and/or particulates in gaseous waste streams. Exemplary packing materials may include polypropylene, metal alloys, polymers, alumina, ceramics, etc., that are barrel-shaped, ring-shaped, bead-shaped and/or otherwise shaped. Other shapes and/or materials may be used (e.g., such as for high temperature or corrosive applications). The first packed bed chamber **110** may, in some embodiments, have an interior volume of approximately between four and eight liters. Packed bed chambers of larger or smaller volumes may be employed, as appropriate.

[**0053**] Note that a gaseous waste stream may be flowed in a counter-current and/or optionally a co-current manner through the packing with and/or against the flow of water. Air may be injected to provide direct cooling and promote reduction of the humidity of the exiting gaseous waste stream.

Pressure Regulator

[**0054**] Blower **118** may be constructed of plastic or other corrosion resistant materials, and may be attached directly to the first packed bed chamber **110**, the catalyst bed **120**, or indirectly to either or both of these units via appropriate conduits (as shown in FIGS. **1**A-C). The blower **118** may serve to apply positive pressure to the catalyst bed **120**. In some embodiments, the pressure applied may be approximately five in. W.C., although more or less pressure may be applied as appropriate. In the same or alternative embodiments, the blower **118** may be controllable in real time to maintain an approximately constant pressure within the system **100**, especially within the catalyst bed **120**, as will be discussed below.

[**0055**] In an alternative embodiment, the blower **118** may be replaced by a passive device, such as an eductor or another pressure regulator. Use of such a passive device may reduce operating expenses. In such an embodiment, the eductor may take in a small amount of high pressure CDA ("Clean Dry Air") that is mixed with the gaseous waste stream from the first packed bed chamber **110**. This increases the flow rate of the gaseous waste stream sent to the catalyst bed **120**.

[**0056**] In some embodiments, it may be desirable to track and/or control pressure and/or flow in the abatement system **100**. For example, pressure in the abatement system **100** may be measured by one or more pressure indicators **138***a-c*. Pressure indicators **138***a-c* may measure pressure at the first packed bed chamber **110** outlet, the catalyst bed **120** inlet, and/or immediately before passing to house exhaust **130**, respectively. These locations may be utilized to determine pressure in and/or pressure drop across the catalyst bed **120**.

Additional pressure indicators may be located wherever it is desirable to track and/or control pressure in the abatement system **100**.

[**0057**] The pressure indicators **138***a-c* may detect clogging in the second packed bed chamber **122** and the catalyst bed **120**. Also, the pressure indicators **138***a-c* may allow balancing of the pressure at the first packed bed chamber **110** outlet and the catalyst bed **120** outlet. This balancing may prevent water from being drawn from the sump **114** into the first packed bed chamber **110** and/or into the catalyst bed **120** should a large pressure differential be created across these components. Pressure indicators **138***a-c* may be any sensors capable of detecting pressure or differential pressure such as slant manometers, orifice plates, diaphragms, etc. Blower **118** may also be equipped with a damper and/or pressure switch to assist control of pressure within the abatement system **110**.

[**0058**] Flow into blower **118** (or an eductor) may be controlled by a flow regulator **140**. Flow regulator **140** may be any device capable of controlling gas and/or liquid flow such as a mass flow controller.

[**0059**] A controller **142** may be connected to and capable of receiving information from and/or transmitting command signals to blower **118**, pressure indicators **138***a-c*, and/or flow regulator **140**. For example, the controller **142** may adjust (e.g., in real time) the pressure in the abatement system **100**, such as the pressure drop across catalyst bed **120**. In some embodiments, the controller **142** may control the speed of the blower **118** to regulate pressure, or control the flow rate of CDA, compressed air, or other motive into an eductor to regulate pressure. Controller **142** may be a computer, microcontroller or any other appropriate hardware and/or software.

Catalyst Bed

[**0060**] The catalyst bed **120** may, in some embodiments, be formed from a conventional thermal oxidation and/or combustion chamber. For example, the catalyst bed **120** (and the second packed bed **122**) may be a retrofitted CDO chamber **143**, such as a retrofitted version of the EcoSys CDO863 manufactured by Metron Technology, Inc. of San Jose, Calif. Such a CDO chamber **143** is generally cylindrical and includes heaters **144** adapted to heat an inner cavity **146** of the chamber (defined by a liner **148**) during thermal oxidation processes. In an exemplary embodiment, the catalyst bed **120** may have an interior volume of approximately 4.7 to 6.4 liters, although larger or smaller volumes may be used.

[**0061**] It will be understood that the abatement system **100** may use a catalyst bed **120** that is not formed from a retrofitted CDO chamber. However, use of existing, on-site abatement equipment such as a CDO chamber that is retrofitted to abate PFCs can result in a significant cost savings when compared to the expense of installing an entirely new PFC abatement system.

[**0062**] FIG. **5** is a partial perspective view of a CDO chamber **502** that may be used as the catalyst bed **120** in accordance with the present invention. The CDO chamber **502** may be a cylindrical, tubular or other shape. To allow the CDO chamber **502** to abate PFCs, the CDO chamber **502** is filled with a catalyst (e.g., as the CDO chamber **502** typically cannot be heated to a sufficient temperature to directly abate PFCs). In some embodiments, the interior of the CDO chamber **502** and/or catalyst bed **120** may be lined with and/or constructed of corrosion resistant metals or ceramics (e.g., Inconel™ or Hastelloy™, nickel, yttria doped alumina, titania with alumina, etc.) and/or other corrosion resistant materials with high thermal conductivity.

[**0063**] A catalyst may be directly placed into the CDO chamber **502** (filling or partially filling the CDO chamber **502**). In an alternative embodiment, a removable and/or readily serviceable catalyst cartridge **504** that is prefilled with a catalyst may be inserted into the CDO chamber **502**. The catalyst cartridge **504** may also be of a cylindrical or tubular shape, and in some embodiments capped on each end by screens **506** or other porous structures that allow gaseous waste streams to travel through the catalyst trapped by the screens **506**.

[**0064**] As stated, the catalyst may aid in the reaction and/or destruction of components of gaseous waste streams by lowering the reaction temperature for the abatement of PFCs. Destruction of PFCs may require reaction temperatures in the range of approximately 950° C. to approximately 1300° C. Use of a catalyst may lower a reaction temperature for PFCs to approximately 500° C. in some embodiments.

[**0065**] Exemplary catalysts may include: ceramics; calcium magnesium; barium or strontium oxide; hydroxide; carbonate; nitrate; phosphates of aluminum, boron, alkali earth metal, titanium, zirconium, lanthanum, cerium, yttrium, rare earth metal, vanadium, niobium, chromium, manganese, iron, cobalt and/or nickel; metals of groups 4 to 14 of the periodic table; iron oxide; alumina; zirconia; titania; silica; vanadium oxide; tungsten oxide; tin oxide; platinum; palladium; rhodium; gamma alumina; cobalt oxide; and/or cerium. Other catalysts may be used. In one particular embodiment, inverse spinel crystal structure manganese may be used. Reaction catalysts may be formed or be of any appropriate shape (e.g., rings, beads, barrels, honeycomb, etc.).

[**0066**] FIG. **6** is a top view of an exemplary embodiment of the cartridge **504**. With reference to FIG. **6**, to control temperature of the catalyst and/or within the catalyst bed **120**, the heaters **144** (FIGS. **1**A-C) may be employed. The heaters **144** may be cylindrical so as to conform to the shape of outer chamber **502** and provide heat to the liner **148** and the catalyst bed **120**. To allow more uniform heating across the catalyst bed, thermal fins **602***a-h* may be provided within the cartridge **504**. The thermal fins **602***a-h* may be constructed of metal or another thermally conductive material, run the vertical length of the heaters **144**, and/or may be arranged radially toward the center of catalyst bed **120**. Heat thereby may be more uniformly transferred from the heaters **144** to the catalyst bed **120**. Other numbers of thermal fins or other types of thermal conduction mechanisms may be employed. The cartridge **504** may be formed from the same or a different material than the thermal fins **602***a-h*.

[**0067**] In some embodiments, the catalyst bed **120** may be double contained by use of an outer shell (not shown) such that gaseous waste streams may not escape abatement system **100** at the catalyst bed **120**. In the same or other embodiments, the catalyst bed **120** may have additional exhaust to remove some portion of a gaseous waste stream.

[**0068**] As another example, the catalytic bed **120** may include a catalytic surface that catalyzes a reaction for

reducing the hazardous gas content in gaseous waste streams. For example, PFCs, as well as residual halogens (e.g., fluorine), HAPs and/or VOCs, may be abated via a reaction between a gaseous waste stream and a catalyst present in the catalytic bed **120**.

[**0069**] The catalytic surface of the catalyst bed **120** may be, for example, a structure made from catalytic material or supporting a finely divided catalyst, a bed of foam or pellets, or a coating on a wall or component of the catalytic bed **120**. For example, the catalytic surfaces may comprise surfaces of a support structure comprising a honeycomb member with the catalyst embedded therein to form a high surface area member over and through which the effluent passes as it flows from an inlet to an outlet of the catalyst bed **120**. The catalytic surfaces may be on, for example, a structure comprising a ceramic material, such as cordierite, Al_2O_3, alumina-silica, alumina-titania, mullite, silicon carbide, silicon nitride, zeolite, and their equivalents; or may comprise a coating of materials, such as ZrO_2, Al_2O_3, TiO_2 or combinations of these and other oxides. The catalytic surfaces may also be impregnated with catalytic metals, such as Mn, Pt, Pd, Rh, Cu, Ni, Co, Ag, Mo, W, V, La or combinations thereof or other materials known to enhance catalytic activity.

[**0070**] In general, decreasing the size of the grains or other structure of the catalyst in the catalyst bed **120** may increase the surface area and effectiveness of the catalyst. However, such size reduction may also increase the pressure drop of gas flowing through the catalyst bed **120**.

[**0071**] In some embodiments, a vacuum generator (not shown, such as a vacuum pump) may be employed at or near the end of the catalyst bed **120** to compensate for any pressure drop produced by the catalyst bed **120**. In the same or other embodiments, pressure drop through the catalyst bed **120** may be reduced by the geometry of the catalyst bed **120**. For example, FIGS. **7**A and **7**B are a top view and a side view, respectively, of an exemplary reduced-pressure-drop catalyst bed **700** provided in accordance with the present invention that may be used in any of the abatement systems described herein.

[**0072**] With reference to FIGS. **7**A and **7**B, the catalyst bed **700** includes a reactor chamber **702** having an annular plenum **704** along the length of the reactor chamber **702** outside of catalyst material **706** of the catalyst bed **700**, and an inner plenum **708** that extends through a central region of the reactor chamber **702** and catalyst material **706**.

[**0073**] The outer plenum **704** may be formed, for example, by positioning an outer porous liner **710** within the reactor chamber **702** and spaced from an inner surface of the reactor chamber **702** so as to define the outer plenum **704**. The inner plenum **708** may be formed from an inner porous liner **712** positioned within a central region of the reactor chamber **702** so as to define the inner plenum **708**. The outer and inner liners **710**, **712** contain the catalyst material **706** within the reactor chamber **702**. In the embodiment shown, the outer and inner liners **710**, **712** may be formed from porous tubes, sheets or cylinders, such as porous ceramic, perforated metal, etc., tubes, sheets or cylinders. Other materials and/or shapes may be used.

[**0074**] In operation, a gaseous waste stream to be abated flows into the outer plenum **704** of the catalyst bed **700** (arrow **714***a* in FIG. **7**B) and may flow freely along the length of the reactor chamber **702** (arrows **714***b* in FIG. **7**B). Due to the porous nature of the outer liner **710**, the gaseous waste stream travels radially through the outer liner **710** (arrows **714***c* in FIG. **7**B), through the catalyst material **706**, through the inner liner **712** and into the inner plenum **708** (arrows **714***d* in FIG. **7**B) as shown. The gaseous waste stream then exits the catalyst bed **700**.

[**0075**] The geometry of the catalyst bed **700** significantly enhances and/or maximizes the cross sectional area of catalyst material **706** that contacts the gaseous waste stream, while significantly reducing and/or minimizing pressure drop across the catalyst bed **700**. It will be understood that gas flow direction may be reversed. For example, a gaseous waste stream may enter the catalyst bed **700** from the inner plenum **708** and travel through the inner liner **712**, through the catalyst material **706**, through the outer liner **710** and into the outer plenum **704** where it exits the catalyst bed **700**.

[**0076**] In at least one embodiment, the reactivity of the catalyst in the catalyst bed **700** (or any other catalyst bed described herein) may be enhanced with electromagnetic radiation. For example, pulsed microwaves may be applied to a catalyst bed so as to cause a polarizability catastrophe to a catalyst surface that enhances catalytic reactivity. U.S. Pat. No. 6,190,507, which is hereby incorporated by reference herein in its entirety, describes the use of short burst, high-power microwave fields to increase the reactivity of the surface of a catalyst. In one embodiment, microsecond bursts of about 5 GHz microwaves with about 40 psec rise times may be employed.

[**0077**] Most catalytic PFC abatement systems utilize a granular or pellet form of catalyst or catalyst support. These pack tightly and typically exhibit high pressure drop.

[**0078**] In some embodiments of the invention, porous yttrium doped, zirconia stabilized alumina may be employed as a high surface area catalyst support to significantly reduce the pressure drop in the catalytic bed **120**. Such as support is capable of withstanding a corrosive high temperature environment without breaking down. A catalytic support may be fabricated in various different shapes. For example, a support may be fabricated in cylinders, disks or other suitable shapes that fit within the inner cavity of the catalyst bed **120**. The vertical dimension of the catalyst bed **120** may be filled by stacking these cylindrical or disk-shaped catalyst supports. If the catalytic bed **120** becomes plugged, the plugging generally is confined to the upper portions of the bed, and may be resolved by simply replacing only the top catalyst cylinders or disks as needed.

[**0079**] PFCs require high temperatures for complete destruction, especially CF4 which requires temperatures in excess of about 1100° C. These high temperatures may be difficult to achieve with electrically heated systems. Using catalysts specific for PFCs allows PFC destruction temperatures to be reduced, in some embodiments, to between about 500-800° C.

[**0080**] PFC catalysts typically require water, or a source of hydrogen and oxygen to keep from being deactivated. In some embodiments, the water may be provided by a pre-scrubber before the catalyst bed **120**, such as by the wet scrubber **102** and/or the first packed bed chamber **110**.

[0081] The gas stream may be heated before contacting the catalyst within the catalyst bed **120**, such as via a recuperator and/or heater as previously described with reference to FIG. **1**B.

[0082] FIG. **8** illustrates a schematic view of a first apparatus **800** for heating a catalyst bed, such as the catalyst bed **120**, **700** of FIGS. **1**A-**7**B, provided in accordance with the present invention. With reference to FIG. **8**, the first apparatus **800** includes a heat exchanger **802** inside of a reactor pipe **804** adapted to convey a waste stream (e.g., process by-products) entering in the direction shown by an arrow **806**. The reactor pipe **804** may also have an abatement bed **808**, such as a catalyst bed, in a portion of the reactor pipe **804**. In this embodiment, the abatement bed **808** may be disposed about an inner pipe **810**. As shown in FIG. **8**, the inner pipe **810** may be coupled to the heat exchanger **802**. The heat exchanger **802** may also be coupled to an exhaust pipe **812** through a wall of the reactor pipe **804** at an interface **814**. The exhaust pipe **812** may be coupled to a quench **816**. For example, the quench **816** may be the second packed bed chamber **122** of FIGS. **1**A-C. The quench **816** may be coupled to a waste pipe **818** adapted to dispose of the treated waste stream (e.g., to the sump **114** of FIGS. **1**A-C).

[0083] The first apparatus **800** may also include a reactor heater **820** and an insulator **822** disposed about the reactor pipe **804**. As shown in FIG. **8**, the reactor heater **820** and the insulator **822** are depicted in cross section views. A waste stream heater **824** may be disposed inside the reactor pipe **804**. The waste stream heater **824** may be coupled to a power supply **826**.

[0084] The heat exchanger **802** may be a coiled pipe of a steel alloy such as a Nickel-based alloy, for example Inconel 600 or 625™ available from Inco Corporation in Huntington, W.V., although any suitable shape and/or material may be employed. For example, although a coil shape may be employed in the present embodiment, in the same or alternative embodiments a multi-fin shape may be used. Also, the material may be any suitable material adapted to carry a waste stream and transfer heat between a region inside the heat exchanger **802** and a region outside the heat exchanger **802**. In some embodiments, the waste stream temperature may be about 800 to about 900 degrees Celsius although higher or lower temperatures may be present.

[0085] Similarly, the reactor pipe **804**, the inner pipe **810**, the exhaust pipe **812**, and the waste pipe **818** may be formed from Inconel 600 or 625™, although any suitable material may be used. For example, in some embodiments a less expensive stainless steel alloy may be employed in the exhaust pipe **812** when the properties (e.g., corrosiveness, temperature, etc.) of the waste stream are not detrimental to the stainless steel. Although the reactor pipe **804**, the inner pipe **810**, the exhaust pipe **812**, and the waste pipe **818** may be round pipes, in general, any suitable shape and/or sizes may be employed. The temperature of the waste stream carried by the reactor pipe **804**, the inner pipe **810**, the exhaust pipe **812**, and the waste pipe **818** may range from about room temperature to about 900 degrees Celsius although higher or lower temperatures may be present.

[0086] The reactor heater **820** may be a ceramic heater from, for example, the ceramic heater product line available from Watlow Corporation in St. Louis, Mo., although any suitable heater may be employed. The ceramic portion of the reactor heater **820** may provide some insulation. To provide additional insulation, the insulator **822** or any suitable insulation may be provided. The insulator **822** may also prevent injuries to operators and/or damage to equipment. As shown in FIG. **8**, the insulator **822** may be wrapped around the reactor heater **820** although any suitable configuration of the reactor heater **820** and the insulator **822** may be employed to heat the reactor pipe **804** and the waste stream.

[0087] The waste stream heater **824** may be an electric heating device although any suitable heating device may be employed. As shown in FIG. **8**, the waste stream heater **824** may have a portion inside the reactor pipe **804** so as to contact the waste stream inside the reactor pipe **804**. Although FIG. **8** depicts the waste stream heater **824** as a rod, other configurations may be employed in the same or alternative embodiments. The waste stream heater **824** may be at a temperature that is higher than the temperature of the waste stream. Accordingly, the waste stream heater **824** may heat the waste stream around the waste stream heater **824** to a desired temperature. The waste stream heater **824** may heat the waste stream by using electricity supplied by the power supply **826** although any suitable power source may be employed.

[0088] In operation, the waste stream may enter the reactor pipe **804** as depicted by the arrow **806**, and flow about the outer surface of the heat exchanger **802**. As will be explained below, the heat exchanger **802** may be at a temperature that is greater than the temperature of the waste stream. Accordingly, heat is transferred from the heat exchanger **802** to the waste stream to heat the waste stream. The waste stream may flow past the heat exchanger **802** and the waste stream heater **824**. The waste stream heater **824** may be at a temperature higher than the heat exchanger **802** although any suitable temperature may be employed. The waste stream heater **824** may heat the waste stream to a desired temperature (e.g., for abatement). Subsequently, the waste stream may filter through the abatement bed **808** (e.g., catalyst bed **120**, **700** of FIGS. **1**A-**7**B). During this filtering the waste stream may react (e.g., chemically, physically, etc.) with the abatement bed **808** so as to change the chemical composition of the waste stream to a more desirable chemical composition. The reaction may occur at an elevated temperature.

[0089] Note that, as shown in FIG. **8**, the waste stream is heated by the heat exchanger **802** prior to being heated by the waste stream heater **824**. Accordingly, the heat exchanger **802** may use the heat retained in the waste stream after the reaction with the abatement bed **808** to preheat the incoming waste stream.

[0090] After filtering through the abatement bed **808**, the waste stream may flow through the inner pipe **810** into the heat exchanger **802**. Because the waste stream may cool during the filtering, it may be at a temperature that is slightly less than the abatement temperature. However, the temperature of the waste stream after abatement is generally higher than the temperature of the entering waste stream. Accordingly, as discussed above, the heat exchanger **802** may heat the incoming waste stream. The abated waste stream may flow through the heat exchanger **802** and the exhaust pipe **812** towards the quench **816** (e.g., second packed bed chamber **122** of FIGS. **1**A-C). The quench **816** may further cool and/or abate chemistries in the waste stream. Subsequently, the waste pipe **818** may dispose of the waste stream (e.g., to the sump **114** of FIGS. **1**A-C).

[0091] FIG. **9** illustrates a schematic view of a second apparatus **900** for heating a catalyst bed, such as the catalyst bed **120**, **700** of FIGS. **1**A-**7**B, provided in accordance with the present invention. With reference to FIG. **9**, the second apparatus **900** may include an abatement bed **808'** (e.g., a catalyst bed) that may be similar to the abatement bed **808** of the first apparatus **800**. As shown in FIG. **9**, the second abatement bed **808'** is present inside the inner pipe **810**.

[0092] In operation, the waste stream may flow as described above with reference to FIG. **8**. The waste stream flows through the second abatement bed **808'** along a path that is longer than as described with reference to FIG. **8**. Accordingly, the waste stream may have greater reaction and/or residence times with the second abatement bed **808'**. Accordingly, the chemical composition of the waste stream may be abated more extensively.

[0093] FIG. **10** illustrates a schematic view of a third apparatus **1000** for heating a catalyst bed, such as the catalyst bed **120**, **700** of FIGS. **1**A-**7**B, provided in accordance with the present invention. With reference to FIG. **10**, the third apparatus **1000** may include an external pipe **1002** coupled to the reactor pipe **804** and the heat exchanger **802**. The third apparatus **1000** may also include some components of the second apparatus **900**. Note that the quench **816** is coupled to the reactor pipe **804**. As shown in FIG. **10**, a portion of the external pipe **1002** may be disposed outside the reactor pipe **804** and between the insulator **822** and the reactor heater **820** although any suitable configuration may be employed. For example, in alternative embodiments, the external pipe **1002** may be disposed between the reactor heater **820** and the reactor pipe **804**. The external pipe **1002** may be similar to the inner pipe **810** described above with reference to FIG. **8**. For example, the external pipe **1002** may be made of a nickel-alloy such as Inconel™ or another suitable material.

[0094] In operation, a waste stream may travel through the reactor pipe **804**, through the abatement bed **808** and enter the external pipe **1002** at an elevated temperature. The abated waste stream may be conveyed by the external pipe **1002** between the reactor heater **820** and the insulator **822**, thereby heating or preserving the temperature of the waste stream in the external pipe **1002**. Subsequently, similar to the first apparatus **800** and the second apparatus **900**, the abated waste stream may flow into the heat exchanger **802** to heat the heat exchanger **802** to a temperature higher than the temperature of the incoming waste stream. Accordingly, the heat exchanger **802** may preheat the incoming waste stream as described above with reference to FIGS. **8** and **9**.

[0095] FIG. **11** illustrates a schematic view of a fourth apparatus **1100** for heating a catalyst bed, such as the catalyst bed **120**, **700** of FIGS. **1**A-**7**B, provided in accordance with the present invention. With reference to FIG. **11**, the fourth apparatus **1100** may include a pipe **1102** in addition to some of the components described above with reference to FIG. **8**. The pipe **1102** may be disposed in the abatement bed **808** inside the reactor pipe **804**. As shown in FIG. **11**, the pipe **1102** is disposed approximately center in the abatement bed **808** although any suitable location may be employed. A portion of the pipe **1102** extends beyond the abatement bed **808** into a region of the reactor pipe **804** in proximity to where the waste stream enters the reactor pipe **804**.

[0096] The pipe **1102** may be a heat pipe although any suitable device may be employed. For example, the pipe **1102** may be a hollow heat pipe with a heat pipe fluid disposed inside the heat pipe. The heat pipe fluid may include a working fluid such as reduced pressure water, acetone, solvents, ammonia, etc., although any suitable fluid may be employed. The pipe **1102** may be similar to the material of the inner pipe **810** described above with reference to FIG. **8** although any suitable material may be employed. In FIG. **11**, the pipe **1102** is a cylinder, although any suitable shape may be employed.

[0097] In operation, a first region of the pipe **1102** in the reactor heater **820** may increase to an abatement temperature (e.g., a temperature of the waste stream within the abatement bed **808**, which may be, for example, a catalyst bed). Consequently, the heat pipe fluid may raise in temperature throughout the heat pipe **1102**. For example, a portion of the heat pipe fluid may become gaseous and rise to a second region in proximity to where an incoming waste stream enters the reactor pipe **804**. Because the heat pipe fluid is at a temperature greater than the temperature of the incoming waste stream, the heat pipe may transfer heat to the waste stream. The temperature of the incoming waste stream may increase, and the heat pipe fluid may condense back to a liquid form and flow back to the first region.

[0098] FIG. **12** is a schematic diagram of an exemplary cross heat exchanger **1200** that may be used for the heat exchanger **160** of FIG. **1**B. Such a heat exchanger is similar to those described in previously incorporated U.S. Pat. No. 6,824,748.

[0099] With reference to FIG. **12**, a gaseous waste stream to be abated (e.g., within the catalytic bed **120** of FIG. **1**B) enters the cross heat exchanger **1200** at a first inlet **1202**, and is dispersed into a first set of multiple channels **1204**. An abated gas stream (e.g., catalytic bed **120**) enters the heat exchanger at a second inlet **1206** and is dispersed into a second set of multiple channels **1208** which are adjacent and capable of transferring heat to the first multiple channels **1204** that carry the gaseous waste stream to be abated. Heat from the abated gas stream thereby is transferred to the gaseous waste stream to be abated. An insulating material **1210** may surround the heat exchanger **1200** to prevent the loss of heat to the atmosphere and to increase the efficiency of the heat exchanger **1200**. The heat exchanger **1200** may be made of a corrosion resistant material such as a nickel-based alloy (e.g., Inconel®), or another suitable material.

[0100] Other types and/or number of heat exchangers may be used. For example, concentric tube heat exchangers in which hot gas flows within an inner tube and cold gas flows within an outer tube (or vice versa) may be employed, as may gas-to-gas heat exchangers.

Second Packed Bed Chamber

[0101] In some embodiments, the second packed bed chamber **122** may be of similar design and/or construction to the first packed bed chamber **110**, discussed above. In at least one embodiment, the second packed bed chamber **122** may be part of the EcoSys CDO863 manufactured by Metron Technology, Inc. of San Jose, Calif. Other packed bed chambers may be used.

[0102] Referring again to FIGS. **1**A-C, the second packed bed chamber **122** primarily removes acids and/or other

undesirable by products of the PFC abatement that occurs in the catalyst bed **120**. In some embodiments, the second packed bed chamber **122** may include a packed bed of beads, barrels and/or other shapes (not shown) formed from a corrosion resistant material such as ceramic or any other suitable material. A plurality of nozzles **150** near an outlet of the second packed bed chamber **122** create a stream or rainfall of water that flows (via gravity) down the packed bed to the sump **114**. In this manner, acids (e.g., HF) and/or other components introduced to the gaseous waste stream(s) by the catalyst bed **120** are removed. The nozzles **150** may operate continuously or intermittently.

Exemplary System Operation

[**0103**] In operation, gaseous waste streams from one or more process chambers (e.g., metal and/or dielectric etch chambers) are exhausted via exhaust lines **108***a-d* to wet scrubber **102**. Water passed through high pressure pump **104** is atomized (e.g., pressed into droplets approximately 50 microns in size) and/or electrically charged at spray nozzles **208***a-h*. The gaseous waste streams are swirled around inner cavity **206** of wet scrubber **102** and through the fog of electrically charged water droplets, which react with the gaseous waste streams to remove and suspend in-water pollutants (e.g., SiF_4) that may harm downstream abatement equipment. Tangential insertion of the gaseous waste streams, as shown in FIG. **2**, increases the residence time of the gaseous waste streams in wet scrubber **102**. In an exemplary embodiment, the gaseous waste streams have a minimum residence time of at least approximately 0.1 seconds. Preferably, the residence time is approximately 2.5-5 seconds or more. Other residence times may be used as appropriate.

[**0104**] As water droplets contact grid **404**, the water, SiF_4, and any other materials suspended in the water may flow out of water scrubber **102**, through conduit **112** and branch **116** to sump **114**. The unaffected portions of the gaseous waste streams may also flow through conduit **112** and then upward into the first packed bed chamber **110**.

[**0105**] The first packed bed chamber **110** removes water (mist), contaminants, and/or particulates from the gaseous waste streams. The separated water, contaminants, and/or particulates may be directed to the sump **114** as described above. After passing through the first packed bed chamber **110**, the gaseous waste streams may be directed to the blower **118** or an eductor (not shown). At this location within the abatement system **100**, the gaseous waste streams primarily comprise a mixture of PFCs, nitrogen, non-soluble gases, and water vapor with acids, readily soluble by-products, particles, etc., from the process tool **106** removed.

[**0106**] When an eductor is employed in place of the blower **118**, CDA, compressed air or another suitable gas may be added to the gaseous waste streams to affect pressure on the catalyst bed **120**, and/or enhance, improve the efficiency of, and/or enable a reaction within the catalyst bed **120**. When the blower **118** is employed, blower speed may be adjusted to achieve these objectives.

[**0107**] In the catalyst bed **120**, the gaseous waste streams may be combusted, thermally oxidized, and/or otherwise reacted to abate PFCs (e.g., by converting PFCs to HF or other scrubbable by-products). After passing through the catalyst bed **120**, the reacted gaseous waste streams are passed into conduit **124** through spray nozzles **126** to remove particulates and other contaminants generated by the catalyst bed **120**. Particulates and other contaminants removed from the gaseous waste streams by spray nozzle water may be flowed with the water into the sump **114** via conduit **124** and branch **128**.

[**0108**] The remaining gaseous waste streams may be flowed upwardly through the second packed bed chamber **122**. Acids and/or particulates and contaminants thereby may be removed from the gaseous waste streams using the second packed bed chamber **122**. Water from the sump **114** may be recirculated into the second packed bed scrubber **122**.

[**0109**] Though not explicitly diagrammed in FIG. **1**, it is understood that water that flows to high pressure pump **104** may also be flowed directly to first packed bed chamber **110**, catalyst bed **120**, water sprayers **126**, the second packed bed chamber **122** and/or any water inlet and/or sprayer in the abatement system **100**. Similarly water from sump **114**, in some embodiments, may be recirculated to any desired location such as to the wet scrubber **102**, the first packed bed chamber **110**, the water sprayers **126**, the second packed bed chamber **122**, etc.

[**0110**] Gaseous waste streams may be passed to the house exhaust **130** for further abatement or exhaust after processing in the second packed bed chamber **122**.

[**0111**] The foregoing description discloses only exemplary embodiments of the invention. Modifications of the above disclosed apparatus and method which fall within the scope of the invention will be readily apparent to those of ordinary skill in the art. For instance, to enhance PFC abatement, gaseous waste streams may be pre-heated before entering the catalyst bed **120**. For example, hot nitrogen may be introduced to the gaseous waste streams near the inlet of the catalyst bed **120**. Oxygen, air or enriched oxygen similarly may be injected into the gaseous waste streams near the inlet of the catalyst bed **120** to enhance abatement.

[**0112**] As stated, an eductor or air amplifier may be used in place of the blower **118**. Additionally or alternatively, a blower, eductor or air amplifier may be used at the output of the second packed bed chamber **122** to affect, control and/or regulate pressure within the abatement system **100**.

[**0113**] In some embodiments, the abatement system **100***a-c* may be used to abate hazardous air pollutants (HAPs) and/or volatile organic compounds (VOCs). The abatement system **100***a-c* may also include means for controlling pH at a desired location, such as near the recirculation pump **134** (e.g., using a port (not shown) for caustic injection).

[**0114**] Any number of scrubbers may be used before and/or after the catalyst bed **120** (e.g., 1, 2, 3, 4, etc.). Other types and/or number of heat exchangers may be used. For example, concentric tube heat exchangers in which hot gas flows within an inner tube and cold gas flows within an outer tube (or vice versa) may be employed, as may gas-to-gas heat exchangers.

[**0115**] In some embodiments, the catalytic bed **120** may be insulated and/or water-tight. The scrubbers may be co-current, counter-current, or a combination of the same. Other

configurations may be used. An additional water heat exchanger may be used (e.g., for cooling recirculated water from the scrubbers).

[0116] In some embodiments, a blower or eductor (described above) may be positioned after the catalyst bed **120** and/or after the second packed bed chamber **122**.

[0117] In some embodiments, a vacuum source, pump, or other vacuum generator **123** (FIG. **1**C) may be employed at or near the end of the catalyst bed **120** to compensate for any pressure drop produced by the catalyst bed **120**.

[0118] Any of the catalysts described herein may be formed or be of any appropriate shape (e.g., rings, beads, barrels, honeycomb as indicated, for example, by reference numeral **716** in FIG. **7**A, or the like).

[0119] The catalytic surface of the catalyst bed **120** may be, for example, a structure made from catalytic material or supporting a finely divided catalyst, a bed of foam or pellets, or a coating on a wall or component of the catalytic bed **120**. For example, the catalytic surfaces may comprise surfaces of a support structure comprising a honeycomb member (e.g., as indicated, for example, by reference numeral **716** in FIG. **7**A) with the catalyst embedded therein to form a high surface area member over and through which the effluent passes as it flows from an inlet to an outlet of the catalyst bed **120**.

[0120] In at least one embodiment, the reactivity of the catalyst in the catalyst bed **700** (or any other catalyst bed described herein) may be enhanced with electromagnetic radiation (e.g., from an electromagnetic radiation source **720**). Note that any suitable location for a radiation source may be used.

[0121] Accordingly, while the present invention has been disclosed in connection with exemplary embodiments thereof, it should be understood that other embodiments may fall within the spirit and scope of the invention, as defined by the following claims.

The invention claimed is:

1. An apparatus for abating perfluorocarbons (PFCs) in a controlled decomposition oxidation (CDO) thermal reaction chamber comprising:

a cartridge insertable into the thermal reaction chamber having gas-permeable first and second ends and including a catalyst material; and

thermally-conductive fixtures positioned within the cartridge.

2. The apparatus of claim 1, wherein the thermally-conductive features comprise vertically-extending thermal fins arranged radially within the cartridge.

3. The apparatus of claim 1, wherein the cartridge includes porous structures that allow the gaseous waste stream to travel through the catalyst material.

4. The apparatus of claim 1, wherein the catalyst material includes one or more of: ceramics; oxides of calcium, magnesium, barium, strontium, iron, tungsten, cobalt, aluminum, zirconium, titanium, silicon, vanadium and tin; hydroxides of calcium, magnesium, barium, and strontium; carbonates of calcium, magnesium, barium, and strontium; nitrates of calcium, magnesium, barium, and strontium; phosphates of aluminum, boron, an alkali earth metal, titanium, zirconium, lanthanum, cerium, yttrium, a rare earth metal, vanadium, niobium, chromium, manganese, iron, cobalt and nickel; a metal of groups 4 to 14 of the periodic table; platinum; palladium; rhodium; gamma alumina; and cerium.

5. The apparatus of claim 4, wherein the catalyst material is formed as one or more of: rings, pellets, beads, barrels and a honeycomb structure.

6. The apparatus of claim 1, wherein the catalyst material includes inverse spinal structure manganese.

7. The apparatus of claim 1, wherein the cartridge includes a support structure having catalytic surfaces that support catalyst material.

8. The apparatus of claim 7, wherein the catalytic surfaces are coated with one or more of: oxides of zirconium, aluminum, titanium.

9. The apparatus of claim 7, wherein the catalytic surfaces are impregnated with catalytic metals.

10. The apparatus of claim 7, wherein the support structure comprises a honeycomb member.

11. The apparatus of claim 1, wherein the cartridge has an interior volume of approximately 4.7 to 6.4 liters.

12. The apparatus of claim 1, wherein the cartridge comprises an annular catalyst bed having an outer porous liner and an inner porous liner, the inner porous liner positioned within a central region of the thermal reaction chamber so as to define an inner plenum.

13. The apparatus of claim 12, wherein a gaseous waste stream introduced into the thermal reaction chamber may flow freely through the outer porous liner through the catalyst bed and into the inner plenum.

14. An apparatus for abating perfluorocarbons (PFCs) in a controlled decomposition oxidation thermal reaction chamber comprising:

a cartridge insertable into the thermal reaction chamber having gas-permeable first and second ends and including a catalyst material.

15. The apparatus of claim 14, wherein the cartridge includes porous structures that allow the gaseous waste stream to travel through the catalyst material.

16. The apparatus of claim 14, wherein the catalyst material includes one or more of: ceramics; oxides of calcium, magnesium, barium, strontium, iron, tungsten, cobalt, aluminum, zirconium, titanium, silicon, vanadium and tin; hydroxides of calcium, magnesium, barium, and strontium; carbonates of calcium, magnesium, barium, and strontium; nitrates of calcium, magnesium, barium, and strontium; phosphates of aluminum, boron, an alkali earth metal, titanium, zirconium, lanthanum, cerium, yttrium, a rare earth metal, vanadium, niobium, chromium, manganese, iron, cobalt and nickel; a metal of groups 4 to 14 of the periodic table; platinum; palladium; rhodium; gamma alumina; and cerium.

17. The apparatus of claim 16, wherein the catalyst material is formed as one or more of: rings, pellets, beads, barrels and a honeycomb structure.

18. The apparatus of claim 14, wherein the catalyst material includes inverse spinal structure manganese.

19. The apparatus of claim 14, wherein the cartridge includes a support structure having catalytic surfaces that support catalyst material.

20. The apparatus of claim 19, wherein the catalytic surfaces are coated with one or more of: oxides of zirconium, aluminum, titanium.

21. The apparatus of claim 19, wherein the catalytic surfaces are impregnated with catalytic metals.

22. The apparatus of claim 19, wherein the support structure comprises a honeycomb member.

23. The apparatus of claim 14, wherein the cartridge has an interior volume of approximately 4.7 to 6.4 liters.

24. The apparatus of claim 14, wherein the cartridge comprises an annular catalyst bed having an outer porous liner and an inner porous liner, the inner porous liner positioned within a central region of the thermal reaction chamber so as to define an inner plenum.

25. The apparatus of claim 24, wherein a gaseous waste stream introduced into the thermal reaction chamber may flow freely through the outer porous liner through the catalyst bed and into the inner plenum.

26. An apparatus for abating perfluorocarbons (PFCs) in a controlled decomposition oxidation (CDO) thermal reaction chamber comprising:

an annular catalyst bed embedded in the thermal reaction chamber having an outer porous liner and an inner porous liner, the inner porous liner positioned within a central region of the thermal reaction chamber so as to define an inner plenum;

wherein a gaseous waste stream introduced into the thermal reaction chamber may flow through the outer porous liner through the catalyst bed and into the inner plenum.

27. The apparatus of claim 26, wherein the catalyst bed includes catalyst material positioned between the outer and inner porous liners.

28. The apparatus of claim 27, wherein the catalyst material comprises a high-surface area catalyst support including porous yttrium doped, zirconia stabilized alumina.

29. The apparatus of claim 28, wherein the catalyst support is formed using at least one of cylinders and disks.

30. The apparatus of claim 27, further comprising:

an electromagnetic radiation generator adapted to direct electromagnetic energy onto the catalyst material so as to increase a reactivity of the catalyst material.

31. The apparatus of claim 30, wherein the electromagnetic radiation generator is adapted to emit pulsed microwaves.

32. An apparatus for abating perfluorocarbons (PFCs) in a gaseous waste stream comprising:

a controlled decomposition oxidation (CDO) thermal reaction chamber having an inlet adapted to receive the gaseous waste stream; and

a catalyst bed including a catalyst material positioned within the CDO thermal reaction chamber so as to expose the gaseous waste stream to the catalyst material.

33. The apparatus of claim 32, wherein the catalyst bed comprises a cartridge.

34. The apparatus of claim 33, wherein the cartridge is insertable into the CDO thermal reaction chamber and includes gas-permeable first and second ends, and thermally-conductive fixtures extending through the cartridge.

35. The apparatus of claim 34, wherein the thermally-conductive features comprise fins arranged radially within the cartridge.

36. The apparatus of claim 33, further comprising:

a heating device positioned proximate to and upstream from the inlet of the CDO thermal reaction chamber adapted to pre-heat the gaseous waste stream before the gaseous waste stream enters the CDO thermal reaction chamber.

37. The apparatus of claim 36, wherein the heating device comprises an electric heater.

38. The apparatus of claim 36, wherein the heating device comprises:

a chamber through which the gaseous waste stream is conveyed coupled to and adapted to receive combustible fuel supplied from a combustible fuel source; and

a pilot device positioned within the chamber adapted to ignite combustible fuel provided to the chamber.

39. The apparatus of claim 36, wherein the heating device comprises a heat exchanger.

40. The apparatus of claim 39, further comprising:

a first conduit adapted to convey the gaseous waste stream to the CDO thermal reaction chamber, the heat exchanger positioned in the first conduit proximate to the inlet of the CDO thermal reaction chamber; and

a second conduit having a first end coupled to the catalyst bed and a second end coupled to the heat exchanger.

41. The apparatus of claim 33, wherein the catalyst material includes one or more of: ceramics; oxides of calcium, magnesium, barium, strontium, iron, tungsten, cobalt, aluminum, zirconium, titanium, silicon, vanadium and tin; hydroxides of calcium, magnesium, barium, and strontium; carbonates of calcium, magnesium, barium, and strontium; nitrates of calcium, magnesium, barium, and strontium; phosphates of aluminum, boron, an alkali earth metal, titanium, zirconium, lanthanum, cerium, yttrium, a rare earth metal, vanadium, niobium, chromium, manganese, iron, cobalt and nickel; a metal of groups 4 to 14 of the periodic table; platinum; palladium; rhodium; gamma alumina; and cerium.

42. The apparatus of claim 41, wherein the catalyst material is formed as one or more of: rings, pellets, beads, barrels and a honeycomb structure.

43. The apparatus of claim 33, wherein the catalyst material includes inverse spinal structure manganese.

44. The apparatus of claim 33, wherein the cartridge includes a support structure having catalytic surfaces that support catalyst material.

45. The apparatus of claim 44, wherein the support structure comprises a honeycomb member.

46. The apparatus of claim 33, wherein the cartridge comprises an annular catalyst bed having an outer porous liner and an inner porous liner, the inner porous liner positioned within a central region of the CDO thermal reaction chamber so as to define an inner plenum.

47. The apparatus of claim 46, wherein a gaseous waste stream introduced into the CDO thermal reaction chamber may flow through the outer porous liner through the catalyst bed and into the inner plenum.

48. The apparatus of claim 33, wherein the cartridge has an interior volume of approximately 4.7 to 6.4 liters.

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