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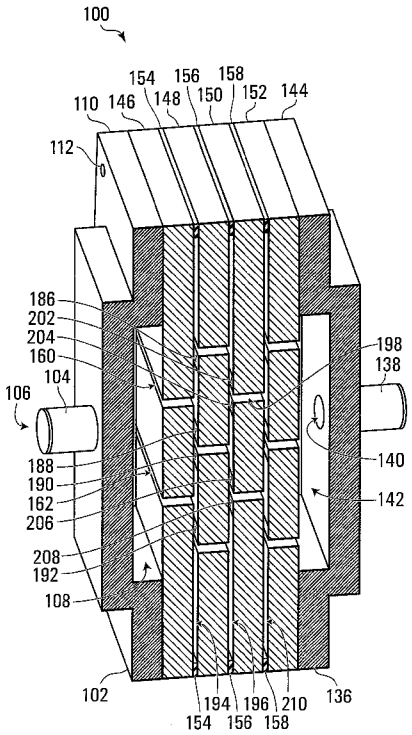

FIG. 2

(57) Abstract: Apparatuses for determining whether a substance is carried in a fluid are disclosed. One such apparatus includes a body having: a plurality of spaced-apart capture surfaces configured to contact the fluid and capture the substance from the fluid; and a plurality of fluid guiding surfaces spaced apart by a predetermined distance from respective at least portions of respective ones of the plurality of capture surfaces. Another such apparatus includes: a fluid conduit to direct flow of the fluid; and at least one element removably positioned in the fluid conduit and having at least one capture surface configured to contact the fluid and capture the substance from the fluid.

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APPARATUSES FOR DETERMINING WHETHER A SUBSTANCE IS CARRIED IN A FLUID

RELATED APPLICATION

This application claims the benefit of United States Provisional Patent Application No. 61/295,097 entitled ROBUST METHOD FOR CAPTURE AND DETECTION OF WATERBORNE PATHOGENS and filed on January 14, 2010, which is incorporated herein by reference.

BACKGROUND

1. Field

The invention relates generally to apparatuses for determining whether a substance is carried in a fluid.

2. Related Art

In some circumstances, it may be desirable to determine whether a substance is carried in a fluid. For example, various pathogens may be present in water intended for human consumption, and determining whether such pathogens are present in such water may advantageously prevent consumption of such pathogens and thus prevent waterborne disease.

One method for determining whether pathogens are present in water involves measuring turbidity of the water. However, turbidity may indicate substances other than pathogens, and also pathogens may be present in relatively clear water. Therefore, measuring turbidity of water may be an unreliable method for determining whether pathogens are present in the water.

Another method for determining whether pathogens are present in water involves measuring a quantity of coliform bacteria in the water. Coliform bacteria are naturally present in the digestive tracts of many animals, and therefore may indicate fecal contamination in the water. However, coliform bacteria in the water may not reveal some other pathogens in the water, and measuring a quantity of coliform bacteria may require 24 to 48 hours, for example, for growth of the coliform bacteria to a measurable quantity.

Another method for determining whether protozoan pathogens (such as *Cryptosporidium parvum* or *Giardia lamblia*, for example) are present in water involves filtering the water and examining the filter for such pathogens. However, filtering water may not reveal smaller pathogens, and examining a filter for protozoan pathogens may require time-consuming laboratory analysis.

Another method for determining whether pathogens are present in water involves passing the water over a plurality of beads having capture surfaces configured to capture the pathogens. An apparatus including such a plurality of beads may be referred to as a "packed bed" apparatus. However, in such an apparatus, the spaces between the surfaces of the beads are inconsistent. In some regions, the space between adjacent beads may be so small that water flow on such regions is unduly restricted. In other regions, the space between adjacent beads may be so large that some pathogens in the water pass between the adjacent beads sufficiently far from the capture surfaces that the pathogens escape capture. Such inconsistent spacing may therefore decrease efficiency of such a packed bed apparatus.

SUMMARY

In accordance with one illustrative embodiment, there is provided an apparatus for determining whether a substance is carried in a fluid. The apparatus includes a body having: a plurality of spaced-apart capture surfaces configured to contact the fluid and capture the substance from the fluid; and a plurality of fluid guiding surfaces spaced apart by a predetermined distance from respective at least portions of respective ones of the plurality of capture surfaces.

The body may define a fluid conduit surrounding the plurality of capture surfaces to direct flow of the fluid.

The capture surfaces may be coated with a plurality of capture molecules having respective binding affinities with the substance.

The capture molecules may include proteins. The proteins may include antibodies, antibody fragments, lectins, or protein aptamers.

The capture molecules may include nucleic acids. The nucleic acids may include nucleic acid aptamers.

The body may include at least one element having the capture surfaces. The at least one element may be removable.

The at least one element may include a plurality of cylindrical elements.

The plurality of fluid guiding surfaces may include, for each one of the plurality of capture surfaces, at least a portion of a surface of an adjacent one of the plurality of cylindrical elements.

The cylindrical elements may extend generally parallel to each other.

The at least one element may include a plurality of longitudinally spaced-apart plates each having at least one of the plurality of capture surfaces.

Each one of the plurality of plates may define at least one longitudinal fluid through-opening longitudinally aligned with the at least one wall of each adjacent one of the plurality of plates.

The plurality of fluid guiding surfaces may include, for each one of the plurality of capture surfaces, at least a portion of a surface of the at least one wall of an adjacent one of the plurality of plates.

The apparatus may further include at least one spacer separating adjacent ones of the plurality of plates.

The at least one spacer may surround a respective region between adjacent ones of the plurality of plates and in fluid communication with the at least one fluid through-opening of the adjacent ones of the plurality of plates.

Each spacer may have a thickness equal to the predetermined distance.

The at least one spacer may seal the respective region.

The apparatus may further include a plurality of longitudinally spaced walls longitudinally spaced from opposite sides of each one of the plurality of plates and defining a respective region surrounding each one of the plurality of plates.

The body may define at least one opening for communicating fluid between adjacent ones of the regions. The plurality of fluid guiding surfaces may include, for each one of the plurality of capture surfaces, at least a portion of a surface an adjacent one of the plurality of walls.

Each one of the plurality of plates may have first and second opposite and generally circular sides each having a center and a peripheral region. The at least one opening may be configured to communicate fluid between the centers of adjacent sides of adjacent ones of the plurality of plates. For each one of the plurality of plates, the respective region surrounding the plate may be configured to direct fluid received at the center of the first side of the plate to the peripheral region of the first side of the plate, then to the peripheral region of the second side of the plate, and then to the center of the second side of the plate.

The plates may extend generally parallel to each other.

The plurality of capture surfaces and the plurality of fluid guiding surfaces may be configured to generate electric fields between each one of the plurality of capture surfaces and each respective one of the plurality of fluid guiding surfaces.

Each one of the plurality of spaced-apart capture surfaces may be electrically grounded, and each one of the plurality of fluid guiding surfaces may be electrically connected to a voltage source.

At least one of the plurality of capture surfaces may be oriented in the apparatus to be contacted by the fluid in an incidental flow.

In accordance with another illustrative embodiment, there is provided an apparatus for determining whether a substance is carried in a fluid. The apparatus includes: a fluid conduit to direct flow of the fluid; and at least one element removably positioned in the fluid conduit and having at least one capture surface configured to contact the fluid and capture the substance from the fluid.

The at least one capture surface may be coated with a plurality of capture molecules having respective binding affinities with the substance.

The capture molecules may include proteins. The proteins may include antibodies, antibody fragments, lectins, or protein aptamers.

The capture molecules may include nucleic acids. The nucleic acids may include nucleic acid aptamers.

The apparatus may further include a plurality of fluid guiding surfaces spaced apart by a predetermined distance from respective at least portions of respective ones of the plurality of capture surfaces.

The at least one element may include a plurality of cylindrical elements.

The plurality of fluid guiding surfaces may include, for each one of the plurality of capture surfaces, at least a portion of a surface of an adjacent one of the plurality of cylindrical elements.

The cylindrical elements may extend generally parallel to each other.

The at least one element may include a plurality of longitudinally spaced-apart plates each having at least one of the plurality of capture surfaces.

Each one of the plurality of plates may have at least one wall and may defines at least one longitudinal fluid through-opening longitudinally aligned with the at least one wall of each adjacent one of the plurality of plates.

The plurality of fluid guiding surfaces may include, for each one of the plurality of capture surfaces, at least a portion of a surface of the at least one wall of an adjacent one of the plurality of plates.

The apparatus may further include at least one spacer separating adjacent ones of the plurality of plates.

The at least one spacer may surround a respective region between adjacent ones of the plurality of plates and in fluid communication with the at least one fluid through-opening of the adjacent ones of the plurality of plates.

Each spacer may have a thickness equal to the predetermined distance.

The at least one spacer may seal the respective region.

The apparatus may further include a plurality of longitudinally spaced walls longitudinally spaced from opposite sides of each one of the plurality of plates and defining a respective region surrounding each one of the plurality of plates. The apparatus may define at least one opening for communicating fluid between adjacent ones of the regions. The plurality of fluid guiding surfaces may include, for each one of the plurality of capture surfaces, at least a portion of a surface an adjacent one of the plurality of walls.

Each one of the plurality of plates may have first and second opposite and generally circular sides each having a center and a peripheral region. The at least one opening may be configured to communicate fluid between the centers of adjacent sides of adjacent ones of the plurality of plates. For each one of the plurality of plates, the respective region surrounding the plate may be configured to direct fluid received at the center of the first side of the plate to the peripheral region of the first side of the plate, then to the peripheral region of the second side of the plate, and then to the center of the second side of the plate.

The plurality of capture surfaces and the plurality of fluid guiding surfaces may be configured to generate electric fields between each one of the plurality of capture surfaces and each respective one of the plurality of fluid guiding surfaces.

Each one of the plurality of spaced-apart capture surfaces may be electrically grounded, and each one of the plurality of fluid guiding surfaces may be electrically connected to a voltage source.

At least one of the plurality of capture surfaces may be oriented in the apparatus to be contacted by the fluid in an incidental flow.

Other aspects and features of the present invention will become apparent to those ordinarily skilled in the art upon review of the following description of specific embodiments in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings that illustrate various embodiments:

Figure **1** is an oblique view of an illustrative apparatus for determining whether a substance is carried in a fluid;

Figure **2** is a cross-sectional view of the apparatus of Figure **1** taken along the line II-II in Figure **1**;

Figure **3** is an elevational view of a first plate of the apparatus of Figure **1**;

Figure **4** is an elevational view of a second plate of the apparatus of Figure **1**;

Figure **5** is an elevational view of a third plate of the apparatus of Figure **1**;

Figure **6** is an exploded oblique view of another illustrative apparatus for determining whether a substance is carried in a fluid;

Figure **7** is another oblique view of the apparatus of Figure **6**;

Figure **8** is a cross-sectional view of the apparatus of Figure **6** taken along the line VIII-VIII in Figure **7**;

Figure **9** is an exploded oblique view of another illustrative apparatus for determining whether a substance is carried in a fluid;

Figure **10** is another oblique view of the apparatus of Figure **9**;

Figure **11** is a cross-sectional view of the apparatus of Figure **9** taken along the line XI-XI in Figure **10**;

Figure **12** is a cross-sectional view of another illustrative apparatus for determining whether a substance is carried in a fluid;

Figure **13** is a schematic illustration of an illustrative capture assembly;

Figure **14** is a schematic illustration of a first illustrative model apparatus;

Figure **15** is a schematic illustration of a second illustrative model apparatus;

Figure **16** is a schematic illustration of a third illustrative model apparatus;

Figures **17** to **21** are illustrations numerical predictions of concentrations of a substance over the capture surfaces of the model apparatus of Figure **15**;

Figures **22** to **31** are illustrations numerical predictions of concentrations of a substance over the capture surfaces of the model apparatus of Figure **16**;

Figure **32** is an illustration of numerical predictions of capture efficiency of capture surfaces of the model apparatuses of Figures **15**, **16**, and **17**;

Figure **33** is a schematic illustration of another illustrative capture assembly;

Figure **34** is an oblique view of a microretroreflector shown in Figure **33**;

Figure **35** is a side view of the microretroreflector shown in Figure **34**; and

Figure **36** is a schematic illustration of an illustrative detection apparatus.

DETAILED DESCRIPTION

First Embodiment

Referring to Figures **1** and **2**, an illustrative apparatus for determining whether a substance is carried in a fluid is shown generally at **100** and includes an inlet coupling unit **102**. The inlet coupling unit **102** includes an inlet pipe portion **104** defining therethrough a fluid inlet shown generally at **106**. The inlet coupling unit **102** defines a cavity shown generally at **108** and in fluid communication with the fluid inlet **106**, and the inlet coupling unit **102** includes a flange **110** surrounding the cavity **108**. The flange **110** defines four fastener through-openings (such as those shown generally at **112**, **114**, and **118**) for receiving respective fasteners **120**, **122**, **124**, and **126**. In the embodiment shown, the fasteners **120**, **122**, **124**, and **126** are threaded for threadedly engaging respective nuts **128**, **130**, **132**, and **134**.

The apparatus **100** also includes an outlet coupling unit **136** that includes an outlet pipe portion **138** defining therethrough a fluid outlet shown generally at **140**. The outlet coupling unit **136** defines a cavity shown generally at **142** and in fluid communication with the fluid outlet **140**, and the outlet coupling unit **136** includes a flange **144** surrounding the cavity **142**. The flange **144** also defines fastener through-openings (not shown) for receiving the fasteners **120**, **122**, **124**, and **126**.

The apparatus **100** includes first, second, third, and fourth longitudinally spaced-apart plates **146**, **148**, **150**, and **152**, which may also be referred to as "elements". The apparatus **100** also includes a first separator **154** between the first and second plates **146** and **148**, a second separator **156** between the second and third plates **148** and **150**, and a third separator **158** between the third and fourth plates **150** and **152**.

Referring to Figure **3**, the first plate **146** defines elongate rectangular fluid through-openings shown generally at **160** and **162**. Referring back to Figure **2**, the fluid through-openings **160** and **162** are positioned on the first plate **146** so that when the first plate **146** is positioned adjacent the flange **110**, the fluid through-openings **160** and **162** are in fluid communication with the cavity **108**. In general, the position, length, and width of the fluid through-openings **160** and **162** are determined based on the critical shear path of the flow, which is a function of the fluid viscosity and velocity and the physical properties of the substance, for example. Referring back to Figure **3**, the first plate **146** also defines fastener through-openings shown generally at **164**, **166**, **168**, and **170** for receiving the fasteners **120**, **122**, **124**, and **126** respectively. The portions of the first plate **146** other than the through-openings may be referred to as a "wall".

Referring to Figure **4**, the second plate **148** defines elongate rectangular longitudinal fluid through-openings shown generally at **172**, **174**, and **176**. The second plate **148** also defines fastener through-openings shown generally at **178**, **180**, **182**, and **184** for receiving the fasteners **120**, **122**, **124**, and **126** respectively. The portions of the second plate **148** other than the through-openings may be referred to as a "wall". The second plate **148** also has a first

capture surface **186** proximate the fluid through-opening **172**, second and third capture surfaces **188** and **190** proximate the fluid through-opening **174**, and a fourth capture surface **192** proximate the fluid through-opening **176**. The fourth plate **152** is substantially the same as the second plate **148**.

The capture surfaces **186**, **188**, **190**, and **192** are configured to capture one or more substances carried by a fluid proximate the capture surfaces. The substance may, for example, be a protozoan pathogen such as *Cryptosporidium parvum* or *Giardia lamblia*, a bacterial pathogen such as coliform, a virus, or a chemical contaminant. To capture such a substance, the capture surfaces **186**, **188**, **190**, and **192** may be coated with a plurality of capture molecules (which may also be referred to as "ligands") having respective binding affinities with the substance. Capture molecules having such binding affinities may be identified by one skilled in the art depending on the substance to be captured. In general, such capture molecules may include, for example, proteins such as antibodies, antibody fragments, lectins, or protein aptamers, or nucleic acids such as nucleic acid aptamers. For example, the antibodies may include one or more of IgG, IgA, IgE, or IgM forms, and the antibody fragments may include one or more of Fab', $F(ab')_2$, and Fab forms. The capture molecules coated on the capture surfaces may have binding affinities for only one substance, such as a particular pathogen for example, or the capture molecules coated on the capture surfaces may include different capture molecules having respective binding affinities for respective different substances. Such different capture molecules may be arranged in arrays on the capture surfaces so that capture molecules having binding affinities for particular substances are in known positions on the capture surfaces. Such arrays advantageously permit identification of a detected substance based on the type of capture molecules known to be in the location where the substance is detected. The capture surfaces **186**, **188**, **190**, and **192** may include one or more of silicon, glass (such as any type of silica or quartz, for example), plastic (such as polypropylene, poly(ethylene)terephthalate, polyethylene, poly(tetrafluroethylene), tetrafluroethylene, or polydimethylesiloxane, for example), metal (such as gold, for example), avidin, streptavidin, and protein A, or other hydrophobic

materials known in the art of protein binding chemistry, for example, to facilitate adhesion of the capture molecules. For example, antibody fragments having a free –SH group may bond with gold to form a self-assemble monolayer.

Referring back to Figure **2**, when the first separator **154** is positioned adjacent the first plate **146** and the second plate **148** is positioned adjacent the first separator **154**, the first and second plates **146** and **148** are separated by a first region shown generally at **194**. The first region **194** is surrounded by the first separator **154** and has a thickness equal to a thickness of the first separator **154**. The fluid through-openings **172**, **174**, and **176** are positioned on the second plate **148** so that when the first separator **154** is positioned adjacent the first plate **146** and the second plate **148** is positioned adjacent the first separator **154**, the fluid through-openings **160**, **162**, **172**, **174**, and **176** are in fluid communication with the first region **194** and staggered relative to the fluid through-openings **160** and **162**. When the first separator **154** is positioned adjacent the first plate **146** and the second plate **148** is positioned adjacent the first separator **154**, the second plate **148** is longitudinally spaced apart from the first plate **146**.

Fluid received in the first region **194** from the fluid through-opening **160** may be directed through one of the fluid through-openings **172** and **174**; such fluid passes over one of the capture surfaces **186** and **188** so that the capture surfaces can capture a substance carried by the fluid. Also, fluid received in the first region **194** from the fluid through-opening **162** may be directed through one of the fluid through-openings **174** and **176**; such fluid passes over one of the capture surfaces **190** and **192** so that the capture surfaces can capture a substance carried by the fluid.

Advantageously, when fluid passes from one of the fluid through-openings **160** and **162** to one of the fluid through-openings **172**, **174**, and **176**, such fluid passes over one of the capture surfaces **186**, **188**, **190**, and **192** within a predetermined distance of the capture surfaces, namely the thickness of the first region **194** as determined by the thickness of the first separator **154**. Portions of the surface of the first plate **146** that are opposite the capture

surfaces **186**, **188**, **190**, and **192** are thus fluid guiding surfaces that are spaced apart from the capture surfaces **186**, **188**, **190**, and **192** by that predetermined distance. The predetermined distance may be determined from properties such as electrophoresis mobility of the substance, flow rate of the fluid, and length of a flow path, for example. The fluid passes over the capture surfaces consistently at that predetermined distance, advantageously avoiding inefficiency from fluid passing over the capture surfaces at smaller or larger distances.

Still referring to Figure **2**, when the second separator **156** is positioned adjacent the second plate **148** and the third plate **150** is positioned adjacent the second separator **156**, the second and third plates **148** and **150** are separated by a second region shown generally at **196**. The second region **196** is surrounded by the second separator **156** and has a thickness equal to a thickness of the second separator **156**.

Referring to Figure **5**, the third plate **150** is substantially the same as the first plate **146**, and the third plate **150** defines elongate rectangular longitudinal fluid through-openings shown generally at **198** and **200** that are in substantially the same positions on the third plate **150** as the fluid through-openings **160** and **162** on the first plate **146**. The portions of the third plate **150** other than the through-openings may be referred to as a "wall". However, the third plate also has first and second capture surfaces **202** and **204** proximate the fluid through-opening **198**, and third and fourth capture surfaces **206** and **208** proximate the fluid through-opening **200**. The capture surfaces **202**, **204**, **206**, and **208** are coated with a plurality of capture molecules substantially as discussed above for the capture surfaces **186**, **188**, **190**, and **192**. When the second separator **156** is positioned adjacent the second plate **148** and the third plate **150** is positioned adjacent the second separator **156**, the third plate **150** is longitudinally spaced apart from the second plate **148**, and the capture surfaces **202**, **204**, **206**, and **208** are thus spaced apart from the capture surfaces **186**, **188**, **190**, and **192**.

Referring back to Figure **2**, when the second separator **156** is positioned adjacent the second plate **148** and the third plate **150** is positioned adjacent

the second separator **156**, the fluid through-openings **172**, **174**, and **176** of the second plate **148** and the fluid through-openings **198** and **200** of the third plate **150** are in fluid communication with the second region **196**. Further, fluid received in the second region **196** from the fluid through-opening **172** may be directed through the fluid through-opening **198**; such fluid passes over the capture surface **202**. Also, fluid received in the second region **196** from the fluid through-opening **174** may be directed through one of the fluid through-openings **198** and **200**; such fluid passes over one of the capture surfaces **204** and **206**. Also, fluid received in the second region **196** from the fluid through-opening **176** may be directed through the fluid through-opening **200**; such fluid passes over the capture surface **208**.

Advantageously, when fluid passes from one of the fluid through-openings **172**, **174**, and **176** to one of the fluid through-openings **198** and **200**, such fluid passes over one of the capture surfaces **202**, **204**, **206**, and **208** within a predetermined distance of the capture surfaces, namely the thickness of the second region **196** as determined by the thickness of the second separator **156**. Portions of the surface of the second plate **148** that are opposite the capture surfaces **202**, **204**, **206**, and **208** are thus fluid guiding surfaces that are spaced apart from the capture surfaces **202**, **204**, **206**, and **208** by that predetermined distance. Again, fluid passes over the capture surfaces consistently at a predetermined distance, advantageously avoiding inefficiency from fluid passing over the capture surfaces at smaller or larger distances.

Still referring to Figure **2**, when the third separator **158** is positioned adjacent the third plate **150** and the fourth plate **152** is positioned adjacent the third separator **158**, the third and fourth plates **150** and **152** are longitudinally spaced-apart and separated by a third region shown generally at **210**. The third region **210** is surrounded by the third separator **158** and has a thickness equal to a thickness of the third separator **158**. The fluid through-openings of the third and fourth plates **150** and **152** are in fluid communication with the third region **210**, and the capture surfaces and fluid through-openings of the

fourth plate **152** function substantially the same as the capture surfaces and fluid through-openings of the second plate **148** as described above.

Also, when the outlet coupling unit **136** is positioned adjacent the fourth plate **152**, the fluid through-openings of the fourth plate **152** are in fluid communication with the cavity **142**. Thus the coupling units **102** and **136**, the plates **146**, **148**, **150**, and **152**, and the separators **154**, **156**, and **158** form a fluid conduit between the inlet **106** and the outlet **140**. In the embodiment shown, the separators **154**, **156**, and **158** seal the regions **194**, **196**, and **210** respectively to prevent leakage from the fluid conduit, and the fasteners **120**, **122**, **124**, and **126** may be tightened to facilitate such sealing and form a body including the coupling units **102** and **136**, the plates **146**, **148**, **150**, and **152**, and the separators **154**, **156**, and **158**. Further, the fasteners **120**, **122**, **124**, and **126** may be removed from the apparatus to release the plates **146**, **148**, **150**, and **152** from the coupling units **102** and **136** and from the separators **154**, **156**, and **158**. The plates **146**, **148**, **150**, and **152** are thus removable from the apparatus **100**.

Referring back to Figure **2**, fluid that flows from the inlet **106** to the outlet **138** does not flow only parallel to the capture surfaces, but rather some fluid flow is incidental to the capture surfaces. The capture surfaces may thus be said to form a “packed bed”. Such incidental flow (which may also be referred to as “impact flow”) advantageously increases diffusion of the substance and thus capture efficiency of the capture surfaces.

The coupling units **102** and **136** and the plates **146**, **148**, **150**, and **152** are metallic in the embodiment shown, but in alternative embodiments may be glass or thermoplastic materials, for example. Also in the embodiment shown, the separators **154**, **156**, and **158** are thermoplastic gaskets, but in alternative embodiments may include other materials. In alternative embodiments, the apparatus **100** may be unitarily formed by etching a metallic or thermoplastic material, for example. In some embodiments, such as unitarily formed embodiments for example, the apparatus may be transparent to facilitate detection of captured substances from outside of the apparatus. Also, the plates **146**, **148**, **150**, and **152** include capture surfaces as discussed above,

but alternatively the plates **146**, **148**, **150**, and **152** may include capture surfaces in different areas or on other sides of the plates.

The embodiment shown includes four plates **146**, **148**, **150**, and **152** separated by three separators **154**, **156**, and **158**, although alternative embodiments may include more or fewer plates and spacers. Also, although the plates **146** and **150** are shown having two fluid through-openings each and the plates **148** and **152** are shown having three fluid through-openings each, alternative embodiments may include more or fewer fluid through-openings in the plates. Also, although the fluid through-openings **160**, **162**, **172**, **174**, **176**, **198**, and **200** are elongate and rectangular, fluid through-openings in alternate embodiments may have other shapes. Further, although four threaded fasteners **120**, **122**, **124**, and **126** are shown, alternative embodiments may include different fasteners or a different number of fasteners. Still further, the fasteners **120**, **122**, **124**, and **126** may be omitted and the coupling units **102** and **136**, the plates **146**, **148**, **150**, and **152**, and the separators **154**, **156**, and **158** may alternatively be held together by adhesives or clamps, for example. Also, the embodiment shown includes coupling units **102** and **136**, plates **146**, **148**, **150**, and **152**, and separators **154**, **156**, and **158** having generally square cross-sectional shapes. However, the apparatus **100** may alternatively include such components having rectangular, circular, or other shapes, for example.

Second Embodiment

Referring to Figure **6**, another illustrative apparatus for determining whether a substance is carried in a fluid is shown generally at **212** and includes a fluid conduit **214** defining a fluid inlet shown generally at **216** and a fluid outlet shown generally at **218**. The fluid conduit **214** has first and second laterally opposite walls **220** and **222** between the inlet **216** and the outlet **218**. The first wall **220** defines five circular openings shown generally at **224**, **226**, **228**, **230**, and **232**, and the second wall **222** defines five circular openings shown generally at **234**, **236**, **238**, **240**, and **242** laterally opposite to the circular openings **224**, **226**, **228**, **230**, and **232** respectively.

The apparatus **212** also includes five cylindrical elements **244**, **246**, **248**, **250**, and **252**. The cylindrical element **244** has gaskets **254** and **256** at opposite ends thereof, the cylindrical element **246** has gaskets **258** and **260** at opposite ends thereof, the cylindrical element **248** has gaskets **262** and **264** at opposite ends thereof, the cylindrical element **250** has gaskets **266** and **268** at opposite ends thereof, and the cylindrical element **252** has gaskets **270** and **272** at opposite ends thereof. The gaskets **254**, **256**, **258**, **260**, **262**, **264**, **266**, **268**, **270**, and **272** are sized and positioned to be sealingly and removably received in the circular openings **224**, **234**, **226**, **236**, **228**, **238**, **230**, **240**, **232**, and **242** respectively, as shown in Figure **7**. The cylindrical elements **244**, **246**, **248**, **250**, and **252** are thus removable from the fluid conduit **214**. Also, the fluid conduit **214** is thus a sealed fluid conduit between the inlet **216** and the outlet **218**, and the cylindrical elements **244**, **246**, **248**, **250**, and **252** extend parallel to each other between the first and second laterally opposite walls **220** and **222**.

Referring to Figures **6** and **8**, the cylindrical elements **244**, **246**, **248**, **250**, and **252** have outer surfaces **274**, **276**, **278**, **280**, and **282** respectively, and some or all of those outer surfaces are capture surfaces coated with capture molecules as described above. Referring to Figure **8**, the outer surfaces **274**, **276**, **278**, **280**, and **282** are spaced apart from each other and from inner surfaces of opposite side walls **284** and **286** that extend between the first and second laterally opposite walls **220** and **222**. Therefore, fluid passing through the fluid conduit **214** from the inlet **216** to the outlet **218** passes through one or more of a gap shown generally at **290** between the side wall **284** and the cylindrical element **244**, a gap shown generally at **292** between the cylindrical elements **244** and **246**, a gap shown generally at **294** between the cylindrical elements **246** and **248**, a gap shown generally at **296** between the cylindrical element **248** and the side wall **286**, a gap shown generally at **298** between the cylindrical elements **244** and **250**, a gap shown generally at **300** between the cylindrical elements **246** and **250**, a gap shown generally at **302** between the cylindrical elements **246** and **252**, and a gap shown generally at **304** between the cylindrical elements **248** and **252**.

The gaps **290**, **292**, **294**, **296**, **298**, **300**, **302**, and **304** have minimum widths as shown in Figure **8**. The dimensions of the circular openings **224**, **226**, **228**, **230**, **232**, **234**, **236**, **238**, **240**, and **242** (shown in Figure **6**), of the cylindrical elements **244**, **246**, **248**, **250**, and **252**, and of the gaskets **254**, **256**, **258**, **260**, **262**, **264**, **266**, **268**, **270**, and **272** (shown in Figure **6**) may be chosen so that those minimum widths have a predetermined width. The outer surfaces **274**, **276**, **278**, **280**, and **282** and the inner surfaces of the opposite side walls **284** and **286** thus guide fluid in the fluid conduit **214** to within that predetermined width of the capture surfaces on the outer surfaces **274**, **276**, **278**, **280**, and **282**. As discussed above, passing the fluid over the capture surfaces consistently within that predetermined width advantageously avoids inefficiency from fluid passing over the capture surfaces at smaller or larger distances.

Referring back to Figure **8**, fluid that flows from the inlet **216** to the outlet **218** does not flow only parallel to the capture surfaces, but rather some fluid flow is incidental to the capture surfaces, and the capture surfaces may thus be said to form a "packed bed". Again, such incidental flow advantageously increases diffusion of the substance and thus capture efficiency of the capture surfaces.

The fluid conduit **214** and the cylindrical elements **244**, **246**, **248**, **250**, and **252** are metallic in the embodiment shown, but in alternative embodiments may be glass or thermoplastic materials, for example. Also in the embodiment shown, the gaskets **254**, **256**, **258**, **260**, **262**, **264**, **266**, **268**, **270**, and **272** include thermoplastic material, but in alternative embodiments may include other materials. In alternative embodiments, the apparatus **212** may be unitarily formed by etching a metallic or thermoplastic material, for example. In some embodiments, such as unitarily formed embodiments for example, the apparatus may be transparent to facilitate detection of captured substances from outside of the apparatus.

The embodiment shown includes five cylindrical elements **244**, **246**, **248**, **250**, and **252**, although alternative embodiments may include more or fewer cylindrical elements. Further, the embodiment shown includes the fluid

conduit **214** having a generally square cross-sectional shape, but the fluid conduit **214** may alternatively have rectangular, circular, or other shapes, for example. Still further, the embodiment shown includes cylindrical elements **244**, **246**, **248**, **250**, and **252** having circular cross-sectional shapes, but the apparatus **212** may alternatively include such elements having rectangular, hexagonal, octagonal, circular, or other shapes, for example.

Third Embodiment

Referring to Figure **9**, another illustrative apparatus for determining whether a substance is carried in a fluid is shown generally at **306** and includes a fluid conduit **308** defining a fluid inlet shown generally at **310** and a fluid outlet shown generally at **312**. The fluid conduit **308** has first and second laterally opposite walls **314** and **316** between the inlet **310** and the outlet **312**. The first wall **314** defines three oblong openings shown generally at **318**, **320**, and **322** and extending along the first wall **314** in a direction parallel to a direction between the inlet **310** and the outlet **312**. The second wall **316** defines three oblong openings shown generally at **324**, **326**, and **328** laterally opposite to the oblong openings **318**, **320**, and **322** respectively.

The apparatus **306** also includes three oblong elements **330**, **332**, and **334**. The oblong element **330** has gaskets **336** and **338** at opposite ends thereof, the oblong element **332** has gaskets **340** and **342** at opposite ends thereof, and the oblong element **334** has gaskets **344** and **346** at opposite ends thereof. The gaskets **336**, **338**, **340**, **342**, **344**, and **346** are sized and positioned to be sealingly and removably received in the oblong openings **318**, **324**, **320**, **326**, **322**, and **328** respectively, as shown in Figure **10**. The oblong elements **330**, **332**, and **334** are thus removable from the fluid conduit **308**. Also, the fluid conduit **308** is thus a sealed fluid conduit between the inlet **310** and the outlet **312**, and the oblong elements **330**, **332**, and **334** extend parallel to each other between the first and second laterally opposite walls **314** and **316**.

Referring to Figure **11**, the oblong element **330** has opposed outer surfaces **348** and **350**, the oblong element **332** has opposed outer surfaces **352** and

354, and the oblong element **334** has opposed outer surfaces **356** and **358**. Some or all of those outer surfaces are capture surfaces coated with capture molecules as described above. The outer surfaces **348**, **350**, **352**, **354**, **356**, and **358** are spaced apart from each other and from inner surfaces of opposite side walls **360** and **362** that extend between the first and second laterally opposite walls **364** and **366**. Therefore, fluid passing through the fluid conduit **308** from the inlet **310** to the outlet **312** passes through one or more of a gap shown generally at **368** between the side wall **364** and the oblong element **330**, a gap shown generally at **370** between the oblong elements **330** and **332**, a gap shown generally at **372** between the oblong elements **332** and **334**, and a gap shown generally at **374** between the oblong element **334** and the side wall **366**.

The gaps **368**, **370**, **372**, and **374** have widths as shown in Figure **11**. The dimensions of the oblong openings **318**, **320**, **322**, **324**, **326**, and **328** (shown in Figure **9**), of the oblong elements **330**, **332**, and **334**, and of the gaskets **336**, **338**, **340**, **342**, **344**, and **346** (shown in Figure **9**) may be chosen so that those widths have a predetermined width. The outer surfaces **348**, **350**, **352**, **354**, **356**, and **358** and the inner surfaces of the opposite side walls **364** and **368** thus guide fluid in the fluid conduit **308** within that predetermined width of the capture surfaces on the outer surfaces **348**, **350**, **352**, **354**, **356**, and **358**. As discussed above, passing the fluid over the capture surfaces consistently within that predetermined width advantageously avoids inefficiency from fluid passing over the capture surfaces at smaller or larger distances.

Referring back to Figure **11**, fluid that flows from the inlet **310** to the outlet **312** does not flow only parallel to the capture surfaces, but rather some fluid flow is incidental to the capture surfaces, and the capture surfaces may thus be said to form a "packed bed". Again, such incidental flow advantageously increases diffusion of the substance and thus capture efficiency of the capture surfaces.

The fluid conduit **308** and the oblong elements **330**, **332**, and **334** are metallic in the embodiment shown, but in alternative embodiments may be glass or thermoplastic materials, for example. Also in the embodiment shown, the

gaskets **336**, **338**, **340**, **342**, **344**, and **346** include thermoplastic material, but in alternative embodiments may include other materials. In alternative embodiments, the apparatus **306** may be unitarily formed by etching a metallic or thermoplastic material, for example. In some embodiments, such as unitarily formed embodiments, the apparatus may be transparent to facilitate detection of captured substances from outside of the apparatus.

The embodiment shown includes three oblong elements **330**, **332**, and **334**, although alternative embodiments may include more or fewer oblong elements. Further, the embodiment shown includes the fluid conduit **308** having a generally square cross-sectional shape, but the fluid conduit **308** may alternatively have rectangular, circular, or other shapes, for example. Still further, the embodiment shown includes oblong elements **330**, **332**, and **334**, but the apparatus **306** may alternatively include such elements having other shapes cross-sectional shapes.

Fourth Embodiment

Referring to Figure **12**, another illustrative apparatus for determining whether a substance is carried in a fluid is shown generally at **376** and includes a fluid conduit **378** defining a fluid inlet shown generally at **380** and a fluid outlet shown generally at **382**. The fluid conduit **378** includes first, second, third, and fourth longitudinally spaced-apart annular walls **384**, **386**, **388**, and **390**. The first annular wall **384** surrounds the inlet **380**. The second and third annular walls **386** and **388** surround respective openings shown generally at **392** and **394**. The fourth annular wall **390** surrounds the outlet **382**. The inlet **380**, outlet **382**, and openings **392** and **394** are aligned along an axis of the fluid conduit **378**.

The fluid conduit **378** also includes a fifth annular wall **396** surrounding and the adjacent first, second, third, and fourth longitudinally spaced-apart annular walls **384**, **386**, **388**, and **390**. Thus the first, second, and fifth annular walls **384**, **386**, and **396** define a first cylindrical region shown generally at **398**, the second, third, and fifth annular walls **386**, **388**, and **396** define a second cylindrical region shown generally at **400**, and the third, fourth, and fifth

annular walls **388**, **390**, and **396** define a third cylindrical region shown generally at **402**. The first region **398** is in fluid communication with the inlet **380**. The first and second regions **398** and **400** are in fluid communication through the opening **392**. The second and third regions **400** and **402** are in fluid communication through the opening **394**. The third region **402** is in fluid communication with the outlet **382**.

The apparatus **376** also includes a first cylindrical element **404** removably positioned in the first region **398** and spaced apart from the first and second annular walls **384** and **386**. The first cylindrical element **404** has a center shown generally at **406** proximate the inlet **380** and opening **392**, and a peripheral region shown generally at **408** proximate the fifth annular wall **396**. The apparatus **376** also includes a second cylindrical element **410** removably positioned in the second region **400** and spaced apart from the second and third annular walls **386** and **388**. The second cylindrical element **410** has a center shown generally at **412** proximate the openings **392** and **394**, and a peripheral region shown generally at **414** proximate the fifth annular wall **396**. The apparatus **376** also includes a third cylindrical element **416** removably positioned in the third region **402** and spaced apart from the third and fourth annular walls **388** and **390**. The third cylindrical element **416** has a center shown generally at **418** proximate the opening **394** and outlet **382**, and a peripheral region shown generally at **420** proximate the fifth annular wall **396**.

Fluid received at the inlet **380** contacts a first circular surface **422** of the first cylindrical element **404** and flows generally radially outward along the first circular surface **422** from the center **406** to the peripheral region **408** of the first cylindrical element **404**. The fluid then passes to a second circular surface **424** opposite the first circular surface **422** and flows generally radially inward along the second circular surface **424** from the peripheral region **408** to the center **406** of the first cylindrical element **404**, and then through the opening **392**. Fluid flows in substantially the same manner around first and second opposite circular surfaces **426** and **428** of the second cylindrical element **410**, through the opening **394**, around first and second opposite

circular surfaces **430** and **432** of the third cylindrical element **416**, and out the outlet **382**.

Some or all of the circular surfaces **422**, **424**, **426**, **428**, **430**, and **432** are capture surfaces coated with capture molecules as described above. Therefore, when fluid passes from the inlet **380** to the outlet **382**, such fluid passes over the capture surfaces on the circular surfaces **422**, **424**, **426**, **428**, **430**, and **432**, and adjacent surfaces of the annular walls **384**, **386**, **388**, and **390** guide the fluid to within a predetermined distance of the capture surfaces. Again, passing fluid over such capture surfaces consistently at that predetermined distance advantageously avoids inefficiency from fluid passing over the capture surfaces at smaller or larger distances.

Fluid that flows from the inlet **380** to the outlet **382** does not flow only parallel to the capture surfaces, but rather some fluid flow is incidental to the capture surfaces, and the capture surfaces may thus be said to form a "packed bed". Again, such incidental flow advantageously increases diffusion of the substance and thus capture efficiency of the capture surfaces.

The fluid conduit **378** and the cylindrical elements **404**, **410**, and **416** are metallic in the embodiment shown, but in alternative embodiments may be glass or thermoplastic materials, for example. In some embodiments, such as unitarily formed embodiments, the apparatus may be transparent to facilitate detection of captured substances from outside of the apparatus. Also, the embodiment shown includes three cylindrical elements **404**, **410**, and **416**, although alternative embodiments may include more or fewer cylindrical elements. Further, in the embodiment shown, the fluid conduit **378** and the cylindrical elements **404**, **410**, and **416** are generally axially symmetric, but the fluid conduit **378** and the cylindrical elements **404**, **410**, and **416** may alternatively have rectangular or other cross-sectional shapes, for example.

Electric Field

In the embodiments described above, capture of the substance on the capture surfaces may be facilitated by applying an electric field around the capture surfaces. For example, referring to Figure **13**, an illustrative capture assembly

is shown generally at **434** and includes a first metallic plate **436** having a capture surface **438**. As discussed above, the capture surface **438** is coated with a plurality of capture molecules (not shown). The first metallic plate **436** is electrically grounded at **440**.

The capture assembly **434** also includes a second metallic plate **442** having a fluid guiding surface **444**. The fluid guiding surface **444** guides fluid in a region **446** between the capture surface **438** and the fluid guiding surface **444**, and the fluid guiding surface **444** is a predetermined distance from the capture surface **438** to guide the fluid within the predetermined distance from the capture surface **438**.

The second metallic plate **442** is electrically coupled to a voltage source **448**, which provides a negative voltage to the second metallic plate **442**. The fluid and other substances in the region **446** are generally dielectric, and therefore the first and second metallic plates **436** and **442** function as a capacitor to generate an electric field (shown as $\vec{E}$ in Figure **13**) in the region **446**. If substances in the fluid have an electrophoretic mobility μ_e, then for a relatively low Reynolds number, the electric field $\vec{E}$ imparts a velocity $\vec{v}$ to the substances given by $\vec{v} = \overrightarrow{\mu_e E}$. The electric field $\vec{E}$ thus facilitates capture of substances in the fluid on the capture surface **438**, and thus when compared to a capture assembly without the electric field $\vec{E}$, the electric field $\vec{E}$ may advantageously increase capture efficiency of the capture surface **438**. The electric field $\vec{E}$ may also advantageously permit a greater distance between the capture surface **438** and the fluid guiding surface **444** to enable a greater rate of fluid flow through the region **446**. Any or all of the capture surfaces and fluid guiding surfaces discussed above and illustrated in Figures **1** to **12** may advantageously be modified to include such an electric field as shown in Figure **13**.

Although the capture assembly **434** in the embodiment shown includes first and second metallic plates **436** and **442**, alternative embodiments may include other conductors or materials capable of generating an electric field. Also, although the voltage source **448** provides a negative voltage to the

second metallic plate **442**, voltage sources in other embodiments may include voltage sources for alternating current or other voltage sources, for example.

Numerical Models

Flow of a fluid through an apparatus, such one of the apparatuses described above, may be predicted with numerical models. One such numerical model is described by Sina Jomeh and Mina Hoorfar in *Numerical Modeling of Mass Transport in Microfluidic Biomolecule-Capturing Devices Equipped with Reactive Surfaces* published in *Chemical Engineering Journal* 165 (2010) at 668-677 and in *Numerical Investigation of the Effect of Geometric and Physiochemical Parameters on Biomolecule Capture Efficiency* published in *Proceedings of the ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and 8th International Conference on Nanochannels, Microchannels, and Minichannels*, both of which are incorporated herein by reference. In that model, two-dimensional incompressible Navier-Stokes equations and the continuity equation provide that

$$\nabla \cdot \mathbf{u} = 0$$

and

$$\rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u}$$

where **u** is velocity of the fluid, p is pressure, ρ is the density of the fluid, and μ is the dynamic viscosity of the fluid.

At a steady state of flow, the fluid enters an inlet of an apparatus carrying a substance at an initial concentration C_0. Where D is the diffusion coefficient of the substance, the transient two-dimensional mass transport equation provides that

$$\frac{\partial C}{\partial t} + \mathbf{u} \cdot \nabla C = D \nabla^2 C .$$

where C is the concentration of the substance.

The substance carried by the fluid reacts at detection boundaries of the apparatus with forward and backward reaction rates of k_{on} and k_{off} respectively. If the detection boundaries have an initial concentration C_{s0} of capture molecules, a concentration of C_s of the substance is captured at the detection boundaries, and the substance has a concentration C_{wall} at the detection boundaries, then

$$\frac{\partial C_s}{\partial t} = k_{on} C_{wall} (C_{s0} - C_s) - k_{off} C_s .$$

At an outlet of the apparatus, convective flux is specified as

$$\mathbf{n} \cdot (-D \nabla C) = 0$$

where $\mathbf{n}$ is a vector normal to the boundary. All other boundaries of the apparatus are assumed to be insulated or symmetric, meaning that

$$\mathbf{n} \cdot (-D \nabla C + C\mathbf{u}) = 0 .$$

The foregoing equations may be expressed in dimensionless forms as

$$\frac{\partial C^*}{\partial t^*} + \left(u^* \frac{\partial C^*}{\partial x^*} + y^* \frac{\partial C^*}{\partial y^*} \right) = \frac{1}{Pe^2} \frac{\partial^2 C^*}{\partial x^{*2}} + \frac{\partial^2 C^*}{\partial y^{*2}}$$

and

$$\frac{\partial C_s^*}{\partial t^*} = \varepsilon Da \left[C_{wall}^* (1 - C_s^*) - K_D C_s^* \right]$$

where $u^* \equiv \frac{u}{u_{avg}}$, $v^* \equiv \frac{v}{u_{avg}}$, $C^* \equiv \frac{C}{C_0}$, $C_s^* \equiv \frac{C_s}{C_{s0}}$.

Further, in the dimensionless equations above, $x^* \equiv \frac{x}{hPe}$ and $y^* \equiv \frac{y}{t}$ are dimensionless coordinates, $t^* \equiv \frac{Dt}{h^2}$ is dimensionless time, h is a characteristic length or flow path width, u_{avg} is average inlet velocity of the fluid, Pe is a Peclet number, Da is a Damkohler number, ε is the relative adsorption capacity, and K_D is the equilibrium dissociation constant.

In this model, effectiveness of an apparatus may be measured by capture efficiency defined as

$$CE \equiv 1 - C^*_{b,outlet}$$

where $C^*_{b,outlet}$ is the non-dimensional form of the bulk concentration at the outlet and is defined as

$$C^*_{b,outlet} \equiv \frac{1}{C_0 u_{avg} h} \int_0^h C_{outlet} u_{outlet} dy \, .$$

To illustrate some advantages of apparatuses such as those discussed above, the aforementioned model has been numerically applied to a first illustrative model apparatus shown generally at **450** in Figure **14**, a second illustrative model apparatus shown generally at **452** in Figure **15**, and a third illustrative model apparatus shown generally at **454** in Figure **16**. The dimensions shown in Figures **14**, **15**, and **16** are in meters.

The numerical model was applied with the following parameter values:

Parameter	Value
Forward reaction rate (k_{on})	105 m^3/(mol s)
Backward reaction rate (k_{off})	10^{-2} s^{-1}
Ligand concentration (C_{s0})	10^{-8} mol/m^2
Diffusion coefficient (D)	10^{-11} m^2/s
Inlet concentration (C_0)	10^{-6} mol/m^3
Average inlet velocity (u_{avg})	10^{-4} m/s
Peclet number (Pe)	100
Damkohler number (Da)	1000
Relative adsorption capacity (ε)	0.01
Equilibrium dissociation constant (K_D)	0.1

Referring to Figure **14**, the first model apparatus **450** includes an inlet shown generally at **456**, an outlet shown generally at **458**, a capture surface **460** extending between the inlet **456** and the outlet **458**, and another surface **462** opposite the capture surface **460**. In the first model apparatus **450**, fluid

simply passes between the surfaces **460** and **462** when flowing from the inlet **456** to the outlet **458**.

Referring to Figure **15**, the second model apparatus **452** includes an inlet shown generally at **464**, an outlet shown generally at **466**, and five capture surfaces **468**, **470**, **472**, **474**, and **476** as shown in Figure **15**. The second model apparatus **452** therefore includes capture surfaces similar to those discussed above in the apparatus **100** illustrated in Figures **1** and **2**.

Referring to Figure **16**, the third model apparatus **454** includes an inlet shown generally at **478**, an outlet shown generally at **480**, and ten capture surfaces **482**, **484**, **486**, **488**, **490**, **492**, **494**, **496**, **498**, and **500**, each extending over a respective 90° circular arc as shown in Figure **16**. The third model apparatus **454** therefore includes capture surfaces similar to those discussed above in the apparatus **212** illustrated in Figures **6**, **7**, and **8**.

In the model described above, a concentration of C_s of the substance is captured at detection boundaries. Therefore, predictions of C_s over the various detection surfaces of the second and third model apparatuses **452** and **454** may facilitate identifying locations where capture surfaces may be ideally positioned in the apparatuses **100** and **212** discussed above.

Referring to Figures **15** and Figure **17** to **21**: Figure **17** illustrates numerical predictions of C_{s1}, namely concentration of the substance over the capture surface **468**; Figure **18** illustrates numerical predictions of C_{s2}, namely concentration of the substance over the capture surface **470**; Figure **19** illustrates numerical predictions of C_{s3}, namely concentration of the substance over the capture surface **472**; Figure **20** illustrates numerical predictions of C_{s4}, namely concentration of the substance over the capture surface **474**; and Figure **21** illustrates numerical predictions of C_{s5}, namely concentration of the substance over the capture surface **476**.

Also, referring to Figures **16** and Figure **22** to **31**: Figure **22** illustrates numerical predictions of C_{s1}, namely concentration of the substance over the capture surface **482**; Figure **23** illustrates numerical predictions of C_{s2}, namely concentration of the substance over the capture surface **484**; Figure **24**

illustrates numerical predictions of C_{s3}, namely concentration of the substance over the capture surface **486**; Figure **25** illustrates numerical predictions of C_{s4}, namely concentration of the substance over the capture surface **488**; Figure **26** illustrates numerical predictions of C_{s5}, namely concentration of the substance over the capture surface **490**; Figure **27** illustrates numerical predictions of C_{s6}, namely concentration of the substance over the capture surface **492**; Figure **28** illustrates numerical predictions of C_{s7}, namely concentration of the substance over the capture surface **494**; Figure **29** illustrates numerical predictions of C_{s8}, namely concentration of the substance over the capture surface **496**; Figure **30** illustrates numerical predictions of C_{s9}, namely concentration of the substance over the capture surface **498**; and Figure **31** illustrates numerical predictions of C_{s10}, namely concentration of the substance over the capture surface **500**.

As indicated above, capture surfaces may be positioned on surfaces where numerical predictions of C_s are higher in order to improve efficiency of the capture surfaces per unit area of the capture surfaces.

Referring to Figure **32**, numerical predictions of capture efficiency (*CE*), at various Peclet numbers, are illustrated for the first model apparatus **450** (shown in Figure **14**) with diamond-shaped points, for the second model apparatus **452** (shown in Figure **15**) with square-shaped points, and for the third model apparatus **454** (shown in Figure **16**) with circle-shaped points. The numerical predictions illustrated in Figure **32** show that over the various Peclet numbers, the second and third model apparatuses **452** and **454** are predicted to have greater capture efficiency than the first model apparatus **450**. Accordingly, it is believed that the apparatuses discussed above provide for improved capture efficiency when compared to apparatuses such as the first model apparatus **450**.

The model described above may be used to test different parameters, such as average inlet velocity u_{avg} and characteristic length h, for example, to identify preferably such parameters for a particular fluid for or particular reaction rates of a substance to be captured. The model may also be used to test different

variations of the apparatus described above, such as variation in shape and number of surfaces, to identify preferable such variations.

Detection

Referring to Figure **33**, an illustrative capture assembly **502** includes a metallic plate **504** having a capture surface **506**. As discussed above, the capture surface **506** is coated with a plurality of capture molecules, which in the embodiment shown are antibodies shown generally at **508**. Alternative embodiments may include other capture molecules. In the embodiment shown, two pathogens **510** and **512** were carried by water past the capture surface **506** and bonded to respective antibodies **508**. Alternative embodiments may include other detected substances, such as other protozoans, bacteria, viruses, or chemical contaminants, for example.

To detect the pathogens **510** and **512**, the metallic plate **504** is subjected to a plurality of capture molecules including capture molecules **514** and **516**. Such capture molecules again having binding affinities with the substance. Again, such capture molecules may be identified by one skilled in the art depending on the substance to be captured. In general, such capture molecules may include, for example, proteins such as antibodies, antibody fragments, lectins, or protein aptamers, or nucleic acids such as nucleic acid aptamers. For example, the antibodies may include one or more of IgG, IgA, IgE, or IgM forms, and the antibody fragments may include one or more of Fab', $F(ab')_2$, and Fab forms. In the embodiment shown, the capture molecule **514** is bonded to the pathogen **510**, and the capture molecule **515** is bonded to the pathogen **512**.

The capture molecules **514** and **516** in the embodiment shown are bonded to respective microretroreflectors **518** and **520** before being subjected to the capture surface **506**. Referring to Figures **34** and **35**, the microretroreflector **518** includes a generally transparent cubic portion **522** having three mutually orthogonal reflectors **524**, **526**, and **528** on respective adjacent faces. Thus, referring to Figure **35**, a first incident light beam **530** reflects back from the reflectors **524** and **528** in a first reflected light beam **532** that is generally

parallel to the first incident light beam **530**. Further, a second incident light beam **534** nonparallel to the first incident light beam **530** also reflects back from the reflectors **524** and **528** in a second reflected light beam **536** that is generally parallel to the second incident light beam **534**. The microretroreflector **518** is thus an efficient reflector of light from various incident angles. More generally, microretroreflectors and some method of their manufacture are discussed in United States Patent Publication No. 2006/0088946 entitled OPTICAL MICROLABELS: SHAPES AND REFLECTORS and published April 27, 2006, which is incorporated herein by reference.

Referring back to Figure **33**, the capture molecules **514** and **516** advantageously indicate the presence of the pathogens **510** and **512** by being previously bound to the reflectors **518** and **520** respectively, and by binding to the pathogens **510** and **512**. Thus, a quantity of light reflected from a portion of the capture surface **506** after exposing the capture surface **506** to capture molecules such as the capture molecules **514** and **516** may be proportional to a concentration of the pathogens on that portion of the capture surface **506**.

Although the embodiment shown includes microretroreflectors **518** and **520**, in alternative embodiments, the capture molecules may include other reflectors, or fluorescent molecules, for example. Such microretroreflectors and fluorescent molecules may generally and collectively be referred to as "signalers".

Referring to Figure **36**, an illustrative detection apparatus is shown generally at **538** and includes a light source **540** directing a light beam **542** to a beam splitter **544**. A portion of the light beam **542** passes through the beam splitter **544** in a light beam **546** towards a portion of the capture surface **506** of the assembly **502** (illustrated in Figure **33**). The light beam **546** is reflected from that portion of the capture surface **506** in a reflected light beam **548** that is generally parallel to the light beam **546** and in an intensity proportional to the concentration of pathogens on that portion of the capture surface **506**. The reflected light beam **548** is received at the beam splitter **544**, and a portion of the reflected light beam **548** is reflected in a reflected light beam **550** to an

optical sensor, which in the embodiment shown is a digital camera **552**. Alternative embodiments may include other types of optical sensor. Accordingly, the intensity of light received at the digital camera may be proportional to the concentration of pathogens on the portion of the capture surface **506** reflecting light from the beam splitter **544**. Capture surfaces, such as those discussed above, may be moved relative to the light beam **546** so that over a time series of measurements, the digital camera **552** may record intensities of light indicating a number of pathogens on the capture surfaces.

By measuring a number of pathogens on the capture surfaces as described above, a concentration of pathogens may be determined in relatively less time than when compared to filtration or other methods for detecting such pathogens. For example, the process described above may require less than an hour to determine whether a particular substance or substances are carried in a sample of a fluid such as water.

While specific embodiments have been described and illustrated, such embodiments should be considered illustrative only and not as limiting the invention as construed in accordance with the accompanying claims.

What is claimed is:

1. An apparatus for determining whether a substance is carried in a fluid, the apparatus comprising:

a body having:

a plurality of spaced-apart capture surfaces configured to contact the fluid and capture the substance from the fluid; and

a plurality of fluid guiding surfaces spaced apart by a predetermined distance from respective at least portions of respective ones of the plurality of capture surfaces.

2. The method of claim **1** wherein the body defines a fluid conduit surrounding the plurality of capture surfaces to direct flow of the fluid.

3. The apparatus of claim **1** or **2** wherein the capture surfaces are coated with a plurality of capture molecules having respective binding affinities with the substance.

4. The apparatus of claim **3** wherein the capture molecules comprise proteins.

5. The apparatus of claim **4** wherein the proteins comprise antibodies.

6. The apparatus of claim **4** wherein the proteins comprise antibody fragments.

7. The apparatus of claim **4** wherein the proteins comprise lectins.

8. The apparatus of claim **4** wherein the proteins comprise protein aptamers.

9. The apparatus of claim **3** wherein the capture molecules comprise nucleic acids.

10. The apparatus of claim **9** wherein the nucleic acids comprise nucleic acid aptamers.

11. The apparatus of any one of claims **1** to **10** wherein the body comprises at least one element having the capture surfaces.

12. The apparatus of claim **11** wherein the at least one element is removable.

13. The apparatus of claim **11** or **12** wherein the at least one element comprises a plurality of cylindrical elements.

14. The apparatus of claim **13** wherein the plurality of fluid guiding surfaces comprises, for each one of the plurality of capture surfaces, at least a portion of a surface of an adjacent one of the plurality of cylindrical elements.

15. The apparatus of claim **13** or **14** wherein the cylindrical elements extend generally parallel to each other.

16. The apparatus of claim **11** or **12** wherein the at least one element comprises a plurality of longitudinally spaced-apart plates each having at least one of the plurality of capture surfaces.

17. The apparatus of claim **16** wherein each one of the plurality of plates defines at least one longitudinal fluid through-opening longitudinally aligned with the at least one wall of each adjacent one of the plurality of plates.

18. The apparatus of claim **17** wherein the plurality of fluid guiding surfaces comprises, for each one of the plurality of capture surfaces, at least a portion of a surface of the at least one wall of an adjacent one of the plurality of plates.

19. The apparatus of claim **17** or **18** further comprising at least one spacer separating adjacent ones of the plurality of plates.

20. The apparatus of claim **19** wherein the at least one spacer surrounds a respective region between adjacent ones of the plurality of plates and in fluid communication with the at least one fluid through-opening of the adjacent ones of the plurality of plates.

21. The apparatus of claim **20** wherein each spacer has a thickness equal to the predetermined distance.

22. The apparatus of claim **20** or **21** wherein the at least one spacer seals the respective region.

23. The apparatus of claim **16** further comprising a plurality of longitudinally spaced walls longitudinally spaced from opposite sides of each one of the plurality of plates and defining a respective region surrounding each one of the plurality of plates, wherein:

the body defines at least one opening for communicating fluid between adjacent ones of the regions; and

the plurality of fluid guiding surfaces comprises, for each one of the plurality of capture surfaces, at least a portion of a surface an adjacent one of the plurality of walls.

24. The apparatus of claim **23** wherein:

each one of the plurality of plates has first and second opposite and generally circular sides each having a center and a peripheral region;

the at least one opening is configured to communicate fluid between the centers of adjacent sides of adjacent ones of the plurality of plates; and

for each one of the plurality of plates, the respective region surrounding the plate is configured to direct fluid received at the center of the first side of the plate to the peripheral region of the first side of the plate, then to the peripheral region of the second side of the plate, and then to the center of the second side of the plate.

25. The apparatus of any one of claims **16** to **24** wherein the plates extend generally parallel to each other.

26. The apparatus of any one of claims **1** to **25** wherein the plurality of capture surfaces and the plurality of fluid guiding surfaces are configured to generate electric fields between each one of the plurality of capture surfaces and each respective one of the plurality of fluid guiding surfaces.

27. The apparatus of claim **26** wherein each one of the plurality of spaced-apart capture surfaces is electrically grounded, and wherein each one of the plurality of fluid guiding surfaces is electrically connected to a voltage source.

28. The apparatus of any one of claims **1** to **27** wherein at least one of the plurality of capture surfaces is oriented in the apparatus to be contacted by the fluid in an incidental flow.

29. An apparatus for determining whether a substance is carried in a fluid, the apparatus comprising:

a fluid conduit to direct flow of the fluid; and

at least one element removably positioned in the fluid conduit and having at least one capture surface configured to contact the fluid and capture the substance from the fluid.

30. The apparatus of claim **29** wherein the at least one capture surface is coated with a plurality of capture molecules having respective binding affinities with the substance.

31. The apparatus of claim **30** wherein the capture molecules comprise proteins.

32. The apparatus of claim **31** wherein the proteins comprise antibodies.

33. The apparatus of claim **31** wherein the proteins comprise antibody fragments.

34. The apparatus of claim **31** wherein the proteins comprise lectins.

35. The apparatus of claim **31** wherein the proteins comprise protein aptamers.

36. The apparatus of claim **30** wherein the capture molecules comprise nucleic acids.

37. The apparatus of claim **36** wherein the nucleic acids comprise nucleic acid aptamers.

38. The apparatus of any one of claims **29** to **37** further comprising a plurality of fluid guiding surfaces spaced apart by a predetermined distance from respective at least portions of respective ones of the plurality of capture surfaces.

39. The apparatus of claim **38** wherein the at least one element comprises a plurality of cylindrical elements.

40. The apparatus of claim **39** wherein the plurality of fluid guiding surfaces comprises, for each one of the plurality of capture surfaces, at least a portion of a surface of an adjacent one of the plurality of cylindrical elements.

41. The apparatus of claim **39** or **40** wherein the cylindrical elements extend generally parallel to each other.

42. The apparatus of claim **38** wherein the at least one element comprises a plurality of longitudinally spaced-apart plates each having at least one of the plurality of capture surfaces.

43. The apparatus of claim **42** wherein each one of the plurality of plates has at least one wall and defines at least one longitudinal fluid through-opening longitudinally aligned with the at least one wall of each adjacent one of the plurality of plates.

44. The apparatus of claim **43** wherein the plurality of fluid guiding surfaces comprises, for each one of the plurality of capture surfaces, at least a portion of a surface of the at least one wall of an adjacent one of the plurality of plates.

45. The apparatus of claim **43** or **44** further comprising at least one spacer separating adjacent ones of the plurality of plates.

46. The apparatus of claim **45** wherein the at least one spacer surrounds a respective region between adjacent ones of the plurality of plates and in fluid communication with the at least one fluid through-opening of the adjacent ones of the plurality of plates.

47. The apparatus of claim **46** wherein each spacer has a thickness equal to the predetermined distance.

48. The apparatus of claim **46** or **47** wherein the at least one spacer seals the respective region.

49. The apparatus of claim **42** further comprising a plurality of longitudinally spaced walls longitudinally spaced from opposite sides of each one of the plurality of plates and defining a respective region surrounding each one of the plurality of plates, wherein:

the apparatus defines at least one opening for communicating fluid between adjacent ones of the regions; and

the plurality of fluid guiding surfaces comprises, for each one of the plurality of capture surfaces, at least a portion of a surface an adjacent one of the plurality of walls.

50. The apparatus of claim **49** wherein:

each one of the plurality of plates has first and second opposite and generally circular sides each having a center and a peripheral region;

the at least one opening is configured to communicate fluid between the centers of adjacent sides of adjacent ones of the plurality of plates; and

for each one of the plurality of plates, the respective region surrounding the plate is configured to direct fluid received at the

center of the first side of the plate to the peripheral region of the first side of the plate, then to the peripheral region of the second side of the plate, and then to the center of the second side of the plate.

51. The apparatus of any one of claims **38** to **50** wherein the plurality of capture surfaces and the plurality of fluid guiding surfaces are configured to generate electric fields between each one of the plurality of capture surfaces and each respective one of the plurality of fluid guiding surfaces.

52. The apparatus of claim **51** wherein each one of the plurality of spaced-apart capture surfaces is electrically grounded, and wherein each one of the plurality of fluid guiding surfaces is electrically connected to a voltage source.

53. The apparatus of any one of claims **29** to **52** wherein at least one of the plurality of capture surfaces is oriented in the apparatus to be contacted by the fluid in an incidental flow.

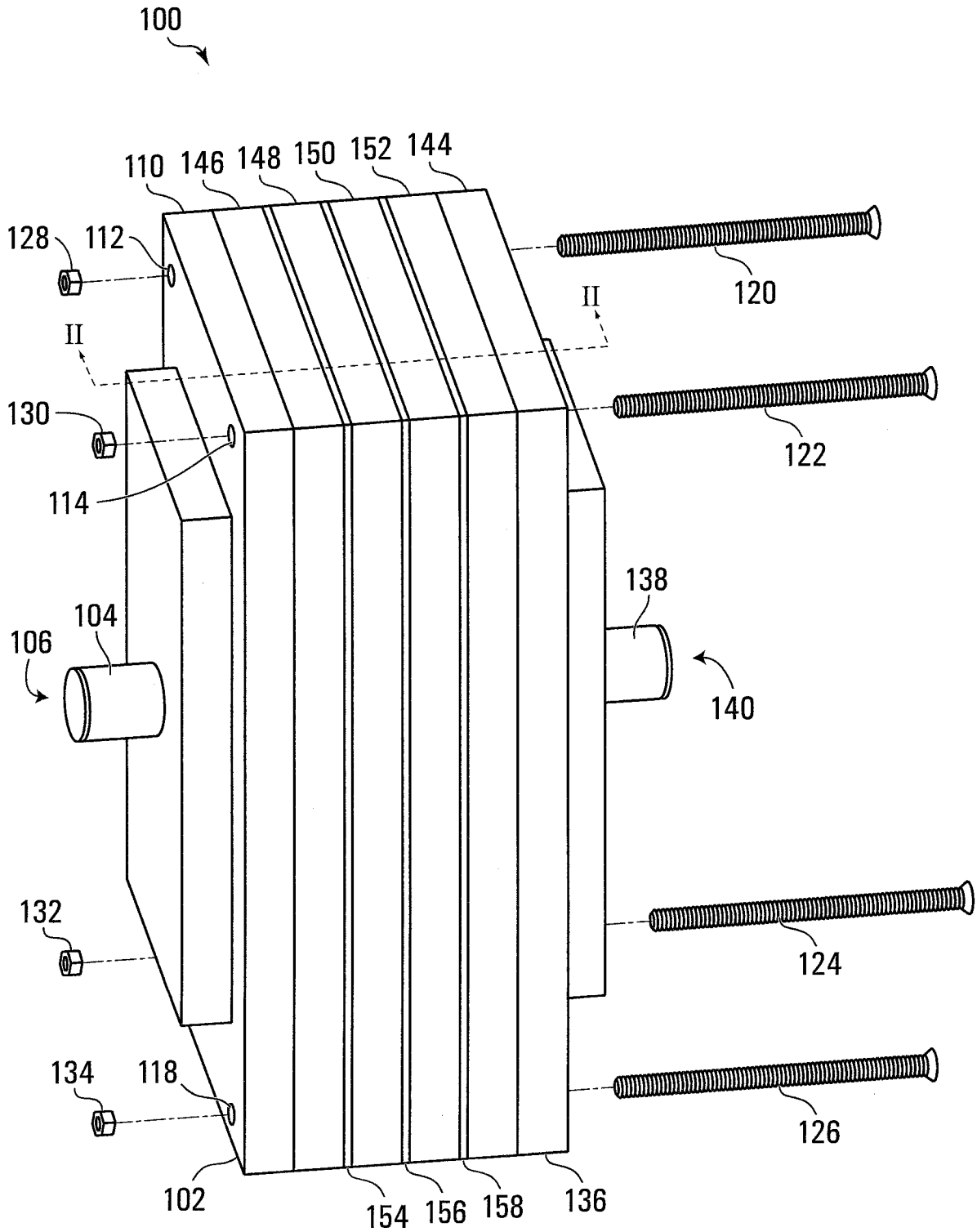
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FIG. 1

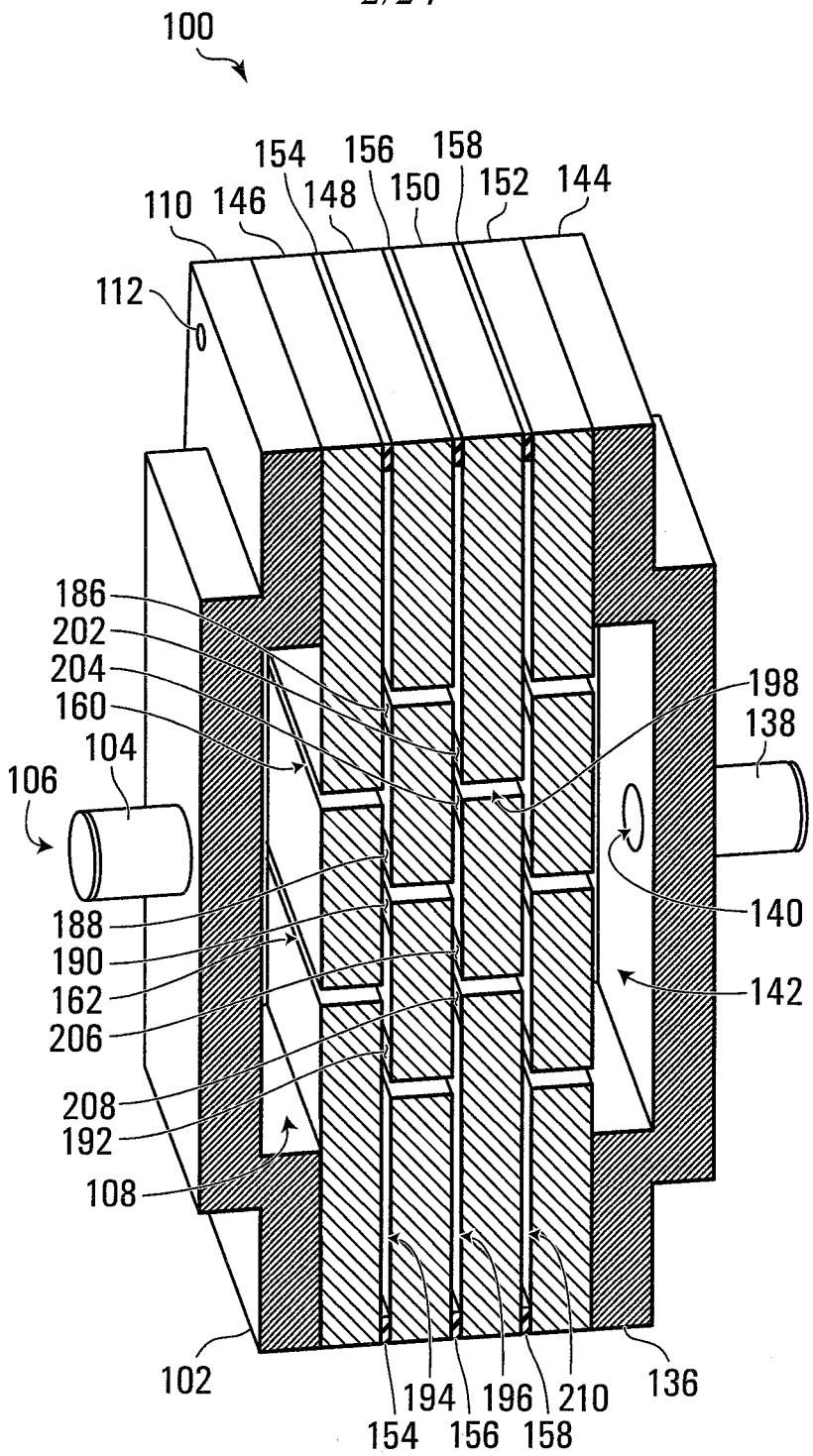
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FIG. 2

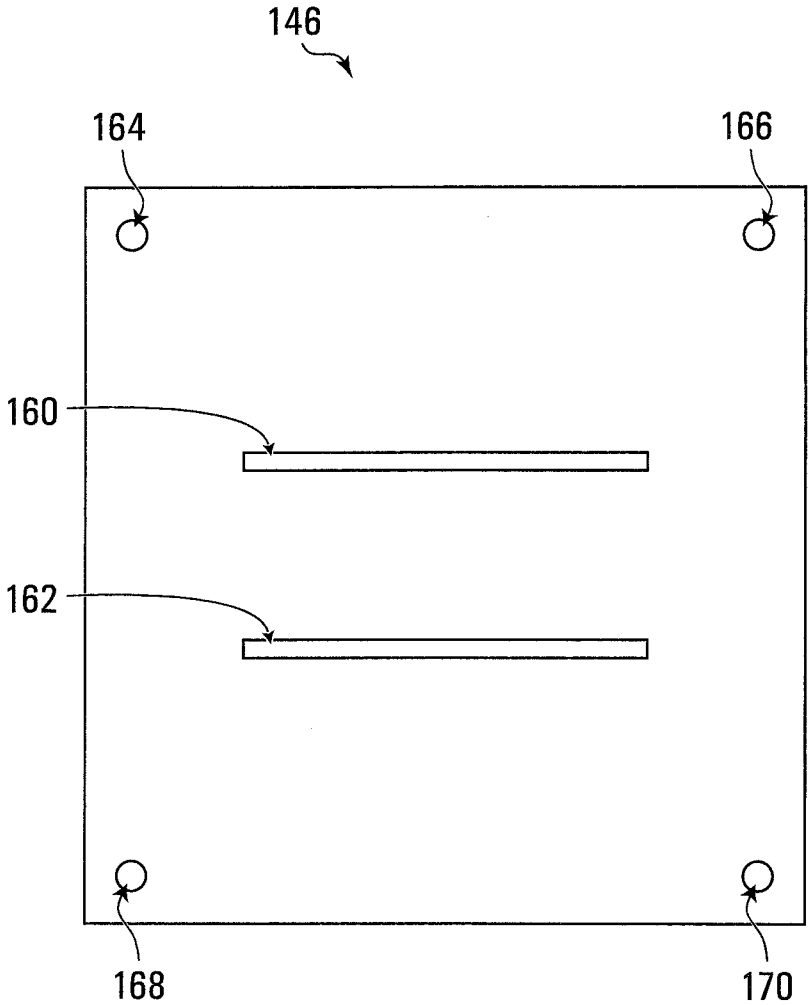

FIG. 3

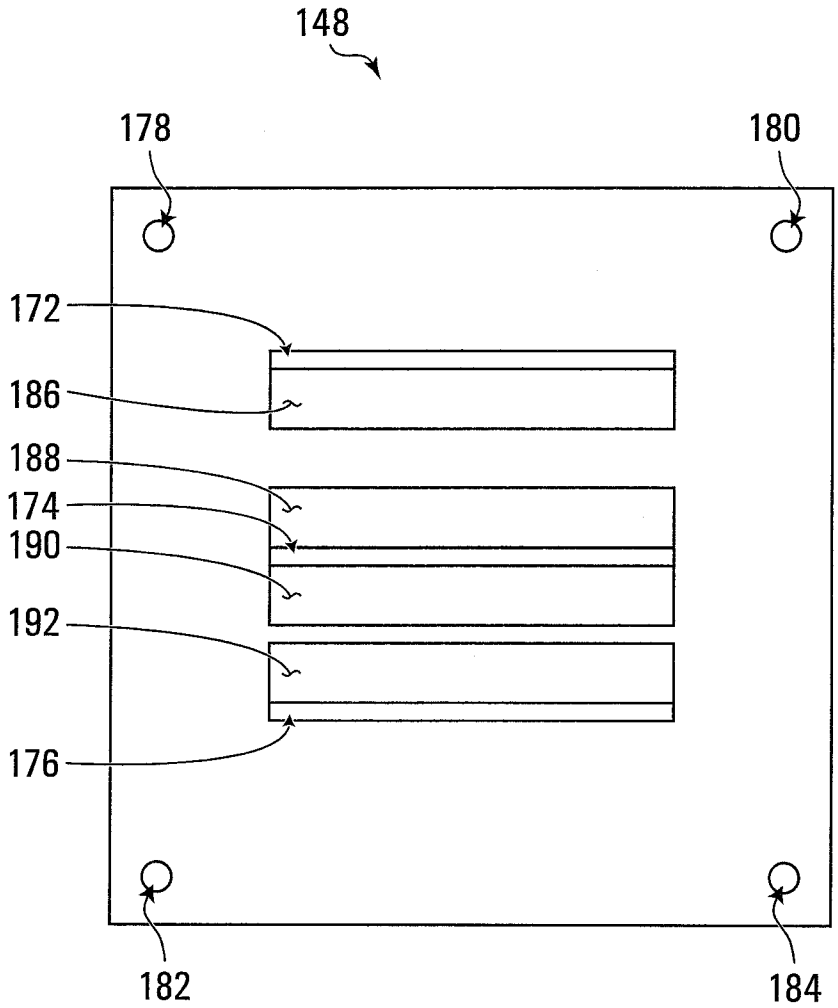

FIG. 4

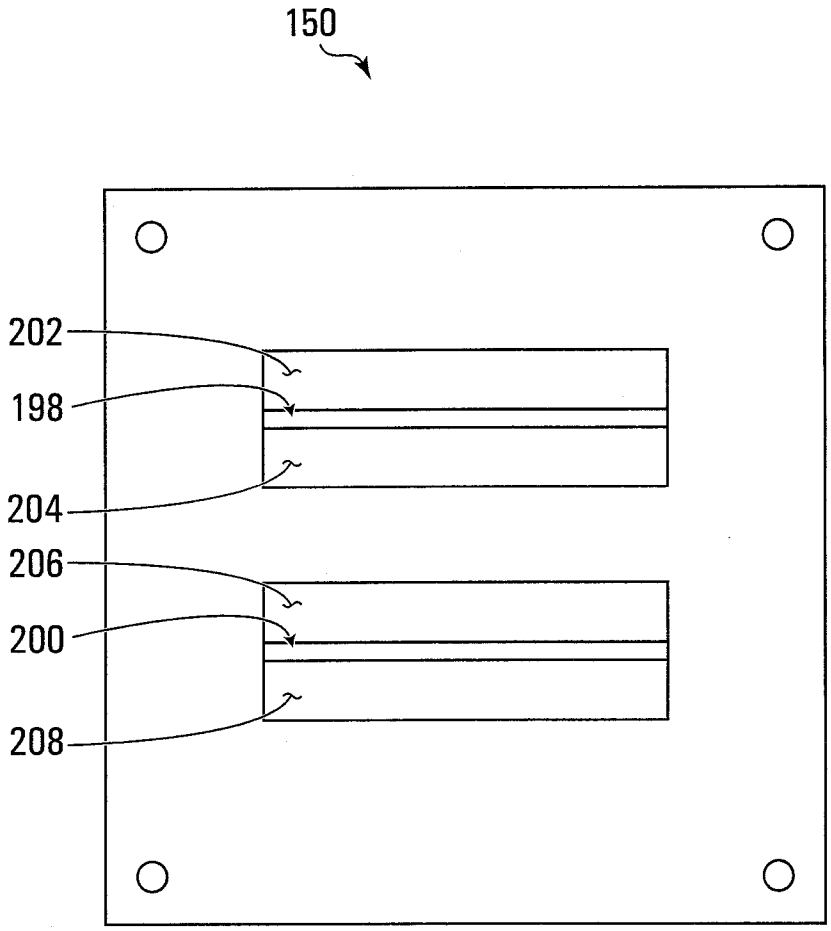

FIG. 5

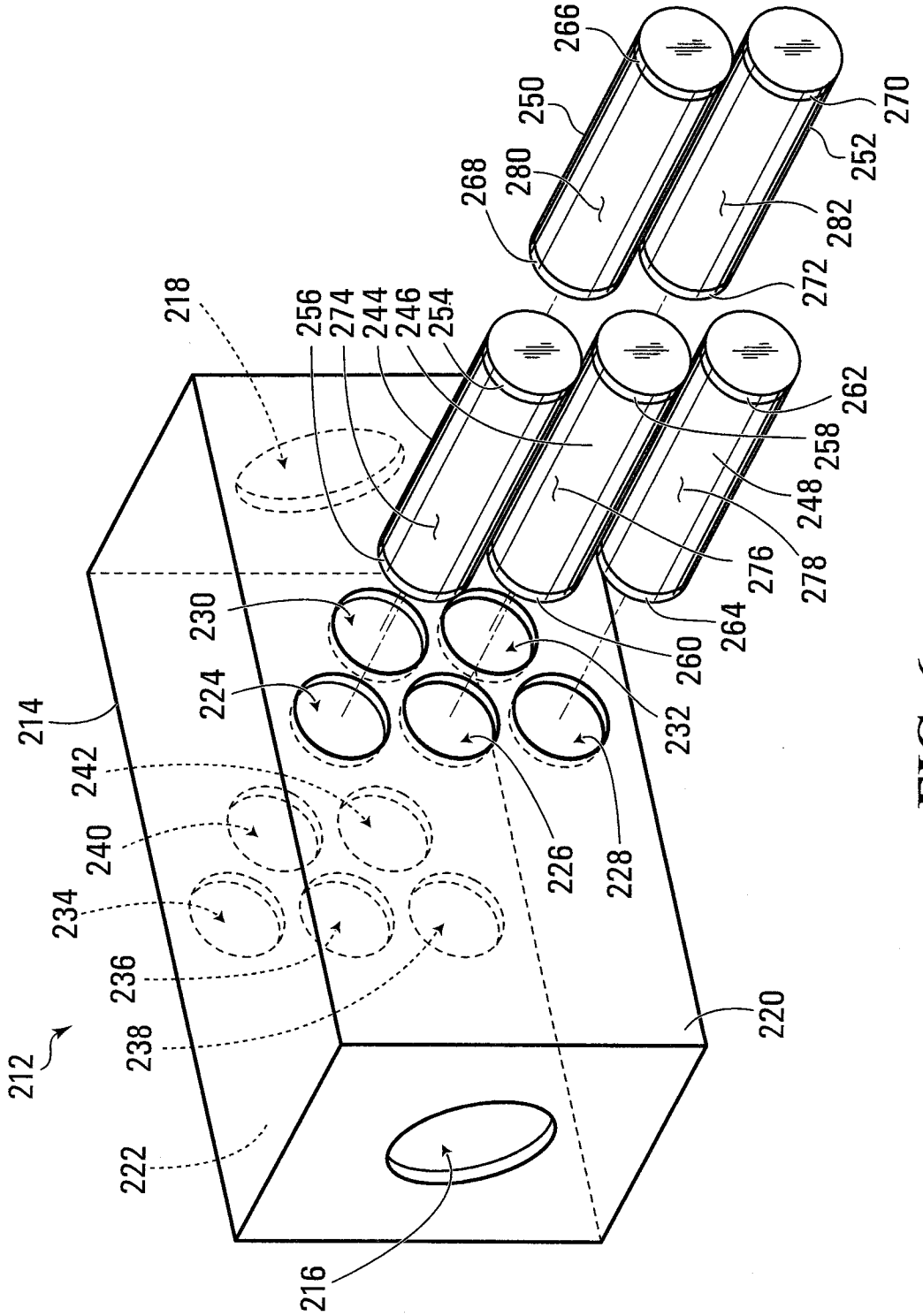
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FIG. 6

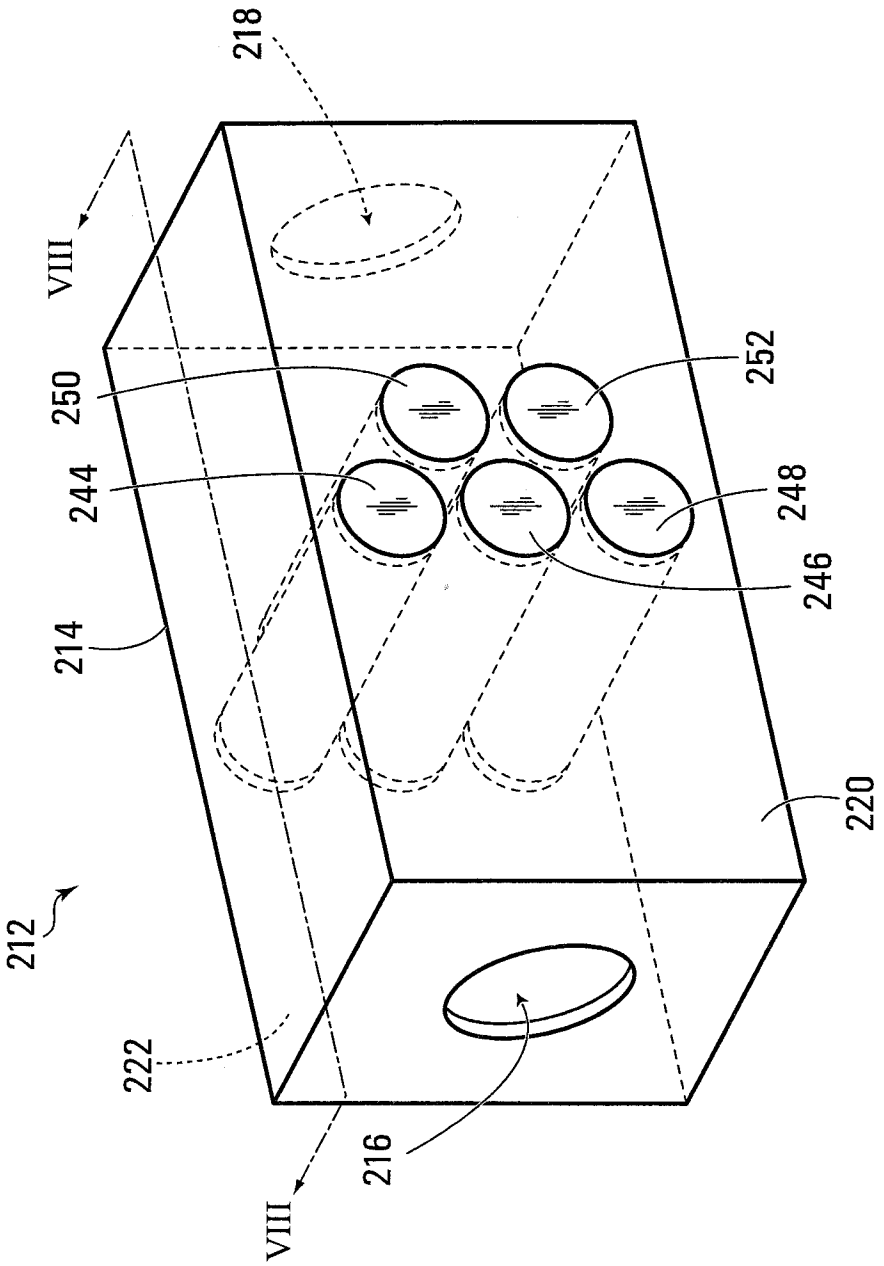

FIG. 7

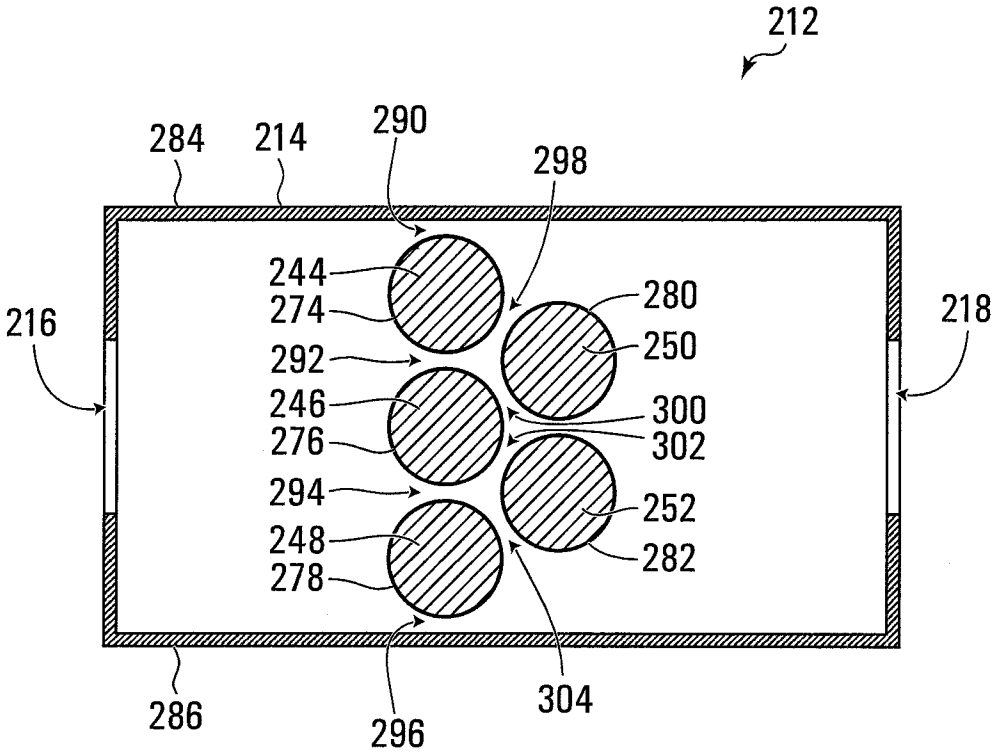
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FIG. 8

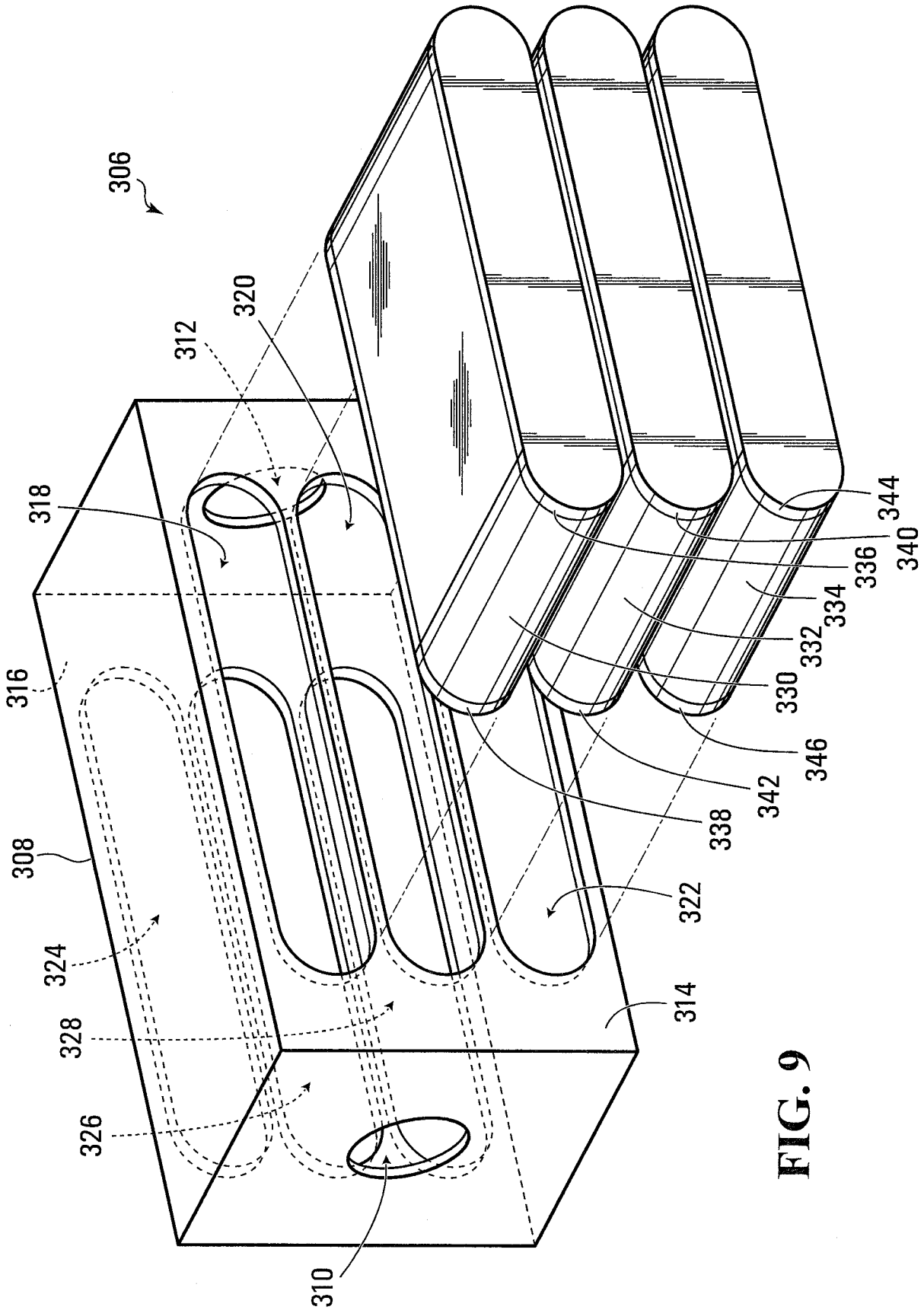
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FIG. 9

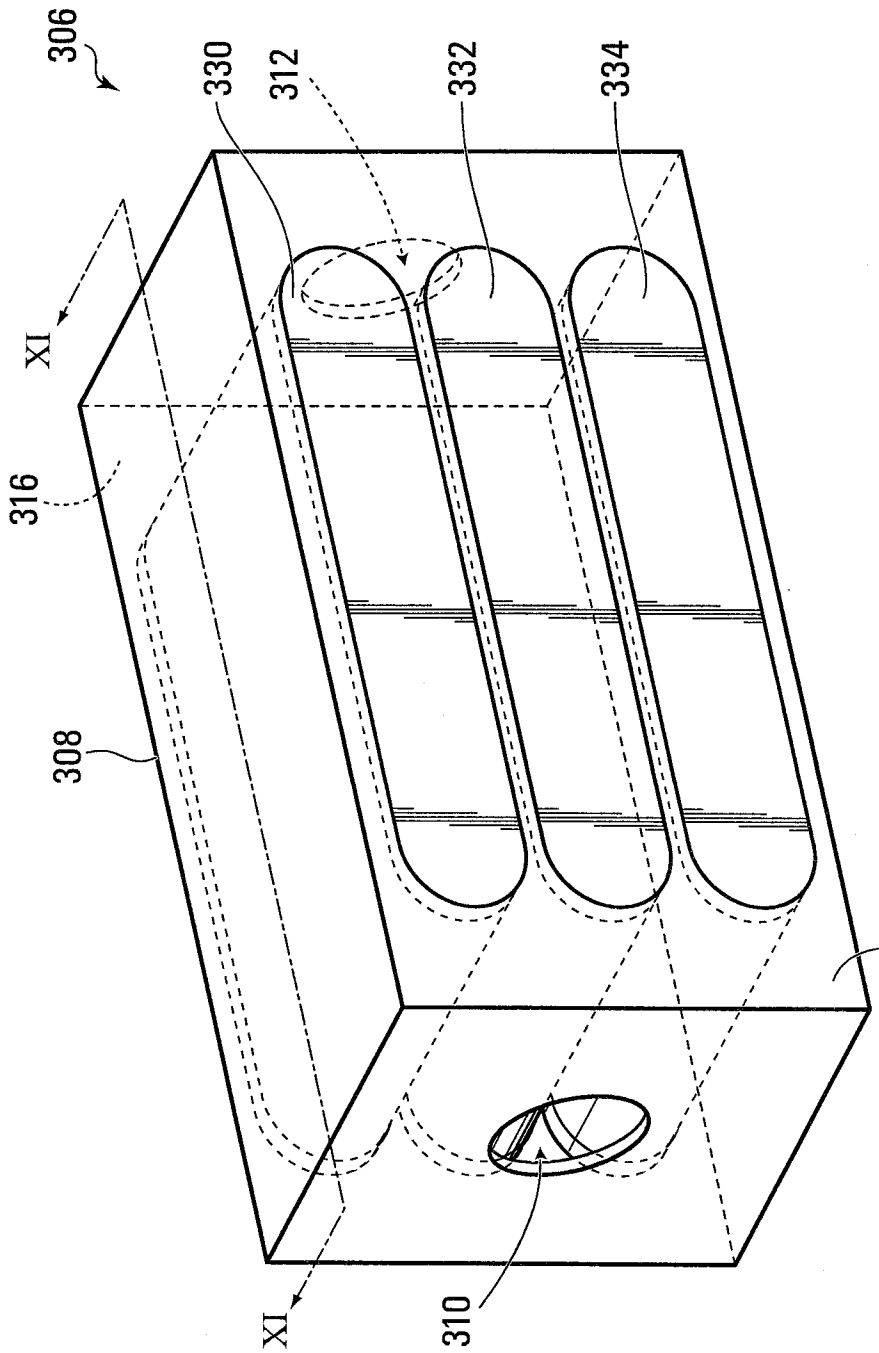

FIG. 10

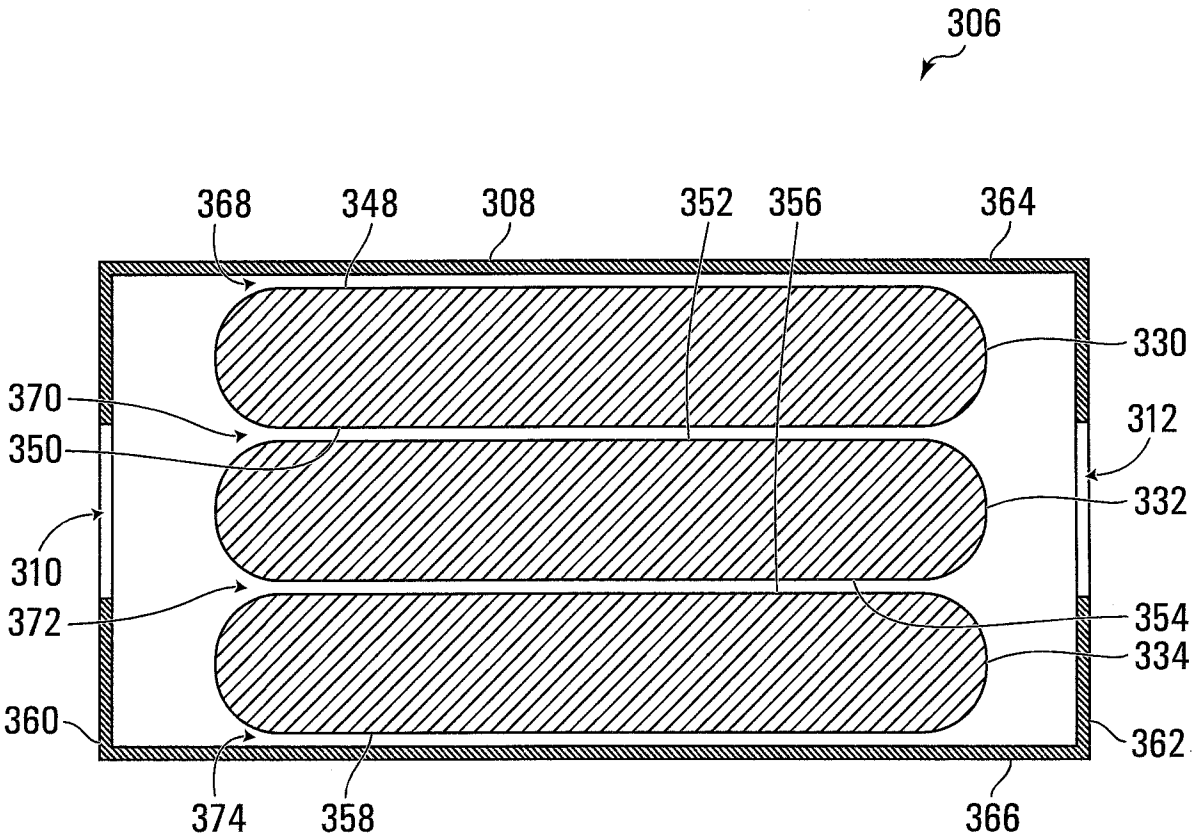
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FIG. 11

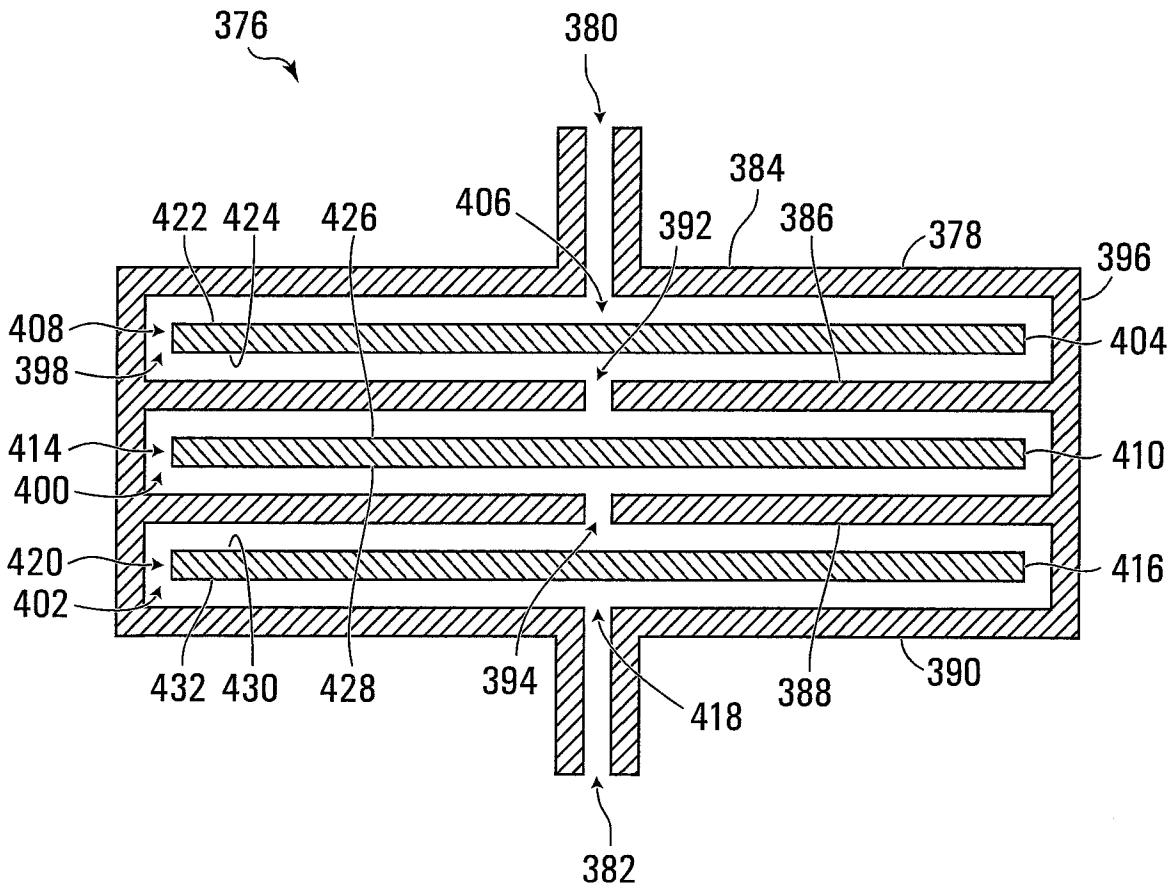
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FIG. 12

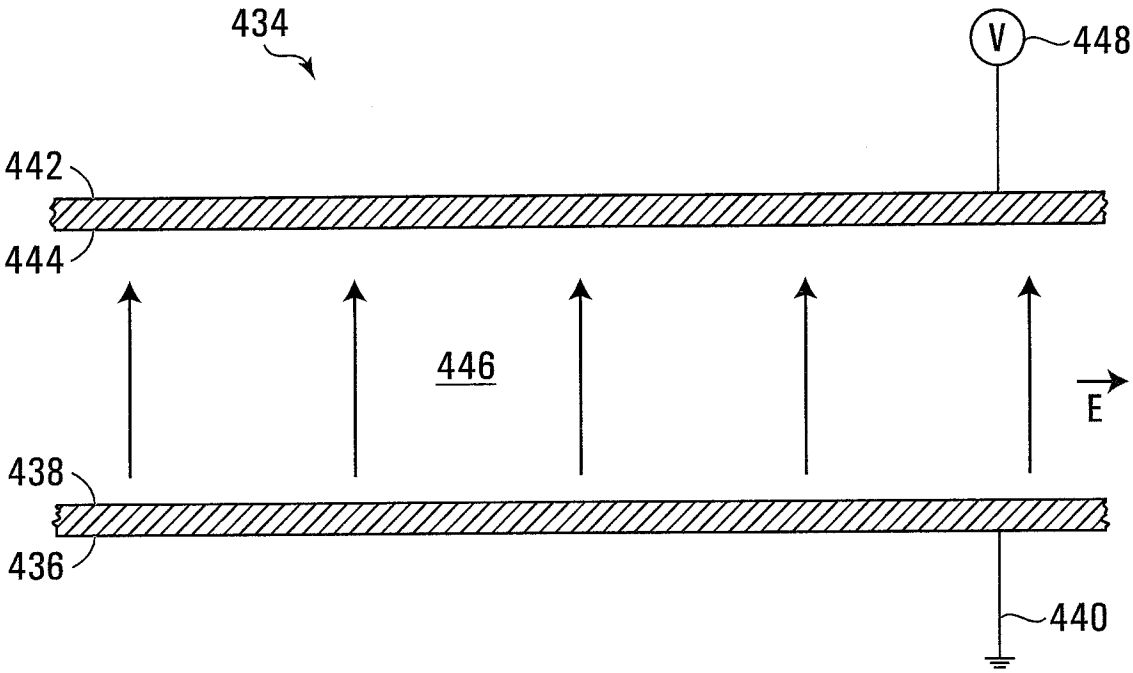
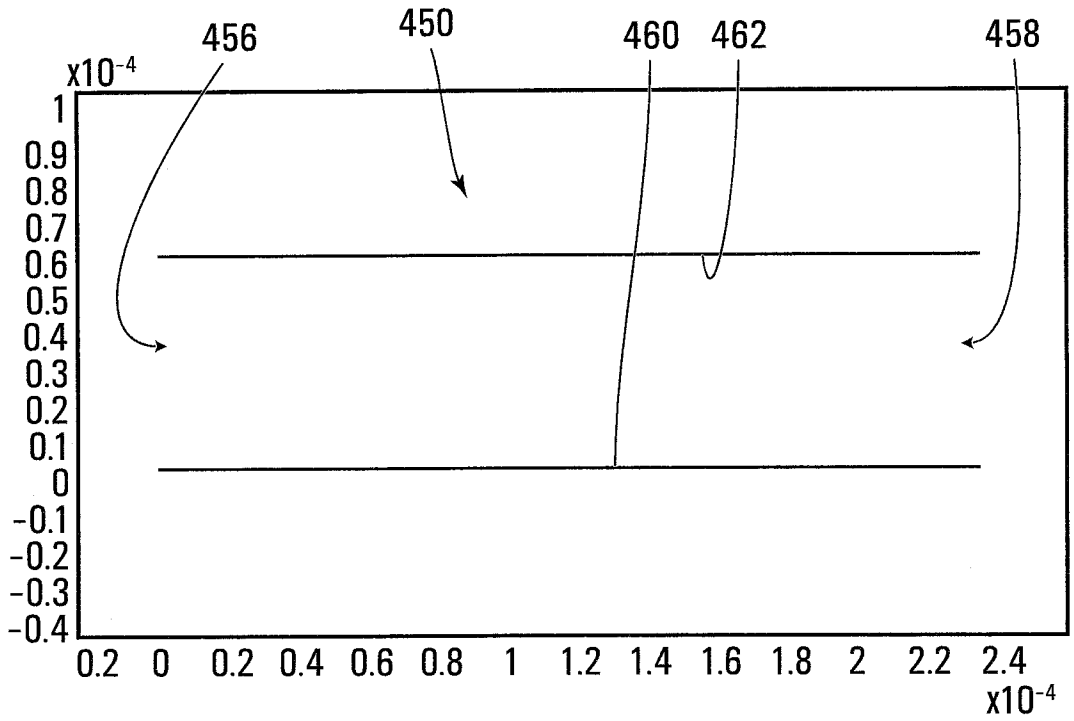


FIG. 13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460
462
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x10-4
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0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0.2
0
0.2
0.4
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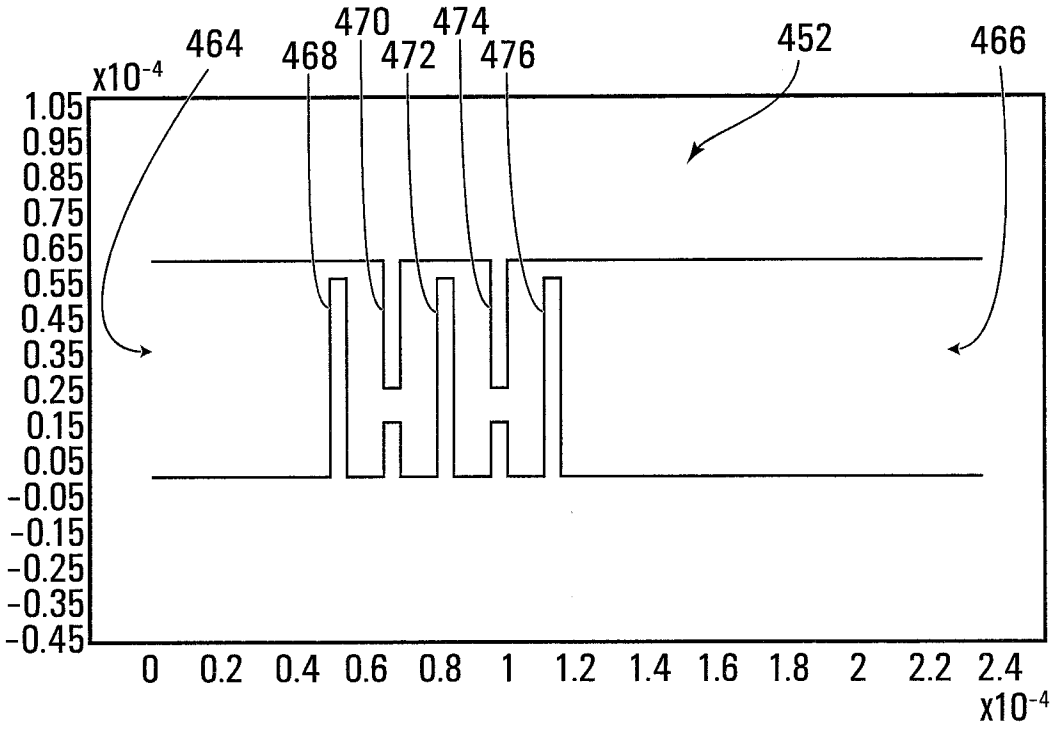
1.6
1.8
2
2.2
2.4
x10-4

FIG. 14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0.95
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0.75
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0.45
0.35
0.25
0.15
0.05
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0
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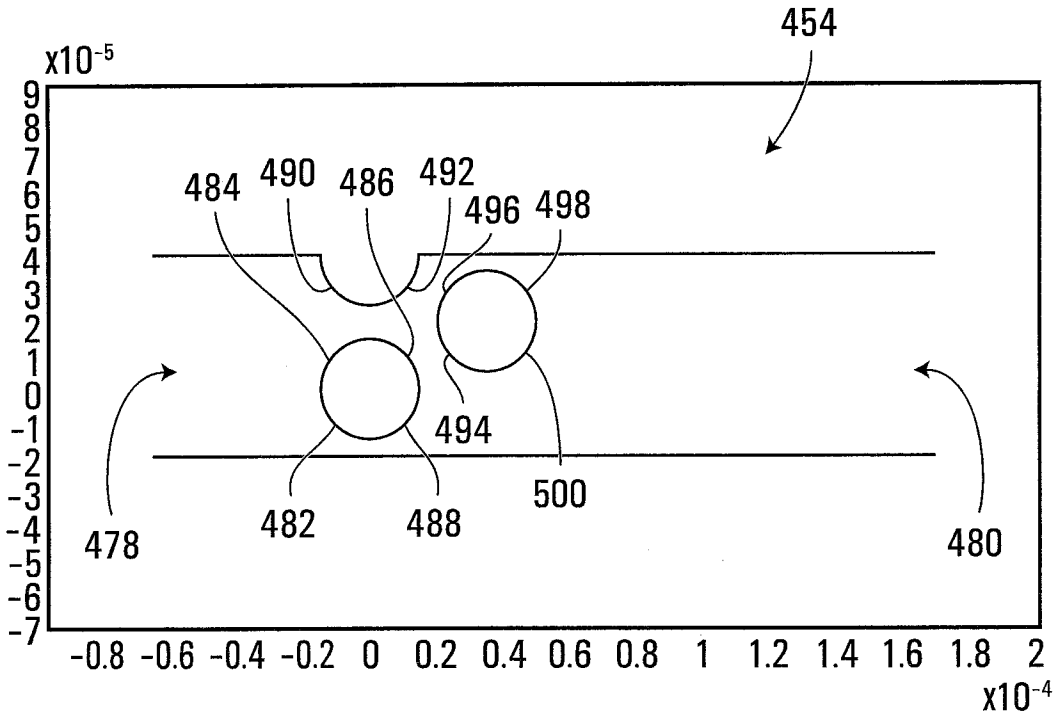
x10-4

FIG. 15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-7
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498
494
500
482
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x10-4

FIG. 16

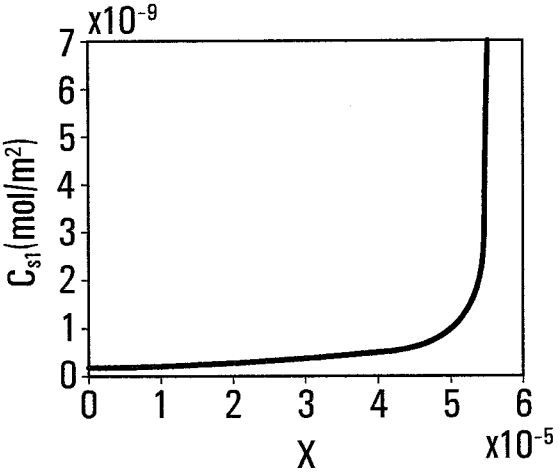

FIG. 17

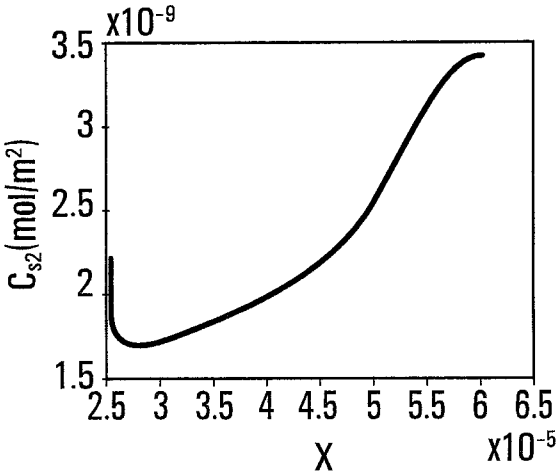

FIG. 18

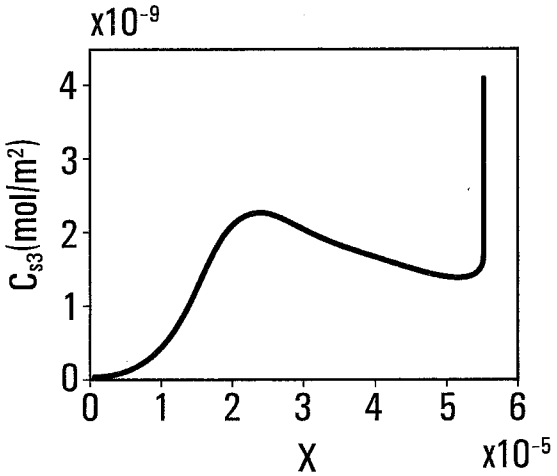

FIG. 19

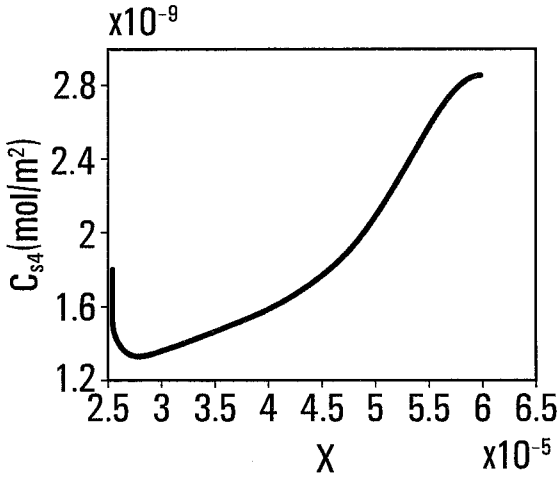

FIG. 20

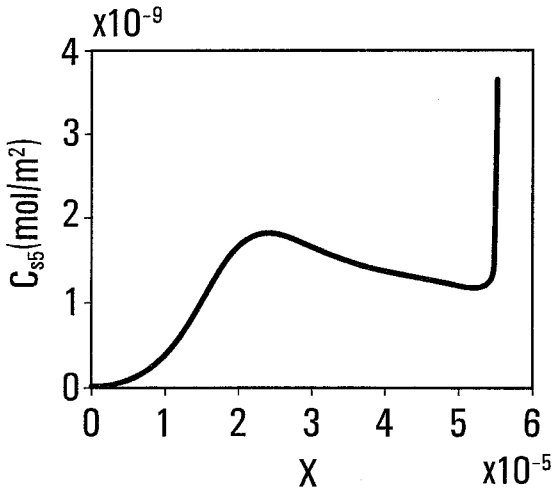

FIG. 21

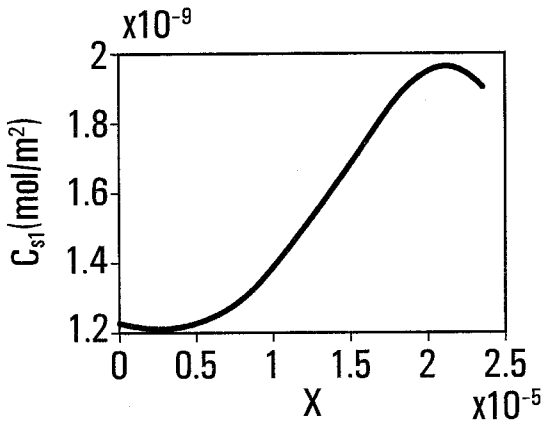

FIG. 22

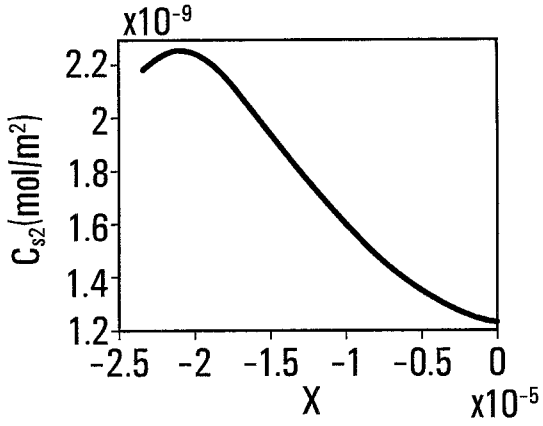

FIG. 23

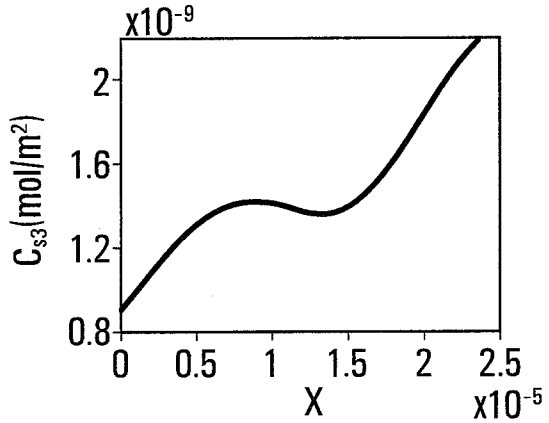

FIG. 24

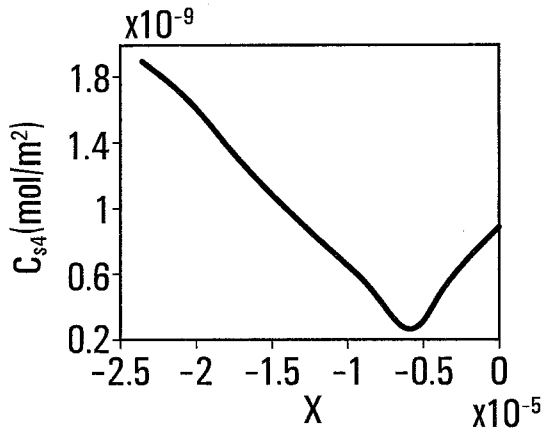

FIG. 25

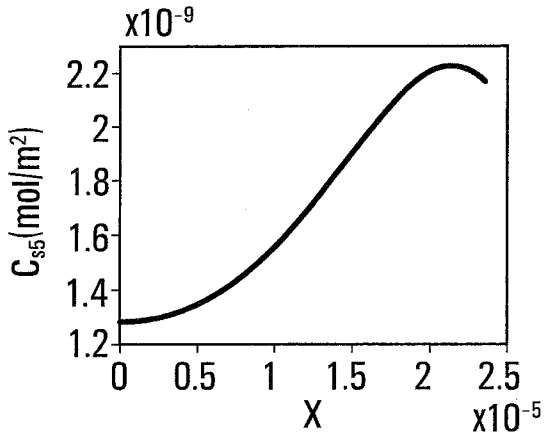

FIG. 26

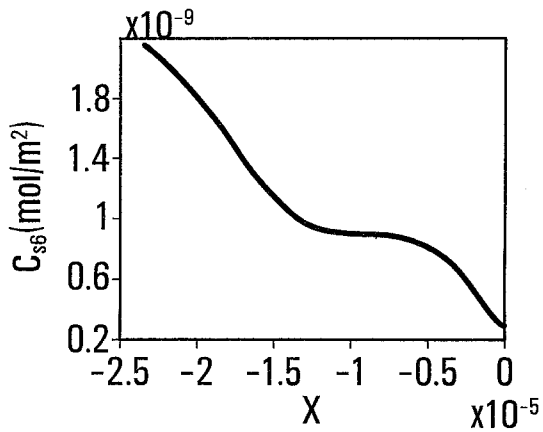

FIG. 27

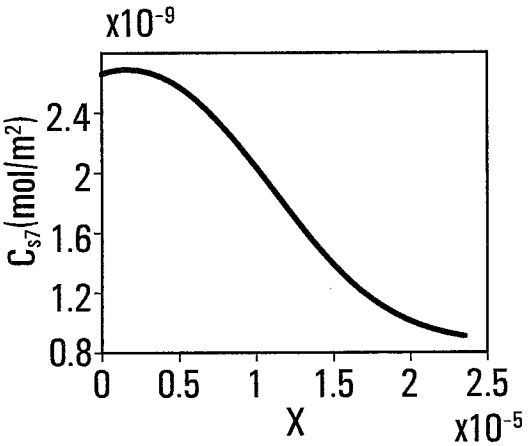

FIG. 28

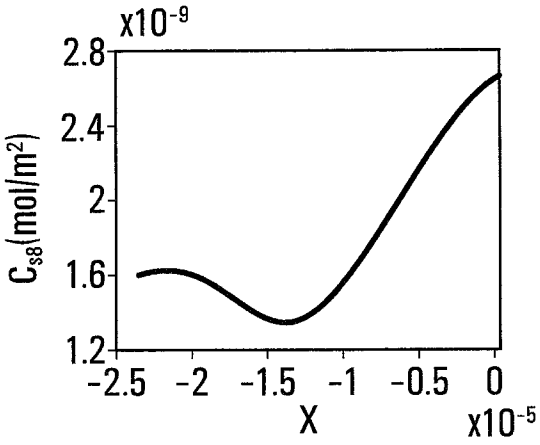

FIG. 29

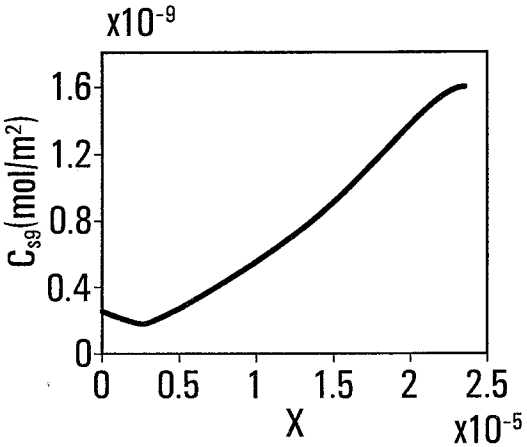

FIG. 30

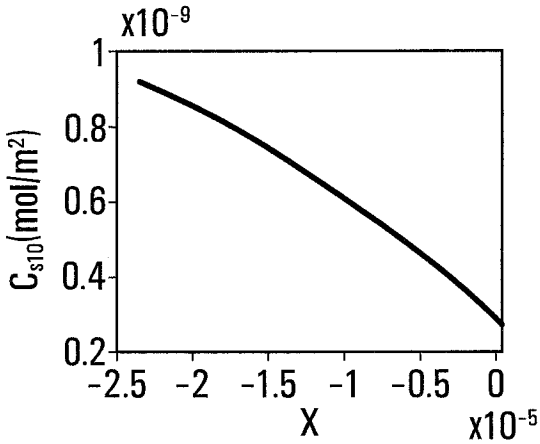

FIG. 31

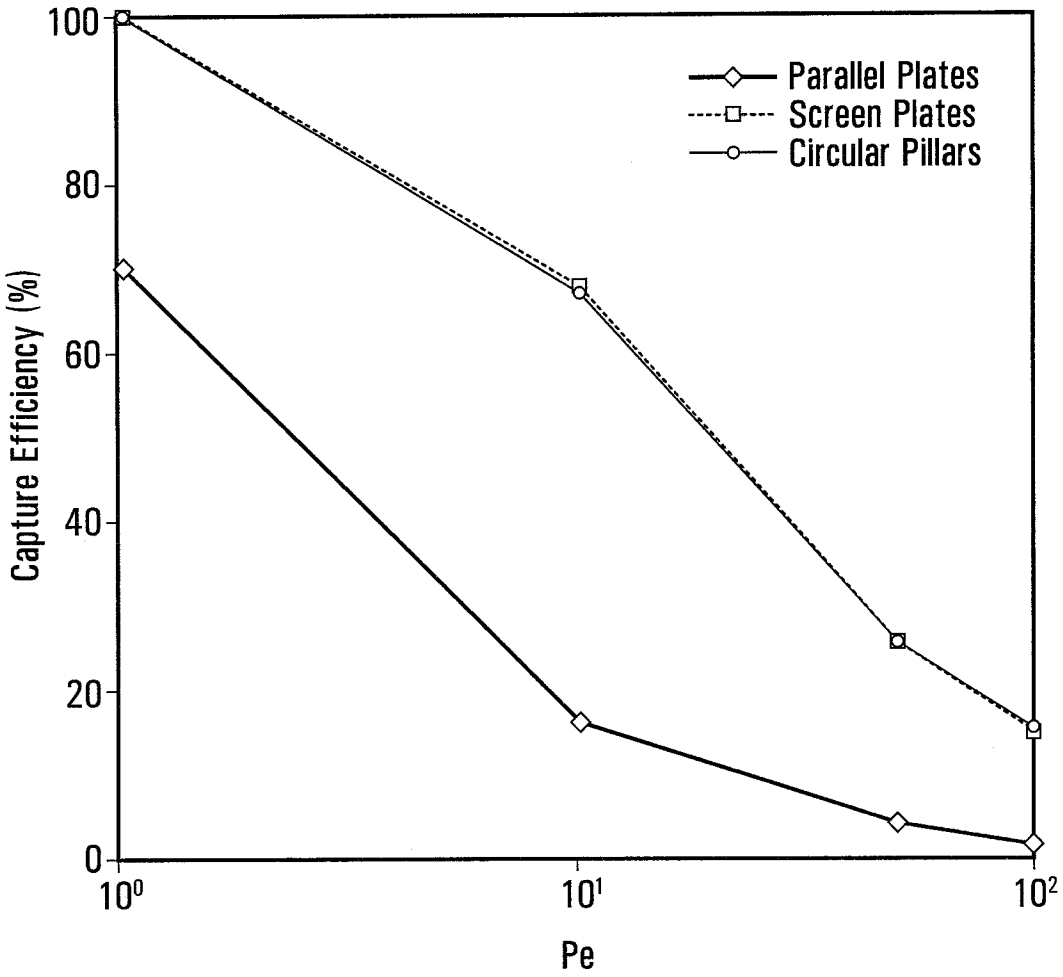
100
80
60
40
20
0
Capture Efficiency (%)
Parallel Plates
Screen Plates
Circular Pillars
10^0
10^1
10^2
Pe

FIG. 32

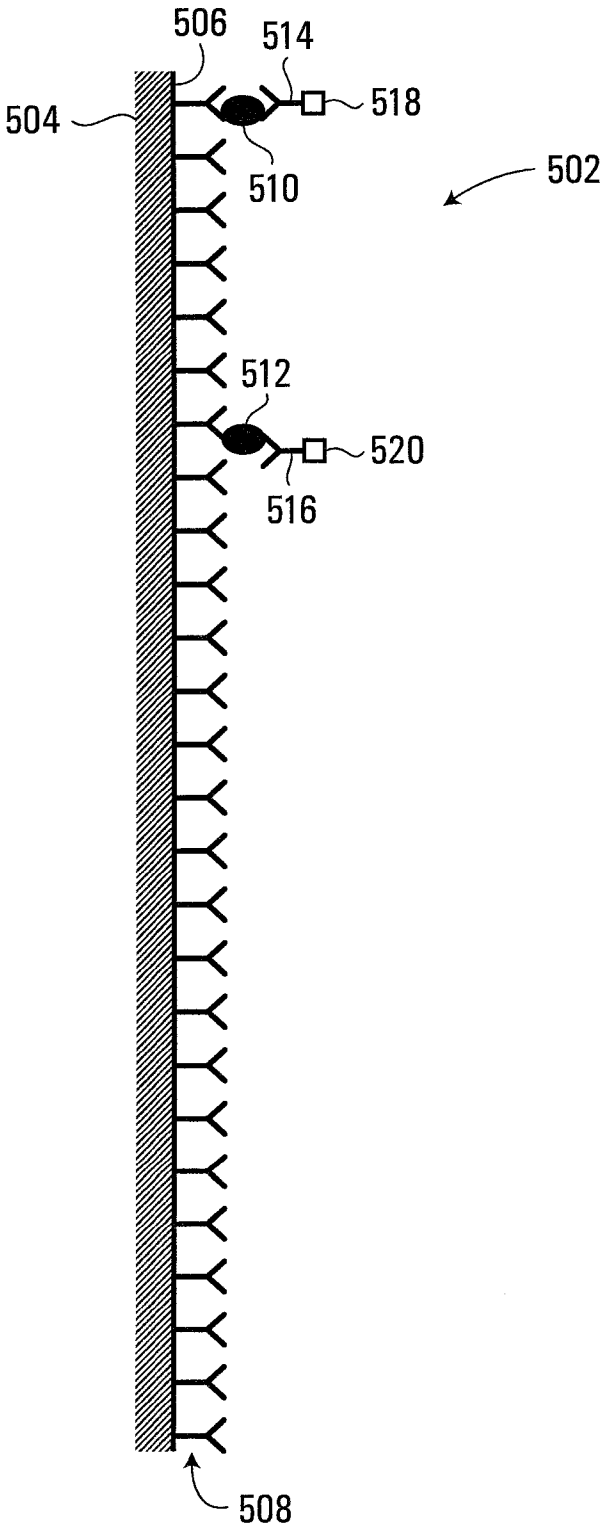

FIG. 33

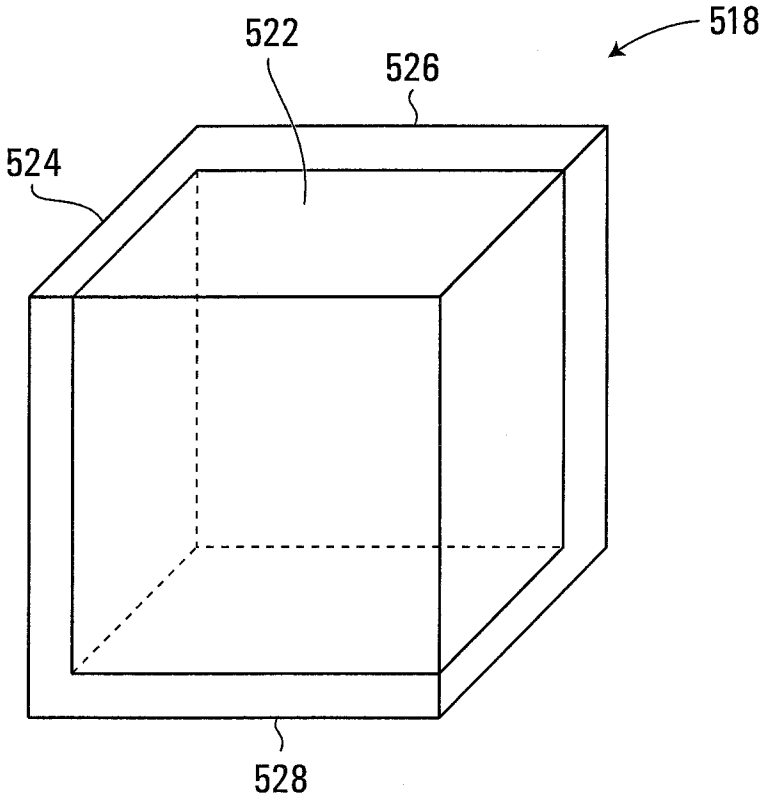

FIG. 34

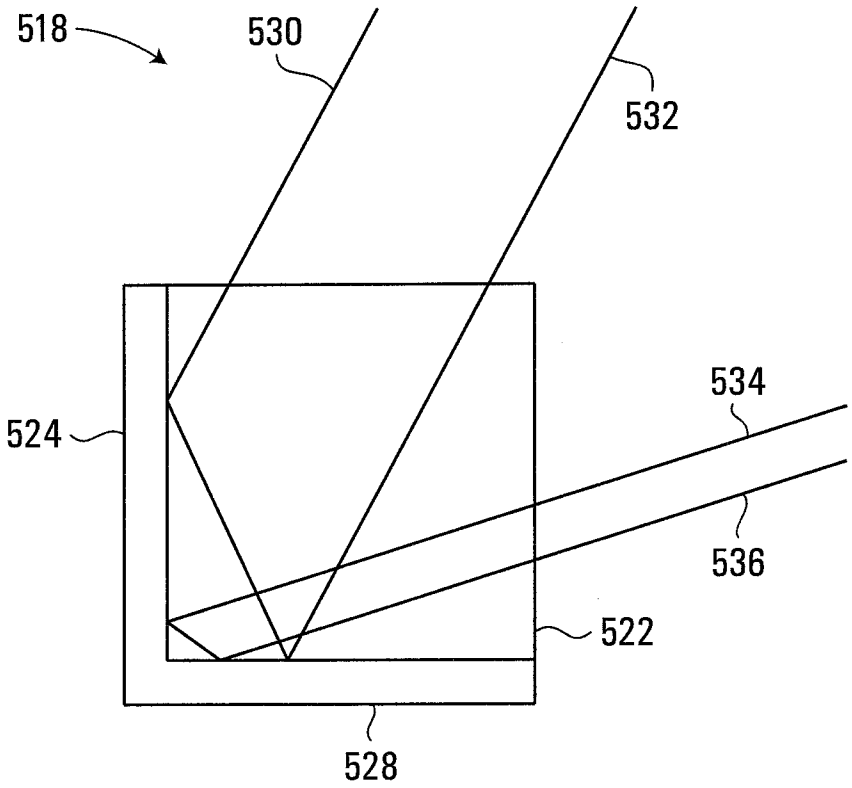

FIG. 35

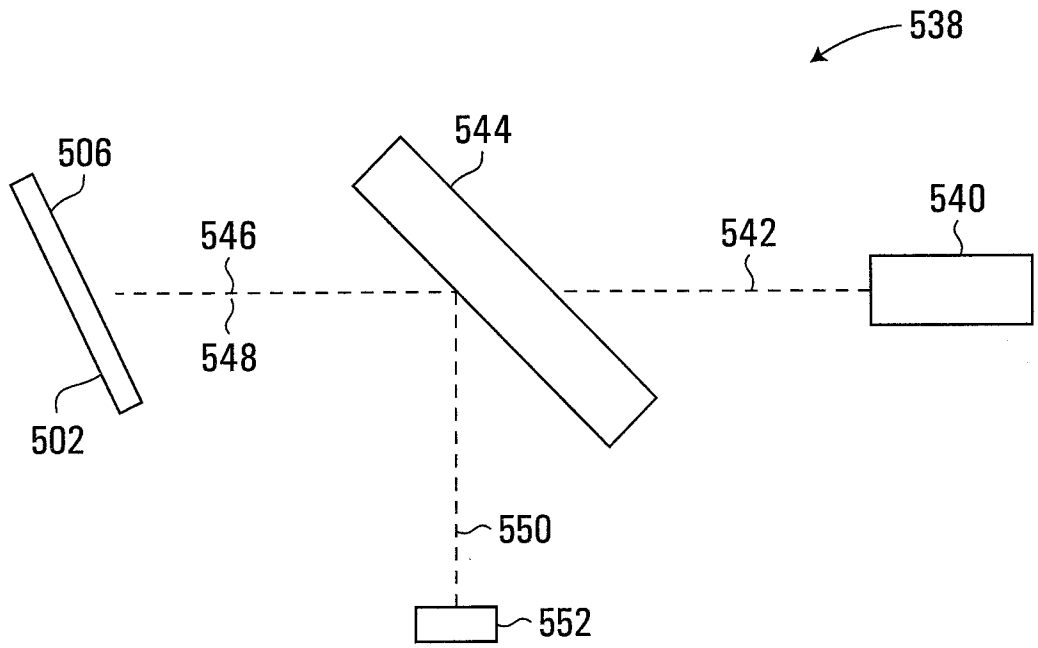

FIG. 36

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2011/000051

A. CLASSIFICATION OF SUBJECT MATTER

IPC: ***G01N 33/18*** (2006.01) , ***G01N 33/53*** (2006.01) , *C40B 60/00* (2006.01) , *C12M 1/34* (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: ***G01N 33/18*** (2006.01) , ***G01N 33/53*** (2006.01) , *C40B 60/00* (2006.01) , *C12M 1/34* (2006.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)

Epoque, CPD, Scopus, Google

search terms: capture surface fluid pathogen water guide

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2006/0246501 A1 (NORTHRUP, A.) 02 November 2006 (02-11-2006), see entire document.	1-11, 13-15, 26-28
X	US 2010/0003666 A1 (LEE, L.P. et al.) 7 January 2010 (07-01-2010), see entire dcoument.	1-11, 26-28
X	WO 2005/001411 A2 (POZDIN, O.V.) 6 January 2005 (06-01-2005), see entire document.	1-11, 28
X	WO 2009/077913 A1 (WIMBERGER-FRIEDL, R. et al.) 25 June 2009 (25-06-2009), see entire document.	1-11, 28

[ ] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 April 2011 (12-04-2011)	18 April 2011 (18-04-2011)

Name and mailing address of the ISA/CA	Authorized officer
Canadian Intellectual Property Office Place du Portage I, C114 - 1st Floor, Box PCT 50 Victoria Street Gatineau, Quebec K1A 0C9 Facsimile No.: 001-819-953-2476	Kathryn Blackwell (819-934-9088)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2011/000051

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of the first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons :

1. [ ] Claim Nos. :
because they relate to subject matter not required to be searched by this Authority, namely :

2. [ ] Claim Nos. :
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically :

3. [ ] Claim Nos. :
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows :

see extra sheet

1. [ ] As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. [ ] As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claim Nos. :

4. [X] No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim Nos. : 1-28

Remark on Protest

[ ] The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

[ ] The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

[ ] No protest accompanied the payment of additional search fees.

Continuation of Box No. III

The claims are directed to a plurality of inventive concepts as follows:

Group A - Claims 1-28 are directed to an apparatus for determining whether a substance is carried in a fluid, the apparatus comprising a body having a plurality of spaced-apart capture surfaces to contact the fluid and capture the substance therefrom, and a plurality of fluid guiding surfaces.

Group B - Claims 29-53 are directed to an apparatus for determining whether a substance is carried in a fluid, the apparatus comprising a single fluid conduit and at least one element removably positioned in the fluid conduit to contact the fluid and capture the substance therefrom.

The claims must be limited to one inventive concept as set out in Rule 13 of the PCT. In particular, the apparatus of group B does not include a plurality of fluid guiding surfaces, and indeed, only contains a single fluid conduit. Further, the body of the apparatus of group A comprises both the capture surfaces and the fluid guiding surfaces, whereas the apparatus of group B requires the capture surface to be removable from the apparatus.

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US2006246501A1	02 November 2006 (02-11-2006)	CA2583498A1	16 March 2006 (16-03-2006)
		CA2656335A1	10 January 2008 (10-01-2008)
		EP1807211A1	18 July 2007 (18-07-2007)
		EP2041258A2	01 April 2009 (01-04-2009)
		JP2008512128T	24 April 2008 (24-04-2008)
		JP2009543054T	03 December 2009 (03-12-2009)
		US2006051252A1	09 March 2006 (09-03-2006)
		WO2006029387A1	16 March 2006 (16-03-2006)
		WO2008005166A2	10 January 2008 (10-01-2008)
		WO2008005166A3	16 October 2008 (16-10-2008)
US2010003666A1	07 January 2010 (07-01-2010)	AU2006283518A1	01 March 2007 (01-03-2007)
		CA2616504A1	01 March 2007 (01-03-2007)
		CN101548004A	30 September 2009 (30-09-2009)
		EP1915467A2	30 April 2008 (30-04-2008)
		WO2007024701A2	01 March 2007 (01-03-2007)
		WO2007024701A3	14 May 2009 (14-05-2009)
WO2005001411A2	06 January 2005 (06-01-2005)	AU2003304256A1	13 January 2005 (13-01-2005)
		WO2005001411A3	29 December 2005 (29-12-2005)
WO2009077913A1	25 June 2009 (25-06-2009)	CN101903105A	01 December 2010 (01-12-2010)
		EP2070594A1	17 June 2009 (17-06-2009)
		EP2227329A1	15 September 2010 (15-09-2010)
		US2010266450A1	21 October 2010 (21-10-2010)