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(54) **ELECTROCHEMICAL MICROBIAL SENSOR SYSTEM AND METHOD OF USING SAME**

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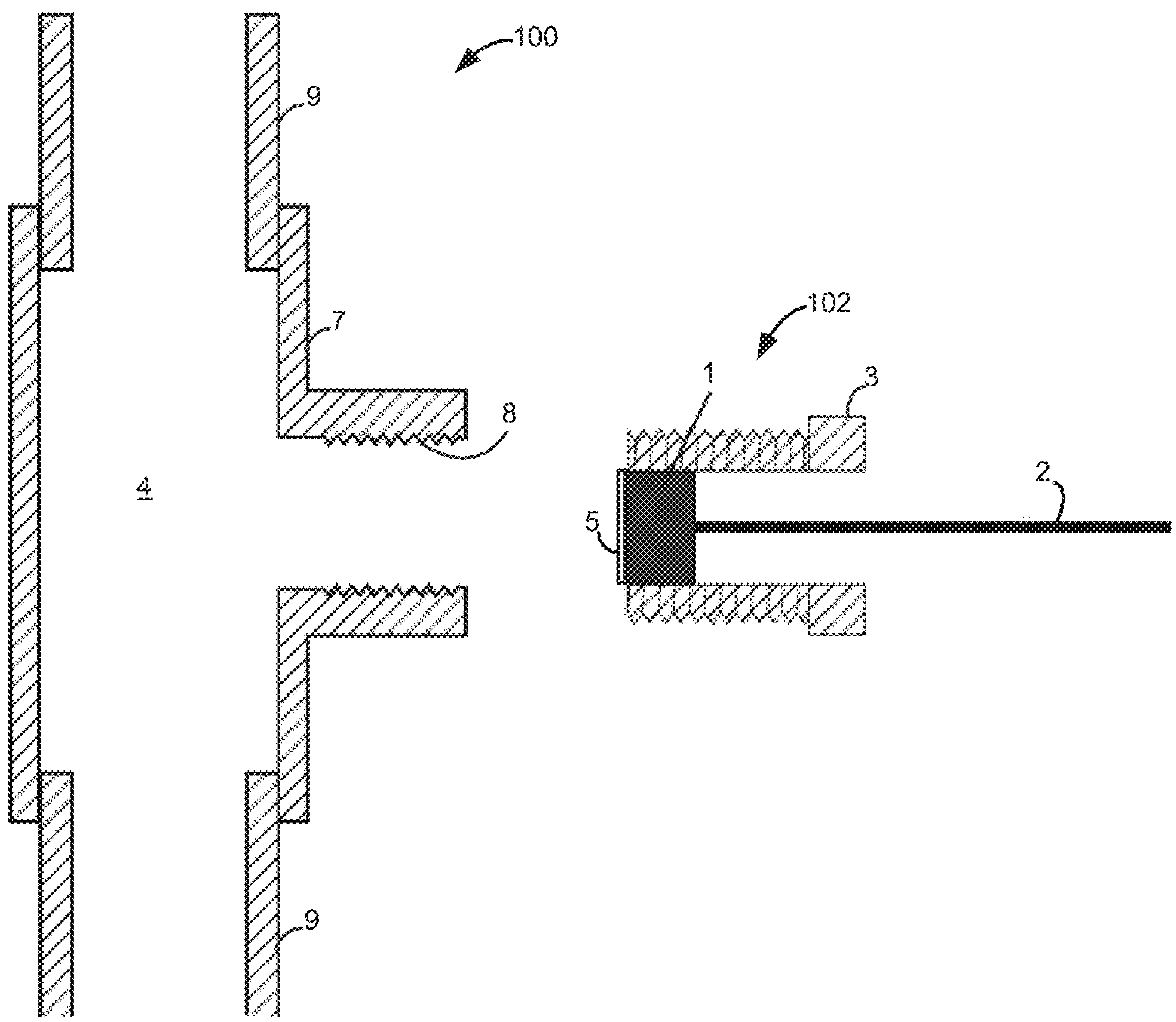
(52) **U.S. Cl.**

CPC ***C12M 41/46*** (2013.01); ***G01N 27/4035*** (2013.01); *C12M 41/32* (2013.01); ***G01N 27/411*** (2013.01); ***G01N 27/404*** (2013.01)

(57) **ABSTRACT**

A microbial sensor, system and method that can be used to determine the chemical environment and/or substrate concentrations in saturated and unsaturated natural and environments, such as soils, aquifers and sediments are disclosed. The system may be used for monitoring municipal and industrial treatment facilities and sites where chemicals or contaminants were released to natural environments. The electrochemical microbial sensor system can be referenced using either a cathode exposed to oxygen or a reference cell (silver/silver chloride or calomel) for monitoring natural or man-made environments.



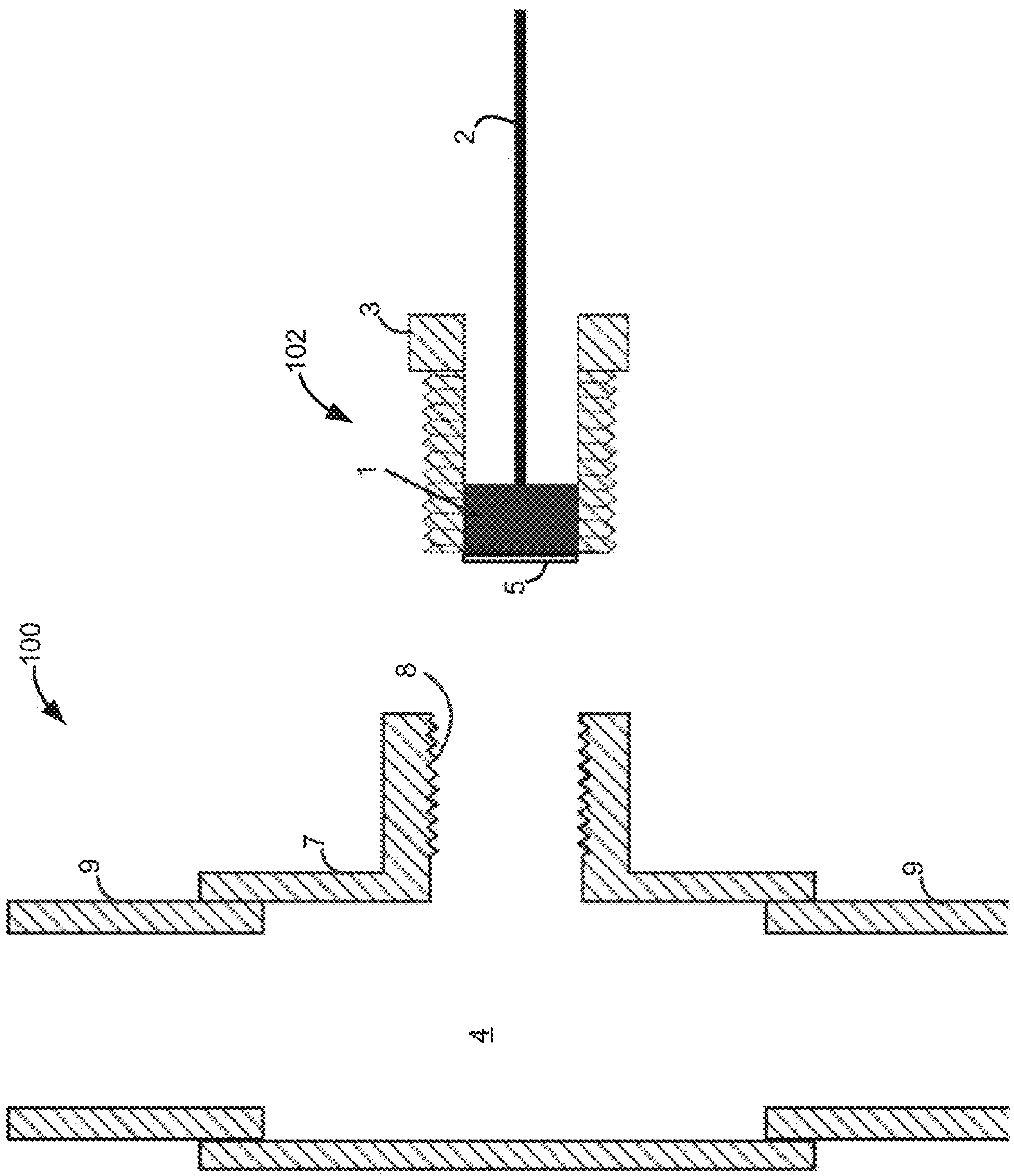


FIG. 1

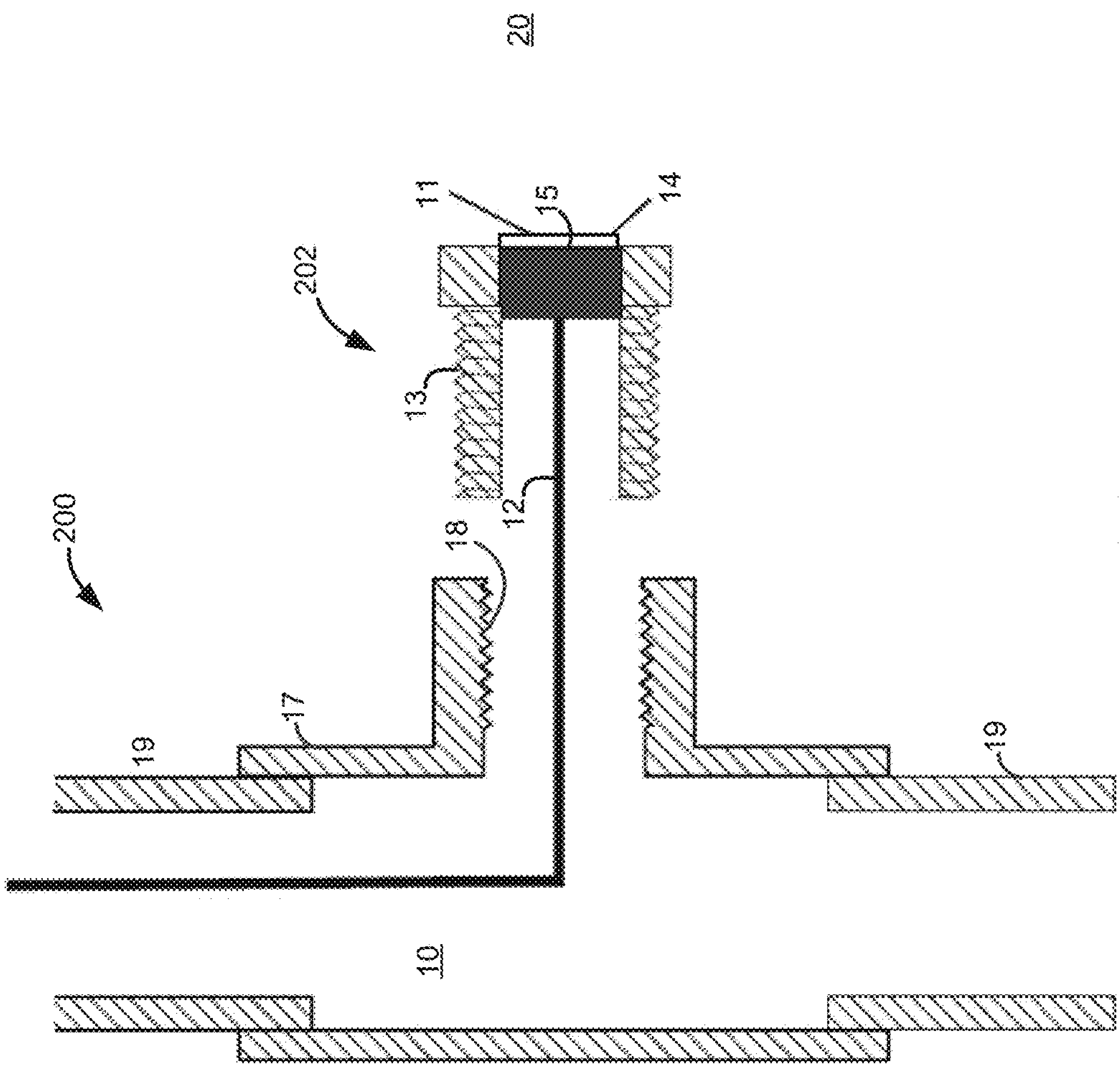


FIG. 2

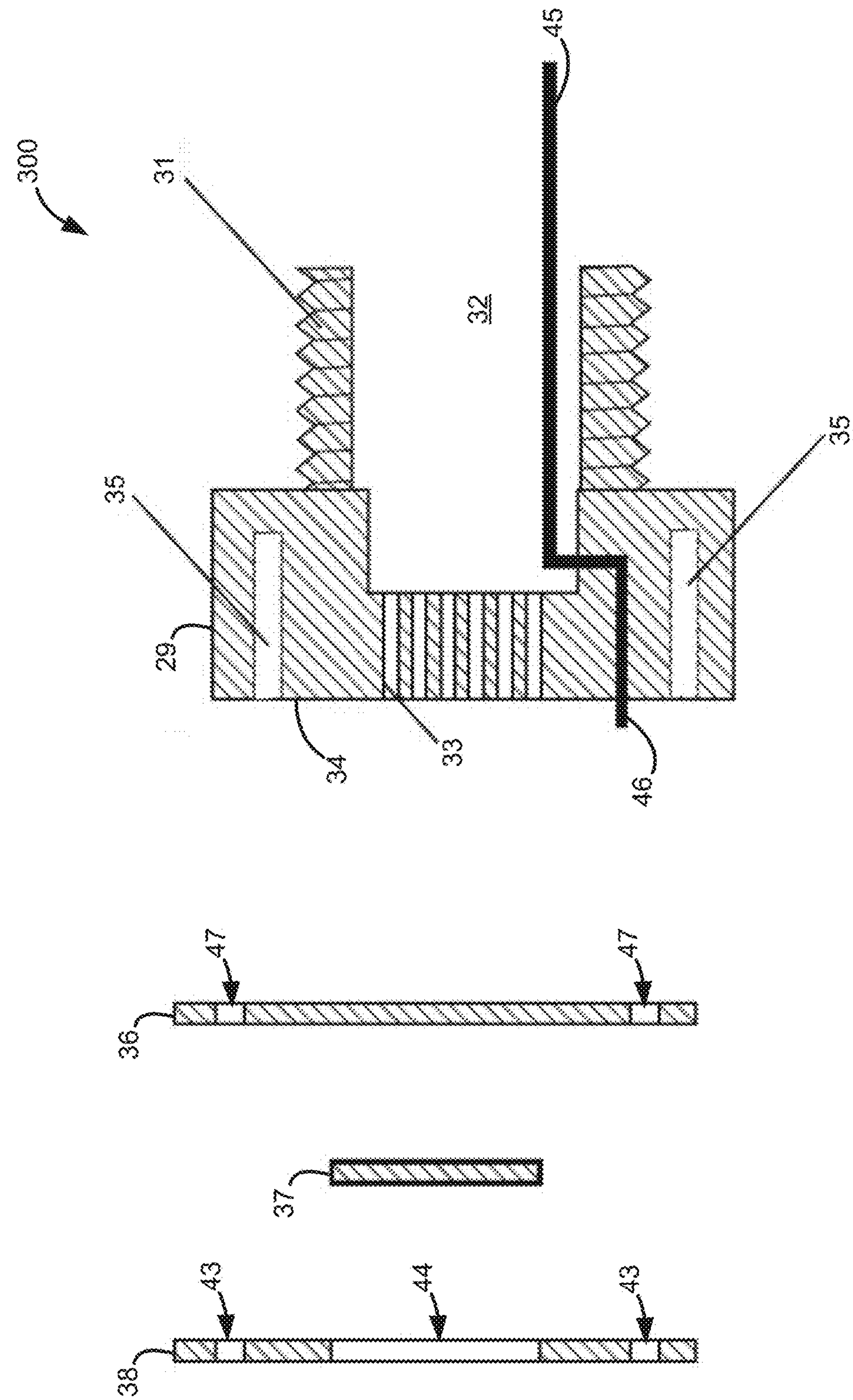


FIG. 3(A)

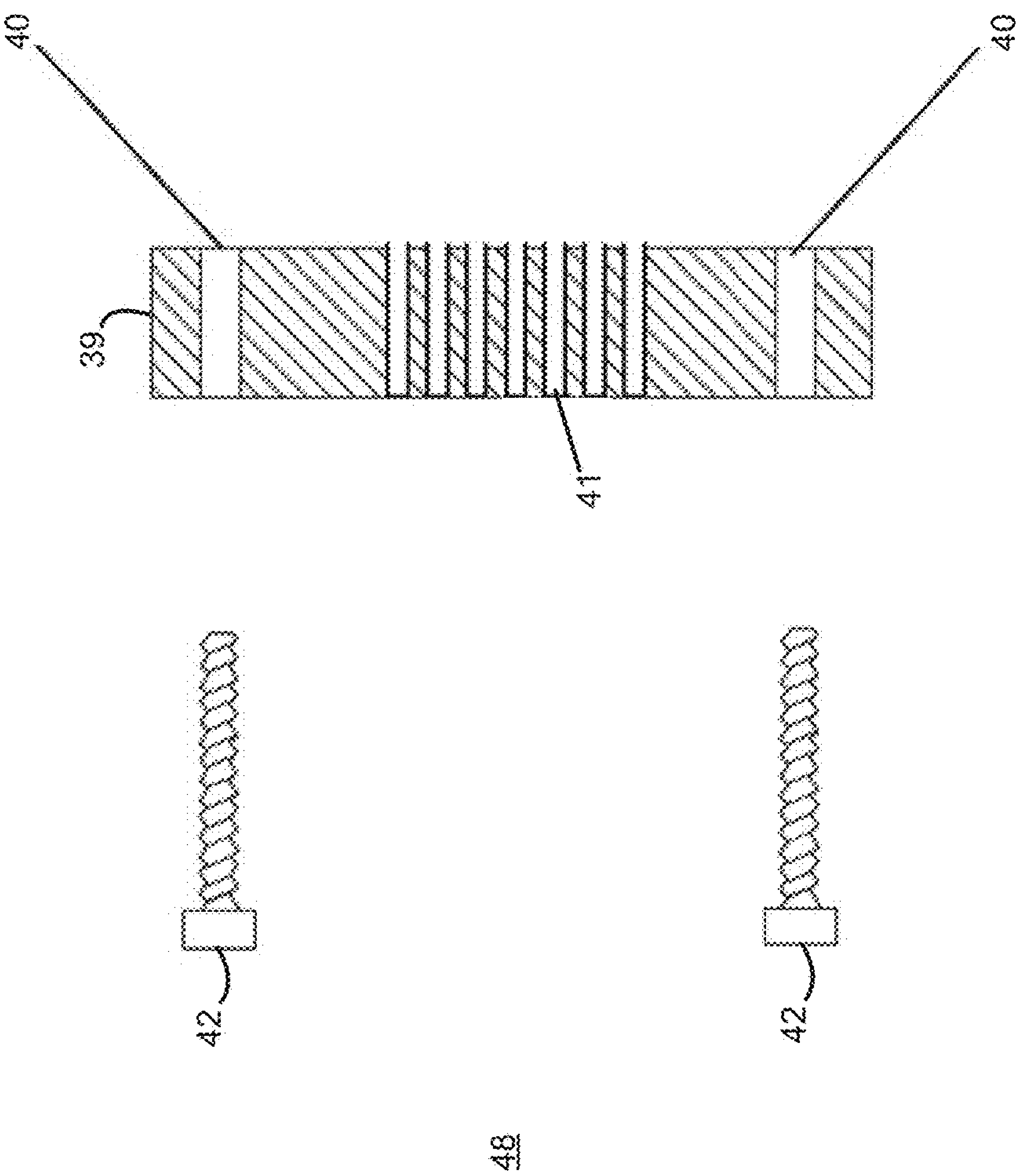


FIG. 3(B)

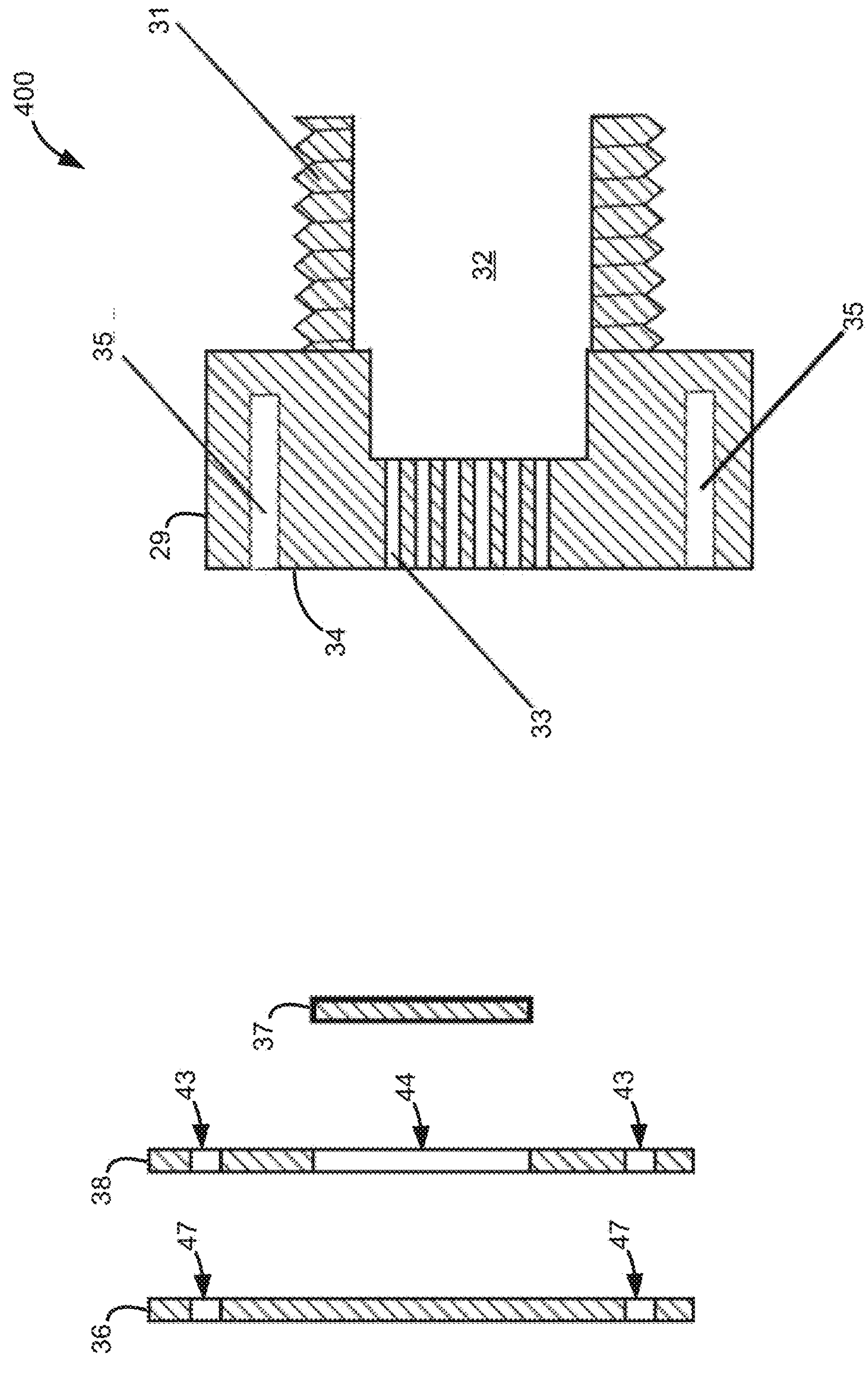


FIG. 4(A)

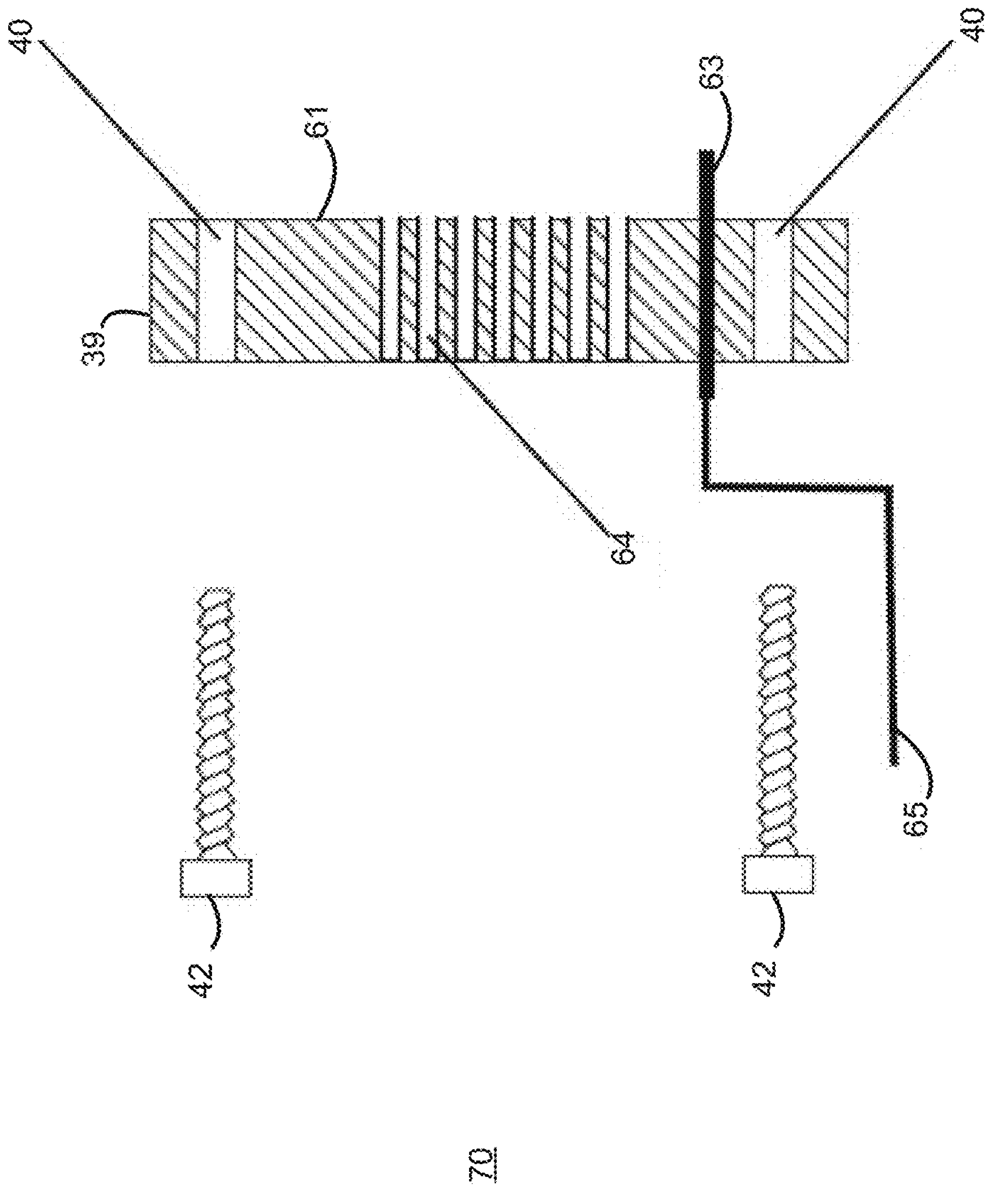
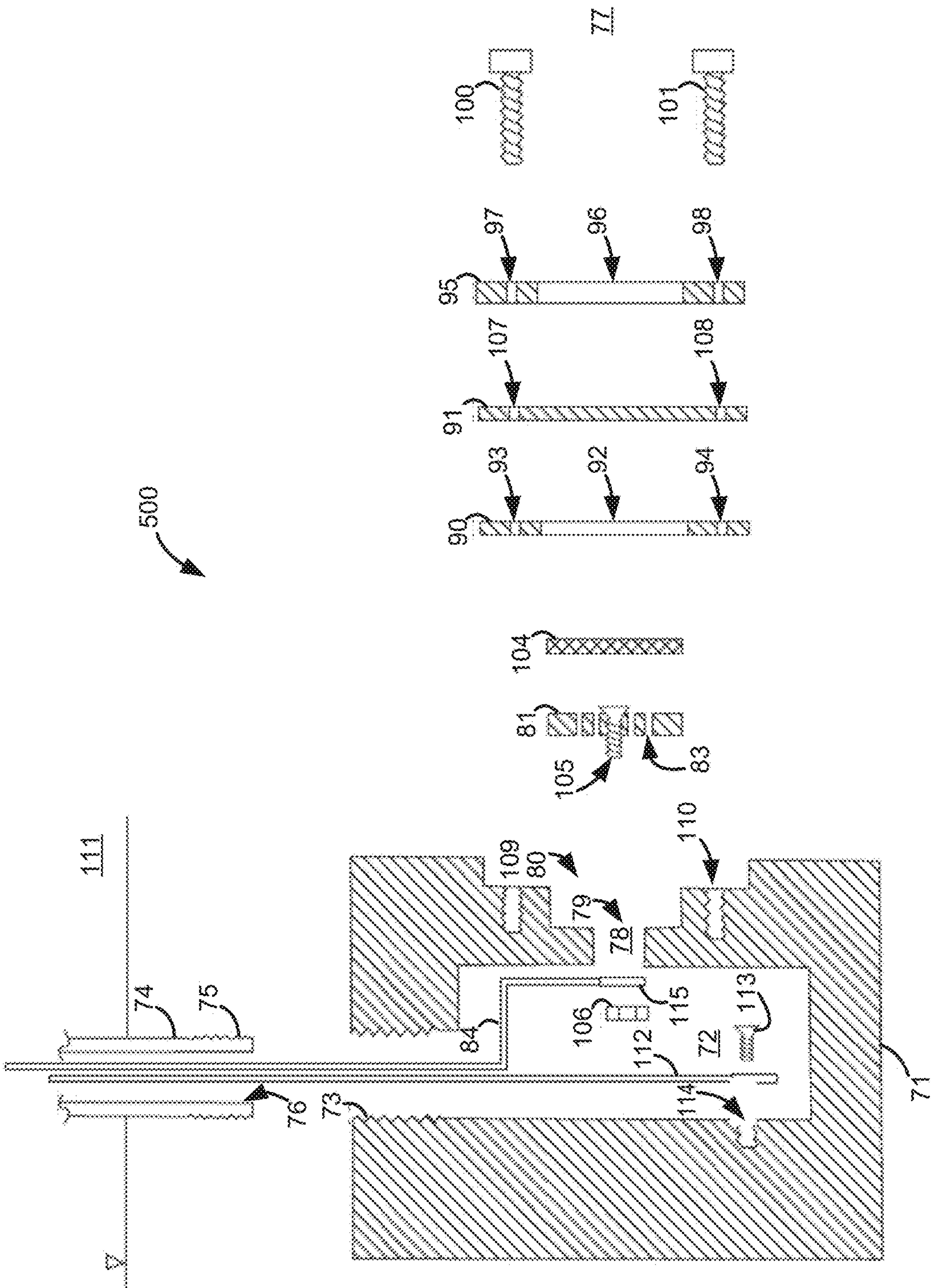


FIG. 4(B)


500
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93
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81
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76
73

FIG. 5

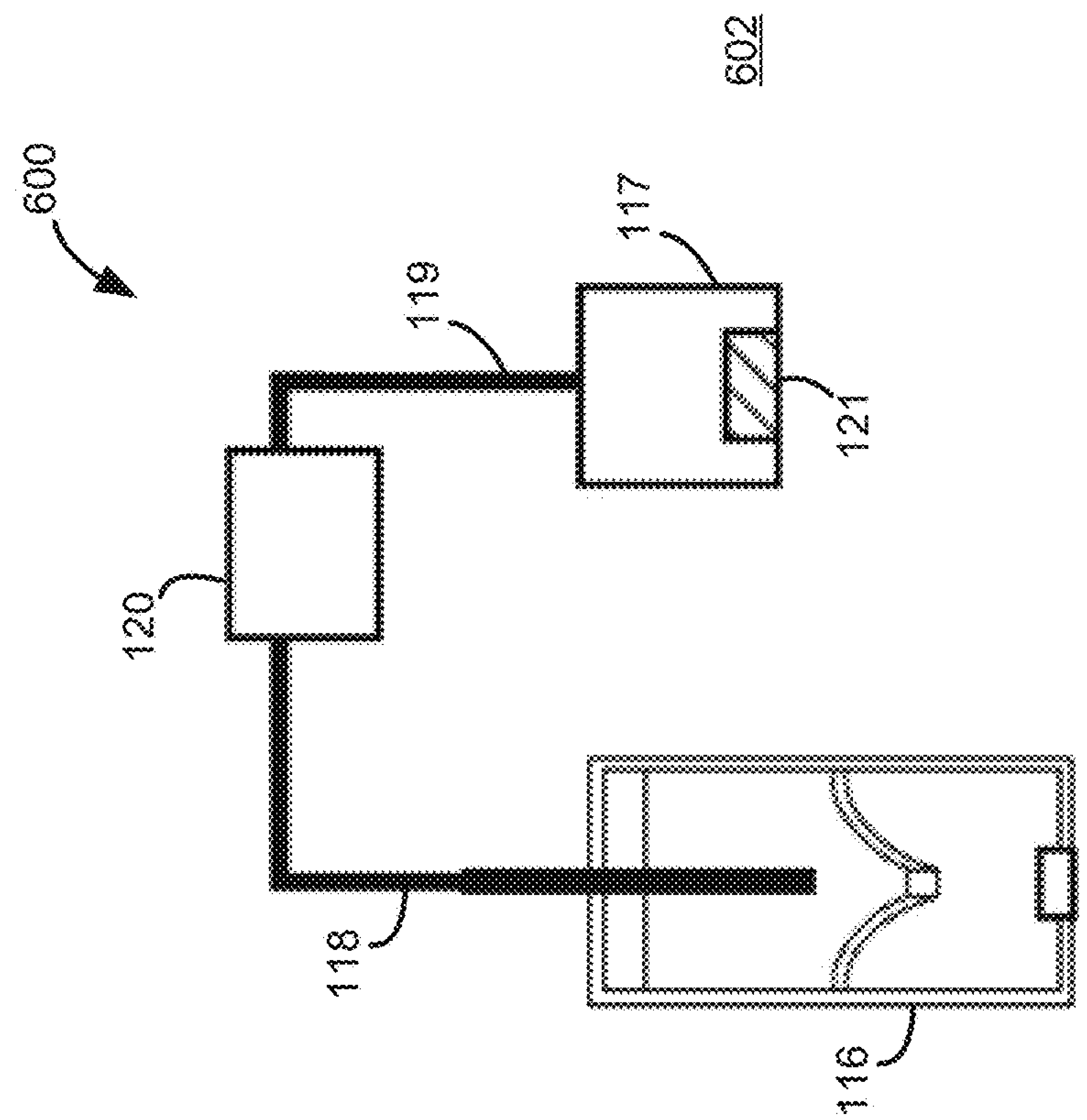


FIG. 6

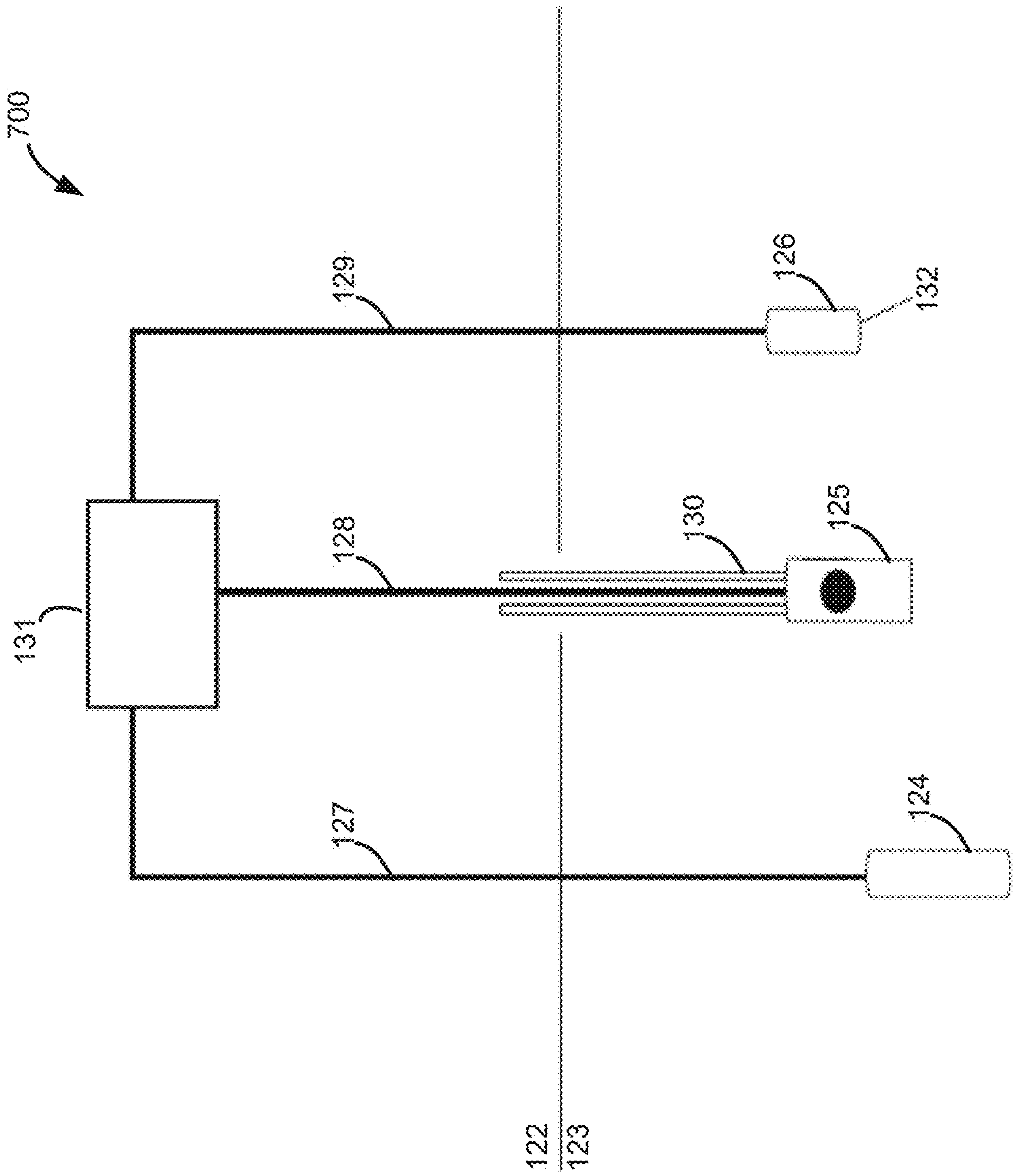
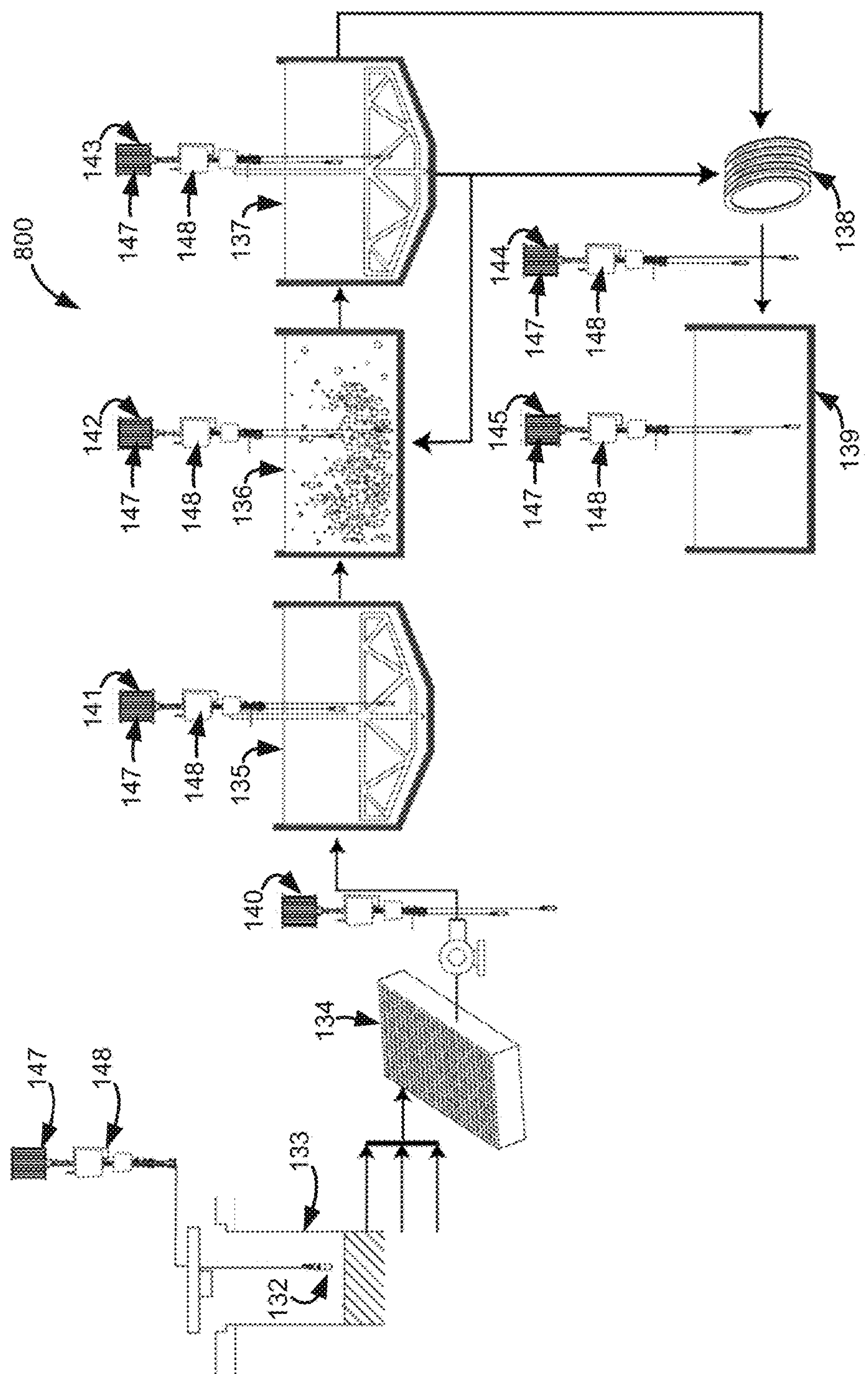


FIG. 7


800
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133
134
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FIG. 8

ELECTROCHEMICAL MICROBIAL SENSOR SYSTEM AND METHOD OF USING SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62/541,338, filed Aug. 4, 2017, and entitled "Universal Field Deployment System for Microbial Sensor Systems for Monitoring Industrial, Waste, Natural and Groundwater," U.S. Provisional Application No. 62/570,186, filed Oct. 10, 2017, and entitled "Microbial Sensor System for Monitoring the Rhizosphere and Adjacent Soils," and U.S. Provisional Application No. 62/586,602, filed Nov. 15, 2017, and entitled "Microbial Sensor System for Monitoring Sediments, Natural and Waste Waters." The contents of the above provisional applications are incorporated herein by reference to the extent such contents do not conflict with the present disclosure.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support by the Office of Science grant DE-FOA-0001405 awarded by the Department of Energy. The government has certain rights in the invention.

FIELD OF DISCLOSURE

[0003] The present disclosure generally relates to microbial sensors and systems, and to methods of using the sensors and systems. More particularly, the present disclosure relates to sensors and systems that employ open-circuit voltage and/or recovery voltage measurements to provide information concerning microbial activity, reduction/oxidation conditions and/or substrate concentrations of saturated and unsaturated environments.

BACKGROUND OF THE DISCLOSURE

[0004] Microbial fuel cells were developed for the conversion of waste products (sewage, farming wastes, etc.) into electrical energy. However, other applications of microbial fuel cells include use as analytical sensors and in bioremediation. The analytical sensors using microbial fuel cells typically measure the flow of current between the anode and cathode as the metric for determining substrate concentrations and other analytical parameters (e.g., biological oxygen demand, BOD).

[0005] Disadvantages of such sensors using a reactor design for analytical applications for characterizing submerged sediments and natural waters include: (1) The reactor design requires the substrate in water to be passed through an anode chamber. This is not a desired option if the anode is being directly inserted in sediments, soils and groundwater. (2) Reconfiguration of reactor designs to match the actual site conditions is difficult and not suitable for a majority of the sites. (3) Most reactor designs are optimized (anode and cathode size, microbial composition, and performance) for energy production that is not an important parameter for an analytical sensor. (4) Reactor design is not convenient for the deployment of multiple sensors to characterize the chemical (oxidizing and reducing) environment of a site. (5) Current measurement to determine microbial activity/substrate concentration may not be sensitive enough to measure desired microbial activity. Accordingly, improved sensors, sensor systems, and techniques for using the sensors and sensor systems are desired.

SUMMARY OF THE DISCLOSURE

[0006] Various embodiments of the present disclosure relate to methods and systems for characterizing natural and contaminated saturated environments. While the ways in which various embodiments of the disclosure address the drawbacks of the prior art are discussed in more detail below, in general, the disclosure provides sensors that are relatively sensitive (can detect very low substrate concentrations), have a relatively simple design, have a reconfigurable design—allowing for use of the sensor in a wide variety of applications, and/or can have a relatively long lifetime in the environment, systems including the sensors, and methods of using the sensors and systems. Exemplary sensor systems can be used to, for example, determine: 1) redox conditions using open-circuit voltage measurements, and 2) substrate concentrations performing recovery voltage measurements. Exemplary microbial sensors can connect with control/communication circuitry configured to provide real-time collection of data and/or the transmission of the data using wireless (e.g., cellular) communications to remote users. Exemplary microbial sensors can be used for monitoring natural and contaminated environments, wastewater and industrial treatment facilities, and other environments where redox conditions are an important parameter to be monitored.

[0007] In accordance with further exemplary embodiments of the disclosure, field deployment systems for the microbial sensors for a variety of environments are presented. The design of the systems employs commonly available construction materials (e.g., PVC piping) for monitoring a variety of different environments including saturated and unsaturated zones in the environment, industrial wastewater and municipal wastewater treatment facilities.

[0008] In accordance with further exemplary embodiments of the disclosure, a reversible cathode capable of monitoring solutions within a piping system and monitoring saturated environments exterior of a piping system is disclosed.

[0009] In accordance with further exemplary embodiments of the disclosure, a microbial monitoring system for measurement of redox and other conditions in saturated zones employs a standard reference electrode (e.g., Ag/AgCl, calomel), in lieu of a traditional cathode, as the reference cell. Microbial activity can be measured by measuring a voltage between the reference electrode/cell and one or more anodes populated by biofilms.

[0010] In accordance with further exemplary embodiments of the disclosure, a microbial monitoring system includes a standard reference cell, a cathode, and anode (e.g., populated with a biofilm) and control circuitry/measurement device. The control circuitry can be configured to control the flow of current between the cathode and the anode (e.g., covered with a biofilm). The control circuitry/measurement device can be further configured to measure a recovery voltage between the reference cell and anode (e.g., covered with a biofilm).

[0011] In accordance with yet further exemplary embodiments of the disclosure, a monitoring system for characterizing a wastewater treatment facility is disclosed. The monitoring system can include separate measurement/communication modules capable of assessing each of the treatment stages within a treatment facility.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

[0012] A more complete understanding of exemplary embodiments of the present disclosure may be derived by referring to the detailed description and claims when considered in connection with the following illustrative figures.

[0013] FIG. **1** illustrates an exemplary anode assembly suitable for monitoring solutions within an interior of pipes in accordance with at least one embodiment of the disclosure.

[0014] FIG. **2** illustrates an exemplary anode assembly suitable for monitoring solutions in natural or industrial environments located exterior to piping and/or a conduit in accordance with at least one embodiment of the disclosure.

[0015] FIGS. **3**(A) and **3**(B) illustrate an exemplary reversible cathode assembly suitable for monitoring solutions and/or environments exterior of the piping and/or conduit in accordance with at least one embodiment of the disclosure.

[0016] FIGS. **4**(A) and **4**(B) illustrate a reversible cathode assembly suitable for monitoring solutions located within the piping.

[0017] FIG. **5** illustrates a configuration of cathode assembly including an ion-specific membrane in accordance with at least one embodiment of the disclosure.

[0018] FIG. **6** illustrates a sensor system including a of a reference cell in accordance with at least one embodiment of the disclosure.

[0019] FIG. **7** illustrates a configuration of a microbial sensor system using a reference cell, a cathode, and one or more anode(s) in accordance with at least one embodiment of the disclosure.

[0020] FIG. **8** illustrates a sensor system suitable for monitoring municipal and industrial wastewater treatment facilities using individual communication/control components transmitting the water quality data from microbial activity of each stage of a treatment facility to the internet in accordance with at least one embodiment of the disclosure.

[0021] It will be appreciated that elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale. For example, the dimensions of some of the elements in the figures may be exaggerated relative to other elements to help to improve understanding of illustrated embodiments of the present disclosure.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS OF THE DISCLOSURE

[0022] The description of exemplary embodiments of methods, systems, and probes provided below is merely exemplary and is intended for purposes of illustration only; the following description is not intended to limit the scope of the disclosure or the claims. Moreover, recitation of multiple embodiments having stated features is not intended to exclude other embodiments having additional features or other embodiments incorporating different combinations of the stated features.

[0023] As noted above, prior microbial sensor technologies (energy production, bioremediation, analytical sensors) are primarily based on the measurement of electrical current between an anode and a cathode. The measurement of constant current allows for the determination of substrate concentration in a solution. In contrast, the inventors surprisingly found that measurements of open-circuit voltage (OCV) and recovery voltage (RV) are capable of providing information distinct from the measurement of constant current and can use less sensitive instrumentation to provide meaningful information regarding substrates and concentrations thereof that are or may be present in an environment.

[0024] U.S. patent application Ser. No. 15/237,230, in the name of Burge et al., filed Aug. 15, 2016 (hereinafter "the '230 Application"), discloses a microbial sensor system using open-circuit voltage and recovery voltage as the metric for determining redox conditions and substrate concentrations, respectively. As set forth below, various embodiments of the present disclosure provide alternatives and/or improvements to various designs set forth in the '230 Application. For example, improved anode assemblies, cathode assemblies, sensor systems, and methods of using the same are set forth below.

[0025] This disclosure presents a microbial sensor system for monitoring of both saturated and unsaturated zones in natural environments. Additionally, the system can be used to characterize releases of hazardous chemicals to the environments, industrial treatment facilities, and sanitary treatment facilities.

[0026] The description below provides examples of various illustrative embodiments of the present disclosure. The examples below are merely illustrative, and unless otherwise noted, the present invention is not limited to such examples.

Embodiment 1

[0027] Referring to FIG. **1**, a microbial monitoring system **100** for monitoring an area (e.g., a fluid) located within the interior **4** of a pipe **9**, is illustrated. System **100** includes an anode assembly **102**, including an anode **1**, coupled to pipe **9**. Pipe **9** can be composed of, for example, polymer pipe, such as commercially-available polychlorinated (PVC) pipe used for water and irrigation applications. In the illustrated example, anode **1** is located within a threaded (e.g., polymer) fitting **3**. Anode **1** can be oriented within the threaded polymer fitting **3** to monitor solutions within the interior **4** of the pipe **9**. Unthreaded (e.g., polymer) fittings may be used as an alternative to the threaded fitting **3**. The anode **1** can be or comprise graphite or other inert material (e.g., gold, titanium, or the like). A microbial biofilm **5** populates the surface of the anode **1**. An anode cable **2** electrically connects to the anode **1**. The threaded polymer fitting **3** connects to a threaded port **8** of a tee fitting **7**. The tee fitting **7** connects to the pipe **9**. A slip fitting or other method of attachment may be used in lieu of a threaded fitting **3** and threaded port **8**.

[0028] Operation

[0029] The contents of the interior **4** of the pipe **9** interact with the biofilm **5** located on the surface of the anode **1**, creating a voltage. The anode cable **2** is used to transmit the voltage to, for example, a measurement device, described in more detail below.

Embodiment 2

[0030] Referring to FIG. **2**, a microbial monitoring system **200**, for monitoring a surrounding environment, e.g., water, solutions, sediments, soils, industrial environments, or the like, is illustrated. System **200** includes pipe **19** and anode assembly **202**, which includes an anode **15**. Pipe **19** can be used as a conduit to protect an anode cable **12** from an exterior environment **20**. Anode cable **12** is passed through an interior **10** of the pipe **19**. An anode **15** is located within a threaded fitting **13**. The anode **15** is oriented within the threaded fitting **13** to monitor environments **20** exterior of the pipe **19**. Unthreaded fittings and other methods of attachment may be used as an alternative to the threated fitting **13**. The anode **15** can be composed of, for example, graphite, or other inert material (e.g., gold, titanium, or the like). A microbial biofilm **14** can populate the surface **11** of the anode **15**. The anode cable **12** electrically connects to the anode **15**. The threaded polymer fitting **13** connects to a threated port **18** of a tee fitting **17**. The tee fitting **17** connects to the pipe **19**. Multiple anodes may be deployed within the pipe **19** using multiple tee fittings **17**.

[0031] Operation

[0032] The environment **20** interacts with the biofilm **14** located on the surface of the anode **11** creating a voltage. The anode cable **12** is used to transmit the voltage to, for example, a measurement device, described in more detail below.

Embodiment 3

[0033] FIGS. **3**(A) and **3**(B) illustrate a reversible cathode assembly **300**, including a body **29**, a cathode **37**, a gas-permeable membrane **36**, and a cathode seal **38**. The illustrated cathode assembly **300** uses a permeable membrane (e.g., available from several material supply houses including McMaster Carr) for the transport of oxygen from the atmosphere to the cathode. The design monitors solutions and/or environments exterior of the piping and/or conduit. Reversible cathode assembly **300** can be configured to monitor solutions and other media either 1) exterior of the piping/conduit (Embodiment 3) or 2) as reconfigured and within a pipe, as described below and illustrated in FIG. **4**.

[0034] In the example illustrated in FIGS. **3**(A) and **3**(B), cathode assembly body **29** includes a threaded terminal end **31** and a (e.g., flat) surface **34** located opposite of the threaded terminal end **31**. The surface **34** has a pattern of small holes **33** (e.g., having a diameter or similar cross section of about 0.05 to about 0.125 inches) passing through the surface **34** to an interior **32** of the body **29**. The pattern of small holes **33** allows the diffusion of oxygen from the hollow interior **32** through the surface **34** of the cathode assembly body **29**. An electrical contact **46** slightly extends beyond the surface **34** of the body **29**. A cathode cable **45** electrically connects to the electrical contact **46** and to, for example, a measurement device, described in more detail below. The electrical contact **46** can be fabricated from an inert metal such a titanium, gold or platinum. The cathode cable **45** passes through the hollow interior **32** of the cathode assembly body **29** to, for example, a pipe connection.

[0035] Gas-permeable membrane **36**, cathode seal **38**, and cathode **37** can be secured against the surface **34** with a cathode frame **39**, illustrated in FIG. **3**(B). The cathode **37** fits within a cathode seal port **44** of the cathode seal **38**. Cathode frame screws **42** are passed through cathode frame mounting holes **40**, cathode seal mounting holes **43**, and the gas-permeable membrane mounting holes **47**. The cathode frame screws **42** can be used to fasten cathode frame **30** to cathode body mounting holes **35** to secure the cathode frame **39** with the cathode body **29**. Securing the cathode frame **39** to the cathode body **29** can result in a waterproof seal, which can prevent an environment (e.g., water) **48** from entering the interior **32** of the cathode assembly body **29**. Electrical contact **46** electrically contacts the cathode **37** after the cathode mounting screws **42** are secured to body **39**.

[0036] A pattern of small holes **41** pass through the cathode frame **39**. The environment **48** interacts with the cathode **37** through the pattern of small holes **41** of the cathode frame **39**.

[0037] Operation

[0038] Oxygen passes from the interior **32** of the cathode assembly body **29** through the permeable membrane **36** to the cathode **37**. The cathode **37** interacts with the environment **48** and the electrical contact **46** to provide the reference voltage. The reference voltage is transmitted from the electrical contact **46** through the cathode cable **45** to, for example a measurement device, such as a measurement device described herein.

Embodiment 4

[0039] FIGS. **4**(A) and **4**(B) illustrate a configuration of reversible cathode assembly **400** for monitoring solutions located within the interior of the pipe. The cathode assembly **400** uses a permeable membrane for the transport of oxygen from the atmosphere to the cathode. This design monitors solutions located within the piping.

[0040] Reversible cathode assembly **400** is the same as cathode assembly **300**, except the order of the gas-permeable membrane **36**, a cathode seal **38**, and a cathode **37** is changed, such that the cathode **37** is interposed between surface **34** and cathode seal **38**, with the gas permeable membrane on an opposite surface of cathode seal **38** relative to the cathode **37**. In this case, the pattern of small holes **33** allows solutions located within the hollow interior **32** of the body **29** to contact the cathode **37**.

[0041] An electrical contact **63** slightly extends beyond a (e.g., flat) surface **61** of a cathode mounting frame **39**. A cathode cable **65** electrically connects to the electrical contact **63**. The electrical contact **63** is fabricated from, for example, an inert metal, such a titanium, gold or platinum.

[0042] The cathode mounting frame **39**, illustrated in FIG. **4**(B), has a pattern of small holes **64**, allowing atmospheric oxygen **70** to pass through the cathode mounting frame **39** and contact a gas-permeable membrane **36**.

[0043] As above, the gas permeable membrane **36**, cathode seal **38**, and cathode **37** are secured against the surface **34** of the body **29** with the cathode frame **39**. The cathode **37** fits within a cathode seal port **44** of the cathode seal **38**. Cathode frame screws **42** are passed through cathode frame mounting holes **40**, cathode seal mounting holes **43** and gas-permeable membrane mounting holes **47**. The cathode frame screws **42** fasten to body holes **35** to provide the pressure to secure the cathode frame **39** with the cathode body **29**. The securing of the cathode frame screws **42** can form a waterproof seal preventing water within the interior **32** of the body **29** from passing to the atmosphere **70**. The electrical contact **63** can electrically contact the cathode **37** after the cathode mounting screws **42** are secured.

[0044] Operation

[0045] Oxygen diffuses from the environment **70** through the small pattern of holes **64** of cathode frame **39** through the permeable membrane **36** to the cathode **37**. The cathode **37** interacts with the solutions within the interior **32** of the body **29**.

[0046] The electrical contact **63** provides the reference voltage. The reference voltage is transmitted from the electrical contact **63** and cathode cable **65** to, for example, a measurement device, as described herein.

Embodiment 5

[0047] FIG. **5** illustrates a cathode assembly **500** in accordance with additional embodiments of the disclosure. Cathode assembly **500** includes a cathode body **71**, a cathode mounting plate **81**, a cathode **104**, a cathode mounting seal **90**, an ion-permeable membrane **91**, and an exterior plate **95**. The ion-permeable membrane **91** can be an ion-specific membrane that allows the transport of the hydrogen ion to the cathode.

[0048] The cathode body **71** is fabricated with a hollow interior **72**. Threads **73** of the cathode body **71** connect to a threaded end **75** of a tube **74**. Other forms of connection may be used to connect the tube **74** to the cathode body **71**. A hollow interior **76** of the tube **74** connects with the hollow interior **72** of the cathode body **71** to form a pathway, allowing a free exchange of atmospheric oxygen **111** with a cathode **104**. The combination of the hollow interior **76** of the tube **74** and the hollow interior of the cathode body **72** forms a snorkel.

[0049] The cathode mounting plate **81** connects to a cathode mounting port **79** located on a face of the cathode body **71** through a port **78** in the cathode body **71**. A screw **105** attaches a cathode cable **84** to the cathode mounting plate **81** with a nut **106**. The screw **105** electrically contacts the cathode **104**. A pattern of small holes **83** pass through the cathode mounting plate **81**. The cathode mounting plate **81** supports the cathode **104**. The pattern of small holes **83** in the cathode mounting plate **81** provides a pathway for atmospheric oxygen **111** to pass from the hollow interior **72** of the cathode body **71** to the cathode **104**.

[0050] The cathode **104** is positioned within a recess **92** within a cathode mounting seal **90** between the cathode mounting plate **81**, an ion-permeable membrane **91** and an exterior plate **95**. The cathode mounting seal **90**, ion-permeable membrane **91**, and the exterior plate **95** connect within the sealing port **80** of the cathode body **71** using mounting screws **100**, **101**. The mounting screws **100**, **101** are passed through the mounting holes **93**, **94** of the cathode mounting seal **90**, the mounting holes **107**, **108** of the ion-permeable membrane **91**, and the mounting holes **97**, **98** of the exterior plate **95**. The screws **100**, **101** are secured to mounting holes **109**, **110** located in the sealing port **110** on the cathode body **101**. Securing the mounting screws **100**, **101** with exterior plate **95**, cathode mounting seal **90**, and ion-permeable membrane **91** to the cathode body **71** forms a water-proof seal preventing water from the environment **77** from entering the interior **72** of the of the cathode body **71**.

[0051] The ion-permeable membrane **91** allows the transfer of hydrogen ions from the surrounding environment **77** through a port **96** located in the exterior plate **95**. The cathode mounting seal **90** provides for a waterproof seal between the polymer membrane **91** and the cathode mounting port **80**. The water-proof seal prevents water from the environment **77** entering in the interior **72** of the cathode body **71**.

[0052] A leak detection cable **112** connects to the interior of the cathode body **71** with a screw **113** and a threated hole **114**. The purpose of the leak detection cable **112** allows the detection of water within the interior **72** of the cathode body **71**.

[0053] The ion-permeable membrane **91** can be fabricated with Nafion™ or other membranes allowing the transport of hydrogen ion through the membrane.

[0054] Operation

[0055] Oxygen passes from the atmosphere **111** through the interior **76** of the tube **74** and into the hollow interior **72** of the cathode body **71**. The oxygen passes from the interior **72** of the cathode body **71** through the holes **83** of the cathode mounting plate **81** and interacts with the cathode **104**.

[0056] Hydrogen ions from the environment **77** pass through the port **96** of the exterior plate **95** and pass through the ion-permeable membrane **91**. The ions then pass to the cathode **104** and interact with the oxygen from the atmosphere **111**.

[0057] The cathode **104** electrically connects to the screw **105**. The electrical signal is transferred from the screw **105** to a connector **115** to the cathode cable **84**. The cathode cable **84** transfers the electrical signal through the cathode body **71** and the tube **74**.

Embodiment 6

[0058] FIG. **6** illustrates a sensor system **600**, sometimes referred to herein as s system, in accordance with exemplary embodiments of the disclosure. Sensor system **600** includes a first electrode (e.g., an anode) **117** in a first environment **602** to be monitored, a reference cell **116** (e.g., a standard reference cell), and a measurement device **120** electrically coupled to the first electrode and the reference electrode, wherein the measurement device measures a voltage between the first electrode **117** and the reference cell **116** to characterize microbial activity in the first environment **602**. In accordance with various aspects of these embodiments, the voltage comprises an open-circuit voltage.

[0059] The illustrated embodiment uses a standard reference cell (such as silver/silver chloride or calomel) in lieu of a cathode when performing measurements of the environment **602**. The reference cell **116** can be in a second environment (i.e., not in environment **602**). Standard reference cells are commercially available.

[0060] A reference cell **116** electrically connects to an electronic circuitry/measurement device **120** with an insulated reference cable **118**. First electrode (e.g., anode) **117** connects to the electronic circuitry **120** with an insulated anode cable **119**. The surface of the anode **117** is populated with a biofilm **121**. Multiple anodes may be connected to the electronic circuitry/measurement device **120**.

[0061] Measurement device/electronic circuitry **120** can include, for example, high-impedance voltage measurements, 4-20 mA inputs and cellular communications.

[0062] Operation

[0063] This embodiment replaces the cathode with commercially-available reference cells. The measurement (e.g., open-circuit voltage) of the anode(s) **117** is measured against the reference cell **116** using measurement device **120** to determine microbial activity.

Embodiment 7

[0064] Referring to FIG. **7**, a sensor system **700** including a standard reference cell **124**, a second electrode or cathode

125 and a first electrode or anode 126, is illustrated. The surface of the anode 126 is populated with a biofilm 132. In this case, standard reference cell 124 connects to the electronic circuit/measurement device 131 with an insulated reference cable 127. The standard reference cell may include, for example, an Ag/AgCl or a calomel reference cell. The cathode assembly 125 connects to the electronic circuitry/measurement device 131 with a cathode cable 128 through a tube 130. The anode cable 129 connects the anode 126 to the electronic circuitry/measurement device 131.

[0065] Operation

[0066] This embodiment allows the electronic circuitry/measurement device 131 to control the flow of current (e.g., automatically shunting through a 20000 to 500 ohm resistor) between the anode assembly 126 and cathode assembly 125, while the recovery voltage (OCV) is measured between the anode assembly 126 and the reference cell 124 to determine microbial activity on or proximate the anode 126.

Embodiment 8

[0067] Referring to FIG. 8, the embodiment illustrates a microbial sensor system 800 deployed at various locations—e.g., throughout a wastewater treatment facility. Examples of the disclosure can include any combinations of the illustrated sensors coupled to one or more measurement devices as described herein. In the illustrated example, a pretreatment microbial monitoring system 132 is located in a manhole 133. The pretreatment location may include lift stations and other locations where a microbial sensor may be deployed to monitor the wastewater before discharge into the treatment facility. A headworks microbial sensor system 140 is deployed at a headworks 134 of the facility. A settling basin microbial sensor system 141 is deployed at a primary settling basin 135. A reaction cell microbial sensor system 142 is deployed at a reaction cell 136. A secondary settling basin microbial sensor 143 is deployed at a secondary settling basin 137. A filter monitoring microbial sensor system 144 is deployed at a filtering operation of the facility 138. A disinfectant microbial sensor system 145 is deployed at the disinfectant operation of the facility 139.

[0068] The sensor systems can include a solar cell 147 and a signal/communication box 148. The solar cell 147 provides the power to the sensor system(s) and the signal/communication box 148 acquires the signal from one or more sensors—e.g., sensor 132. The signal is transmitted using cellular or other type of communications to transmit the data to a remote user. The data can be used to monitor and control the various processes to optimize (including the use of artificial intelligence) and improve the efficiency of the processes at the treatment facility.

We claim:

1. A sensor system comprising:

a first electrode in a first environment to be monitored;

a reference cell; and

a measurement device electrically coupled to the first electrode and the reference cell, wherein the measurement device measures a voltage between the first electrode and the reference cell to characterize microbial activity in the first environment.

2. The sensor system of claim **1**, wherein the voltage comprises an open-circuit voltage.

3. The sensor system of claim **1**, wherein the reference cell is in the first environment.

4. The sensor system of claim **1**, wherein the reference cell comprises a standard reference cell.

5. The sensor system of claim **1**, wherein the reference cell comprises a silver/silver chloride standard reference cell.

6. The sensor system of claim **1**, wherein the reference electrode cell a calomel standard reference cell.

7. The sensor system of claim **1**, wherein the first electrode comprises an anode.

8. The sensor system of claim **1**, wherein the sensor system comprises a plurality of first electrodes coupled to the measurement device.

9. The sensor system of claim **1**, wherein the sensor system further comprises a second electrode.

10. The sensor system of claim **9**, wherein the second electrode comprises a cathode.

11. The sensor system of claim **10**, wherein the sensor system comprises a cathode assembly comprising the cathode.

12. The sensor system of claim **11**, wherein the cathode assembly comprises a reversible cathode assembly.

13. The sensor system of claim **10**, wherein the voltage comprises a recovery voltage.

14. The sensor system of claim **11**, further comprising a current controller to control a flow of current between the first electrode and the cathode assembly.

15. The sensor system of claim **1**, wherein the first electrode comprises a biofilm.

16. A method of measuring microbial activity, the method comprising the steps of:

providing a first electrode in a first environment to be monitored;

providing a reference cell; and

measuring a voltage between the first electrode and the reference cell to characterize microbial activity in the first environment.

17. The method of measuring microbial activity of claim **16**, further comprising a step of providing a second electrode.

18. The method of measuring microbial activity of claim **17**, further comprising a step of controlling a current between the first electrode and the second electrode.

19. The method of measuring microbial activity of claim **17**, wherein the step of measuring a voltage comprises measure a recovery voltage.

20. A sensor system comprising:

a first electrode;

a second electrode;

a reference cell; and

a measurement device electrically coupled to the first electrode, the second electrode, and the reference cell, wherein the measurement device measures a voltage between the first electrode and the reference cell to characterize microbial activity in the first environment.

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