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(54) Title: CAPACITIVE DEVICE COMPRISING ELECTRICAL INSULATOR

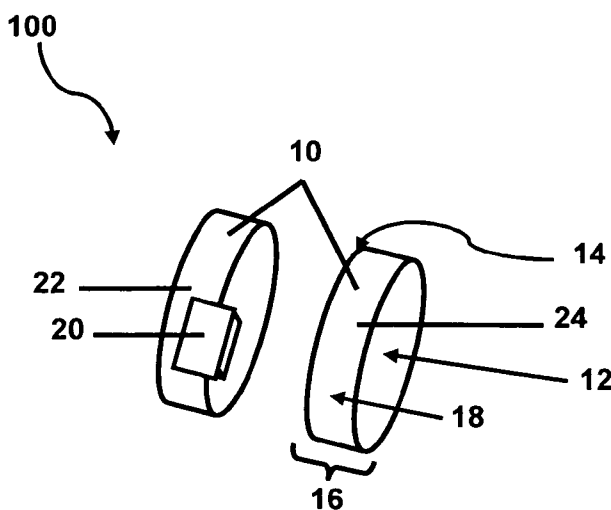


Figure 1

(57) Abstract: Capacitive devices are described having electrical isolators for electrodes which possess efficient electrical contact between current collectors, electrical isolation of electrodes, and/or electrochemical stability, while minimizing the mechanical stress and strain applied to the electrodes. The capacitive devices are adaptable to a wide range of electrode diameters and electrode stack lengths.



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- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

CAPACITIVE DEVICE COMPRISING ELECTRICAL INSULATOR

Cross-Reference To Related Applications

[0001] This application claims the benefit of priority to U.S. application no. 11/947,141, filed on November 29, 2007, which is incorporated by reference herein.

BACKGROUND**Field of the Invention**

[0002] The present invention relates generally to an electrical isolator and more particularly to an electrical isolator for electrodes in a capacitive device useful for electric double layer capacitors and/or for capacitive deionization.

Technical Background

[0003] Capacitors, like batteries, store energy in the electrical field between a pair of oppositely charged conductive plates. Developed more than 250 years ago, capacitors are frequently used in electrical circuits as energy storage devices. In recent years, new families of capacitive devices have been developed which are based on charge separation of ions in solution and the formation of electrical double layers.

[0004] An electric double layer capacitor (EDLC) is an example of a capacitor that typically contains porous carbon electrodes (separated via a porous separator), current collectors and an electrolyte solution. When electric potential is applied to an EDLC cell, ionic current flows due to the attraction of anions to the positive electrode and cations to the negative electrode. Electric charge is stored

in the electric double layer (EDL) formed along the interface between each polarized electrode and the electrolyte solution.

[0005] EDLC designs vary depending on application and can include, for example, standard jelly roll designs, prismatic designs, honeycomb designs, hybrid designs or other designs known in the art. The energy density and the specific power of an EDLC can be affected by the properties thereof, including the electrode and the electrolyte utilized. With respect to the electrode, high surface area carbons, carbon nanotubes, activated carbon and other forms of carbon and composites have been utilized in manufacturing such devices. Of these, carbon based electrodes are used in commercially available devices.

[0006] Capacitive Deionization (CDI) is a promising deionization technology, for instance, for the purification of water. In this context, alternating positively and negatively charged electrodes are used to attract ions from a stream or bath of fluid. The ions form electric double layers on the surfaces of the electrodes, which are fabricated from some form of high surface area material, for example, a form of activated carbon. After interaction with the electrodes during the charging period, the fluid contains a lower overall ion content and is discharged. A volume of purge fluid is then introduced to the electrodes. The electrodes are then electrically discharged, thus releasing the trapped ions into the purge fluid. The purge fluid is then diverted into a waste stream and the process repeated.

[0007] Physically spacing electrodes from adjacent electrodes while electrically isolating those electrodes from current collectors in a stack configuration is a challenging aspect for EDLC and CDI applications. Discrete insulators and spacers are typically needed to electrically isolate the

electrodes. Further, electrodes are delicate, thus mechanical stressing and straining of the electrodes should be minimized. Minimizing the deformations applied to the electrodes is difficult, especially while attempting to maximize the electrical and mechanical integrity of an electrical interconnect to the electrodes.

[0008] Another challenging aspect is providing a robust mechanical package. The porous, permeable nature of the electrodes makes it difficult to isolate any electrical connection from the fluid being deionized. For this reason, the materials to be considered for use should survive a fairly harsh electrochemical corrosion environment, while providing adequate electrical conductivity and contact resistance with the electrodes.

[0009] U.S. Patent No. 5,954,937 relates to an interconnection for resorcinol/formaldehyde carbon aerogel/carbon paper sheet electrodes. The fluid flow path is located between the surfaces of the electrode sheets. The electrodes are physically spaced, and the space provides the fluid flow path. The active surfaces of these electrode sheets are delicate and should be protected from mechanical stressing. The electrode sheets are bonded to a current collector, in this case, a titanium sheet using a conductive carbon filled adhesive. The large area of contact between the electrode sheet and the current collector insures relatively low overall resistance despite the moderately high resistivity of the adhesive interface.

[0010] US Patent No. 6,778,378 relates to electrodes which may be rolled from carbon and fibrillated polytetrafluoroethylene (PTFE). Electrodes formed in this fashion are thin flexible sheets which can be contacted by high normal compressive forces. Electrodes may be stacked up with sheets of current

collector material and a separator material and then clamped with a compressive force to obtain good electrical contact. By controlling which electrodes and current collectors are in physical contact, a capacitive cell may be formed.

[0011] A flow-through (rather than parallel plate) flow geometry is described in commonly owned U.S. Patent No. 6,214,204. In this reference, monolithic, low back pressure porous electrodes are made by one of several methods, which include honeycomb extrusion, casting or molding from a phenolic resin-based batch. After curing, these parts are carbonized and activated to create high surface area carbon monoliths with good electrical conductivity. Discs are made and assembled in a stack and spaced such that the discs are electrically isolated from each other. The discs are connected to anode and cathode current collector/bus bar assemblies utilizing wires.

[0012] US Patent No. 6,661,643 relates to the use of ionically-conductive spacers to separate adjacent electrodes in a CDI module and relates to the use of the CDI modules to deionize liquids. The CDI module provides simultaneous deionization and regeneration along with energy recovery. The spacers are in the form of a web or mesh and are interposed between electrodes. However, electrical interconnection must be accomplished on an electrode-by-electrode basis and as such is a major challenge to providing robust CDI modules.

[0013] US Patent No. 7,147,785 relates to the use of an electrodeionization device for water purification. Spacers are described which define depletion and concentration volumes and provide electrical insulation. As such, the spacers must function as water-tight seals to adequately separate liquid volumes and furthermore for high temperature applications must be dimensionally stable.

[0014] It would be advantageous to have a capacitive device comprising an electrical interconnect to a linear stack of electrodes, which does not jeopardize the mechanical integrity of the electrodes. Also, it would be advantageous to have the electrical interconnect be electrochemically inert. Further, it would be advantageous to develop a capacitive device, comprising interconnected monolithic high surface area carbon electrodes, which is capable of non-impeded fluid flow through the electrodes, which is useful for, for example, CDI.

[0015] It would be advantageous to have a capacitive device comprising an electrical isolator for a linear stack of electrodes, which does not jeopardize the mechanical integrity of the electrodes. It would be advantageous to have the electrical isolator provide an electrical insulating function for the electrode/current collector interface and also an electrical spacing function for adjacent electrodes. Also, it would be advantageous to have the electrical isolator be electrochemically inert. Further, it would be advantageous to develop a capacitive device utilizing such electrical isolators and comprising interconnected monolithic high surface area carbon electrodes, which is capable of non-impeded fluid flow through the electrodes, which is useful for, for example, CDI.

SUMMARY

[0016] Capacitive devices and features thereof, as described herein, address one or more of the above-mentioned disadvantages of conventional capacitive devices and/or electrical insulators/spacers and provide one or more of the following advantages: efficient electrical contact between current collectors, electrical isolation of electrodes, and electrochemical stability, while minimizing the mechanical

stress and strain applied to the electrodes. The capacitive devices and features of the present invention are adaptable to a wide range of electrode diameters and electrode stack lengths.

[0017] One embodiment of the invention is a capacitive device comprising two or more electrodes arranged in series. Each electrode comprises a first face, an opposing second face and a thickness defined by an outer surface extending from the first face to the opposing second face. An electrical isolator comprising a compliant material is disposed between faces of adjacent electrodes and covers at least a portion of the outer surface of the first electrode.

[0018] Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from the description or recognized by practicing the invention as described in the written description and claims hereof, as well as the appended drawings.

[0019] It is to be understood that both the foregoing general description and the following detailed description are merely exemplary of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed.

[0020] The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings illustrate one or more embodiment(s) of the invention and together with the description serve to explain the principles and operation of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] The invention can be understood from the following detailed description either alone or together with the accompanying drawing figures.

[0022] **Figure 1** is an exploded view schematic of features of a capacitive device according to one embodiment of the invention.

[0023] **Figure 2** is a photograph of features of a capacitive device according to one embodiment of the invention.

[0024] **Figure 3** is a schematic of features of an electrical isolator for a capacitive device, according to one embodiment.

[0025] **Figure 4a, Figure 4b, Figure 4c, Figure 4d, and Figure 4e** are schematics of features of a capacitive device according to some embodiments of the invention.

[0026] **Figure 5a, Figure 5b, Figure 5c, Figure 5d, and Figure 5e** are schematics of features of a capacitive device according to some embodiments of the invention.

[0027] **Figure 6** is an illustration of features of a capacitive device, according to one embodiment of the invention.

[0028] **Figure 7a and Figure 7b** are illustrations of features of an electrical isolator for a capacitive device, according to one embodiment.

[0029] **Figure 8** is an illustration of a capacitive device according to one embodiment of the invention.

DETAILED DESCRIPTION

[0030] Reference will now be made in detail to various embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

[0031] Features **100** of a capacitive device, according to one embodiment of the invention, are shown in **Figure 1**. The capacitive device, in this embodiment, comprises two or more electrodes **10** arranged in series. Each electrode comprises a first face **12**, an opposing second face **14** and a thickness **16** defined by an outer surface **18** extending from the first face to the opposing second face. An electrical isolator **20** comprising a compliant material is disposed between faces of adjacent electrodes **22** and **24** and covers at least a portion of the outer surface of the first electrode **22**.

[0032] In a parallel plate capacitive device, electrodes are arranged in series such that at least a portion of the opposing second face of the first electrode and at least a portion of the first face of a second electrode are adjacent to each other.

[0033] In a flow-through capacitive device, electrodes are arranged in series from upstream to downstream such that at least a portion of a fluid conveyed through the first face of a first electrode is subsequently conveyed through at least a portion of the opposing second face of the first electrode and at least a portion of the fluid is subsequently conveyed through at least a portion of the first face of a downstream second electrode.

[0034] Features **200** of an electrical isolator for a capacitive device, according to one embodiment, are shown in **Figure 2**. Shown in this embodiment, are two adjacent electrodes **22** and **24**, each electrode having an electrical isolator **20** and **21** respectively.

[0035] Features **300** of an electrical isolator, according to another embodiment, are shown in **Figure 3**. The electrical isolator **20** is disposed between the faces **12** and **14** of each pair of adjacent electrodes and covers a portion of the outer

surface **18** of each electrode. This structure can provide mechanical support across the faces of the electrodes. This is advantageous as the diameter of the electrodes increase or as the thickness of the electrodes decrease.

[0036] Features **600** of an electrical isolator, according to another embodiment, are shown in **Figure 6**. The electrical isolator **20**, in this embodiment, covers a portion of the outer surface **18** of one electrode **22** in a position diametrically opposing the position of the electrical isolator **21** contacting the outer surface **19** of an adjacent electrode **24**.

[0037] Features **400**, **401**, **402**, **403**, **404**, **500**, **501**, **502**, **503**, **504**, **700**, and **701** of an electrical isolator, according to some embodiments, are shown in **Figure 4a**, **Figure 4b**, **Figure 4c**, **Figure 4d**, **Figure 4e**, **Figure 5a**, **Figure 5b**, **Figure 5c**, **Figure 5d**, **Figure 5e**, **Figure 7a**, and **Figure 7b** respectively. The electrical isolator **20** comprises a compliant material and, in some embodiments, covers from 10 percent to 90 percent, for example, from 25 percent to 75 percent of the perimeter of the outer surface **18** of the electrode on which it is disposed, as shown in **Figure 5a**, **Figure 5b**, **Figure 5c**, **Figure 5d**, and **Figure 5e**.

[0038] In some embodiments, as shown in **Figure 4a**, **Figure 4b**, **Figure 4c**, **Figure 4d**, **Figure 4e**, **Figure 7a** (exploded view), and **Figure 7b**, the outer surface **18** of the electrode is circular and the compliant material of the electrical isolator **20** covers from 45 degrees to 315 degrees of the circumference of the outer surface **18**, for example, from 60 degrees to 180 degrees of the circumference of the outer surface.

[0039] The compliant material, according to one embodiment, is selected from a silicone, an elastomer, natural rubber, silicone rubber, butyl rubber, polybutadiene, nitrile rubber, polyurethane rubber, fluoroelastomers and combinations

thereof. The electrical isolator can be made according to several methods, for example, by injection molding, machining or by other methods known in the art.

[0040] In some embodiments, the electrical isolator can be bonded to one or more of the electrodes in the linear stack, for example, molded to or adhesively attached to the outer surface and/or to either the first face or the second face of one or more of the electrodes. It is advantageous that the electrical isolator does not appreciably restrict fluid flow along the axis of the two or more adjacent electrodes in a flow-through capacitive device.

[0041] The capacitive device **800**, according one embodiment, as shown in **Figure 8**, further comprises a first current collector **28** insulated from the outer surface **18** of the first electrode **22** through contact with the electrical isolator **20**, and in electrical contact with the outer surface **19** of another electrode **25** in the series.

[0042] The capacitive device, according to another embodiment, also shown in **Figure 8**, further comprises a second current collector **29** in electrical contact with the outer surface **18** of the first electrode **22**. In one embodiment, also shown in **Figure 8**, the second current collector **29** is insulated from the second electrode **24** contacting the first current collector **28** through contact with the compliant material of the electrical isolator **21**. In one embodiment, the first current collector and the second current collector are diametrically opposed.

[0043] According to one embodiment, the first current collector and the second current collector are, independently, a material selected from nickel, carbon, graphite, titanium, aluminum, nickel, copper, silver, gold, platinum and combinations thereof. The first current collector and the

second current collector can be in the form of a compliant sheet or foil.

[0044] When the first current collector carries, for example, a positive charge and the second current collector carries, for example, a negative charge, these above-mentioned configurations can be used to form a capacitive device having a series of alternating anodes and cathodes.

[0045] In one embodiment, the electrode material is selected from a carbon, a carbon-based composite, a carbon-based laminate, a conductive metal oxide and combinations thereof. As shown in **Figure 7a** (exploded view) and **Figure 7b**, each of the electrodes **10** can comprise a plurality of inner channels **30** having surfaces defined by porous walls and extending through the electrode from the first face **12** to the second face **14**, for example, each electrode can be in the form of a honeycomb monolith.

[0046] The electrodes can be any shape or size providing the electrode comprises a first face, an opposing second face and a thickness defined by an outer surface extending from the first face to the opposing second face. An electrode having flattened areas on the outer surface may facilitate improved electrical connections to a current collector also having a surface with flattened areas contacting the electrodes. The electrodes can be, for example, polygonal, circular, cylindrical, square, cubed, triangular, pentagonal, hexagonal or a combination thereof.

[0047] The present invention provides one or more of the following advantages: insulation of alternating electrodes arranged in series from a common current collector, for example, one current collector for positive electrodes and one current collector for negative electrodes; electrical isolation for electrodes in an interconnected, interdigitated

stack of electrodes, for example, flow-through monolithic carbon electrodes; easier assembly, in part, due to the incorporation of an insulator function and a spacer function into a single piece; increased chemical inertness in a harsh electrochemical environment, for example, in CDI applications; and improved electrical performance. Further, since the electrical isolator comprises a compliant material, the electrical isolator provides increased mechanical integrity when compared to a rigid material.

CLAIMS

What is claimed is:

1. A capacitive device comprising:

two or more electrodes arranged in series, wherein each electrode comprises a first face, an opposing second face and a thickness defined by an outer surface extending from the first face to the opposing second face; and

an electrical isolator comprising a compliant material disposed between faces of adjacent electrodes and covering at least a portion of the outer surface of the first electrode.

2. The capacitive device according to claim 1, wherein the compliant material further covers a portion of the outer surface of the second electrode.

3. The capacitive device according to claim 2, wherein the electrical isolator is disposed between the faces of each pair of adjacent electrodes and covers a portion of the outer surface of each electrode.

4. The capacitive device according to claim 3, wherein the electrical isolator covers a portion of the outer surface of one electrode in a position diametrically opposing the position of the electrical isolator contacting the outer surface of an adjacent electrode.

5. The capacitive device according to claim 1, further comprising a first current collector insulated from the outer surface of the first electrode through contact with the electrical isolator, and in electrical contact with the outer surface of another electrode in the series.

6. The capacitive device according to claim 5, further comprising a second current collector in electrical contact with the outer surface of the first electrode.

7. The capacitive device according to claim 6, wherein the second current collector is insulated from another electrode in the series contacting the first current collector through contact with the compliant material.

8. The capacitive device according to claim 1, wherein the electrode material is selected from a carbon, a carbon-based composite, a carbon-based laminate, a conductive metal oxide and combinations thereof.

9. The capacitive device according to claim 1, wherein each electrode is a flow-through electrode.

10. The capacitive device according to claim 9, wherein each electrode comprises a plurality of inner channels having surfaces defined by porous walls and extending through the electrode from the first face to the second face.

11. The capacitive device according to claim 10, wherein each electrode is a honeycomb monolith.

12. The capacitive device according to claim 1, wherein the compliant material covers from 10 percent to 90 percent of the perimeter of the outer surface of the electrode on which it is disposed.

13. The capacitive device according to claim 1, wherein the outer surface of the electrode is circular and the compliant

material covers from 45 degrees to 315 degrees of the circumference of the outer surface.

14. The capacitive device according to claim 13, wherein the compliant material covers from 60 degrees to 180 degrees of the circumference of the outer surface.

15. The capacitive device according to claim 1, wherein the compliant material is selected from a silicone, an elastomer, natural rubber, silicone rubber, butyl rubber, polybutadiene, nitrile rubber, polyurethane rubber, fluoroelastomers and combinations thereof.

16. The capacitive device according to claim 1, wherein the electrical isolator is bonded to one or more of the electrodes.

1/4

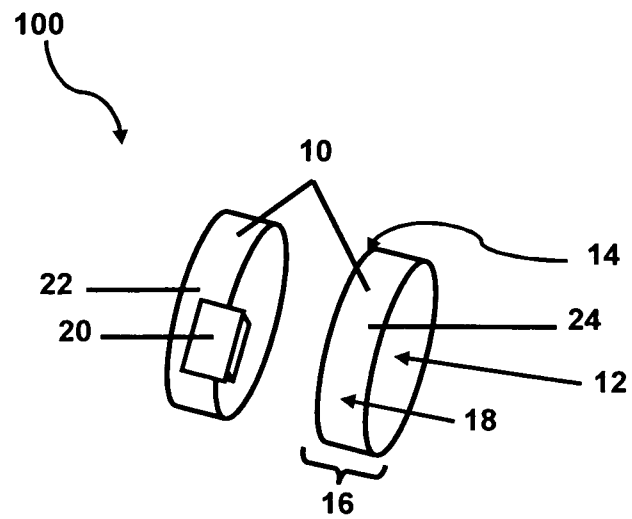


Figure 1

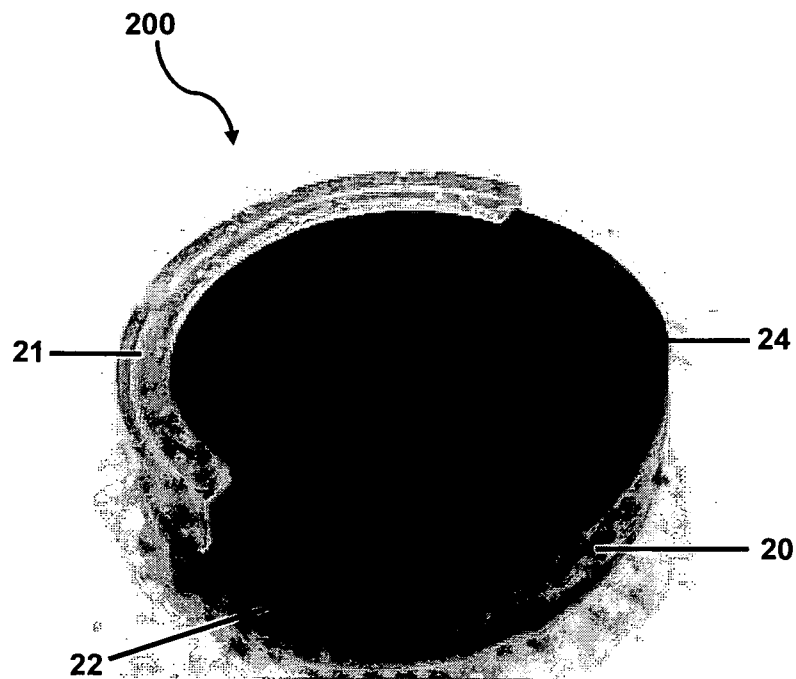


Figure 2

2/4

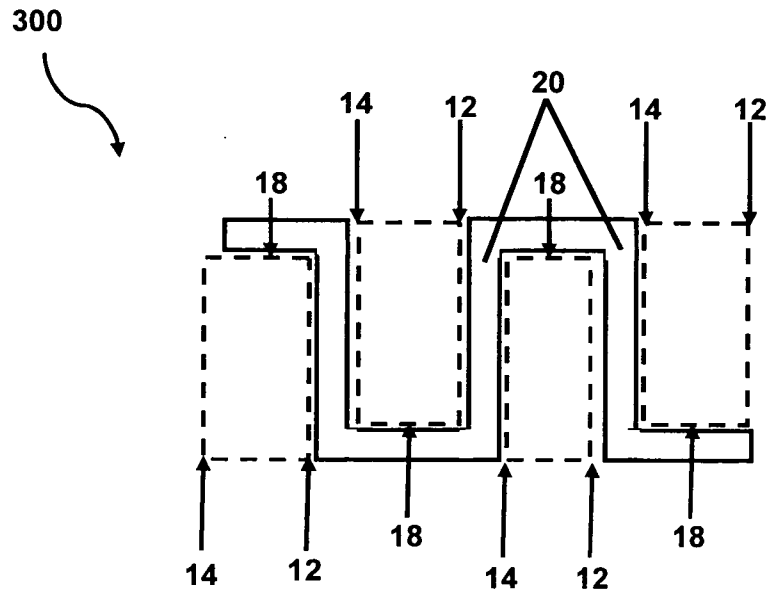
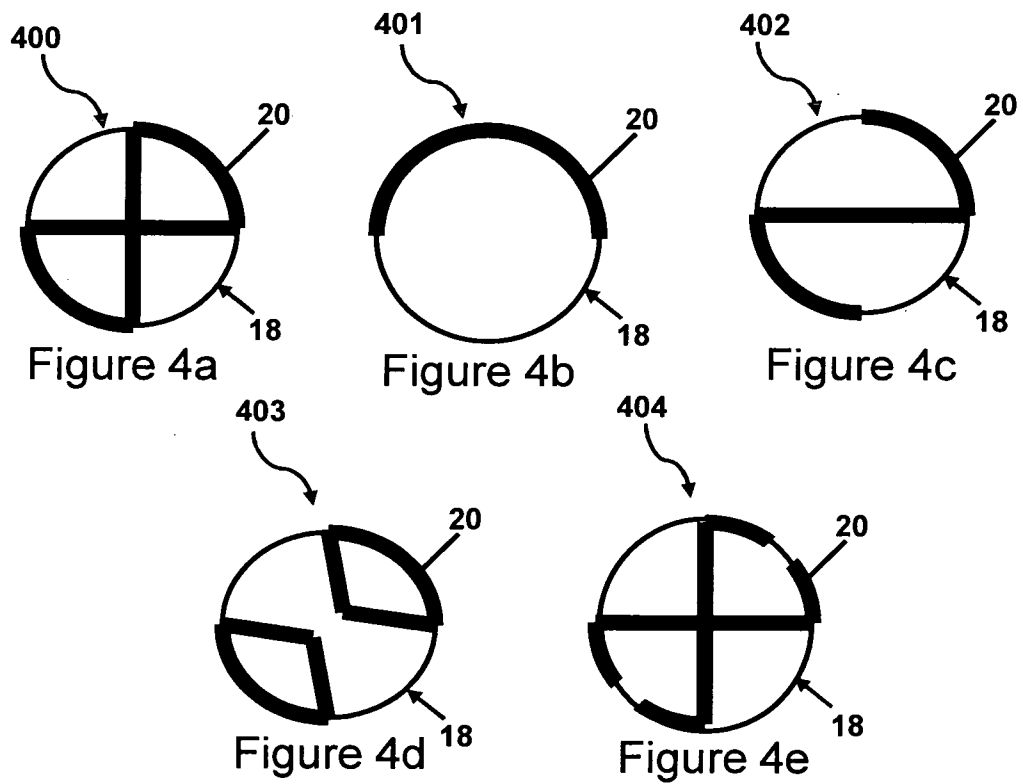


Figure 3



3/4

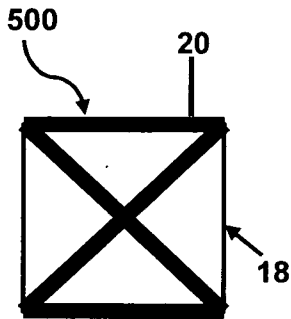


Figure 5a

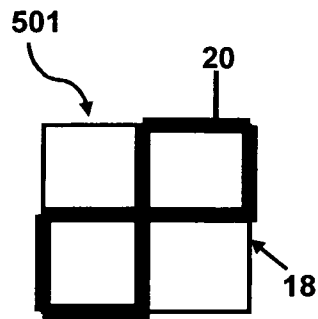


Figure 5b

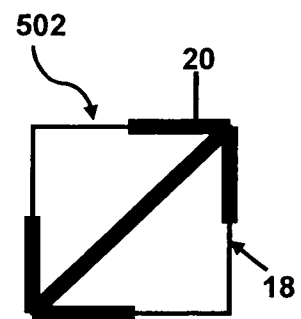


Figure 5c

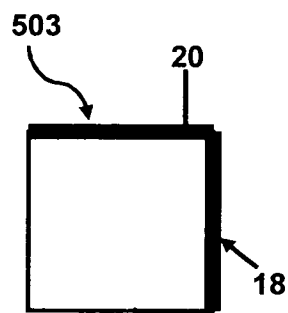


Figure 5d

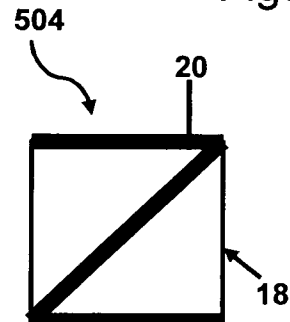


Figure 5e

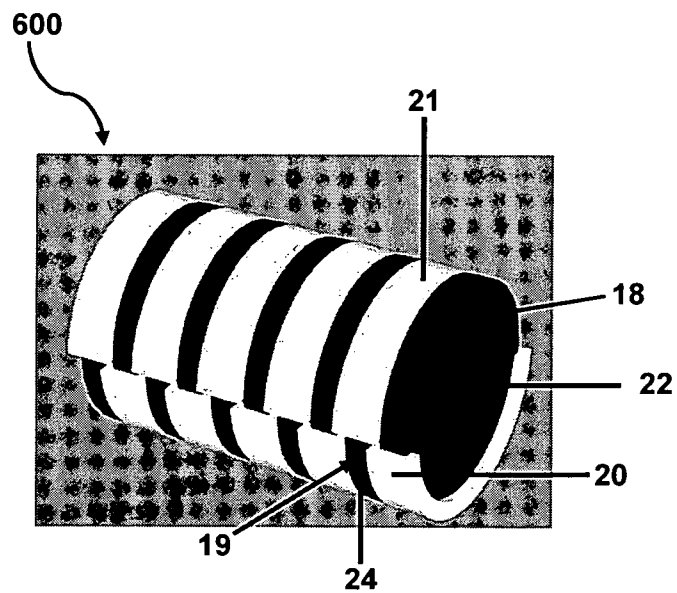


Figure 6

4/4

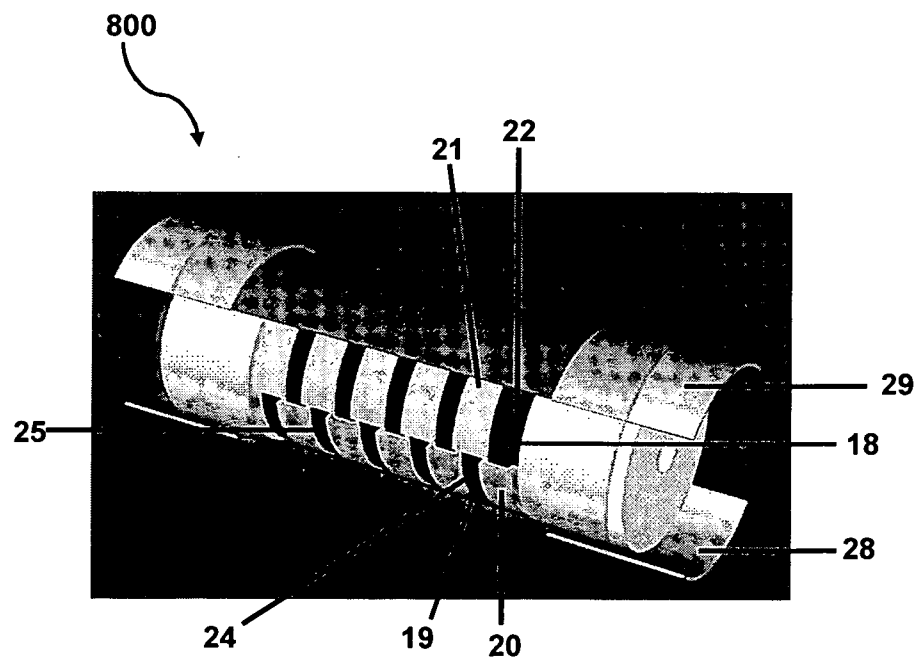
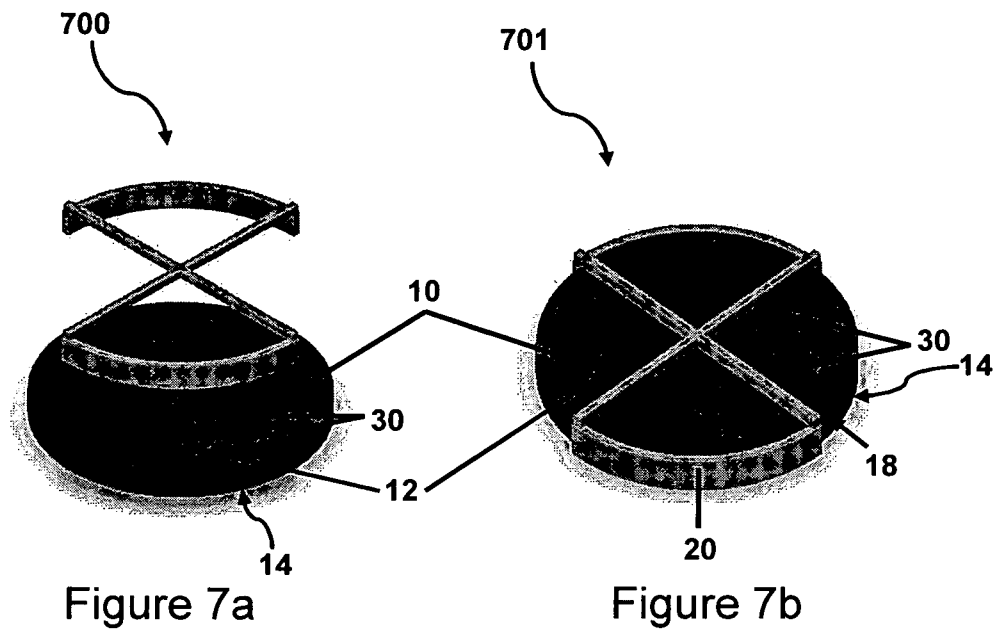


Figure 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2008/012954

A. CLASSIFICATION OF SUBJECT MATTER
INV. C02F1/461 C02F1/469

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)
C02F H01G

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

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 415 768 A (ANDELMAN MARC D [US]) 16 May 1995 (1995-05-16) column 5, line 16 - line 32; figures 5-12 column 10, line 7 - line 40 column 11, line 4 - line 25	1-16
A	WO 2004/089832 A1 (NEW EARTH SYSTEMS INC [US]; BRADLEY KIRK D [US]) 21 October 2004 (2004-10-21) page 16, paragraph 3; claims 1-40; figure 16	1-16
A	US 3 859 195 A (WILLIAMS JOHN M) 7 January 1975 (1975-01-07) claims 1-9; figures 1-5	1-16

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search

31 March 2009

Date of mailing of the international search report

06/04/2009

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2008/012954

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
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