



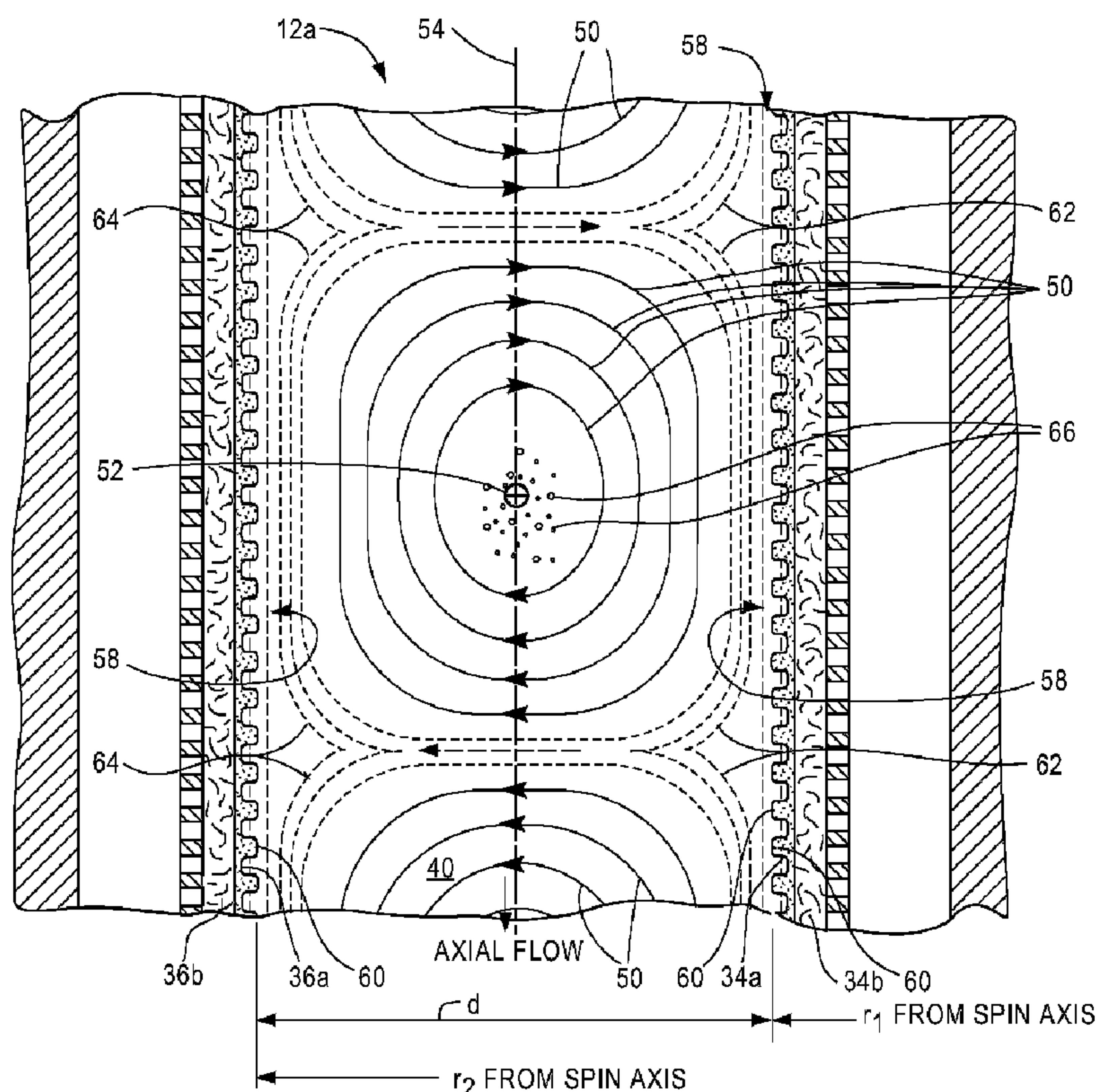
(86) Date de dépôt PCT/PCT Filing Date: 2010/06/25
(87) Date publication PCT/PCT Publication Date: 2010/12/29
(85) Entrée phase nationale/National Entry: 2012/12/14
(86) N° demande PCT/PCT Application No.: US 2010/039885
(87) N° publication PCT/PCT Publication No.: 2010/151716
(30) Priorités/Priorities: 2009/06/26 (US61/220,583);
2010/05/20 (US12/800,658); 2010/05/20 (US12/800,709);
2010/05/20 (US12/800,672); 2010/05/20 (US12/800,657);
2010/05/20 (US12/800,710)

(51) Cl.Int./Int.Cl. *H01M 8/04* (2006.01),
H01M 8/06 (2006.01), *H01M 8/08* (2006.01),
H01M 8/10 (2006.01)
(71) Demandeur/Applicant:
GLOBAL ENERGY SCIENCE, LLC, US
(72) Inventeurs/Inventors:
FISCHEL, HALBERT, US;
LUBIN, PHILIP MICHAEL, US;
LUBIN, DANIEL TIMOTHY, US
(74) Agent: NORTON ROSE CANADA
S.E.N.C.R.L., S.R.L./LLP

(54) Titre : CELLULES CHIMIQUES ET ELECTROCHIMIQUES UTILISANT DES ECOULEMENTS DE VORTEX DE TAYLOR

(54) Title: CHEMICAL AND ELECTROCHEMICAL CELLS UTILIZING TAYLOR VORTEX FLOWS

FIG. 2C-1



(57) **Abbrégé/Abstract:**

Chemical and electrochemical cells (10) such as fuel cells (12), fuel reformers (14) and batteries (B10) with rotating elements or electrodes (34, 24) that generate Taylor Vortex Flows (28, 50) and Circular Couette Flows (58) in fluids such as electrolytes and fuels are disclosed.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau(43) International Publication Date
29 December 2010 (29.12.2010)(10) International Publication Number
WO 2010/151716 A3

(51) International Patent Classification:

H01M 8/04 (2006.01) H01M 8/10 (2006.01)
H01M 8/06 (2006.01) H01M 8/08 (2006.01)

(21) International Application Number:

PCT/US2010/039885

(22) International Filing Date:

25 June 2010 (25.06.2010)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

61/220,583	26 June 2009 (26.06.2009)	US
12/800,658	20 May 2010 (20.05.2010)	US
12/800,710	20 May 2010 (20.05.2010)	US
12/800,657	20 May 2010 (20.05.2010)	US
12/800,672	20 May 2010 (20.05.2010)	US
12/800,709	20 May 2010 (20.05.2010)	US

(71) Applicant (for all designated States except US): **GLOBAL ENERGY SCIENCE, LLC** [US/US]; 4170 Mariposa Drive, Santa Barbara, California 93110 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **FISCHEL, Halbert** [US/US]; 4170 Mariposa Drive, Santa Barbara, California 93110 (US). **LUBIN, Philip Michael** [US/US]; 3156 Calle Fresno, Santa Barbara, California 93105-2773 (US). **LUBIN, Daniel Timothy** [US/US]; 3156 Calle Fresno, Santa Barbara, California 93105-2773 (US).

(74) Agent: **CURBELO, Pamela, J.**; Cantor Colburn LLP, 20 Church Street, 22nd Floor, Hartford, Connecticut 06103 (US).

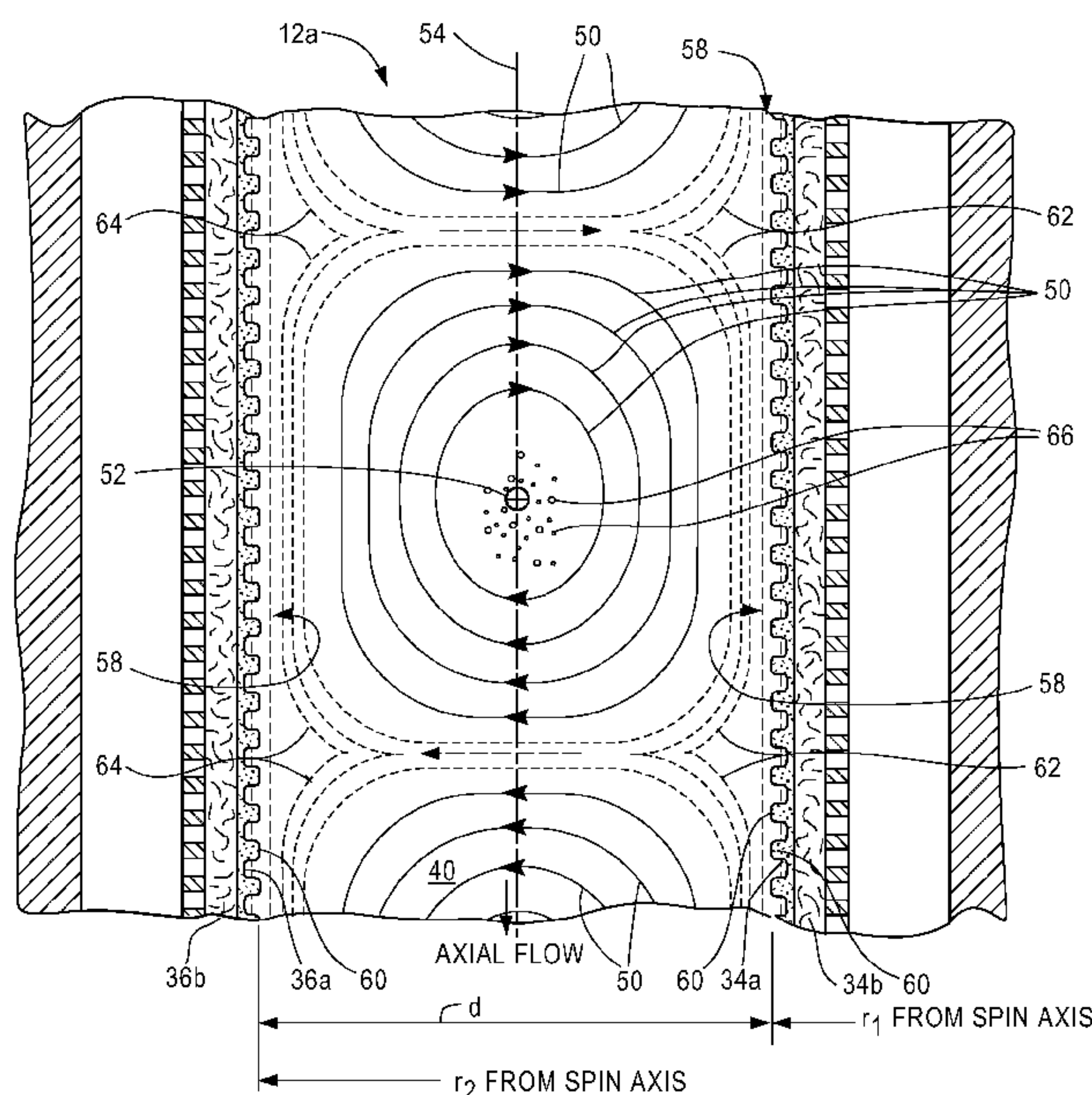
(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG,

[Continued on next page]

(54) Title: CHEMICAL AND ELECTROCHEMICAL CELLS UTILIZING TAYLOR VORTEX FLOWS

FIG. 2C-1



(57) Abstract: Chemical and electrochemical cells (10) such as fuel cells (12), fuel reformers (14) and batteries (B10) with rotating elements or electrodes (34, 24) that generate Taylor Vortex Flows (28, 50) and Circular Couette Flows (58) in fluids such as electrolytes and fuels are disclosed.

WO 2010/151716 A3

ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

- *with international search report (Art. 21(3))*
- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

Declarations under Rule 4.17:

- *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

(88) Date of publication of the international search report:

5 May 2011

DESCRIPTION

**CHEMICAL AND ELECTROCHEMICAL CELLS
UTILIZING TAYLOR VORTEX FLOWS**

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This patent application claims the benefit of U.S. Provisional Application No. 61/220,583 filed 26 JUN 2009 by Halbert Fischel, which is incorporated herein by reference.

[0002] This application is related to Halbert Fischel's following United States of America applications filed on 20 MAY 2010:

Case A: *Electrochemical Cells Utilizing Taylor Vortex Flows*, Application Serial No. US 12/800,658;

Case B: *Fuel Reformers Utilizing Taylor Vortex Flows*, Application Serial No. US 12/800,710;

Case C: *Chemical Process Accelerator Systems Comprising Taylor Vortex Flows*, Application Serial No. US 12/800,657; and

Case D: *Direct Reaction Fuel Cells Utilizing Taylor Vortex Flows*, Application Serial No. US 12/800,672; and

Case E: *Dynamic Accelerated Reaction Batteries*, filed Application Serial No. US 12/800,709 with Philip Michael Lubin and Daniel Timothy Lubin.

All of these applications have been assigned to the same assignee. These applications are incorporated herein by reference.

**STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR
DEVELOPMENT**

[0003] Not Applicable

THE NAMES OF PARTIES TO A JOINT RESEARCH AGREEMENT

[0004] Not Applicable

INCORPORATION-BY-REFERENCE OF MATERIAL SUBMITTED ON A COMPACT
DISC

[0005] Not Applicable

BACKGROUND OF INVENTION

Field Of The invention

[0006] This invention is in the field of chemical cells, including those used to convert chemical energy into electrical energy (e.g., fuel cells, batteries, flow cells), having means to provide relative motion between a chemically-active surface, such as an electrode and a fluid such as an electrolyte – including means for rotating a rotatable catalytic surface such as an electrode (U.S. Class 429/67-69, Int. Class H01M), to achieve accelerated chemical reaction rates promoted by high shear rates, such as those induced by *Circular Couette Flows* (CCF) generated by *Taylor Vortex Flows* (TVF).

Description Of Related Art

[0007] Chemical cells, such as fuel reformers used to extract H₂ from hydrocarbon compounds, are well known. Electrochemical cells, such as fuel cells, batteries and flow cells used to convert chemical energy into electrical energy, also are well known. In general, cells comprise a chemically-active or catalytic surface interacting with a fluid (e.g, a fuel or an electrolyte) for the purpose of obtaining a desired reaction product (e.g., H₂) or electricity. For example, fuel cells comprise an anode electrode reactive with a hydrogen-based or reducing fuel (reductant) and a cathode electrode reactive with an oxidizer. The electrodes are separated from each other by an electrolyte fluid that transports, 1) protons from the anode to the cathode where they react with both the oxidizer and with electrons travelling from the anode through an external electrical circuit to the cathode to form a compound, such as water or 2) hydroxyl ions from the cathode to the anode to form water there.

[0008] Chemical cells rely on molecular kinetics, e.g., temperature, reactant concentration and catalysis to induce molecules to react at a catalytic surface. Prior art teaches that there are five principal methods to increase reaction rates and thereby increase output current. They are 1) raise temperature and/or pressure, 2) improve catalyst activity, 3) augment electrode surface activity by adding other forms of resonant energy to electrodes or to reactants (US Pat. No. 7,482,072 to, Brooks et al), 4) increase reactant transport rates to or from reaction surfaces (mass transport) and 5) raise the catalyst surface area / electrode area ratio. Nevertheless, prior art cells are reaching asymptotic limits where further improvement is modest in terms of cost.

[0009] Operational data for prior art fuel cell, battery and flow cell electric currents disclose that these currents do not exceed 1.0 ampere/cm^2 and generally are in a range of 0.4 to 0.8 ampere under load at about 0.75 volt. This equates to about 0.3 to 0.5 watt/cm² of anode or cathode surface. Some of the more common limits are imposed by a) mass-transport losses of ions moving through electrolytes, b) surface losses at catalysts caused by intermediate reaction products attracted to active sites, c) mass-transport losses of fuel, oxidizer and ions moving within electrodes to reach catalysts where they can react and d) overpotential decrement due to limited catalyst activity.

[0010] In most fuel cells, a proton exchange membrane (also known as a polymer electrolyte membrane or PEM) that is permeable to protons, but not to some fuels or oxidizers, is located within the electrolyte to prevent wasteful and dangerous *cross-over* of fuel and oxidizer within the electrolyte. The membrane causes both decreased conversion efficiency and increased loss of fuel or oxidizer.

SUMMARY OF THE INVENTION

[0011] Common beliefs about fundamental principles governing operation of chemical cells is that fluid interactions with catalytic surfaces must either be limited to low-shear rate, laminar flows or conversely be accelerated to rapid, turbulent flows. Each of these alternatives has its advocates; however, neither has been able to provide a significant operating or economic advantage over the other.

[0012] For fuel cells, there is a consensus that the PEM must be present to conduct ions selectively from one electrode to the other. That is false. Prior art PEMs are used to

prevent unprocessed fuel and oxidizer from crossing a gap between their facing electrodes and they must not concomitantly prevent at least one ion from crossing that gap. The presence of the PEM significantly increases the cell's internal resistance to ionic flow and consequently reduces the cell's current capacity. An ion's charge and direction is dictated by an internal cell balance for the external electron current. A fuel cell that does not incorporate any PEM is disclosed in Embodiment A, below.

[0013] Hydrogen gas is a preferred fuel for most fuel cells. Because pure hydrogen gas may be unavailable or inconvenient to handle, hydrogen-based fuels such as methane, methanol and ethanol provide feedstock to fuel reformers that provide H₂.

[0014] Prior art fuel reformers generally produce large quantities of CO₂ and CO as undesirable byproducts. H₂ acquired in this way has to be further purified for use as fuel in most fuel cells, with the exception of those based upon molten carbonate electrolyte. External fuel reforming adds complexity to a portable system. A chemical cell configured as a reformer invention is described as Embodiment B, below.

[0015] Some prior art electrochemical cells incorporate rotating, rotatable, or moving electrodes that generate flows to the electrode surfaces. However, these electrodes are found only in applications where an electrode is immersed in an electrolyte bath to expose it to an aggregation of a reductant, oxidizer and electrolyte. It is well known that use of electrode surfaces in such systems that produce turbulence are preferred to enhance constituent mixing, which is basically incompatible with operation of fuel cells.

[0016] This invention uses Taylor Vortex Flows ("TVF" - also known as *Taylor – Couette Flows*) in chemical cells to achieve enhanced reaction rates by a) reducing mass-transport losses, b) preventing fuel and oxidizer crossover, c) capturing reaction products that can degrade catalysts and electrolytes and d) eliminating those degrading reaction products from the cells, e) increasing temperature to reduce electrode overpotentials and raise reaction rates and f) permitting higher pressures and concentrations to accelerate reactions at both electrodes.

[0017] TVF can occur when a viscous fluid (e.g. electrolyte) is confined in a gap between two cylinders where one cylinder is rotating or rotatable with respect to the other. For low differential angular velocities, in terms of circumferential Reynolds number, R_c , the

flows are steady, purely azimuthal and known as *Circular Couette Flows*. Chemical process accelerator systems that comprise chemically-active surfaces and electrodes with high surface area/projected area ratios of catalytic surfaces to reactive chemicals that incorporate TVF to generate accelerated, high-shear-rate, stable, laminar are described in Embodiment C.

[0018] These chemical process accelerator systems make it practical to build direct reaction fuel cells that consume fuels without need of reformers, as disclosed in Embodiment D, below. Similarly, these accelerator systems also make it practical to build dynamic accelerated reaction batteries as disclosed in Embodiment E, below.

[0019] TVF occurs when a viscid fluid (e.g. fuel) is confined in a gap between two cylinders where one cylinder is rotating or rotatable with respect to the other. A viscid fluid is a viscous fluid that is capable of adhering or wetting an electrode or catalyst surface. A viscous fluid that cannot adhere or wet a surface is called an inviscid fluid. This disclosure describes viscid fuels and electrolytes; however, its teachings also apply to cells for reacting other chemicals.

[0020] For low differential angular velocities, in terms of circumferential Reynolds number, R_c , the viscid flow is steady, purely azimuthal and known as *Circular Couette Flow*. Catalytic surfaces described here use TVF that automatically generate accelerated, stable laminar flows of viscid fluids at the catalyst and the filtering surfaces. These laminar flows increase the rate of H_2 generation in gaseous fuel/catalyst reactions and facilitate removal of the H_2 through filter media.

[0021] TVF was first described by Sir Geoffrey Ingram Taylor in his seminal paper *Stability of a Viscous Liquid contained between Two Rotating Cylinders*, Phil. Trans. R. Soc. London (08 FEB 1923), Vol. 223 – A 612, pp. 289-343. It was a ground-breaking paper on stability of the Couette flow. He reported that when the differential velocity, between the opposing cylinder surfaces forming a gap, is increased to a range within observed minimum and maximum speeds, Couette flow becomes unstable. Then, a secondary steady-state is created that is characterized by contra-rotating, axisymmetric, toroidal vortices with unique properties. This secondary steady-state is known as TVF.

[0022] Mechanical systems generating TVFs are well known in the prior art of particulate filtration. For example, the following U.S. patents, hereby incorporated herein by

reference, describe systems employing TVFs for filtering blood without clogging a plasmapheresis membrane filter:

<u>#</u>	<u>Date</u>	<u>Title</u>	<u>Inventor</u>
4,755,300	07/1988	<i>Couette Membrane Filtration Apparatus ...</i>	<i>Fischel, R et al.</i>
4,808,307	02/1989	<i>Couette Membrane Filtration Apparatus ...</i>	<i>Fischel, R et al</i>
4,919,817	04/1990	<i>Blood Cell Washing Systems & Method</i>	<i>Schoendorfer et al</i>
5,034,135	07/1991	<i>Blood Fractionation System & Method</i>	<i>Fischel, H.</i>
5,053,121	10/1991	<i>Blood Cell Washing System & Methods</i>	<i>Schoendorfer et al</i>
5,194,145	03/1993	<i>Method ... For Separation of Matter ...</i>	<i>Schoendorfer</i>
5,376,263	12/1994	<i>Pump Control Apparatus ... Rotating ...</i>	<i>Fischel, H.</i>
5,464,534	11/1995	<i>Blood Fractionation System & Method</i>	<i>Fischel, H.</i>
5,738,792	04/1998	<i>Method For Separation of Matter ...</i>	<i>Schoendorfer</i>
5,783,085	07/1998	<i>Blood Fractionation Method</i>	<i>Fischel, H.</i>

[0023] Particulate filters are readily distinguished from chemical cells, such as fuel cells, because 1) the filters lack chemically-active surfaces and 2) the direction of flow of reactant fluids is diametrically opposite to that of chemical cells.

[0024] In particulate filters such as these blood filters, a fluid, such as blood, containing a suspended particulate, such as blood cells, is pumped through a gap between opposing cylinder walls. One wall, usually the outer, is solid while the other is porous. The porous wall usually incorporates filter media and rotates within the outer wall. Fluid penetrates the filter media on the inner wall where TVF-accelerated high-shear-rate laminar shear prevents particulates from entering and clogging the filter media pores. TVF trap the particulates and transport them to an exit from the gap to be purged from the system.

[0025] Chemical cells, such as fuel cells, of this invention comprise different structures and employ TVF in a different manner. For example, fuel cells incorporate porous anode and cathode electrodes separated by electrolyte. Fuel and oxidizer pass, respectively, from chambers behind their associated electrodes toward the electrolyte; but, do not react with each other in the electrolyte or with the opposite electrode because 1) electrolyte flow keeps them separated and 2) they are in this invention almost fully converted to ions within their respective electrodes. Fluid media, contaminants or reaction byproducts are not expunged from fuel or oxidizer entry chambers because they are eliminated when the electrolyte is recycled outside of the cell.

[0026] This disclosure describes systems and methods for management of any type of fluid chemical cells. Cells of this invention have reactant, reductant, oxidizer and ionic

conductivities that are orders of magnitude greater than prior art cells so that mass and ionic transfer time between electrodes and reductant/oxidizer/ion access to catalyst surfaces that have been a mass transport limitation for chemical reactions now are negligible.

[0027] For fuel cells incorporating PEM electrolytes, the dominant limitation on ionic conductivity is the rate at which a single ion dragging several water molecules can migrate through a polymer molecular structure while two phases; namely a) ions dissolved in liquid, and a gas can arrive at one electrode or b) water molecules and gas at a different electrode can attach to a third phase solid catalyst surface, react and depart as water (steam or condensed liquid) or ions in solution, respectively.

[0028] U.S. Patent No. 6,713,206 issued to L.J. Markoski et al and a paper by R. Ferrigno et al (JACS Communications, vol. 124, 2002, pp.12930-12931, "Membraneless Vanadium Redox Fuel Cell Using Laminar Flow") teaches that a laminar boundary layer on the electrode surface has a protective effect preventing fuel/oxidizer crossover. In order to maintain laminar flow in the cited art, electrolyte velocities must be kept sufficiently low so that the critical turbulent Reynolds Number, Re (not R_c), is not exceeded. Thus, prior art laminar flow shear-rates are less than 38,000 seconds⁻¹. The present invention of this disclosure succeeds because its cells have electrolyte velocities that result in much higher circumferential Reynolds Numbers, R_c , and laminar shear rates stabilized by generated TVFs. Because a requirement for laminar flow can be achieved at high laminar shear rates in excess of 114,000 seconds⁻¹ using TVF, as taught here, fuel cells of this invention achieve multiple orders of magnitude higher current densities than non-TVF laminar flow cells.

[0029] The controlling factor for laminar shear rates is the minimum value of the hydro-dynamically defined Taylor number, T_c above which desirable energetic vortices are fully established within the electrolyte or, in some cases, the gaseous fuel. Axial Poiseuille-type flow can be further imposed by virtue of recirculation. Also, there is a strong dependence of the critical T_c on the strength of the latter flow by way of its characteristic axial-flow Reynolds number, R_a .

[0030] Furthermore, there is a requirement to maintain laminar flow at electrochemical cell electrode surfaces while promoting TVF within the electrolyte. Care must be taken to restrict the circumferential Reynolds number, R_c , to non-turbulent values. A

set of distinct variables define a particular range of permissible operating parameters. These variables include predetermined ranges of: 1) temperature, 2) kinematic viscosity of the fluids being employed, 3) their respective rates of recirculation, 4) angular rotation speed, 5) surface characteristics of the electrodes and, 6) physical dimensions of the cell.

[0031] Given appropriate electrochemical cell operating parameters, neither gaseous reductants, oxidizers, gaseous reaction products nor particle precipitates of the redox reaction at the electrodes can penetrate the TVF. Consequently, reductant and oxidizer crossover is effectively prevented, even though reductant, oxidizer, reaction products and particulates are driven by forced convection directly through their respective porous electrodes directly toward TVF in the electrolyte. Only redox product ions in solution can enter the electrolyte and cross rapidly to the opposite electrode, which is an important feature of electrochemical cells utilizing TVF in electrolyte.

[0032] In the case of liquid reductants and oxidizers, such as used in direct methanol and borohydride fuel cells, unreacted liquid fuel or oxidizer should not enter the electrolyte in solution. Optimum results are obtained when residence times of the fuel and oxidizer spent within the catalyzed reaction zones of their respective electrodes exceed their corresponding reaction times to ensure that substantially all the material is processed before the electrode-permeating reaction products, including dissolved ions, enter recirculating electrolyte.

[0033] Fuel cells that use methanol, presently selling for US 12½¢/liter, as fuel would be an economical replacement for internal combustion engines and batteries in vehicles if cell power density could be increased. The Direct Reaction Fuel Cell (DRFC) of Embodiment D utilizing TVF overcome low performance of prior art Direct Methanol Fuel Cells (DMFCs) and Direct Alcohol Fuel Cells (DAFCs). These fuel cells can use 100% undiluted methanol and other fuels to achieve an exceptionally high power.

[0034] The present invention is a robust chemical cell containing a fluid between relatively rotating or rotatable, co-axial cylindrical chemically-active (e.g., catalysts, electrodes) surfaces that cause Taylor Vortex Flows (TVF) and Circular Couette Flows (CCF) within the fluid. TVF eliminates any need for a proton exchange membrane (PEM) to prevent crossover of fuel and oxidizer chemicals through fuel cell electrolytes. CCF reduce mass-transport and reaction-rate limitations at chemically-active surfaces.

[0035] It is therefore a first object of the present invention to provide a robust chemical cell that incorporates TVF and CCF to accelerate reactions at chemically-active cell surfaces.

[0036] It is therefore a second object of the present invention to provide a robust electrochemical cell that eliminates any need for a proton exchange membrane within the cell's electrolyte.

[0037] A third object of the present invention is to provide a robust electrochemical fuel cell and method for converting electrochemical energy into electrical energy through the use of TVF that captures and eliminates reaction byproducts and prevents crossover of fuel and oxidizer in the cells' electrolytes.

[0038] A fourth object of this invention is to provide criteria for pumping electrolyte into and out of an electrochemical cell at a rate that will optimize creation of TVF in the electrolyte.

[0039] A fifth object of this invention is to provide structure for an electrochemical cell that will optimize its performance as a fuel cell for converting chemical energy of a fuel into electrical energy that can be used to power an external electrical load.

[0040] A sixth object of this invention is to provide chemical cells that create dynamic flows within all fluid constituents to induce exceptionally high rates of mass transport to and from chemical reaction surfaces.

[0041] A seventh object of this invention is to provide electrochemical cells that create dynamic flows within all fluid constituents to increase catalytic electrode reaction rates.

[0042] An eighth object this invention to provide a robust fuel reformer and method for converting a hydrogen-containing fuel into separable H₂ through the use of TVF that capture and eliminate reaction byproducts and contaminants.

[0043] A ninth object of this invention is to provide high-shear-rate CCF at catalyst surfaces to promote increased reformer reaction rates.

[0044] A tenth object of this invention is to provide criteria for pumping fuel and inert make-up gas to maintain system pressure, into and reaction products out of a fuel reformer at a rate that will optimize creation of TVF in the fuel.

[0045] A eleventh object of this invention is to provide structure for a fuel reformer that will optimize its performance for extracting H₂ from a fuel and separating H₂ for removal and further use.

[0046] A twelfth object of this invention is to provide fuel reformers that create dynamic flows within all fluid constituents to induce exceptionally high rates of mass transport to and from catalytic members.

[0047] A thirteenth object of this invention is to provide oxygen with the make-up gas as may be required to keep catalyst surfaces free of adsorbed carbon.

[0048] A fourteenth object of this invention is to provide robust chemical process accelerator systems comprising catalysts and TVF that are optimized for use in chemical reactors for reducing surface-limiting and transport-limiting characteristics of the catalysts.

[0049] A fifteenth object of this invention is to provide chemical process accelerator systems that generate high-shear-rate laminar CCF at catalyst surfaces.

[0050] A sixteenth object of this invention is to provide catalysts, TVF and CCF that rapidly remove intermediate products from catalyst surfaces to increase reaction rates in chemical reactors.

[0051] A seventeenth object of this invention is to provide catalysts, TVF and CCF that promote chemical reactions that do not create undesirable intermediate products.

[0052] An eighteenth object of this invention is to provide catalyst compositions optimized for use with TVF and CCF in chemical process accelerator systems of chemical reactors.

[0053] A nineteenth object of this invention is to provide chemical process accelerator systems that bring reactant chemicals to catalyst particle surfaces in high-shear-rate laminar flows having dimensions in the range of 2–5 nanometers, exchange intermediate

reactants and then carry away with little delay ions, intermediate reaction products, fluids (e.g. water) or solids (e.g. carbon) that could reduce reaction rates or poison the catalyst particle surfaces.

[0054] A twentieth object of this invention is to provide chemical process accelerator systems that bring reactant chemicals to catalyst surfaces capable of operating at substantially elevated temperatures that achieve enhanced reaction rates with inexpensive catalysts.

[0055] A twenty-first object of the present invention to provide a robust electrochemical cell that eliminates any need for a PEM or any other selective ion-permeable membrane disposed between electrodes.

[0056] A twenty-second object of the present invention is to provide a robust electrochemical fuel cell and method for converting electrochemical energy into electrical energy through the use of TVF that capture and eliminate reaction byproducts and prevents crossover of fuel and oxidizer in the cells' electrolytes.

[0057] A twenty-third object of this invention is to provide structure for an electrochemical cell that will optimize its performance as a fuel cell for converting chemical energy of a fuel into electrical energy that can be used to power an external electrical circuit or load.

[0058] A twenty-fourth object of this invention is to provide Direct Reaction Fuel Cells (DRFC) that create dynamic flows within all fluid constituents to induce exceptionally high rates of mass transport to and from several redox chemical reactions.

[0059] A twenty-fifth object of this invention is to provide DRFC with low mass-transport-limiting and surface-limiting electrode characteristics.

[0060] A twenty-sixth object of this invention is to provide DRFC capable of operating at substantially elevated temperatures that achieve enhanced reaction rates with inexpensive catalysts.

[0061] A twenty-seventh object of this invention is to provide DRFC batteries that produce higher voltage electrical energy with lower losses.

[0062] A twenty-eighth object of this invention to provide a robust battery utilizing TVF and CCF to provide greatly increased mass transport of ions within the electrolyte and between electrodes.

[0063] A twenty-ninth object of the present invention is to provide a robust battery utilizing TVF and CCF to utilize greatly increased active or exposed electrode areas for a given cell volume exposed to electrolytes.

[0064] A thirtieth object of the present invention is to provide a battery that does not require any membrane disposed between electrodes.

[0065] A thirty-first object of the present invention is to provide a battery that can utilize a membrane, as when required for separating incompatible electrolytes, without increasing internal cell resistance.

[0066] A thirty-second object of this invention is to provide a TVF – CCF battery that is mechanically and electrically compatible with fuel cells, such as TVF – CCF fuel cells of the types disclosed in Embodiment A and Embodiment D.

[0067] A thirty-third object of this invention is to provide Dynamic Accelerated Reaction Batteries (DARB) that create dynamic flows within electrolytes to induce exceptionally high rates of mass transport to and from several redox chemical reactions.

[0068] A thirty-fourth object of this invention is to provide DARB with low mass-transport-limiting and surface-limiting electrode characteristics and dynamic forced convective flow of electrolyte through electrodes that have very high surface area volumetric concentrations.

[0069] An thirty-fifth object of this invention is to provide DARB in synergistic combination with a fuel cell.

[0070] These and other objects of this invention are more fully set forth in the following description of a preferred embodiment of this invention.

BRIEF DESCRIPTIONS OF THE SEVERAL VIEWS OF THE DRAWINGS

[0071] **FIG. 1A** is a fragmentary, cross-sectional view of a chemical cell showing a preferred embodiment as a fuel cell.

[0072] **FIG. 1B** is a magnified view of a portion of **FIG 1A** showing a portion of the cell's fuel cell cathode electrode.

[0073] **FIG. 1C** is a magnified view of a portion of **FIG 1A** showing a portion of the cell's reformer.

[0074] **FIG. 2A, FIG. 2B, FIG. 2C-1, FIG. 2C-2, FIG. 2C-3** and **FIG. 2D** are detailed illustrations of a Taylor Vortex Flows and Circular Couette Flows in an electrochemical cell.

[0075] **FIG. 2E** is a computer-simulated view of a catalytic surface.

[0076] **FIG. 3-1** is a cross-sectional view of a portion of an electrochemical cell fuel cell electrolyte chamber having Taylor Vortex Flows in the electrolyte.

[0077] **FIG. 3-2** is a cross-sectional view of a portion of an electrochemical cell reformer fuel chamber having Taylor Vortex Flows in the fuel.

[0078] **FIG. 4** is a log-log graph of Revolutions Per Minute (**RPM**) as a function of gap width, **d**, for a range or zone of operable conditions.

[0079] **FIG. 5A** is a cross-sectional view of portions of a fuel chamber of an external TVF fuel reformer chemical cell for production of H_2 .

[0080] **FIG. 5B** is a magnified view of a portion of **FIG 5A** showing a portion of the fuel cell's cathode electrode.

[0081] **FIG. 6A** is a log-log graph of Revolutions Per Minute (**RPM**) as a function of gap width, **d**, for a range or zone of operable conditions in a pyrolytic reformer for typical fuel gasses.

[0082] **FIG. 6B** is a log-log graph of Revolutions Per Minute (**RPM**) as a function of gap width, **d**, for a range or zone of operable conditions in a steam or partial oxidation reformer for typical fuel gasses.

[0083] **FIG. 7A** is a perspective view of a chemical reactor catalyst of this invention.

[0084] **FIG. 7B** is a perspective and magnified view of the surface layer of the catalyst of **FIG. 7A**.

[0085] **FIG. 7C** is a highly-magnified view of one embodiment of the catalyst surface layer of **FIG. 7B**.

[0086] **FIG. 7D** is a highly-magnified view of another embodiment of the catalyst surface layer of **FIG. 7B**.

[0087] **FIG. 7E** is a more highly-magnified view of the catalyst surface layer of **FIG. 7C**.

[0088] **FIG. 7F** is a highly-magnified view of one embodiment of an electrode surface for a battery.

[0089] **FIG. 8A** is a cross-sectional view from the top of hexagonal close-packed (HCP) catalyst protrusions similar to protrusions shown in **FIG. 7B** where the protrusion are not in contact and their centers are separated by a distance of $2a\check{r}$.

[0090] **FIG. 8B** is null.

[0091] **FIG. 8C** is a cross-sectional view from the top of hexagonal close-packed (HCP) catalyst protrusions similar to protrusions shown in **FIG. 7B** where the protrusions are in contact.

[0092] **FIG. 8D** is a cross-sectional from a side of HCP catalyst protrusions of **FIG. 8C** where they comprise hemispheres of radii $\check{r}$.

[0093] **FIG. 8E** is a cross-sectional from a side of HCP catalyst protrusions of **FIG. 8C** where they comprise hemispheres of radii $\check{r}$ and height $\check{r}/2$ that extend into CCF.

[0094] **FIG. 8F** is a cross-sectional from the top view of catalyst protrusions that have streamlined profiles that reduce turbulence.

[0095] **FIG. 8G** is a cross-sectional view from a side of catalyst protrusions composed of multiple catalyst layers.

[0096] **FIG. 9A** is a fragmentary, cross-sectional view of a preferred embodiment of a Direct Reaction Fuel Cell.

[0097] **FIG. 9B** is a magnified view of a portion of **FIG 9A** showing a portion of the cell's cathode electrode.

[0098] **FIG. 10** is a cross-sectional view of a preferred embodiment of a Direct Reaction Fuel Cell battery comprising a series of connected cells.

[0099] **FIG. 11A** is a fragmentary cross-sectional view of a first preferred embodiment of Dynamic Accelerated Reaction Batteries comprising a series of connected cells.

[0100] **FIG. 11B** is a magnified view of a portion of **FIG 1A** showing a portion of one of the battery's electrodes.

[0101] **FIG. 12** is a fragmentary cross-sectional view of a second preferred embodiment of a Dynamic Accelerated Reaction Battery comprising interdigitated electrodes.

[0102] **FIG. 13** is a fragmentary cross-sectional view of a third preferred embodiment of a Dynamic Accelerated Reaction Battery for comprising an ion-permeable membrane for use with incompatible electrolytes.

[0103] **FIG. 14** is a fragmentary cross-sectional view of a Dynamic Accelerated Reaction Battery incorporating a Direct Reaction Fuel Cell.

DETAILED DESCRIPTIONS OF THE INVENTION

Embodiment A: *Electrochemical Cells Utilizing Taylor Vortex Flows*

[0104] **FIG. 1A** and **FIG. 1B** are a cross-sectional views of essential features of a preferred embodiment of a chemical cell **10** of this invention configured as a combination fuel cell **12** and fuel reformer **14**. The reformer **14**, located within the fuel cell **12**, extracts H₂ gas from fuels, such as methane mixed with steam. The H₂ gas is subsequently used for powering the fuel cell portion **12** that converts H₂ and an oxidizer (e.g. O₂) into electrical energy and water. Extraction of H₂ in such an electrochemical cell is known as direct internal reforming (DIR) of fuel.

[0105] Reformer **14** comprises a fixed cylinder **16** having a porous reformer inner catalytic surface **18** on its impervious outer wall. Cylinder **16** is fixed to the frame of cell **10** by means not shown. Cylinder **16** may contain a heater (not shown) for providing thermal energy to the reformer's **14** endothermic fuel reforming chemical reaction. More commonly, heat is provided by the exothermic reaction of the fuel cell **12**.

[0106] Cylinder **16** is located within a reformer/fuel cell hollow cylinder **20** that rotates around fuel input tube **22**. The inner wall of cylinder **20** has a porous reformer outer catalytic surface **24**. Reformer catalytic surfaces **18** and **24** define a reformer fuel chamber **26** that is in fluid communication with fuel input tube **22**.

[0107] The reformer **14** is activated by pumping a fuel (from a source not shown), such as a mixture of gaseous methane and steam, through the fuel input tube **22** and causing the cylinder **20** to rotate at a rate adequate to generate TVF **28** in the reformer chamber **26**. Reforming will generate H₂, which will penetrate the reformer outer catalytic surface **24** while CO₂ may be carried out of the reformer chamber **26** through a vent that is not shown or allowed to pass through surface **24**. Other fuels (e.g. methanol, ethanol and sodium borohydride (α NaBH₄)) that can be reformed to extract hydrogen may also be used.

[0108] H₂ that penetrates the reformer outer catalytic surface **24** continues through reformer rotational cylinder porous wall **30** and passes into fuel cell **12**. The H₂, which is a reducing agent or reductant, enters the fuel cell **12** by penetrating through an inner or first porous metal surface **32**, which can be H₂-selective palladium, and then into porous anode electrode **34**. Multiple catalyst particles embedded within the pores of electrode **34**, as disclosed in Embodiment C, then react with the H₂ entering its pores to produce H⁺ ions at the electrode's outer or second surface layer **34'**. The surface layer **34'** is porous and

contains catalyst. The porous metal surface **32** both supports electrode **34** and conducts heavy electrical currents from it. Means for connecting the inner porous metal surface **32** and the anode electrode **34** to an external electrical circuit (e.g. a slip ring or rotary electrical interface) are not shown. Embodiment D discloses a multi-cell fuel cell that does not require slip rings or a rotary electrical interface between its electrodes and the external electrical circuit.

[0109] The fuel cell electrode **34** is within fuel cell **12** porous cathode electrode **36** that is secured to the inner wall of fixed porous cylinder **38**, which cannot rotate. A fuel cell fluid electrolyte chamber **40** is defined by space between the fuel cell's anode electrode **34** and cathode electrode **36** that, in this embodiment, has substantially parallel surface layers **34'** and **36'** that are separated to permit anode electrode **34** to rotate within cathode electrode **36**. The surface layer **36'** is the cathode electrode's **36** inner surface layer, is porous and contains catalyst. The electrolyte chamber **40** is in fluid communication with electrolyte input tube **42** that can be connected to a source (not shown) of electrolyte. Means for draining contents of any unreacted hydrogen or oxygen gas in the electrolyte chamber **40** are not shown. The cathode electrode **36** has an outer or first porous metal surface **44** that supports the cathode electrode **36** and conducts heavy electrical currents from it. Means for connecting the cathode electrode **36** to an external electrical circuit also are not shown.

[0110] Reformer **14** cylinders **16** and **20** and fuel cell **12** electrodes **34** and **36** are shown in the drawings as right-circular and coaxial; however, these attributes are not a requirement and other cylinder-like geometries (e.g. elliptical, conical, hyperbolic, irregular, different axes) may be employed so long as the surfaces do not come in contact. Also, it is practical to build a cell where the inner cylinder is fixed and the outer cylinder rotates or both cylinders rotate at different speeds or directions. All that is required is that one of the cylinders rotates relative to the other so that there is a rotational speed difference between the cylinders.

[0111] Generally, electrodes **34** and **36** and catalytic fuel reforming surfaces **18** and **24** are coextensive, both circumferentially and axially. The gaps between facing surfaces in chambers **26** and **40** may vary somewhat by imparting a slightly cylindrical-conical shape, not shown, to either or both surfaces in order to establish a uniform pressure in axially flowing fluid contained within these chambers **40** and **46**.

[0112] The outer or first porous metal surface **44** of the fuel cell porous cylinder **38** is in fluid communication with oxidizer manifold **46**. The oxidizer manifold is connected to oxidizer input tube **48** that can be connected to an oxidizer source (not shown). Preferred oxidizers include purified, O₂, air or a liquid such as hydrogen peroxide, depending on choice of fuel. The oxidizer penetrates through an outer or first porous metal surface **44** and then into porous anode electrode **36**. Multiple catalyst particles embedded within the pores of the electrode **36**, disclosed in Embodiment C, then react with the oxidizer entering its pores to produce OH⁻ ions at the electrode's inner or second surface layer **36'**.

[0113] The chemical cell **10** is operated to produce electricity for transmission to an external load (not shown) by a process comprising:

1. Pumping a reformable reductant, such as hydrocarbon fuel and steam, through fuel input tube **22** into reformer chamber **26**;
2. Pumping electrolyte through electrolyte input tube **42** into electrolyte chamber **40**;
3. Pumping an oxidizer, such as - but not limited to, O₂, hydrogen peroxide, air or O₂ extracted from air, through oxidizer input tube **48** into oxidizer manifold **46** and through the catalyzed reaction zone of electrode **36** so that the oxygen component is largely converted to O⁼ or OH⁻ ions that a) can enter electrolyte chamber **40** or b) either one of these ions can combine with H⁺ ions to form water that can enter electrolyte chamber **40**;
4. Rotating reformer hollow rotatable cylinder **20** at a rate or rotation adequate to cause –
 - i. fuel reformer **14** Taylor Vortex Flows **28** in reformer chamber **26**,
 - ii. fuel cell **12** Taylor Vortex Flows **50** in the fuel cell electrolyte chamber **40**, and

iii. H₂ from the fuel, and CO₂ produced by the reforming process not otherwise purged from the reformer chamber **26**, to pass through the catalyzed reaction zone of electrode **34** with sufficient residence time to produce H⁺ ions from essentially all the reformed H₂ fuel so that the H⁺ ions either pass into the electrolyte chamber **40** or combine with OH⁻ ions to form water;

5. Venting any residual CO₂ and unreacted fuel from the reformer chamber **26**; and
6. Draining electrolyte containing H₂O and any CO₂ gas created by the reformer's **14** and fuel cell's **12** chemical reactions, as well as any unreacted gas passing through electrode **36**, from the electrolyte chamber **40**.

[0114] Creation of the TVF **50** in the fuel cell **12** electrolyte chamber **40** provides four significant operational advantages, namely:

- ◆ Eliminating need for PEM to prevent fuel/oxidizer crossover;
- ◆ Creating exceptionally high-shear-rate laminar electrolyte CCF at anode electrode **34** and cathode electrode **36** surfaces to facilitate chemical reaction mass transport coupled with accelerated ionic transport between electrodes, all cooperating to promote faster chemical reactions and high electrical current densities;
- ◆ Scavenging reaction byproducts (e.g. water) with electrolyte circulation; and
- ◆ Providing direct access of trans-electrode fuel and oxidizer to catalyst surfaces.

These four principal advantages translate into higher power and energy densities in terms of both size and weight over prior art fuel cells. TVF **28** in the reformer **14** chamber **26** enhance fuel reforming by enhancing mass transport at catalytic surfaces **18** and **24**.

[0115] In every case, in accordance with the invention, fuel and electrolyte, whether or not recirculated for reuse, are contained within a chamber, **26** or **40**, having at least one

facing spinning surface. Rotation of the rotating or spinning rotatable cylinder **20** imparts energetic, but non-turbulent Taylor Vortex Flows **28** or **50** in the fuel or electrolyte immediately upon entry of the fluid into its respective chamber **26** or **40**.

[0116] When H_2 is used for fuel, DIR is not required and therefore the fuel reformer **14** is not needed. If the electrolyte is alkaline, then the TVF may collect water vapor in chamber **26** and the resulting mixture can be recirculated to release or capture steam and to recover any unused fuel. However, H_2 can be driven directly through the anode **34** at elevated pressure and temperature to produce higher power and water, as liquid or vapor, and pass out of chamber **40** with the electrolyte.

[0117] When H_2 is used for fuel and the electrolyte is an acid, the fuel does not need to be purged from chamber **26** because water only appears at the cathode electrode **36** and the only fluid in chamber **26** is H_2 .

[0118] **FIG. 1B**, **FIG. 1C**, **FIG. 2A**, **FIG. 2B**, **FIG. 2C** and **FIG. 2D** are more detailed and somewhat idealized illustrations of Taylor Vortex Flows (TVF) between one set of facing active surfaces layers – such as fuel cell **12a** electrode surface layers **34a** and **36a**, as well as reformer **14** shells **18** and **24**.. Referring to **FIG. 2A** and **FIG. 2B**, the vortex flows **50** resemble doughnuts or, more technically, tori of fluid that spin around their own axes **52**. These tori **50** spin axes **52** define planes that are perpendicular to the cross-section view plane of **FIG 2C**. **FIG. 2D** shows a torus **50** spin axis **52** in perspective. Vortex radii **54'** extend from the cell's spin axis **56** to the center **54** of electrolyte chamber **40a** between the respective stationary and spinning surface layers **34a** and **36a** (**FIG 2B**).

[0119] As shown in **FIG. 2B**, several vortices **50** form an array that extends along the full axial length of the electrolyte chamber **40**. Each vortex **50** is contra-rotating with respect to its adjacent vortex **50**. Diameters of vortices **50** are slightly less than the width of the electrolyte chamber **40** in order to accommodate CCF **58**, **59** shown in **FIG. 2C-1**, **FIG. 2C-2** and **FIG. 2D**, which surround the TVF **50**, **28** and are adjacent to the surfaces **18'** and **24'** and the electrode surface layers **34a** and **36a**. **FIG. 1B** also illustrates the CCF **58** in the fuel cell electrolyte chamber **40** and **FIG. 1C** also illustrates CCF **59** in the reformer fuel chamber **40**.

[0120] Of critical importance to the invention is the fact that the entire arrays of vortices **50, 28** are enveloped by a high-shear-rate laminar boundary layers **58, 59** (**FIG. 2C-1** and **FIG. 2C-2**) of spinning fluid almost fully covering each surface that encloses the arrays of vortices **50, 28**. Thin layers of fluid are moving with high laminar shear perpendicularly to the sectional plane of **FIG. 2C-1** and **FIG. 2C-2**.

[0121] **FIG. 2D** provides a perspective view of the relationship between the CCF **58** and the TVF **50** rotating around the TVF axis **52**. The CCF **58** are orthogonal to the TVF **50** and parallel to the TVF axis **52**. The CCF **58** encompass protuberances **60** that extend from the concave electrode **36** catalytic surface layer **36'** into the CCF **58**. A similar relationship is formed at the convex cylinder surface layer **34'** (not shown in **FIG. 2D**). The nanostructure of the protuberances **60** is illustrated in **FIG. 2E**, which will be described in detail in Embodiment C.

[0122] Referring to **FIG. 2C-1** for the fuel cell **12**, the CCF **58** adjacent the rotating or rotatable surface layer **34a** move most rapidly near the catalytic surface layer **34a** and least rapidly where CCF **58** transition to TVF **50** at **62**, which is a small distance from surface layer **34a**. Conversely, the CCF **58** are nearly static adjacent the stationary shell layer **36a** and move most rapidly where the CCF transition to TVF **50** at **64**, which is a small distance from the surface layer **36a**.

[0123] The high velocity differences of these laminar boundary layer CCF **58** and the very small distances over which they occur produce extremely high shear rates and consequently large mass transport coefficients. The invention takes further advantage of this very desirable condition by incorporating active catalytic surface layers **34'** and **36'** with protuberances **60** of catalytically-active material that extend into the high-shear laminar-flow streams **58** shown in **FIG. 2C-1** and **FIG. 2D** and disclosed in Embodiment C. This greatly increases the amount of catalytic surface exposed to the high shear flow. This same description also applies to CCF (not shown) at fuel reformer **14** catalytic surfaces **18, 24** where they are formed in conjunction with TVF **28** as shown in **FIG. 2C-2**.

[0124] The porous catalytic surface layers **34'** and **36'** are made of electrically conducting filamentary or nanoporous foam material (**FIG. 1E**) supported by heavy porous metal surfaces **34b** and **36b** for conducting large electrical currents. The metal surfaces **34**

and **36** may be easily coated with carbon or a high-molecular-weight compound (e.g. PTFE) to protect the metal from corrosive attack by or premature hydrolysis of some fuels (e.g. borohydrides) and to keep the electrolyte from penetrating past the surface layers **34a**, **36a**.

[0125] An important feature of the TVF is illustrated in **FIG. 2C-1** where particles and bubbles **66** are captured by TVF **50**. The particles **66** are from a precipitate, including water attached to the precipitate (e.g. NaBO₂) and bubbles are from either electrode surface layer **34a** or **36a**. The particles and bubbles **66** are not in actual solution as part of the electrolyte and are therefore subject to the flow dynamics just described. They will experience high pressure gradients caused by the fluid electrolyte TVF **50**. These high gradients appear in both the high-shear laminar CCF **58** and within the vortices **50**. They quickly drive the particles and bubbles **66** to the centers of the nearest vortices **50** where they remain trapped.

[0126] The same facts are true for particles **66'** and bubbles in the reformer **14** as shown in **FIG. 2C-2** where the CCF **58** adjacent the rotating or rotatable shell surface layer **24'** move most rapidly near the catalytic surface layer **24'** and least rapidly where CCF **58** transition to TVF **28** at **62**, which is a small distance from surface layer **24'**. Conversely, the CCF **58** are nearly static adjacent the stationary shell layer **18'** and move most rapidly where the CCF transition to TVF **28** at **64**, which is a small distance from the surface layer **18'**.

[0127] Vortices **50** move in axial flow through the electrolyte chamber **40**. The particles and bubbles **66** trapped within vortices **50** are forced out of the cell **12a** along with their host vortex **50**. Thus, TVF **50** constitute means for extracting unwanted contaminants **66** from the electrolyte. These unwanted contaminants **66** may include reaction precipitates, water, vapor, CO₂ and any gasses exiting either electrode, any of which can degrade the electrolyte. A similar process occurs for unwanted contaminants **66'** in the fuel reformer **14** where pyrolytic hydrocarbon cracking utilizes TVF to prevent fouling of catalytic surfaces, as described in Embodiment B.

[0128] The active electrodes **34** and **36** and the catalytic shells **18** and **24** have a particularly novel structure, to be described in conjunction with Embodiment C. These structures contribute to a 4-fold amplification of effective electrode area and are configured to facilitate laminar flows in adjacent fluids (fuel or electrolyte).

[0129] The high velocity differences of these laminar boundary layers CCF **58** and the very small distances over which they occur produce extremely high shear rates and consequently large mass transport coefficients. The invention takes further advantage of this very desirable condition by incorporating active catalytic surfaces **18'** and **24'** with the protrusions **60** of catalytically-active material that extend into the high-shear laminar-flow streams **58** shown in **FIG. 2C-2** and **FIG. 2D** and disclosed in Embodiment C. This greatly increases the amount of catalytic surface exposed to the high shear flow.

[0130] **FIG. 3-1** is a cross-sectional view of a portion of an electrochemical cell **12c** chamber **40c** having TVF **50c** in a fluid, which could be its electrolyte. One side of the chamber **40c** is a cylinder-like first porous surface **34c** that may or may not have catalytically active surface, at radial distance, from cell spin axis of rotation **56c** about which first porous surface **34c** is caused to spin at an angular rate, Ω_1 . The other side of the chamber **40b** is a cylinder-like second porous surface **36c** that also may or may not have catalytically active surface, at radial distance, r_2 from cell spin axis of rotation **56c**. In this embodiment, the surface **36c** is fixed so that its angular rate, $\Omega_2 = 0$. A gap of thickness, $d = r_2 - r_1 > 0$ is defined between the two surfaces **34c** and **36c**. As used herein, the term 'gap' is synonymous with the width of a chamber such as fuel reformer **14** chamber **26** or fuel cell **12** or **12c** electrolyte chambers **40** or **40c**.

[0131] **FIG. 3-2** is a cross-sectional view of a portion of an electrochemical cell fuel reformer **14** chamber **26** having TVF **28** in a fluid fuel. As **FIG. 3-2** and **FIG. 3-1** are essentially similar, a description of **FIG. 3-2** is essentially similar to that of **FIG. 3-1** in the previous paragraph and will not be repeated.

[0132] As derived from Lathrop, Daniel P., et al, "Transition to shear-driven turbulence in Couette-Taylor flow.", Physical Review A, vol: 46, No. 10, (11/15/1992), pp; 6390-6404, the circumferential Reynolds number, R_c , for fluids contained in a gap between a moving member having rotational speed $\Omega_1 > 0$ and a fixed member having speed $\Omega_2 = 0$ is defined as:

$$R_c = \{\pi(\text{RPM})r_1d/30\nu\} \leq 10^4$$

Equation & Condition (1)

where:

$\Omega_1 = [2\pi(\text{RPM})/60]$ radians/second; and

$\nu = \text{kinematic viscosity} = \mu(\text{poise})/\rho(\text{grams/cc.})$

[0133] The condition that $R_c \leq 10^4$ is required for well-formed Taylor Vortex Flows so that fluid flow contained within the gap d be non-turbulent. The condition that these vortices exist in a form required by the invention can be written as the following lower limit for the critical Taylor number, T_c at which the characteristic vortices begin to form:

$$T_c = 2 r_1 (\pi/30)^2 d^3 (\text{RPM})^2 / \nu^2 (2 + \{d/r_1\}) \geq 1,715 (f\{R_a\}) \quad \text{Equation \& Condition (2)}$$

where:

$f\{R_a\}$ is a function derived in Chandrasekhar, S., "The hydrodynamic stability of viscid flow between coaxial cylinders", Proc. Nat. Acad. Sci., vol: 46, No. 1, (1960) pp. 141-3 and reported to be experimentally verified in R.J. Donnelly and D. Fultz, "Experiments On The Stability Of Spiral Flow Between Rotating Cylinders", *ibid.* No.8, pp; 1150-1154 [see their Fig.1 on page 1153]; and

R_a = the axial Reynolds number for Poiseuille-type axial recirculation flow through the gap, d .

[0134] A convenient way to express R_a is:

$$R_a = (dL/\nu)(\dot{U}/U) \quad \text{Equation (3)}$$

where:

L is the axial length of the active porous member(s),

U is the volume of fluid in the gap of thickness, d ,

$\dot{U}$ is the volumetric rate of axial flow from one end of the gap to the other, and

$\dot{U}/U$ is the rate of exchange of all the volume in the gap.

[0135] A convenient numerical expression for $f\{R_a\}$ is:

$$f\{R_a\} = 1.0 + (0.297)(\log_{10} R_a)^{4.04342} \quad \text{for } R_a > 1.0$$

$$f\{R_a\} = 1.0 \quad \text{for } 0 \leq R_a \leq 1.0$$

[0136] The two Conditions, (1) and (2), defined above should be met for optimum operation. They do not restrict design parameters to specific values; but rather, permit a fairly broad range of permitted values that can be chosen to satisfy other desirable conditions.

[0137] For example, it may be desirable to limit torque driving the spinning member so that it does not consume an appreciable fraction of the power generated. The thickness of the laminar high shear boundary layer on the facing surfaces of each of the porous members can be chosen for optimal mass transport characteristics. The equations that define these properties now follow.

[0138] Torque, T was defined in Lathrop, Daniel P. *et al*, "Transition to shear-driven turbulence in Couette-Taylor flow.", Physical Review A, vol: 46, No. 10, (15 NOV 1992), pp; 6390-6404 as:

$$T = (0.202)\rho v^2 L(r_1 R_c / d)^{5/3} \quad \text{Equation (4)}$$

[0139] Therefore, the power expended in spinning the inner member per cm^2 of surface area is:

$$W = (7.834)\rho v^{1/3} (r_1)^{7/3} (\text{RPM})^{8/3} \times 10^{-12} \text{ Watts/cm}^2 \quad \text{Equation (5)}$$

[0140] The respective stable boundary layer thicknesses, δ_1 and δ_2 are:

$$\delta_1 = (28.45)(v/\text{RPM})^{2/3} (r_1)^{-1/3} \quad \text{Equation (6a)}$$

$$\delta_2 = (1.29)(1+[d/r_1])\delta_1 \quad \text{Equation (6b)}$$

[0141] Neither the power expended, W , nor the boundary layer thicknesses, δ_1 nor δ_2 , depend on the gap dimension, d , between the two porous surfaces. δ_2 is a function of r_2 . The nominal shear rate without TVF would be $\Omega_1 r_1 / d$; but, the shear rate with TVF, for $\Omega_2 = 0$, is $\Omega_1 r_1 / \delta_1$ and $\Omega_1 r_2 / \delta_2$ for the two surfaces, respectively.

[0142] Thus, shear at each surface is multiplied by factors of:

$$\mathbf{d}/\delta_1 = 0.03515(\mathbf{v}/\text{RPM})^{-2/3}(\mathbf{r}_1)^{1/3}\mathbf{d}; \text{ and}$$

$$\mathbf{d}/\delta_2 = 0.775(\mathbf{d}/\delta_1)/(1+\mathbf{d}/\mathbf{r}_1).$$

If $\mathbf{d}$ is small compared to $\mathbf{r}_1$, then stable laminar shear at the outer stationary surface is only slightly less than at the spinning one.

[0143] **FIG. 4** is a log-log graph of Revolutions Per Minute (**RPM**) as a function of gap width, $\mathbf{d}$, for various operating conditions. A Zone of Operable Parameters **70** is bounded by the following six conditions for $0.0067 \leq \mathbf{d}/\mathbf{r}_1 \leq 1.0$ shown as plot lines:

- ◆ **72** - $R_c \leq 10^4$ and $\mathbf{r}_1 \geq 1$ cm;
- ◆ **74** - $R_c \leq 10^4$ and $\mathbf{r}_1 \leq 3$ cm (0.05 watt/cm²);
- ◆ **76** - $R_c \geq 2000$ and $\mathbf{r}_1 \geq 3$ cm;
- ◆ **78** - $R_c \geq 2000$ and $\mathbf{r}_1 \leq 3$ cm;
- ◆ **80** - $R_c \geq 2000$ and $\mathbf{r}_1 \geq 3$ cm (0.05 watt/cm²); and
- ◆ **82** - $T_c \leq 10^4$ and $\mathbf{r}_1 \geq 1$ cm.

Coordinates of typical operating values are shown as circles **84** in the Zone **70**.

[0144] US Patent No. 5,783,085 awarded to Halbert Fischel for a *Blood Fractionation Method* discloses a process for separating plasma from whole blood with TVF. It describes the nature of the vortices and the boundary layer thicknesses δ_1 and δ_2 , defined by Equations 6a & 6b, that envelop them and as illustrated in **FIGS. 2A, 2B, 2C** and **2D**.

[0145] The '085 patent blood plasma collection machine is used to remove undesirable suspended particulates from a fluid. The machine incorporates an inner spinning membrane filter to pass selectively fluid component to be separated from a particulate suspension without having particulates plug pores in the membrane.

[0146] A vortex will act on any particulate discontinuity with a pressure gradient that drives the particle to the low pressure center of the vortex axis. This occurs whether the particle is a buoyant bubble or denser component, such as particles and bubbles **66** of **FIG.**

2C-1 and particles and bubbles **66** of **FIG. 2C-2**. This is a feature that is especially useful for trapping carbon particles being discharged from the hydrogen cracking pyrolysis in the fuel reformer of Embodiment B in conjunction with **FIG. 5A** and **FIG 5B**.

[0147] Ions, on the other hand, are in solution and move hydrodynamically with the fluid or are driven by concentration differences through diffusion accelerated by shear forces. In the case of membrane filtration of suspensions, some particles will be forced against the membrane into the boundary layer which is often referred to as concentration polarization. Although the liquid component is trying to drag particles into and through the pores of the membrane, the extremely high shear rate, referred to above, creates what amounts to a fluidized bed of relatively, but not totally, compacted particles through which the liquid passes.

[0148] The maximum rate of liquid filtration (absent fully compacting the polarization layer that would drive the particles into and through the pores) is a linear function of the boundary layer shear rate. The reason membrane filtration of suspensions is so effective with TVF is due to that amplified boundary layer shear rate.

[0149] H^+ and OH^- ions are carried convectively by TVF from one electrode to the other in the fuel cell **12** (**FIG. 1A**), or **12a** (**FIG. 2C-1**) at a prodigious rate that is far greater than could ever be achieved in a solid polymer PEM or other stationary electrolyte. Once they have arrived near an electrode (e.g. **34** or **36**), they are subjected to exceptionally energetic shear in a laminar CCF **58** covering the electrode which, for most common electrolyte liquids, will be shown to be somewhat thinner than solid membranes or an otherwise stationary electrolyte.

[0150] It is this diffusion that transports ions and reaction products to and from the surface of the catalyst. Because the protuberances **60** of catalyst-bearing, porous electrode **36** material, illustrated in **FIG. 1B**, **FIG. 2C** and **FIG. 2D**, extend into the CCF laminar layer **58**, ions have both a shorter path to travel and a faster diffusion rate. The diffusion rate increases rapidly as a function of shear stress in a viscous fluid.

[0151] Electrolyte is able to penetrate deeper into the catalyst invested pore bed without flooding it by virtue of its flow profile around and over the protuberances **60** and flow and capillary pressure into their meso- and micro-pores, respectively. Neither

convective transport nor accelerated diffusion in combination with higher effective catalyst loading per unit electrode interface area is possible with prior art static electrolyte systems or chemical reaction vessels. Some numerical examples are now described.

[0152] In cases where acid or alkaline electrolytes will probably be most productively employed, the kinematic viscosity and specific gravity for them will be on the order of 10^{-2} stoke and about 1.5, respectively, at 100° to 200° C. Gasses such as CO_2 , methane, propane and air at 500 to 600° C and 10 bar (150 psi) have corresponding kinematic viscosities on the order of 0.06 to 0.08 stoke. The latter values will apply to parametric designs relating to examples of pyrolytic fuel cracking and steam reforming.

[0153] Methane, CH_4 , propane, C_3H_8 , methanol, CH_3OH , and ethanol, $\text{C}_2\text{H}_5\text{OH}$ are among the more suitable choices for fuels because they have high ratios ($> 2.5:1$) of hydrogen to carbon or there are at least three hydrogen atoms in a molecule. These fuels are widely available and are simple molecules to break. There are other hydrocarbons that have similar kinematic viscosity properties.

[0154] In the case of liquid electrolyte fuel cells, engineering procedure starts with calculation of a reasonable value for the parameters of Equation 5 to limit power burden to a small fraction of power generated. The density of gasses used in reaction vessels is low and therefore power burden should not be critical.

[0155] Construction of TVF chemical cells **10** requires mathematical analysis of physical design and operable parameters to select useful values that can be applied to a specific design or embodiment. When the fluid in question is liquid there is a special condition that needs to be imposed, namely, that the power required to spin the interior member not be too great a fraction of the power produced. Applying this condition to typical electrolytes used in fuel cells (e.g. **12**) and choosing a reasonable range of spinning member diameters (e.g. r_1 and r_2 of **FIG. 3-1** and **FIG. 3-2**) will yield an acceptable design and values within a 'Zone of Operable Parameters' **70** of **FIG. 4** where **RPM** is plotted on log-log axes against gap width, **d**.

[0156] Using the stated physical properties, **FIG. 4** displays logarithmic plots of Equation 5 for rotational power decrement of 0.05 watt/cm^2 used to spin the rotating or rotatable element (e.g. fuel reformer **14** rotating cylinder **20** of **FIG. 1A**). This is less than

1% of an expected power density of 5 to 10 watts/cm² in a TVF fuel cell. By comparison, conventional fuel cells produce only 0.5 to 1.0 watt/cm².

[0157] The 'Zone of Operable Parameters' area **70** of **FIG. 4** covers a range of non-turbulent Reynolds numbers, R_c , from 2000 to 10^4 and values of spinner radius (e.g. r_1 in **FIG. 3-1**) from about 1 cm to 3 cm. The range of permissible values of gap width, d , in relation to **RPM** lies between these plot lines **82**, **72**, **76** and **78**. In addition, (Conditions 1 & 2) are shown on the same graph as plot lines **74** and **80**. Together, these plot lines form a central 'Zone of Operable Parameters' **70**.

[0158] For example, one might want to limit the motor speeds to 1800 or 3600 RPM, which are standard 60 Hz electric motor speeds in North America. The range of suitable values for gap, d , appears in **FIG. 4** to be about 0.05 to 0.15 cm; but, a wider gap dimension, $d = r_2 - r_1$, facilitates higher critical Taylor number, T_c , and consequently higher allowed recirculation rates in accordance with the combined application of Equations 2 & 3. This is particularly useful in one configuration that removes water product with the recirculated electrolyte as to be described below. The 'Zone of Operable Parameters' **70** is understood to indicate practical; but not necessarily exclusive, system design parametric values within which useful TVF may be obtained without turbulence.

[0159] The plot lines **78** and **82** in **FIG. 4** bound minimum critical Taylor numbers, T_c , which slightly further limit the operable range of values. The boundary layer thicknesses for typical design parameters such as $d = 0.1$ cm and $r_1 = 2$ cm. are next calculated.

[0160] The following table provides some representative values:

<u>Motor Speed</u> <u>(RPM)</u>	<u>R_c</u>	<u>δ_1 (mm)</u>	<u>Shear Multiplier</u>
1800	3770	0.071	14.12
3600	7540	0.045	22.40

The range of boundary layer thickness values are somewhat less than, but nearly the same as, currently used in PEM solid polymer membranes. A major difference is the rate of shear-amplified diffusion compared to polymer interstitial transport.

[0161] For flow in a pipe as taught in the prior art, the shear rate in terms of the Reynolds number, R_a is:

$$S\{R_a\} = \{8\nu/D^2\}R_a$$

where D is pipe diameter and ν is kinematic viscosity in stoke. For laminar flow, R_a should be typically not more than 2300 and ν for electrolytes used in embodiments taught here is about 2×10^{-2} cm²/sec. Since spaces or gaps (e.g., the electrolyte chamber **40**) on the order of 0.1 cm are being analyzed, the high end shear rate for prior art laminar flow in a very small pipe or between very closely spaced plates is on the order of 37,000 seconds⁻¹.

[0162] Analysis of CCF is more complicated. Pure CCF, before stabilized by TVF, can remain laminar for R_c below 10^4 in terms of the nominally defined circumferential R_c . However, there is a multiplying effect of the shear rate at the surfaces which have been described as associated with CCF. Thus the nominal shear rate prior to the onset of TVF is limited to:

$$S\{R_c\} = \{\nu/D^2\}R_c$$

So the shear rate in laminar CCF prior to TVF is limited to around 20,000 seconds⁻¹. However, this value is multiplied by a factor of 6 to 30 with TVF to attain high- shear-rates on the order of 114,000 to 500,000 seconds⁻¹ or more.

[0163] Typical laminar boundary layer shear for a TVF chemical cell **10** results in a “Shear Multiplier”, as shown above, of as much as 15 to over 20-times the nominal value of $r_1\Omega_1/d$ for a conventional cell. For a TVF fuel cell **12** using liquid electrolyte, the value of $1/\nu$ will be on the order of 100 sec/cm² and gap, d , in the range of about 0.1 cm. R_a will be roughly 10 times the product of the length of a chamber such as **40** and volumetric exchange rate. If that product is on the order of 10 or 20 (e.g., a meter length can change volume every 5 to 10 seconds, etc.), then it is possible to hold R_a to 200 or less so that a value of $T_c > 10^4$ will be sufficient in nearly all cases to ensure the establishment of effective TVF **50**.

[0164] For fuel cell spin rates used in the examples, the Taylor number, T_c , is so far above a critical value that it is not necessary to restrict the volumetric recirculation rate as dictated by Equation 3. The volumetric recirculation rate will ultimately be determined by the molar rate of water production or reaction product gas load that needs to be extracted from the cell and exhausted from a separate chamber as steam and gas.

[0165] The boundaries of the Zone **70** also define several limiting conditions. For example, there are no useful designs for gap widths $d < 0.02$ cm or $d > 1.0$ cm or for spin rates $\Omega < 200$ RPM or $\Omega > 20,000$. Zone **70** displays practical values for a gap width $d = 0.1$ cm. and $1800 \leq \text{RPM} \leq 3600$. Larger gaps on the order of $0.2 \leq d \leq 0.3$ cm. will require spin rates $\Omega \approx 1,000$ rpm.

[0166] For the normalized parameter, $0.0067 \leq d/r_1 \leq 1.0$, spinner diameters should be in the range of $1 \leq r_1 \leq 6$ cm. Smaller or larger diameters will only have a small effect on the stated ranges and are unlikely to be preferred in most fuel cell **12** applications.

[0167] Details of preferred catalytic surface layers (e.g. **34'** and **36'**) surface structures are provided in Embodiment C. Protuberances (e.g. **60** on the electrode surface layer **36'** as shown in **FIG. 1B**, **FIG. 2C-1**, **FIG. 2C-2** and **FIG. 2D**) should reach about half, to at most three-quarters, of the way into the laminar shear layer; but, not into the vortices **50** where they would be subjected to excessive viscous drag and consequent material deterioration or disruption of TVF. That layer does not exceed 0.005 cm. Therefore, the protuberances **60** should have a net height of about 0.00251 cm.

[0168] A plane geometric calculation shows that if $\check{r}$ is the radius of an idealized cylindrical shaped protuberance; then locating the protuberances **60** on the electrode surface layer **36'** in a typical hexagonal array on centers spaced approximately $2.5\check{r}$ apart will cover approximately one-half the electrode surface layer **36'** area with the protuberances **60**. This is explained in greater detail below and in Embodiment C.

[0169] If the height of the cylindrical portion is $2\check{r}$ to $4\check{r}$ and is capped by a hemispherical dome, then the total external surface area of the projection is in the range of 6 to $10\pi\check{r}^2$. Because the area of the portion of surface covered by the projection is $\pi\check{r}^2$, the area multiplier for half the area is simply 6 to 10 and the net area multipliers are 3.5 to 5.5 for an average projected area of 4.5 times the face area.

[0170] With a net height of about 4 times the radius or 0.0025 cm, the projections **88** have diameters of about 12.5 μm and are spaced on centers 15.625 μm apart. The electrode **36** surface will have an appearance and feel of 1000 to 1500 grit abrasive paper of a type used to polish stone.

[0171] **FIG. 2E** is a drawing made from a computer-simulated view of a catalytic surface (e.g. **18, 24, 34, 36**) fabricated from nanoporous metal foam or scaffold **86**. The view appeared as Figure 4 of Pugh et al, “Formation of nanoporous platinum by selective dissolution of Cu from $\text{Cu}_{0.75}\text{Pt}_{0.25}$ ”, J. Material Research, Vol. 18, No. 1, Jan 2003, pages 216-221. Coordinate vectors **x, y, z** are provided as a reference frame. The view covers a volume measuring 14 x 14 x 7 nm. Pugh et al used 0.28 nm pixel spacing in calculating their image, which is the atomic radius of a Pt atom.

[0172] Pugh et al were able to produce isotropic 3-dimensional open-pore-structure foam with 3.4 nm pores **87** surrounded by smaller diameter scaffold struts **88** (called “ligaments” by Pugh et al). Pugh et al estimated sizes by “taking chord length measurements on the image”. They used a process in which one element (e.g., copper) was removed from an alloy (e.g., $\text{Cu}_{0.75}\text{Pt}_{0.25}$) by selective dissolution (e.g., leaching) to yield a nanoporous metal foam sponge **86** that will absorb electrolyte.

[0173] Using the metal alloy face-centered-cubic structural geometry described by Pugh et al and by others (e.g., Erlebacher, J., “An Atomistic Description of Dealloying – Porosity Evolution, the Critical Potential and Rate-Limiting Behavior”, J. Electrochemical Society, Vol. 151, No. 10, 2004, pages C614-C626); the approximate relationship of open pore fraction, ρ_v to the chord length, l_c and diameter, D in Pugh et al is given by:

$$(1 - \rho_v) = (0.75\pi x^2 + x^3)/(1 + x)^3$$

where:

$$x = D/l_c, \text{ and}$$

$$(D + l_c) = \text{nominal pore size}$$

The higher power term cannot be ignored when D is a substantial fraction of l_c . The stated pore volume fraction is 0.75 based upon a starting Pt alloy concentration of 25% so that the chord diameter would calculate to approximately 2.0 nm for the smallest pore. The D/l_c ratio is 0.58, which is a function of foam sponge geometry and pore volume fraction; but, does not vary for larger pore size results reported by Pugh et al. These dimensions can be

increased by varying process parameters, such as de-alloying times, temperatures, applied voltages, solvents and alloy compositions.

[0174] The metal foam or scaffold **86** of **FIG. 2E** is open and permeable in 3-dimensions and has pores **87** of 5 to 15 nm contained by the scaffold struts **88**, which have smaller dimensions. Metal or metal alloy or organic catalyst particles (not shown) decorate the scaffold struts **88**. The catalyst particles are of about 2 to 7 nm in size for best surface area dispersion and catalyst activity. For fuel cells **12** and fuel reformers **14**, metals selected from the Platinum Group Metals (e.g. Pt, Ru) of the Periodic Table of the Elements and their alloys are preferred catalyst materials for the particles and the foam scaffold **86**.

[0175] Pugh et al described their metal foam pictured in their Figure 4 as an open pore structure having 3.4 nm or larger pores **87** and comprising comparably sized Pt struts **88**. Using $x = 0.58$ and $D = 2$ nm as calculated above, the ratio of exposed active catalyst area to projected electrode surface area is:

$$[3\pi x/(1+x)^2](T/P_D)$$

where:

$P_D = (D + 1c) =$ nominal pore **92** diameter,

$T =$ depth thickness of the electrolyte flow permeating electrode surface layers **18, 24, 34', 36'** and

$D =$ diameter of the nanostruts **88** forming the pores **87**.

In a 100 micron thick electrode having 75% open pore volume, 3.4nm pores **87** and 2.0 nm diameter struts **88**, the area multiplication factor is 41,000 cm² of exposed reactive electrode surface area per cm² of projected electrode.

[0176] By comparison, the formula for an equivalent packing volume of spherical particles is $6(1 - \rho_v)(T/D)$. Thus, the Pugh et al foam **86** has an exposed surface area comparable to spherical particles with equivalent Pt volume loading. While supported particles normally lose about half of their exposed area because of attachment requirements, the porous foam struts **88** are fully exposed to reaction kinetics. Consequently, bare

nanoporous foam **86** is at least as effective as a catalyst dispersion mechanism as supported particles of equivalent dimension; but, is a more stable structure.

[0177] Metal foam **86**, with an open pore volume of 75%, is more effective for the mass transport exposure of catalyst to TVF and CCF than supported catalyst particles. Even with pore **87** diameters of 25 nm, the active catalyst area ratio for a 100 micron thick catalyst layer is an unprecedented $8,750 \text{ cm}^2$ to 1 cm^2 of projected electrode area.

[0178] For anode surface layers **34'** and for reformer surface layers **18'** and **24'**, the Pt nanoporous metal foams **67** and **90** can be loaded with Ru particles made from a colloidal suspension of the appropriate salts as taught in the prior art. The foam **86**, containing Ru particles, can be heat-treated so that the particles are absorbed into the Pt struts **88** to form a foam of 50:50 Pt-Ru alloy. Alternatively, a 5 to 15 nm Pt porous foam **90** with 50:50 Pt-Ru particles of 2 to 5 nm size can be thermally attached by heat sputtering to the struts **88**. Pure Pt will work for oxygen cathodes.

[0179] For a direct reaction fuel cell anode of Embodiment D, the Pt nanoporous metal foam sponges **86** can be produced from an alloy having face-centered cubic geometry with a Miller Index of (1,1,1) and can be loaded with Ru or other catalytic particles **136** made from a colloidal suspension of the appropriate salts as taught in the prior art. The foam sponges **86**, containing Ru particles **136**, can be heat-treated so that the particles **136** are absorbed into the Pt struts **88** to form a foam sponge of 50:50 Pt-Ru alloy. Alternatively, a 5 to 15 nm Pt porous foam sponge **86** with 50:50 Pt-Ru particles of 2 to 5 nm size can be thermally attached by heat sputtering to the struts **88**. Pure Pt will work for oxygen cathodes.

[0180] These catalyst surface layers **14**, **18'**, **20**, **24'**, **34'**, **36'** of nanoporous foam or scaffolds **86** can be deposited on or secured to micro-porous metal (e.g., copper) substrates that will provide substantial strength and electrical conductivity for the catalyst surface layers **14**, **18'**, **20**, **24'**, **34'**, **36'**. The porous metal substrates may be easily coated with carbon or a high-molecular-weight compound, such as a polymer (e.g. PTFE), to protect the metal from corrosive attack by or premature hydrolysis of some fuels (e.g. borohydrides) and to keep the electrolyte from penetrating past the surface layers **14**, **18'**, **20**, **24'**, **34'**, **36'**.

[0181] The surface layers **14**, **18'**, **20**, **24'**, **34'**, **36'** comprising catalytic metal foams **67**, **90** can be operated safely in alkaline environment at elevated temperatures in the range of 250 to 350° C and at elevated pressures to achieve accelerated catalytic performance. The same structure and process can be used to build nanoporous catalytic layers from other metal foams **86**, such as gold, copper, tungsten and nickel.

[0182] The catalyst particles need a fluid or an electrolyte to wet, but not flood, them in a thin envelope of fluid or electrolyte so that chemical reactants can diffuse into the molecular fluid or electrolyte coating and react at the catalyst surfaces. For fuel reformers, the boundary layer thicknesses for typical design parameters are about 0.05 mm. For direct reaction fuel cells, the boundary layer thicknesses for typical design parameters are about 0.05 mm, which are somewhat less than the thickness of proton exchange solid polymer membranes. However, one difference in current density is due to the rate of shear-amplified diffusion in a TVF cell compared to polymer interstitial transport. Typical laminar boundary layer shear rate in a DRFC with TVF produces as much as 15 to 20 times the nominal ionic transport rate of a proton exchange membrane fuel cell (PEMFC).

[0183] Conventional electrodes used in current PEM fuel cells contain 2 to 5 nm Pt particles attached to approximately 40 nm diameter carbon spheres. These spheres tend to aggregate into 800 nm diameter clumps that are attached to porous carbon filament webs that conduct electrons to bi-polar plates. If these same catalyst particles and clumps are held in the nanoporous foam **86**, then the longest or deepest shear-enhanced diffusion path for ions or other reactants to reach active catalyst is about 400 nm. By comparison, a typical electrode applied to a PEM, which transports ions by dragging water molecules through its polymer chain interstices, has a depth of about 30,000 nm.

[0184] When gas is disposed in a chamber (e.g. **26**) between rotating and stationary surfaces (e.g. **18** and **24** of **FIG. 1A**), several criteria that limit the range of design parameters for liquids, such as acid and alkaline electrolytes, are much easier to meet. While kinematic viscosities for methane, air and CO₂ are nearly an order of magnitude larger than for the liquids, corresponding specific gravities are somewhat more than two orders of magnitude lower. Since the expended rotational power density varies as $\rho v^{1/3}$, power required to spin the rotating or rotatable member (e.g. **24**) is very much less and can be ignored.

[0185] If there is a reason to construct a miniature device with $r_1 \approx 1$ cm and $d \approx 0.1$ cm, then the criteria for establishing TVF would be met for $RPM > 1000$. To ensure flows will not be turbulent, $1000 < RPM < 6500$.

[0186] For larger devices where $r_1 \approx 5$ cm and $d \leq 1$ cm, there is no difficulty satisfying the Taylor criterion. To avoid turbulence, the RPM should be < 1100 .

[0187] Boundary layer thickness calculations provide an estimate of ionic conductivity through TVF between electrodes. Clearly, the convective mass transport of the vortices themselves is orders of magnitude beyond relevance and will be ignored. For purposes of this calculation, the value of ionic conductivity in siemens/cm is a primary parameter and is understood to equal (amperes/cm²)/(volts/cm).

[0188] Actual performance of conventional solid-polymer PEM cell plate stacks provides ionic conductivity values that are typically $(0.6)/(0.65/t)$ where t is the thickness of the polymer membrane. Thickness is described in prior art as $0.005 \leq t \leq 0.01$ cm. Therefore, the ionic conductivity of a PEM for H^+ ions must be about 4.6×10^{-3} to 9.2×10^{-3} siemens/cm. Values of ionic conductivity for liquid electrolytes at low viscous shear are on the order of 20 to 100×10^{-3} siemens/cm. Given the shear stress multiple of the boundary layer as calculated above, it is clear that ionic diffusion driven by concentration gradients and linearly multiplied by shear rate at the catalyst surface is a further order of magnitude beyond typical cell electrolyte values. For these reasons, ionic conductivity can also be ignored as a limiting factor controlling ionic transport between electrode surface layers (e.g. **34'** and **36'**) in a TVF electrochemical cell.

[0189] The ionic conductivity calculations above indicate that rate limiting reactions occur mainly within the electrode surface layers (e.g. **34'** and **36'**). There is a relationship of current as a function of a dimensionless ratio of *reaction-time:residence-time*, where *reaction-time*, t_a , is the time required for chemical components of a fluid to react with the multiple embedded catalyst particle surfaces in an electrode to form ions and *residence-time*, t_r , is the time that the fluid is in an electrode surface (**34'** or **36'**) reaction zone.

[0190] The electrical current function becomes approximately asymptotic at a maximum current when $(10 \times \text{reaction-time}) < \text{residence-time}$. When *reaction-*

time:residence-time $\approx 1/10$, then mass transport within the electrode surface layers (e.g. **34'** and **36'**) does not limit the rate of current producing chemistry. Means for controlling entry of a chemical into pores of an electrode so that *reaction-time:residence-time* $< 1/10$ may include controls for adjusting fluid pressures in reformer chamber **26** or oxidizer manifold **46**.

[0191] This criterion can be applied to a Pt-surface-catalyzed reaction as follows:

$$W_a = \rho_m \cdot \gamma \cdot E_v \cdot NF(z/t_r) \quad \text{Equation (7a)}$$

$$t_a \leq \rho_m \cdot \gamma \cdot E_v \cdot NF(z/10 \cdot W_a) \quad \text{Condition (7b)}$$

where,

W_a = electrode interface watt density;

ρ_m = molar density of reactants, i.e., fuel and reacting ions;

γ = void fraction of the porous structure (usually about 60%);

E_v = voltage produced at the electrode (usually about 25% of the total at the cathode and the rest at the anode);

N = number of electrons produced in the reaction so that NF is the coulomb charge per mole of reactants,

F = Faraday constant

z = depth of the reaction zone at the interface surface of the electrode;

t_a = reaction time reactants require to produce ions; and

t_r = residence time that reactants spend in the reaction zone.

[0192] The criterion for achieving maximum current density, I_m , is for the time it takes for the molecules to react at the catalyst surface, t_a to be no more than 10% of t_r . Applying characteristic values for various fuel cell types to Equation 7b, it is apparent that there is an area-multiplying benefit in the design of TVF electrode surfaces (e.g. **34'** and **36'**). A projected value of 10 watts/cm² is achieved with a value of W_a of only 2.5 watts/cm².

[0193] Values of ρ_m , E_v , and N for the anode of a H_2/O_2 fuel cell, are typically, 0.035 moles/ml, 0.75 volts and 2 electrons, respectively. The value of z is half the diameter of an electrode protrusion or 6×10^{-4} cm. The result for t_a is ≤ 73 milliseconds.

[0194] For a direct methanol or borohydride fuel cell, described in Embodiment D, the comparable values are 0.0275 moles/ml, 1.24 volts and, respectively, 6 or 8 electrons yielding $t_a = 360$ milliseconds and 10 watts/cm^2 for methanol fuel cells and $t_a = 180$ milliseconds and 20 watts/cm^2 for borohydride fuel cells. These calculations are used to design appropriate electrode catalyzed reaction zone depths and related residence times at the anodes (e.g. **34**) of these high power fuel cells.

[0195] Residence time is controlled by driving fuels and oxidants directly through their respective electrodes having selected active catalyzed reaction zone electrode thickness at a prescribed flow rate. This is only possible if the electrolyte captures and conveys reaction products out of the fuel cell and fuel reformer as provided by this invention.

[0196] For cell spin rates used in the examples, the Taylor number, T_c , is so far above a critical value that it is not necessary to restrict the volumetric recirculation rate as dictated by Equation 3. The volumetric recirculation rate will ultimately be determined by the molar rate of water production or reaction product gas load that needs to be extracted from the cell and exhausted from a separate chamber as steam and gas.

Embodiment B: *Fuel Reformers Utilizing Taylor Vortex Flows*

[0197] Hydrogen extraction reformers, also known as fuel processors, fuel reformers or reformers, are used to extract hydrogen from hydrocarbon fuels such as methane (CH_4), methanol (CH_3OH), ethanol (C_2H_5OH), propane (C_3H_8), butane (C_4H_{10}), octane (C_8H_{18}), kerosene ($C_{12}H_{26}$) and gasoline as well as other hydrogen-bearing chemicals such as ammonia (NH_3) and sodium borohydride ($NaBH_4$). Hydrogen gas is extracted for a number of uses including lighting, chemical manufacturing and fuel for electrochemical fuel cells that generate electricity – as disclosed in Embodiment A, cited above – as well as conventional fuel cells.

[0198] Extraction of hydrogen has been accomplished by several methods. Pyrolysis or “cracking” uses catalysts at high temperatures to force breakage of hydrogen bonds to

other elements. Chemical processes at lower temperatures use additional agents and a catalyst to promote disassociation. Examples of the latter such as steam-reforming or partial oxidation use heat and water to promote oxidation reactions such as $\text{CH}_4 + 3\text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 + 2\text{H}_2\text{O}$ or $\text{CH}_3\text{OH} + \text{H}_2\text{O} \rightarrow 2\text{H}_2 + 2\text{CO}$ usually followed by the water shift reaction, $\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2$. All these reactions are reversible and do not go to completion in either direction unless one of the constituents (e.g. H_2) is continuously removed from the reformer. This occurs in direct internal reformulation (DIR) where H_2 is extracted as soon as it is separated to be used as fuel in a fuel cell (Embodiment A) or conveyed to external storage from a stand-alone reformer.

[0199] The most environmentally benign of the reformer processes is pyrolysis, which generates hydrogen gas containing carbon as soot (C). Other reforming processes, such as steam reforming, produce carbon monoxide (CO) or carbon dioxide (CO_2) as environmental contaminants in various concentrations depending upon specific attributes of the process employed. These gasses can poison catalysts.

[0200] Where fuel contains sulphur (S), sulphur or its compounds also become additional contaminants. Even where sulphur contaminants are present in low concentrations, they can foul or destroy catalysts and other components in chemical reactors. The same is true for free carbon. Some fuel cells chemical processes cannot tolerate even minute amounts of carbon, carbon monoxide, carbon dioxide or sulphur oxides so their reformers require external purifiers that add cost and complexity to the reformers.

[0201] Reformers have been a subject of continuous engineering and improvement for over one-hundred years. Objectives include a) higher reaction rates b) further elimination of contaminants without need of external purifiers, c) reduction of capital and operating costs, especially in connection with catalyst maintenance and d) diminution in size.

[0202] This chemical cell invention addresses all four of the goals described above. As example embodiments, this disclosure describes:

- ◆ A Direct Internal Reformer (DIR) used in conjunction with electrochemical cells utilizing Taylor Vortex Flows (TVF), such as those described in Embodiment A, and

- ◆ An external fuel reformer for use with lighting systems, chemical manufacturing reactors or electrochemical cells, such as fuel cells.

Although their processes and chemical reactants are somewhat different, they have similar structures and features – including a capability of having H₂ withdrawn simultaneously and rapidly with the chemical reforming reaction.

[0203] This invention uses Taylor Vortex Flows (“TVF” - also known as *Taylor – Couette Flows*), described in Embodiment A, in chemical cell fuel reformers to achieve enhanced reaction rates and product extraction efficiencies by a) accelerating mass transport of reactants at catalyst surfaces, b) simultaneously and rapidly removing target reaction products from the reaction, c) preventing strong carbon adhesion to catalyst surfaces, d) capturing reaction contaminants that can degrade both catalyst and filtering surfaces and e) eliminating those degrading reaction products from the reformers.

[0204] **FIG. 1A** is a cross-sectional view of essential features of a preferred embodiment of a chemical cell **10** of this invention, as taught in Embodiment A, cited above. **FIG. 1C** is an enlargement of a portion of **FIG. 1A**. The chemical cell **10** is configured as a combination fuel cell **12** and fuel reformer **14** that performs direct internal reforming (DIR).

[0205] The reformer **14** portion extracts H₂ gas from fuels, such as methane mixed with steam. The H₂ gas is subsequently used for powering the fuel cell **12** portion that converts H₂ and O₂ gases into electrical energy and water. Extraction of H₂ in such an electrochemical cell **10** is known as direct internal reforming of fuel.

[0206] Details of the reformer **14** that are described in the disclosure of Embodiment A, described above, will not be duplicated here.

[0207] Creation of the TVF **28** in the fuel reformer chamber **26** provides three significant operational advantages, namely:

- ◆ Creation of exceptionally high-shear-rate laminar CCF at the reformer’s fixed inner catalytic shell **18** and rotating or rotatable outer catalytic shell **24** to facilitate chemical reaction mass transport to promote faster chemical reactions;

- ◆ Withdrawal of H₂ simultaneously with the chemical reaction to permit the reaction to run to completion without any need to provide additional reactions for intermediate products; and
- ◆ Elimination of reaction byproducts (e.g. water, CO, CO₂ carbon dust and soot) with fuel and/or electrolyte circulation.

These three principal advantages translate into higher H₂ generation in terms of both size and weight over prior art fuel reformers.

[0208] An important feature of the TVF **28** is illustrated in **FIG. 2C-2** where particles **66** from a precipitate, including water attached to the precipitate (e.g. NaBO₂) and bubbles from either surface layer **18'** or **24'** produced during fuel reforming into reformer chamber **26** are drawn into the centers of vortices **28**. The particles and bubbles **66** are not in actual solution as part of the fuel and are therefore subject to the flow dynamics just described. They will experience high pressure gradients caused by the fluid electrolyte TVF **28**. These high gradients appear in both the high-shear laminar CCF **59** and within the vortices **28**. They quickly drive the particles and bubbles **66** to the centers of the nearest vortices **28** where they remain trapped.

[0209] Vortices **28** move in axial flow through the electrolyte chamber **26**. The particles and bubbles **66** trapped within vortices **28** are forced out of the reformer **14** along with their host vortex **28**. Thus, TVF **28** constitute means for extracting unwanted contaminants **66** from the electrolyte. These unwanted contaminants **66** may include reaction precipitates, water, vapor, CO₂ and any gasses exiting either electrode, any of which can degrade the electrolyte.

[0210] **FIG. 3-2** is a cross-sectional view of a portion of fuel reformer **14** chamber **26** having Taylor Vortex Flows **28** in a fuel. One side of the chamber **26** is a cylindrical (or slightly conical) first porous surface layer **18'**, that may or may not have catalytically active surface, at radial distance, r_1 from cell spin axis of rotation **56** about which first porous surface layer **18'** is caused to rotate at an angular rate, Ω_1 . The other side of the chamber **26** is a cylindrical (or slightly conical) second porous surface layer **24'** that also may or may not have catalytically active surface, at radial distance, r_2 from cell spin axis of rotation **56**. The surface layer **24'** is stationary in this embodiment and therefore it has an angular rate of

rotation $\Omega_2 = 0$. A gap of thickness, $\mathbf{d} = \mathbf{r}_2 - \mathbf{r}_1 > 0$ is defined between the two surface layers **18'** and **24'**. As used herein, the term 'gap' is synonymous with the width of the fuel reformer **14** chamber **26**.

[0211] As described for Embodiment A, the Fischel '085 patent awarded for a *Blood Fractionation Method* discloses a process for separating plasma from whole blood with TVF. It describes the nature of the vortices and the boundary layer thicknesses δ_1 and δ_2 , defined by Equations 6a & 6b, that envelop them and as illustrated in **FIGS. 2A, 2B** and **2C**.

[0212] Fuels such as methane, CH_4 , and propane, C_3H_8 , at 250°C to 700°C and 10 to 40 bar (150 to 600 psi) have kinematic viscosities on the order of 0.01 stoke to 0.03 stoke at the lower and higher temperatures and pressures. These values will apply to parametric designs for steam reforming and pyrolytic fuel cracking, respectively.

[0213] As for the fuel cells **12** of Embodiment A, construction of TVF chemical cell **10** fuel reformers **14** requires mathematical analysis of physical design and operable parameters to select useful values that can be applied to a specific design or embodiment. When the fluid in question is liquid there is a special condition that needs to be imposed, namely, that the power required to rotate the interior member not be too great a fraction of the power produced. Applying this condition to typical fluids used in fuel reformers (e.g. **14**) and choosing a reasonable range of rotating or rotatable member diameters (e.g. $\mathbf{r}_1$ and $\mathbf{r}_2$ of **FIG. 3-2**) will yield an acceptable design and values within a 'Zone of Operable Parameters' **70** of **FIG. 4** where **RPM** is plotted on log-log axes against gap width, $\mathbf{d}$. The 'Zone of Operable Parameters' **70** is understood to indicate practical; but not necessarily exclusive, system design parametric values within which useful TVF may be obtained without turbulence.

[0214] Typical laminar boundary layer shear for a TVF chemical cell **10** results in a "Shear Multiplier", as shown above, of as much as 15 to over 20-times the nominal value of $\mathbf{r}_1\Omega_1/\mathbf{d}$ for a conventional cell. For a TVF fuel reformer **14** using liquid fuel, the value of $1/\nu$ will be on the order of $100 \text{ sec}/\text{cm}^2$ and gap, $\mathbf{d}$, in the range of about 0.1 cm. R_a will be roughly 10 times the product of the length of a chamber such as **26** and volumetric exchange rate. If that product is on the order of 10 or 20 (e.g., a meter length can change volume every 5 to 10 seconds, etc.), then it is possible to hold R_a to 200 or less so that a value of $T_c > 10^4$ will be sufficient in nearly all cases to ensure the establishment of effective TVF **28**.

[0215] For the normalized parameter, $0.0067 \leq \mathbf{d}/\mathbf{r}_1 \leq 1.0$, spinner radii should be in the range of $1 \leq \mathbf{r}_1 \leq 6$ cm. Smaller or larger diameters will only have a small effect on the stated ranges and are unlikely to be preferred in most reformer **14** applications.

[0216] When fuel is disposed in a chamber (e.g. **26**) between rotating or rotatable and stationary surface layers (e.g. **18'** and **24'**), several criteria that limit the range of design parameters for liquids, such as methanol, ethanol or kerosene, are much easier to meet with a gas. While kinematic viscosities for methane are nearly an order of magnitude larger than for the liquids, corresponding specific gravities are somewhat more than two orders of magnitude lower. Since the expended rotational power density varies as $\rho v^{1/3}$, power required to spin the rotating or rotatable member (e.g. **24**) is very much less for methane and can be ignored.

[0217] If there is a reason to construct a miniature device with $\mathbf{r}_1 \approx 1$ cm and $\mathbf{d} \approx 0.1$ cm, then the criteria for establishing TVF would be met for **RPM** > 1000. To ensure flows will not be turbulent, $1000 < \mathbf{RPM} < 6500$.

[0218] For larger devices where $\mathbf{r}_1 \approx 5$ cm and $\mathbf{d} \leq 1$ cm, there is no difficulty satisfying the Taylor criterion. To avoid turbulence, the **RPM** should be < 1100.

[0219] **FIG. 5A** and **FIG. 5B** are cross-sectional views of portions of an external TVF fuel reformer **90** suitable for a) pyrolytic or b) steam or partial oxidation reforming of the hydrocarbon fuels, such as those enumerated above, and other fuels such as NH_3 and NaBH_4 . Note that **FIG. 5A** and **FIG. 5B** illustrate common structures that TVF reformers **90** share for each of these fuels. Balance-of-plant (BOP), as well as operating temperatures, pressures, chemical reactions, byproducts and contaminants capable of damaging catalytic surfaces or electrodes, are usually different for each of the different fuels.

[0220] The TVF fuel reformer **90** has one active cylindrical catalytic surface layer **92** having a radius $\mathbf{r}_2''$ forming an outer wall of fuel chamber **94**. The catalytic surface layer **92** is fixed in position. Cylindrical permeable filter layer **96** having a radius $\mathbf{r}_1''$ forms the inner wall of the fuel chamber **94** and is journaled for rotation within catalytic surface layer **92**. The distance between the surface layer **92** and the filter layer **96** constitutes a gap $\mathbf{d}''$ in which TVF **98** and CCF **99** are formed. The TVF fuel reformer **90** could also be constructed with a

rotating or rotatable catalytic surface layer **92** and a fixed filter layer **96** or both layers **92** and **96** could rotate without departing from the scope of this invention.

[0221] In one lower cost embodiment, catalytic surface layer **92** is constructed of catalytic nickel embedded in porous or otherwise permeable stainless steel. A choice of fuels may require use of a different catalytic material such as copper cermets, platinum, palladium or gold on ceramic or precious or transition metal alloys. Iron-chromium catalyst is effective to promote a shift reaction in steam reforming. It is practical to mix several catalysts on the same substrate to cause rapid sequential reactions to drive the overall reaction to the preferred result or end product. The accelerated efficiency of the many reactions that can be implemented without carbon fouling is a direct result of TVF and CCF and is one advantage provided by this invention. This will be described in more detail after the following description of TVF and CCF.

[0222] The catalytic surface layer **92** abuts optional heating element **100**, also shown in **FIG. 5B**, that provides thermal energy for an endothermic fuel reforming chemical reaction at the catalyst surface **92**. The heating element **100** is typically supported by a #316 stainless steel porous web **102**, which is porous to air, nitrogen or any inert gas.

[0223] Fuel for reforming (e.g. CH_4 or CH_3OH) enters the fuel chamber **94** through fuel entry port **104**. Makeup gas, comprising soot-free inert gas from fuel chamber **94** passing through fuel chamber exit port **106**, and additional external gas required to maintain pressure in fuel chamber **94** is pumped from BOP through makeup gas input port **108** and into makeup gas chamber **110**. The makeup gas passes from makeup gas chamber **110** through porous web **102** into fuel reformer chamber **94**. If a steam reforming and/or partial oxidation process is employed, then steam enters at makeup gas input port **108** along with such air supplying oxygen plus inert gas as required. For a basic pyrolysis process, make-up gas consists mainly of nitrogen or other inert gas plus just enough air/oxygen to prevent carbon adsorption on the catalyst surface layers **92**.

[0224] In all cases, the hydrogen formed by interaction of the fuel gas with the hot (e.g. 700°C for pyrolytic reforming) catalytic surface layer **92** passes through hydrogen-permeable filter layer **96** into hydrogen capture chamber **112** and exits at hydrogen chamber exhaust port **114**.

[0225] Because the catalytic surface layer **92** operates at about 700°C for pyrolytic reforming, the entering gasses should be preheated, preferably with the aid of a BOP heat exchanger that utilizes waste heat from another process such as a fuel cell. The catalytic surface layer **92** may be entirely heated by gasses entering at makeup gas input port **108** instead of the separate heating element **100**.

[0226] An electric motor **116** is coupled to cylindrical permeable filter layer **96** to cause it to rotate within cylindrical catalytic surface layer **92**. Boundaries of the Zones Of Operating Regions For A Pyrolytic TVF Reformer **118a** of **FIG. 6A** or Zones Of Operating Regions For A Steam Or Partial Oxidation TVF Reformer **118b** of **FIG. 6B** also define several limiting conditions for rotational speed **RPM** in terms of gap width **d''** for creating stable TVF in the external fuel reformer **90** fuel chamber **94**. The speed of rotation of permeable filter **96** and its protective surface layer **97** is dependent on a number of variables – including the input fuel, temperature and characteristics of the chemical reactor. Once the speed exceeds a minimum value, then the TVF **98** are generated in the chemical reactant, here the fuel, between surface layers **96** and **97** of **FIG. 5A**.

[0227] **FIG. 6A** and **FIG. 6B** apply to external fuel reformers **90** in general or specifically to the DIR section (e.g. **14**) of a fuel cell (e.g. **12**); however, the latter can only use steam with or without partial oxidation because of temperature limitations of fuel cell catalysts and electrodes. Because the densities and viscosities of the several gasses, including steam, vary considerably between the conditions of medium and high temperature reforming; it is necessary to treat pyrolysis at 700°C and steam at 250°C as separate cases.

[0228] Fuel viscosities range between $2-4 \times 10^{-4}$ poise while densities range between $1.4-2.8 \times 10^{-2}$ gm/ml at the temperatures of approximately 700° C and pressures of about 40-bars needed for pyrolysis. For DIR in a fuel cell as taught in Embodiment A, operating pressure is about 10 bars. Most practical engineering values can be obtained by using kinematic viscosities of 3×10^{-2} Stoke for pyrolytic reforming.

[0229] Most practical engineering values can be obtained by using kinematic viscosities of 3×10^{-2} Stoke for pyrolytic reforming and 1.0×10^{-2} Stoke for fuel cell DIR or steam or partial oxidation external reforming. Because fluid densities are low, rotation power consumption may be ignored.

[0230] **FIG. 6A** and **FIG. 6B** have been plotted for a range of rotating or rotatable filter surface layer **96** radii and display boundaries of Zones Of Operable Parameters For A Pyrolytic TVF Reformer **118a** ($1 \text{ cm} \leq r_1 \leq 15 \text{ cm}$) of **FIG. 6A** or Zones Of Operable Parameters For A Steam Or Partial Oxidation TVF Reformer **118b** ($1 \text{ cm} \leq r_1 \leq 3 \text{ cm}$) of **FIG. 6B** for the defined range of rotating or rotatable filter **96** radii r_1 . Fuel reformers can be constructed for different sizes that are outside of the range that has been described and will have different Zones of Operable Parameters. However, the plots in **FIG. 6A** and **FIG. 6B** illustrate the parametric selection protocol.

[0231] In the simplest application of these TVF fuel reformers **90**, namely, pyrolytic cracking, the hydrogen gas may be sufficiently pure that the rotating or rotatable porous filter layer **96** need only be made of gas permeable sintered metal or ceramic capable of withstanding temperatures to 700°C. In this case, no secondary filtering of the hydrogen gas is required because the only possible source of contaminants is leakage of trace amounts of makeup gas through internal seals protecting bearings for rotating or rotatable components. In other processes where the byproduct gas contains objectionable contaminants, the rotating or rotatable permeable filter layer **96** can be made from hydrogen-selective palladium, platinum/palladium or palladium alloy membranes.

[0232] For long term maintenance, it is preferable to introduce a small, continuous amount of oxidizing gas, such as air, into the make-up gas input port **108** and through the makeup gas chamber **110** to porous web **102** and catalyst surface layer **92** to oxidize any carbon adhering to the catalyst surface layer **92**. A specific catalyst should be selected for the fuel being reformed that will preferentially attract hydrogen atoms to its surface layer **92** to form a momentary metal hydride that breaks the carbon bond. This reaction will then release carbon into the flow stream so that the carbon will be drawn into TVF **98**. The reaction will also release the hydrogen through thermal dissociation. Some metal oxides will promote these reactions without additional oxygen. Other catalysts may also promote another reaction in which the oxygen momentarily bonds with H_2 to form water and then a water shift reaction uses the carbon to form CO_2 . Although most of the hydrocarbon bond-breaking will occur in the absence of direct carbon attachment to the catalyst surface **92**, these reactions will prevent carbon buildup as in a continuous self cleaning oven.

[0233] Another means for extracting attached carbon buildup from the catalyst surface layer **92** and into the flow stream where it is easily captured and disposed of by TVF **98** comprises mechanical transducers **122** (e.g. piezoelectric materials) vibrating at 50 to 150 kHz mechanically that are coupled to the catalytic surface layer **92**. These vibrations provide energy for self-cleaning of the catalyst surface layer **92**. Mechanical transducers **122** are easily attached to the catalyst surface layer **92** and facilitate the use of cheaper catalysts.

[0234] The outer active cylindrical catalytic surface layer **92** can be constructed from any of a wide variety of materials, depending upon the reforming process being used. Steam reforming catalysts may contain nickel. Pyrolytic cracking processes can incorporate a less expensive nickel-containing stainless steel.

[0235] Current state of the art systems employing nickel and nickel alloys are susceptible to very damaging carbon fouling issues that are hard to control. Commercially available nickel-alloy catalysts may also contain elements such as copper, potassium and molybdenum to reduce carbon-fouling difficulties; but, these alloys do not always reduce fouling to an acceptable level.

[0236] For direct pyrolysis, sintered stainless steel not necessarily containing nickel can be employed in the catalyst surface layer **92**. When used in a catalyst of a conventional fuel reformer, stainless steel increases the carbon fouling potential. In a TVF reformer **90**, carbon dust has little, if any, opportunity to adhere to the catalytic surface layer **92** because of high shear strength laminar CCF boundary layers **99** (**FIG. 5B**) at the surface layer **92** and because of a very strong negative pressure gradient toward the center of the gap **d''** of fuel chamber **94** between the facing porous surface layers **92** and **96** due to the high-laminar-shear CCF at the boundary layer **99**. Any small amounts of carbon that may adsorb to the catalyst surface layer **92** can be burned or vibrated away, as described above. The carbon dust is rapidly drawn radially inward through the boundary layer where the dust enters TVF **98**. Once inside TVF **98** the carbon dust will be instantly be trapped and moved to the center of the TVF **98** where the dust will be accumulated and carried away with the TVF **98**.

[0237] When a fluid is pumped axially from the entry port **104** to the exit port **106**, it does not flow through the TVF **98**. The TVF **98** move axially while fully retaining their

established form. Consequently, whatever enters and is trapped (e.g. carbon dust, soot, etc.) in the TVF **98** remains trapped as the TVF **98** move all the way to the exit port **106**.

[0238] The fluid media comprising the high-laminar-shear laminar CCF boundary layers **99** and TVF **98** are the fuel and the reactant gasses. These are rapidly and repetitively exchanged between porous surface layers **92** and **96** by convective transport and boundary layer diffusion in the same manner as dissolved ions and water in a fuel cell **12** in accordance with this invention. These factors substantially accelerate fuel reforming per unit area of active surface over any method of current art.

[0239] In TVF fuel reformers **90**, it is desirable to maintain pressure in fuel chamber **94** to support and carry the carbon dust-laden TVF **98** to exit port **106** as fuel is converted to hydrogen and dry carbon. If all the hydrogen is removed, except for contaminants that might oxidize carbon, then there would be little or no gas left in fuel chamber **104**. For this reason, a neutral gas is introduced through makeup gas input port **108** and makeup gas input chamber **110** through the porous catalytic surface layer **92** to maintain gas pressure within the fuel chamber **94**.

[0240] BOP contains a heat exchanger (not shown) for extracting heat energy from hot byproduct gas passing through fuel chamber exit port **106** to raise the temperature of makeup gas entering makeup gas input port **104**. The cooled byproduct gas is filtered to safely deposit entrained carbon dust or soot in a chamber (not shown) designed to trap the carbon dust and recant the gas for recirculation as makeup gas. These external facilities are BOP components.

[0241] Recirculated gas can be pure nitrogen or a noble gas and it can include fresh pressurized air and/or steam that serve a different purpose. For example, some fuels are processed using steam reforming or partial oxidation reactions that make CO₂ or CO that enters a subsequent shift reaction to become CO₂. In some cases, air supplies oxygen to react with the fuel in order to heat and maintain the temperature of the catalytic surface **92** where the fuel → H₂ reaction takes place. It is common practice to limit the amount of oxygen fed to a combustible fuel mixture in order to avoid explosion hazard and to employ steam vapor as an additional protection. As described above, recirculation maintains gas pressure and allows for the measured introduction of air.

[0242] TVF fuel reformers **90** are unique because a combination of these normally separate processes can be carried out simultaneously so that the fraction of C/CO₂ produced per mole of hydrogen extracted can be adjusted. Furthermore, the limited oxygen partial pressure passing over hot surfaces of the catalyst surface **92** will continuously oxidize any carbon that manages to adhere. This feature eliminates a necessity of periodic shut down and maintenance.

[0243] For these additional reactions the catalyst surface layer **92** may comprise alloyed nickel crystallites, copper cermets, platinum, palladium or gold on ceramic. Iron-chromium catalyst is effective to promote the shift reaction in steam reforming and it is entirely possible to mix various catalysts on the same substrate to cause rapid sequential reactions to drive the overall reaction to the preferred result or end product.

[0244] The accelerated efficiency of the many simultaneous reactions that can be implemented without fear of carbon fouling or catalyst damage is a direct consequence of the advantages of TVF fuel reformers **90**. This permits a reduction in the amount of prepared catalytic surface layer **92** area required to process a given amount of fuel. However, to take full advantage of TVF **98**, the catalyst surface layer **92** loading factor per unit area of roughened active surface should be increased over that which is normally practiced. Therefore, the catalyst surface layer **92** cost may be the same as that for conventional fuel reformers of the same size; but, smaller capacity.

[0245] In summary, some of the principal benefits of TVF in a fuel reformer include 1) all fuel is exposed to the catalytic surface layer **92** for rapid reaction, and 2) carbon dust, soot and other contaminants are dislodged, collected and removed from the fuel chamber **94** so that the catalytic surface layer **92** remains clean. Because of their enhanced reaction rates and their inherent ability to purge carbon dust, soot and other contaminants, TVF fuel reformers **90** have lower maintenance costs, smaller sizes and lower capital and operating costs than conventional fuel reformers – whether configured for direct internal reforming or as external fuel reformers.

Embodiment C: *Chemical Process Accelerator Systems*
Comprising Taylor Vortex Flows

[0246] Chemical process accelerator systems are used in chemical cells (e.g. **10**) to increase or decrease speeds of chemical reactions or to selectively control intermediate reactions, compositions of final products or rates at which reactants are converted to final products or to electrical energy. They comprise two essential and cooperating components; namely, a) viscid fluid Taylor Vortex Flows **28, 50, 50c, 98** created in fluid reactant or electrolyte of a chemical reactor or electrochemical cell **10** and b) a catalyst **14, 18', 20, 24', 34', 36, 86, 92** supported in laminar Circular Couette Flows **58, 59, 99** generated by the Taylor Vortex Flows **28, 50, 50c, 98**.

[0247] Chemical processors require catalysts to promote reactions at acceptable commercial rates. Catalysts must be carefully engineered for a particular reaction or application. Although the prior art technologists consider catalysts as the most prominent constituents and they garner an overwhelming share of research investigation, catalysts are only one component of chemical process accelerator systems needed to achieve commercially viable reaction rates.

[0248] In their search for the catalyst equivalent of the *Philosopher's Stone*, researchers have examined numerous substances, metals, alloys, fabrication technologies and methodologies for forming and decorating catalysts and supporting structures. Nevertheless with few exceptions, improvements in catalyst performance have been modestly evolutionary rather than revolutionary. As stated above, prior art fuel cell catalysts have yet to break a longstanding barrier that will enable fuel cell electrodes to generate more than 1-Ampere per cm^2 of electrode surface area over a long operating life without being poisoned by reactants or corroding to the point of uselessness.

[0249] In the case of electrochemical cells – and more specifically fuel cells, extensive research is now being conducted with *half-cell* analyses of a wide variety of catalysts; however, there is yet to be any significant improvement in fuel cell performance. One reason is that catalyst performance in these *half cell* experiments is focused on measuring *Oxygen Reduction Reaction* (ORR) rates for catalytic cathodes paired against either a Standard Hydrogen Electrode (SHE) or a Reversible Hydrogen Electrode (RHE). Because SHE and RHE *half cell* experiments are usually run at or near room temperature, at pressures of about 1-bar and with little or no fluid flow, they cannot replicate operating

conditions in chemical reactors, such as fuel cells, where these parameters and intermediate reaction products will most certainly be different.

[0250] Factors that determine characteristics of catalytic compositions include the purpose of the chemical process, the method of operating the process and choices for reactant chemicals, temperatures, pressures, processing times, intermediate reactions, reaction byproducts capable of poisoning the catalysts, balance of plant (BOP) and other variables. But perhaps more important is the nature of reactions at and very near the surface of the catalyst and these are heavily controlled by characteristics of fluid flows at and near the catalyst surface where turbulence is either intended or a consequence of design (e.g. rough surfaces).

[0251] The rate at which catalytic chemical reactions proceed is restricted by two factors called a) transport-limiting and b) surface-limiting. Transport-limiting occurs because reactants are impeded in reaching or leaving catalyst sites. Surface-limiting occurs because of a tradeoff between the sum of reaction energies from primary and intermediate chemicals, surface attraction of ions such as H^+ and OH^- and poisoning rates by reaction products, such as CO. In addition, there can be tradeoffs between transport-limited and surface-limited factors, such as how changes in flow rates and pressures that promote chemicals moving to or from catalyst sites can change concentrations of intermediate chemicals capable of adhering to the catalyst surfaces, poisoning catalysts or, at least, retarding reactions. Thus in conventional chemical reactors, catalyst compositions are often designed to optimize results by making appropriate tradeoffs.

[0252] This embodiment provides chemical process accelerator systems comprising catalysts and high-shear-rate laminar flows called Circular Couette Flows (CCF) that are created by *Taylor Vortex Flows* (TVF) in a viscid fluid such as a reactant or an electrolyte in a chemical reactor or electrochemical cell. As defined above, a viscid fluid is a viscous fluid that is capable of adhering or wetting a catalyst surface. A viscous fluid that cannot adhere or wet a surface is called an inviscid fluid. Additionally, catalysts optimized for use with TVF laminar flows are also taught.

[0253] Chemical process accelerator systems comprising TVF that are incorporated into chemical cells achieve enhanced reaction rates and product extraction efficiencies by:

- ◆ generating high-shear-rate laminar CCF at catalyst surfaces for accelerating mass transport of reactants,
- ◆ simultaneously and rapidly removing intermediate reaction products that otherwise could adhere to catalyst surfaces from the reaction,
- ◆ promoting reactions that do not create undesirable intermediate reaction products,
- ◆ preventing strong carbon adhesion to catalyst surfaces,
- ◆ capturing reaction contaminants that can degrade both catalyst surfaces, and
- ◆ eliminating those degrading reaction products from the reactors.

When used in combination with catalysts – especially those optimized for use in or with TVF and laminar CCF, reactions rates and extraction efficiencies well beyond those taught by the prior art can be achieved.

[0254] TVF have been investigated by others for use in electrochemical cells; however, results useful for fuel cells, fuel reformers and the like have not been reported. Gabe et al, “The rotating cylinder electrode: its continued development and application”, J. of Applied Electrochemistry, No. 28 (1998), pages 759-780 contains a review of results achieved between 1982-1995 for rotating cylinder electrode applications such as electroplating, silver removal from photographic chemicals, electrophoretic separation of proteins and the like.

[0255] In every case where Gabe et al and others describe a rotating or rotatable electrode, such as a rotating cylindrical electrode (RCE) used in conjunction with TVF, turbulent flow at catalyst surfaces is an objective for the purpose of increasing mass transport of a chemical. Gabe et al describe two of the main features of RCE at Page 760, where they state:

However, it is worth repeating the main features of RCE which give it unique experimental characteristics. These are:

(a) It generates turbulent convection at $Re > 100$, thereby providing simulation conditions of this type of convection at relative low rotation rates.

...

(c) Mass transport is high and be further enhanced through development or use of roughened surface.

They conclude, at Page 778, that *The RCE has now established itself as a major tool for studying electrochemical mass transport especially under turbulent conditions.*

[0256] Gabe et al also describe examples of laminar flow in conjunction with rotating disc electrodes; however, none of these applications describe use of laminar flows that can prevent wasteful or dangerous crossovers of reactive chemicals – such as hydrogen and oxygen in a fuel cell – in a high-energy reactor or cell. There are numerous references teaching the use of laminar flow at catalyst surfaces; however, they describe low-speed, low-power devices that are incapable of producing TVF. What is missing from these teachings is a concept or practice of TVF and both how or why TVF produce many orders of magnitude more powerful laminar flow boundary layers over a catalyst surfaces that provide benefits of laminar flows; but, at enormously more powerful shear rates.

[0257] Chemical reactors and electrochemical cells incorporating catalyst compositions and generating TVF of this invention comprise different structures and employ TVF in a manner different from prior art mechanical filters, chemical reactors and electrochemical cells. For example, fuel reformers incorporate porous catalysts that must not be used as filters because contaminants will degrade catalytic efficiency. Inert make-up gas that compensates for the hydrogen extracted from fuel reformers passes through these catalyst compositions to maintain system pressure. A small amount of oxygen that is just sufficient to oxidize molecular carbon attached to the catalyst surfaces also passes through the porous catalyst compositions. Unconverted fuel, contaminants and especially carbon particles from pyrolysis are trapped by TVF and purged from the reformer as described in Embodiment B.

[0258] TVF also generate laminar flows with high shear rates at catalytic composition surfaces of fuel reformers that promote H_2 production. The controlling factor for laminar

shear rates is the minimum value of the hydro-dynamically defined Taylor number, T_c above which desirable energetic vortices are fully established. Axial Poiseuille-type flow is further induced by injection of fuel and recirculation of make-up gas. Also, there is a strong dependence of the critical T_c on the strength of axial flow, which is related to its characteristic Reynolds number, R_a .

[0259] Furthermore, there is a requirement to maintain laminar flow at catalyst composition surfaces while promoting TVF within fuel. Care must be taken to restrict the circumferential Reynolds number, R_c , to non-turbulent values. This is in direct contrast with some prior art systems, such as described by Gabe et al, where turbulence is used to promote chemical mixing.

[0260] A set of distinct variables define a particular range of permissible operating parameters to obtain TVF with high-shear-rate laminar flows at catalyst surfaces. These variables include predetermined ranges of: 1) temperature and pressure of gaseous fuels, 2) kinematic viscosity and density of the fluids being employed, 3) their respective rates of recirculation, 4) angular rotation speed, 5) surface characteristics of the electrodes and, 6) physical dimensions of the cell.

[0261] The present invention is a chemical process accelerator system comprising robust catalyst compositions in which viscid fuel, electrolyte or other chemical fluids pass between relatively rotating, cylindrical surfaces that cause TVF and high-shear-rate laminar CCF within the fluids to reduce both transport-limiting and surface-limiting of catalytic reactions. In addition, TVF facilitate removal of contaminants that could damage chemical reactors, chemical cells or catalysts.

[0262] A chemical processor accelerator system, such as that contained in the TVF fuel reformer **90** of **FIG. 5A** comprises two principal components; namely, Taylor Vortex Flows (TVF) that generate high-shear-rate laminar Circular Couette Flows (CCF) and catalysts. While these components cooperate to promote chemical reactions in a wide variety of chemical reactors, each will be described separately in relation to the Embodiment B, which describes a fuel reformer used to extract H_2 from fuels. The description for Embodiment B will not be repeated here.

[0263] In a chemical reactor, the molar volume of reactants processed at the catalyst/fluid interface can vary by many orders of magnitude as a function of several rate controlling factors, such as those described above. Chief among these is the amount of catalyst surface area in intimate contact with both the liquid and gas phases per unit area of catalyst/fluid interface.

[0264] **FIG. 7A, FIG. 7B, FIG. 7C, FIG. 7D, FIG. 7E** and **FIG. 2E** illustrate catalyst structures optimized for high liquid and gas phase contact per unit area of catalyst/fluid interface in high-shear-rate laminar CCF **58** generated by TVF (e.g., **50, 50a, 98**). **FIG. 2E** has been described above and will not be repeated here.

[0265] These figures illustrate how to provide catalyst surfaces that provide intimate contact with a vigorously flowing electrolyte. Mass transport of ions by diffusion through stagnant liquid in conventional chemical and electrochemical cells is far slower than the movement of ions to (and product from) the catalyst surface layers adapted for use with high-shear-rate laminar fluid CCF **58** with high rates of viscous shear.

[0266] **FIG. 7A** is a view of a cylindrical catalyst surface layer **130**, such as surface **92**. A magnified view of the surface layer **130** is shown in **FIG. 7B**, where protuberances **132** are in a horizontal close-packed (HCP) array that may be formed by embossing the surface layer of the cylinder **130**. The protuberances **132** have heights of approximately 25 μm and widths (diameters) of about 12 μm are shown extending from the cylinder **130** on a densely covered surface layer (e.g. **92**). Those heights are sufficient for protuberances **60** to reach well into the high-laminar-shear boundary CCF **59** of **FIG. 2C-2**; but, no higher to avoid damage to the protuberances **60, 132** from high-velocity TVF.

[0267] **FIG. 7C** and **FIG. 7D** are further magnified views of the structures of the protuberances **132**. As shown in **FIG. 7C** and **FIG. 7D**, the protuberances **132** are formed from a sparse mesh of fine filaments **134**. Where used in an electrochemical cell, tungsten (W) is often preferred because it is electrically conductive, has a very high melting temperature and is both mechanically and chemically stable. Nanoporous Periodic Table of the Elements Platinum Group Metals (e.g. platinum) element and alloy foam sponge, Periodic Table of the Elements Group 10 (e.g. nickel) foam sponges, copper foam sponges, gold foam sponges and perovskite structure alloy sponges are also suitable for this purpose. The use of

sparse mesh makes the protuberances **132** porous to fluid chemicals, such as fuels and electrolytes.

[0268] Referring to **FIG 7C** and **7E**, there is a successive hierarchy of structures that form the protuberances **132**. **FIG. 7C**, showing a magnification of the protuberances **132**, displays the mesoporosity between aggregate clumps **139** of carbon balls **138** decorated with Platinum Group Metals catalyst particles **136** (**FIG.7E**) adhered to carbon balls **138** that have interstices of approximately 300 to 1000 nm. These are of sufficient width and breadth to permit moderate interstitial laminar flow of fluid through the mesopores. In addition, capillary action through the interstices contributes to the amount of electrolyte available for reaction. The degree of interstitial wetting will depend upon electrolyte viscosity and wetting angle, both of which are very high for electrolytes such as phosphoric acid and simple hydroxides.

[0269] The diameters (widths, if non-circular) of the protuberances **132** are nominally 12.5 μm . Therefore, there each protuberance **132** will contain approximately 12 to 15 aggregate carbon balls **138** across its diameter (width).

[0270] At a higher level of magnification the micro-porous structure of the aggregate 800 nm wide clusters of 40 nm diameter carbon balls **138** decorated with 2 nm width catalyst particles **136** can be identified. Typically for gas fuel or oxidizer, the catalyst bearing carbon particles **138** are held together by interstitial filamentary PTFE (not shown) to promote gas access. By comparison, a typical electrode applied to a PEM membrane that transports ions by dragging water molecules through its polymer chain interstices has a depth of about 30,000 nm.

[0271] Normally, the PTFE polymer would be an acidic-solubilized version of Proton Exchange Membrane (PEM) material for acidic electrolytes. For alkali electrolytes, an alkaline or merely hydrophilic polymer could be used. In either case, the diameter of the aggregate clump of roughly spherical carbon particles **138**, each having a diameter of 40 nm and dotted with 2 nm catalyst particles **136**, is about 800 nm. The longest or deepest shear-enhanced diffusion path for ions or other reactants to reach active catalyst surfaces is about 400 nm.

[0272] The fluid chemicals penetrating the protuberances **132** can wet catalysts, such as platinum (Pt) or its alloys containing ruthenium (Ru), palladium (Pd) or other elements from the Platinum Group Metals. In **FIG. 7E**, catalyst particles **136** decorate clusters of porous carbon balls **138**, which are also shown in **FIG. 7C** attached to the filaments **134**. Alternatively, catalyst particles **138** can decorate the filaments **134** as shown in **FIG. 7D**.

[0273] Current advances in carbon-dispersed Pt catalyst technology, as shown in **FIG. 7E**, have reduced crystallite or grain size of the catalyst particles **136** to 2-nm and increased specific surface area of catalyst to 100-meters² per gram at current loadings of as much as 0.5 to 0.1 mg/cm² for fuel cell electrodes. In other words, it is already possible to multiply the effective catalyst area per unit area of electrode by factors of 500 to 1,000, respectively, and well beyond that by simply restructuring the catalytic surfaces **130, 92**.

[0274] Net catalyst loading factors can be increased by at least an order of magnitude by attaching Pt catalyst particles **136** to conventional, electrically-conducting aggregate carbon balls **138** - the balls each having diameters between 20 and 50-nm. These aggregate carbon balls **38** are normally supported by mesoporous carbon structures, which are fluid permeable. Available versions of these carbon materials have a void volume of 60% after impregnation with 40% by weight of PTFE to make them wet-proof. The composite has approximately 5 to 10 nm nano-pores separating the catalyst decorated carbon spheres **38** that tend to aggregate into clumps of 400 to 800 nm across – similar to that shown in **FIG. 7E**. The spaces between the aggregate carbon balls **138** are also in the range of 400 to 800 nm across. These catalyst structures form the 12,500 nm (12.5 μ m) diameter electrode protuberances **66, 32**.

[0275] When used in fuel cell electrodes- as in Embodiment A and Embodiment D, the protuberances **132** provide an approximate 4-fold increase in electrode/interface area ratio. That, combined with a 250% increase in the catalyst particle **36** loading, contributes to 10-times the catalyst surface area available to electrode reactions over present practice and an expected 10-fold increase in open circuit exchange current. The actual operating current increase under load will be less due to ohmic and other losses; but, these losses can be minimized by using thicker materials.

[0276] These catalyst surface layers **92** of nanoporous foam sponges or scaffolds **86** are excellent electrical conductors and can be deposited on or secured to micro-porous substrates (e.g., stainless steel web **102** of **FIG. 5B**) that will provide substantial strength for the catalyst surface layer **92**. The micro-porous substrates **102** may be easily coated with carbon or a high-molecular-weight compound (e.g., PTFE) to protect them from corrosive attack by or premature hydrolysis of some fuels (e.g., borohydrides) and to keep the electrolyte from penetrating past the surface layer **92**.

[0277] The surface layer **92** comprising metal foam sponges **86** can be operated safely in alkaline environment at elevated temperatures in the range of 250 to 350° C and at elevated pressures to achieve accelerated catalytic performance. The same structure and process can be used to build nanoporous catalytic surface layer **92** from other metal foam sponges **86**, such as gold, copper, tungsten and nickel. These layers, attached to substrates having surface geometries to be described below in conjunction with **FIG. 2D**, **FIG. 4D**, **FIG. 4E**, **FIG. 4F** and **FIG. 4G**, are ideally suited to take the fullest advantage of the unique flow profiles and mass transport enhancement of catalyzed electrochemical processes in fuel cells of this invention.

[0278] The catalyst particles **136** need a fluid or an electrolyte to wet, but not flood, them in a thin envelope of fluid or electrolyte so that chemical reactants can diffuse into the molecular fluid or electrolyte coating and react at the catalyst surfaces. For fuel cells, the boundary layer thicknesses for typical design parameters are about 0.05 mm, which are somewhat less than the thickness of proton exchange solid polymer membranes. However, one difference in current density is due to the rate of shear-amplified diffusion in a TVF cell compared to polymer interstitial transport. Typical laminar boundary layer shear rate enhanced ionic diffusion in a TVF cell is at least 15 to 20 times that of a proton exchange membrane fuel cell (PEMFC).

[0279] As described above, the electrode protuberances **132**, **60** should extend about half, to at most three quarters, of the way into the high-shear-rate laminar flow layer **58**, **59**; but, not into the TVF **50** where the protuberances **132**, **60** would be subjected to excessive viscous drag and possible damage or deterioration. The laminar flow layer **58**, **59** is less than 0.050 mm. thick. Therefore, the protuberances **132** should be approximately 0.025 to 0.038 mm in height.

[0280] Simple plane geometric calculations provide values for a) the fraction of electrode surface, **f**, covered by protuberances and b) the projected area ratio, **m**, of actual catalyst surface area to projected surface area.

[0281] If the radii of idealized cylindrically-shaped protuberances **32** are equal to $\check{r}$ and the protuberances **132** are arranged in a HCP array **140a** with centers spaced $2.5\check{r}$ apart, as shown in **FIG. 8A**, then they will cover very close to half the catalyst projected surface area so that **f** = 50%.

[0282] The surface area of a protuberance **132** is approximated by a hemispherical cap of area, $2\pi\check{r}^2$ plus a supporting cylinder of area, $2\pi\check{r}h$ where h is the height of the projection. If the height, **h**, of each cylindrical portion is between $2\check{r}$ to $4\check{r}$ and is capped by a hemispherical dome of radius, $\check{r}$, as shown in **FIG. 2D**, then the total external surface area of the protuberance is in the range of $6\pi\check{r}^2$ to $10\pi\check{r}^2$. Because the area of the portion of surface covered by a protuberance is $\pi\check{r}^2$, the projected area ratio is 6 to 10 times **f** and the ratio of actual electrode surface area to projected area or area multiplier, **m**, is 3.5 to 5.5 for an average projected area of **m** = 4.5:1.

[0283] **FIG. 8C** shows a HCP array **140c** where circles of radius $\check{r}$ are in contact and the gap between circles is zero. **f** = 90.7% of the catalyst surface area. **FIG. 8D** shows an example where the protuberances are only hemisphere caps of radius $\check{r}$ embossed on the catalyst surface. These protuberances **132** have an effective surface area of $2\pi\check{r}^2$ covering an area of $\pi\check{r}^2$ for a ratio of 2:1 to 1. Therefore, 90.7% of the cylinder **130** area has a weighting factor of 2.0 and 9.3% of the cylinder **130** area has a weighting of 1.0. The total net nominal area multiplier **m** = 1.9:1.

[0284] Even if the caps of the protuberances **132** were only a portion of a hemisphere, e.g., half height or $\check{r}/2$ as shown in **FIG. 8E**, 90.7% of the projected area would have a multiplier of 1.33 for a net multiplier of 1.3, which would represent a reasonable approximation for the minimum area multiplying effect of the projected geometry.

[0285] Whatever geometry of the protuberances **132** that may be selected within the range of this general description, it is intended that the total height, $(h + \check{r})$ of the protuberances **32** be somewhat less than the thickness of CCF boundary layers **58, 59** of **FIG. 2C-1** or **FIG. 2C-2**.

[0286] Using this somewhat idealized geometry of the protuberances **132**, where their centers are separated by a distance of $2a\check{r}$, in the TVF laminar flow **58**, the area multiplier, **m**, is:

$$\mathbf{m} = 1 + (\pi/2a^2\sqrt{3})[(2h/\check{r}) + 1]:1$$

The choice of choice of protuberance parameters will depend upon the reactants and catalyst being used in conjunction with CCF **58**.

[0287] The protuberances **132** preferably may have a streamlined shape, as shown for protuberances **132f** of **FIG. 8F**, for insertion into the laminar CCF **58**. Some prior art catalytic surfaces incorporate turbulent-producing projections that are designed purposely to promote chemical mixing for electrochemical processes and voltammetry. By contrast, the chemical process accelerator systems of this invention avoid turbulence and preserve laminar flow in the catalyzed reaction zone to be effective as a mass transport mechanism conveying reactants to and from actual catalytic surfaces. Also, the protuberances **132** and **132f** should present high active surface areas to the laminar flow **58** per unit area of projected electrode in relation to the reaction zone depth.

[0288] In a typical and practical example for a H₂/O₂ fuel cell, the catalyzed reaction zone could have a depth of several microns and the CCF laminar boundary layer **58** would be somewhat in excess of 25 microns. With a net height of about 4-times the radius as in the just calculated example, the projections could have diameters of about 12.5 microns and are spaced on centers 15.625 μm apart. The electrode surface would have the appearance and smooth feel of 1000 to 1500 grit abrasive paper of the sort used to polish stone.

[0289] When fuel or oxidizer is converted by catalyst to a final molecule or ion in only one or two intermediate steps, it is generally adequate to use only one type of catalyst that is most ideally suited to the reaction in question. These reactions proceed to completion more quickly than those requiring multiple intermediate steps. In these cases, the electrode surface can have geometry similar to **FIG. 2D** with a projected area multiplier on the order of 4.5:1, as calculated above.

[0290] As shown in **FIG. 2D**, **FIG. 8D**, **FIG. 8E** and **FIG. 8F**, both fuel and oxidizer in a fuel cell pass through their respective electrodes in a cross-flow relationship without

mass transport limitation and with sufficient residence time to complete their respective reactions – as taught in Embodiment A and Embodiment D. Neither is possible in PEMFC of the prior art. These cross-flows are orthogonal to high-shear-rate electrolyte CCF that both promote reaction rates and assist in moving undesirable products into TVF for elimination from the reactor or cell.

[0291] Chemical process accelerator systems taught here also improve the overall rate of slower reactions that produce multiple intermediate products prior to completion, such as the oxidation of methanol and other alcohols. **FIG. 8G** shows catalyst protuberances **132g** comprising multiple layers of different types of catalyst materials. These are schematically depicted as catalyst layers **144, 145, 146, 147** and **148**. Each of the layers has a thickness sufficient to provide necessary residence time for an intermediate reaction to complete before the intermediate product converts to a subsequent intermediate or final product.

[0292] It is well known that a particular morphology and composition of a catalyst can be better suited to one intermediate reaction step than other reactions. Therefore, multiple catalyst **139g** layers **144, 145, 146, 147** and **148** having each layer optimized for one or two intermediate reactions reduces or eliminates the need for engineering tradeoffs demanded by homogeneous catalyst structures and permits optimization for specific reactions.

[0293] Finally, electrodes that have been disclosed for use in reactors and cells generating TVF and CCF do not require any membrane and can operate at substantially elevated temperature and pressure (i.e., fuel concentration). This further increases catalyst activity to achieve increased reaction rates at higher voltages and current densities.

[0294] To summarize, several benefits of chemical process accelerator systems incorporating TVF-induced high-shear-rate laminar flows at catalyst surfaces include:

- ◆ Bi-directional mass transport of constituents to and from catalyst surface layers by cross-flow of reactants (e.g. fuel, oxidizer) directly through catalyst structures wetted by TVF-induced high-shear-rate laminar flows,
- ◆ Control of the residence time of reactants at catalyst surfaces to permit very complete reactions,

- ◆ Substantially increased catalyst loading factor and useful catalyzed reaction zone thickness to permit higher area current densities,
- ◆ Layered catalyst compositions and morphologies in coordination with cross-flow fuel/oxidizer transport best suited to the specific intermediate reaction occurring in the zone,
- ◆ Operation of catalysts at higher temperatures, gas pressures and fuel concentrations without significant crossover due to more complete fuel/oxidizer utilization than would be possible with PEM and other crossover barriers,
- ◆ Use of potentially less-expensive active catalyst, and
- ◆ Selection from a wider range of acidic or alkaline fluids capable of sustaining TVF.

These and other advantages will be seen in specific embodiments as further described.

[0295] An example will illustrate these advantages. For Direct Methanol Fuel Cells (DMFC), methanol requires as many as five oxidation steps before it reaches its final composition of CO_2 . The theoretical maximum power and voltage that can be obtained from oxidizing this fuel without irreversible losses is 700 kJ/mol and 1.21 volt at STP. However, catalysts having no rather substantial irreversible energy losses with respect to all five steps and operating at near STP conditions in acidic electrolyte do not yet exist.

[0296] Current typical Pt/Ru catalysts require 0.35 to 0.5 volt of irreversible energy (heat producing) overvoltage to promote all 5 steps of the requisite reaction. Consequently, it has not been possible to gain more than 400 to 500 kJ/mol from direct methanol oxidation or an open circuit voltage (OCV) of greater than 0.7 to 0.85 volt. Further, methanol that is not fully oxidized in DMFC will pass freely through PEM and cause additional losses.

[0297] Ren, et al, "Recent advances in direct methanol fuel cells at Los Alamos National Laboratory", (Journal of Power Sources 86 (2000) 111-116), reported at Page 113 that 'methanol crossover has been considered a severe barrier to faster development of DMFC technology.' They wrote:

The former tool is obvious: with lowering of methanol feed concentration, the rate of crossover drops at zero cell current. The latter tool is more subtle: by using appropriate cell design, a significant drop in methanol crossover can be achieved with increase in cell current, i.e., with increase in rate of anodic consumption of methanol.”

In stark contrast to the Ren et al dual expedients of spreading the reaction over a large area to accommodate slow mass transport and lowering the fuel concentration – both of which are needed to accommodate slow catalyst activity and to assure near-total methanol oxidation to mitigate fuel crossover, chemical process accelerator systems of this invention rely on much higher anode reaction rates and fuel concentrations to oxidize methanol and to remove unreacted methanol from cells before there can be any crossover to cell cathodes.

[0298] The best Ren et al result reported >90% fuel utilization and an implied crossover of the remainder through PEM with an overall *methanol-to-dc* conversion efficiency of 37%. Methanol concentration was 0.0005 mol/ml and the polarization relationship (vs. SHE) was 0.18 (Amp) A/cm² at 0.45 volt with an implied hypothetical OCV of 0.7 volt. These data are useful as estimates of the activity or reaction rate of typical Pt/Ru catalyst surfaces at 333°K for methanol in an acidic environment where reactions are so spread out and dilute that they may be much less subject to mass transport limitations.

[0299] The carbon supported catalyst particles at the anode were 50:50 % atm. Pt/Ru of 3.5 nm average diameter or a surface area of 3.85×10^{-13} cm² about half of which actually participates in the reaction yielding an active area of about 1924 Å² (Angstrom²) per catalyst particle. The mean particle density of 17 gm/ml corresponds to a net 3.8×10^{-19} gm per particle yielding 2.62×10^{15} particles/mg. A 1.0 mg/cm² electrode loading factor means that each particle is fully 5-fold processing 65 molecules of methanol per second. Therefore, the reaction rate per chemical step must be approximately 3 milliseconds.

[0300] At a loading factor of 1.0 mg/cm² there are 1000 cm² of catalyst surface for each cm² of electrode surface, with half of that being available to the reaction. Consequently, the rate metric that can be extracted from the Ren et al data are a catalyst surface current density of 360 μA/cm² and 162 μW/cm² when the catalyst is successfully processing 93% of the methanol molecules coming to its surface. The computed rate is about 300-times slower

than the characteristically slow ORR and 15-times slower than the alkaline model reported in the prior art. . This is due to the exceptionally dilute fuel required to prevent crossover and the mass transport interference of opposing flows of fuel feed and escaping CO₂ within the anode.

[0301] At the methanol dilution and efficiencies described by Ren et al, the available free energy of the fuel is equal to 130 J/ml moving at a velocity of 8.1 nM/sec. to the catalyst surface where there are 65 methanol molecules/sec being fully processed 5 times by each particle. This represents the time required for intermediate specie to move locally to a catalyst surface against a reverse and opposing flow of acid solution carrying CO₂, which is a final product that must escape from the fuel cell through the fuel feed stream.

[0302] Clearly, the computed reaction metric is a worst-case reaction rate for very dilute 60°C methanol on Pt/Ru catalysts. Scott, K. et al, "Electrocatalysis in the Direct Methanol Alkaline Fuel Cell" (Liu, H et al, editors, *Electrocatalysis of Direct Methanol Fuel Cells*, Wiley-VCH, 2009) report at Page 492:

Oxidation kinetics were much better in alkaline than in acid solution; factors of 30 for Pt and 20 for Pt₂Ru₃ at 0.5V at 333K.

It is difficult to estimate what part of the 4.26 millisecond reaction time is due to the PEM mass transport environment in which the reaction product has to make way for fuel trying to diffuse into the anode; but, at least it is possible to estimate that the reaction time would likely be less than 0.213 milliseconds in alkaline solvent.

[0303] A comparison of the Ren et al DMFC with a DMFC of this invention raises a question about requirements for a catalyst surface to be used with concentrated methanol at substantially higher temperature being forced through a catalytic anode into TVF that sweeps away CO₂ gas or carbonate ion plus water formed at the anode. In this case, constituent mass transport is fully assisted by the several flows working in a reaction-promoting direction. However, just as it was not possible to extract the mass transport component from the previous calculation, it will not be taken into account in this one - other than to assume it is at least equally negligible. Attention is mainly focused on reasonable catalyst site reaction rate parameters. These will be compared to prior art activation overvoltages in relation to exchange or 'activation' current, j_0 in two cells using TVF in alkaline electrolytes.

[0304] The thermodynamic Nernst equation can be used to compute increases in free energy due to higher methanol concentrations, temperatures and pressures:

$$\Delta g_f = \Delta g_f^0 - RT \ln (\alpha_m \cdot [\alpha_{O_2}]^{3/2} / \alpha_{CO_2} \cdot [\alpha_w]^2) + T\Delta S$$

where

α_x refers to an activity parameter given by a ratio of elevated partial pressure or concentration in the reaction over the value at STP,

m and **w** refer to methanol and water, respectively,

ΔS is an entropy change mainly associated with a constituent phase change of either sign, and

the Gibbs energies, Δg , are all negative.

[0305] Dividing through the previous equation by 6F, to account for the 6 electrons in the reaction, yields:

$$E = E^0 + (RT/6F) \ln (\alpha_m \cdot [\alpha_{O_2}]^{3/2} / \alpha_{CO_2} \cdot [\alpha_w]^2) - T\Delta S/6F$$

This equation describes an increase in voltage with temperature and activity of the reactants where E^0 is 1.21 volts.

[0306] The principal contribution to the voltage increment in this case is due to the higher pressure of 95% O_2 ; but, the effect is small, with $E \approx 1.25$ volts. A far more significant effect is the influence of temperature and fuel/oxidizer concentration on the rate parameter, j_0 and the concomitant decrease in overvoltage or the OCV relative to E. In the Ren et al example, above, an OCV of 0.7 volt reveals a minimum 0.5 volt of irreversible loss.

[0307] Applying the Tafel equation:

$$j = j_0 \exp(6\alpha F[\Delta V]/RT)$$

where:

α is the charge transfer coefficient (usually assigned a value of 0.5)

to those values would not provide further insight into that experiment as other losses clearly override any further information it would normally yield.

[0308] On the other hand, the overvoltage at a temperature of 533°K will fall to about 0.15 volt as suggested in the prior art. Subtracting a ΔV of 0.1 volt in the Tafel equation result from the OCV leaves 1.0 volt across the DMFC. The value of j_0 can be a reasonable 10 milliamp, which can be easily adjusted by increasing the catalyst loading factor to as high as 1.0 milligram of Pt_2Ru_3 per reaction processing zone, as described above. Applying these values to the Tafel equation yields a net current density of 10 A/cm².

[0309] Assuming the process just described converts 90% of the fuel feed by means similar to that described by Ren et al., then the net yield with respect to reversible free energy will be 522 kJ/mol. If methanol is forced through the anode at approximately one-half concentration of 12.5 mol/liter in a solution of KOH and the target power density is 10 watts/cm², then, at 10,075 joules per ml of flowing power density the velocity of the methanol fuel within the reaction zone, if it is converted at the stated efficiency, must be approximately 10 microns/sec.

[0310] If there are five layers of individually tailored catalyst and the reaction zone is 50 microns thick, then each of the five intermediate reactions has one second for completion. Such residence times are likely to be adequate. In an acid electrolyte such as H_3PO_4 , the fuel concentration is closer to 25 mol/liter and the individual reactions would have nearly 2 seconds to complete, which is helpful as reactions are slower in acid.

[0311] The prior art using PEM in acidic electrolyte overcomes mass transport limitations by spreading the reactions over large areas. DMFC of this invention achieve 10 watts/cm² or 10 amps/cm² at 1.0 volt by using alkaline electrolyte and accelerated catalyst surface area reactions. A kilowatt DMFC of this invention requires 100 cm² of electrode surface area. By comparison a conventional DMFC with a similar total power rating and the same net fuel conversion efficiency would require 2000 cm² anode at 0.5 watt/cm², which is typical in current practice.

[0312] To put this in perspective, an electrode in the high power density example above must process methanol fuel at the rate of 1.9157×10^{-5} mol/cm²-sec. of projected electrode. Using the catalyst parameters earlier calculated and the $m = 1.9$ area projection

factor for one of the electrode surface designs described above and a porous electrode loading factor of 5.0 milligram/cm² divided among the 5 zones with 50% of the catalyst surface participating in the reaction, there are 4,750 cm² of catalyst surface area for every cm² of electrode area.

[0313] Consequently, the average catalyst-surface current density for a DMFC of this invention is a reasonable 2.1 milliamp mA/cm². The gross methanol molecular processing rate is 4.03×10^{-9} mol/cm²-sec. Because the process requires five intermediate steps, the mean specific molecular processing rate increases by a similar factor.

[0314] With the average catalyst particle having an effective processing area of 2×10^{13} cm² or 200 Å² (Angstrom), the fuel requirement is 8×10^{-22} total methanol-mol/particle or about 5 times $482 \approx 2,410$ molecules of methanol species intermediate per catalyst particle per second. That means, even though the fuel has several seconds to undergo reaction processing in the electrode reaction zone, the constituent molecules must approach the catalyst particle surface, react and leave that surface in about 4 milliseconds provided the catalyst particle can process at least 10 molecules simultaneously or 1 molecule per 20 Å². This result is virtually identical to the previous calculation using actual data reported by Ren et al.

[0315] It would not be unreasonable to suggest that the exceptional mass transport characteristics of the high-power alkaline DMFC of this invention could function with less catalyst at higher catalyst activity levels. Such high levels of mass transport rate can only be achieved by the TVF-induced high-shear-rate flow mechanisms of this invention and can be further enhanced by 1) somewhat reducing particle size for increased particle number, 2) increasing particle loading by weight, 3) operating at higher temperature or 4) any combination of the preceding.

[0316] In order to increase fuel efficiently using PEM in a DMFC, the electrode area must be increased until mass transport no longer limits the molecular reaction rate at the catalyst surface. Spreading the catalyst particles over a much larger area which proportionately increases their number, their cost and the time available for molecular exchange. This is the only available option that limitations of relevant mass transport in the PEM prior art permit. It is worth noting that for a power density of 0.081 watt/cm², the Ren

et al DMFC requires 617 cm² of electrode area for 50 watts and 617 milligrams of catalyst at the anode. Despite the higher catalyst load factor the high-power DMFC of Embodiment D only needs 5 cm² and 25 milligrams for the same power.

[0317] Chemical process accelerator systems of this invention also improve ORR at fuel cell cathodes. ORR is known to be a major limiting factor in the power density of current state of the art hydrogen/oxygen fuel cells. Actual operating systems generally yield less than 1.0 Amp/cm² at power levels less than 0.5 watt/cm². If a theoretical single platinum crystal surface is exposed to ORR chemistry without any mass transport limitation and the current and power densities per cathode size are expressed in per unit area of catalyst surface, then ORR of this invention will be much higher than obtainable with prior art electrodes.

[0318] The prior art analysis of ORR is based on quantum density functional theory (DFT), which is a computer simulation model for forecasting with several rate limiting intermediate steps in the ORR that reacts adsorbed oxygen into adsorbed water. If the cathode catalyst were perfect, then every intermediate step would move the cathode potential down to its theoretical minimum of -1.23 volts. For a less than perfect catalyst, some of the intermediate steps are uphill thereby adding to the theoretical minimum. In fact, the calculated energy levels yield -0.78 volts at maximum current per unit area of active catalyst surface, scalable as a function of applied voltage.

[0319] The parameters are referred to in the prior art as j_{limit} , where eU_0 and $U_{\text{ORR}}^{\text{Max}}$ are the maximum theoretical energy for a perfect catalyst at -1.23 volts and the actual maximum energy at -0.78 volts, respectively. The Tafel equation provides a relationship between the hidden exchange current density, j_0 at open circuit and j_{limit} , which can be measured and is reported to be 96 mA/cm². Using a voltage difference of $-1.23 + 0.78 = -0.45$ and a typical electron transfer coefficient of 0.5, then j_0 is calculated to be about 2.64×10^{-9} Amp/cm². This is understood to be the open circuit exchange current density at the active portion of catalyst surface at standard temperature.

[0320] The Butler-Vollmer version of the Tafel equation provides:

$$j = j_0 \exp(2\alpha F[\Delta V]/RT)$$

where:

F is the Faraday constant (96,485 coulombs/mole), and

R is the universal gas constant(8.314 joules per degree per mole).

What is quite remarkable is that even though the exchange current density is very low, as soon as a ΔV operating voltage drop from the open circuit value is applied, generally about 0.45 volt; the current density increases to 0.1 Amp/cm², which is understood to be the current density at the active portion of catalyst surface.

[0321] Finely divided and dispersed 2 to 5 nm Pt has a gross surface area of 100 M²/gm. With only 20% of the area active to produce electrical current, an area multiple $m = 5$ (or 20 cm² of catalyst surface per 1.0 cm² of electrode surface) can be obtained with a Pt catalyst loading factor of 0.1 milligram/cm² or a 100-times improvement with only 0.5 milligram/cm² of platinum.

[0322] In this example, an ORR cathode would produce 10 Amp/cm², which is understood to be more resistant to good fuel cell performance than the hydrogen anode. In short, there is no fundamental reason or law of nature that requires electrode current densities to be limited to 1.0 Amp/cm² at reasonable voltages and power densities other than present catalyst designs and mass transport retardation built into current fuel cells. The chemical process accelerator systems of this invention solve these problems.

[0323] Because chemical activity is a function of temperature, the capability of operating at higher temperatures is an important advantage of the chemical process accelerator systems of this invention. Higher temperature-dependent reactions promote higher current densities in fuel cells and higher yields in chemical cells such as reformers. For example, the chemical accelerator systems described here do not require tetrafluoroethylene (maximum operating temperature of 190° C) or similar materials and therefore are not rate-limited by the maximum operating temperatures of membranes and the like.

[0324] Santos et al “Electrochemical Electron Transfer: From Marcus Theory to Electrocatalysis”, (Koper, M, editor, *Fuel Cell Catalysis – A Surface Science Approach*, Wiley, 2009), Chapter 2, pp. 31-55 contains an extensive quantum mechanical analysis of electron transfer between a catalyst and a solvent a chemical reaction. The analysis contains

a calculation of a potential barrier that must be overcome by an electron and then provides a model of the reaction rate for electron transfer in terms of “high solvent friction”, γ , which can be interpreted as in the a) adiabatic limit of high-mass-transport rate, b) high-laminar-shear rate, or c) no-limit on the availability of reactants at the catalyst surface. The parameter for high solvent friction, γ , can be related to any of these. So the simple expression for reaction rate is:

$$k = \gamma \exp(-E_{\text{act}}/K_{\text{B}}T) \quad (2.10)$$

where:

E_{act} is the computed potential barrier for the electron to overcome by virtue of a fundamentally thermodynamic Fermi-Dirac probability distribution which, is a function of temperature, and

K_{B} is Boltzman’s constant.

The equation (2.10) clearly shows an increased reaction rate with temperature. However, a key to understanding this relationship is in the interpretation of E_{act} . If the potential barrier is unlikely to be overcome by an appreciable population of electrons the formula above is not actually relevant or operative. Santos et al argue that the reason metals are unique as catalysts is that their D-band potential energies are just below the free electron conduction band and therefore can overcome the potential barrier.

[0325] The term, $\exp(-E_{\text{act}}/K_{\text{B}}T)$, is similar to a term in the Fermi-Dirac probability function. The Fermi-Dirac probability distribution function may be written:

$$f(\xi) = \{1 + \exp[(\xi - \zeta)/K_{\text{B}}T]\}^{-1}$$

where:

ζ , is an energy level that has many names and is variously calculated with respect to many baseline references (It can be related to electrochemical potential, the earth and to voltages multiplied by the charge of an electron.), and

both parameters in the difference, $(\xi - \zeta)$ in the probability distribution must have the same reference.

When ζ refers to the conduction band of a metal, it is a strong function of temperature and is called the Fermi level. The distribution function provides the probability that an electron in a given energy band (e.g., the D-band) exists near, at or above that level. Santos et al emphasize, at page 49, the importance of means for raising thermal excitation in the catalyst to increase its D-band energy to near the Fermi level in order to reduce significantly energy of activation for catalysis. For chemical process accelerator systems of this invention incorporating catalysts **92, 92', 30, 32, 32f, 32g, 36, 40, 44, 45, 46, 47, 48** containing Group 10 metals, catalyst temperatures of at least 500° C are recommended.

[0326] Note that it is not the *sp* outer conduction electrons that get transferred in catalysis. The electrons that are quantum-mechanically eligible to move between solvent or reactant molecules and the catalyst must come from bound states. This is an idiosyncrasy of quantum chemistry that escapes many students of the subject. If free electrons could be transferred, then current would flow in a dielectric, which is a much slower process.

[0327] Because of the strong temperature dependence of D-band level energies with respect to the Fermi level energies in low-cost catalysts such as nickel and palladium, means for using exothermic energy to heat catalysts can be substituted for expensive platinum catalysts needed by PEM and similar cell reactors. Chemical reactor systems of this invention with their improved mass-transport rates, higher reaction rates, nanoporous metal foam sponges, TVF, CCF, protuberances and elevated temperatures can well surpass the chemical activity per unit of surface area of the prior art.

Embodiment D: *Direct Reaction Fuel Cells Utilizing Taylor Vortex Flows*

[0328] Direct Reaction Fuel Cells (DRFC) such as Direct Alcohol Fuel Cells (DAFC), Direct Methanol Fuel Cells (DMFC), Direct Borohydride Fuel Cells (DBFC) that convert chemical energy in high-hydrogen-content fuels (e.g., where the hydrogen-to-carbon ratio > 2.5:1 or there are at least three hydrogen atoms in a molecule) directly into electrical energy are well known. High-energy-content fuels include:

- ◆ alkanes (paraffins) – methane, ethane, propane, butane, octane;
- ◆ alcohols – methanol, ethanol, propanol, butanol;

- ◆ kerosene; and
- ◆ borohydrides – LiBH_4 NaBH_4 KBH_4 .

These fuels are easily usable gasses, liquids or powders that can be dissolved in liquids. While they provide operational advantages over H_2 fuel cells, existing DRFC have low energy and power densities per dollar that make them commercially uncompetitive.

[0329] One reason that prior art DRFC cannot compete commercially with H_2 fuel cells is that most existing DRFC require a solid polymer Proton Exchange Membrane (PEM) to prevent fuel-oxidizer crossover in electrolyte between anode and cathode electrodes. As a consequence, all commercially usable PEM for DRFC are based upon essentially acidic electrolyte because alkaline based membranes have not proven to be stable in DRFC environments. Extremely high temperature Solid Oxide Fuel Cells SOFC have limited application to DRFC and suffer from low power density due to the slow transport of ions across the solid membrane.

[0330] Acidic electrolytes in DRFC are slow and promote intermediate reaction products that increase polarization voltages at electrodes, which dramatically reduce power levels. Acidic electrolytes also support reactions that yield undesirable products that can poison electrodes and contaminate DRFC waste streams.

[0331] Hydrocarbon fuels, such as methane, alcohols and kerosene, and NaBH_4 both have high energy densities per unit weight and unit volume. For example, methanol is capable of generating 1.21 volts and 6 electrons @ 700 kilo-Joules per mole (kJ/mole) and NaBH_4 can provide 1.64 volts and 8 electrons @ 1271 kJ/mole based upon their respective reversible Gibbs free energies. Nevertheless, these yields cannot be obtained in prior art DRFC because hydrocarbons and NaBH_4 have relatively slow oxidation catalyst reactions with acidic electrolytes that are required for use with PEMs.

[0332] Hydrocarbon and NaBH_4 DRFC have potentials to produce markedly higher power and energy densities if an alkaline electrolyte could be used because polarization and poisoning would be reduced. However as described above, there are no durable alkaline-electrolyte-compatible ion exchange membranes that can prevent fuel-oxidizer crossover in higher power DRFC.

[0333] As described in Embodiment A, fuel cells comprise an anode electrode reactive with a hydrogen-based or reducing fuel and a cathode electrode reactive with an oxidizer. The electrodes are separated from each other by an electrolyte fluid that transports, 1) protons from the anode to the cathode where they react with both the oxidizer and with electrons travelling from the anode through an external electrical circuit to the cathode to form a compound, such as water or 2) hydroxyl ions from the cathode to the anode to form water there.

[0334] Fuel cells rely on molecular kinetics, e.g., temperature, reactant concentration and catalysis to induce molecules to react at a catalytic surface. Prior art teaches that there are five principal methods to increase reaction rates and thereby increase output current. They are 1) raise temperature and/or pressure, 2) improve catalyst activity, 3) augment electrode surface activity by adding other forms of resonant energy to electrodes or to reactants (e.g., US Pat. No. 7,482,072 to Brooks et al), 4) increase reactant transport rates to or from reaction surfaces (mass transport) and 5) raise the catalyst surface area / electrode area ratio.

[0335] The presence of the PEM significantly increases the cell's internal resistance to ionic flow and consequently reduces the cell's current capacity. While, it is known that PEMs need to be eliminated in order to improve cell performance, prior art techniques such as creating laminar flows in electrolytes do not substantially improve fuel cell performance.

[0336] Some prior art electrochemical cells that do not have or require PEMs incorporate rotating, rotatable or moving electrodes that generate flows to the electrode surfaces. However, these electrodes are found only in applications where an electrode is immersed in an electrolyte bath to expose it to an aggregation of reducing agent, oxidizer and electrolyte. It is well known that use of moving electrode surfaces in such systems produces turbulence to enhance reactant mixing. Turbulence is basically incompatible with operation of energy-efficient fuel cells.

[0337] This invention provides DRFCs that are substantially more powerful than prior art systems and can compete for investment because they eliminate a need for PEM and accommodates use of either acidic or alkaline electrolytes.

[0338] This disclosure will describe three types of fuel cells that use circulating liquid electrolyte without a PEM; namely:

- a. Acid-electrolyte direct methanol fuel cell (“DMFC”) fueled with 100% methanol and using recirculating acidic electrolyte. This direct reaction fuel cell (“DRFC”) is the most powerful and long range liquid-fueled fuel cell for use in vehicles. It’s only undesirable characteristic is a molecule of CO₂ exhaust produced for every molecule of methanol consumed; however, methanol derived from bio-fuel will yield a net carbon footprint of virtually zero. The example is equally applicable to ethanol.
- b. Alkali-electrolyte DMFC fueled with methanol or ethanol and using recirculating alkali electrolyte. While CO₂ can be eliminated from the cell’s exhaust by forming precipitating carbonates in the cell’s waste stream, the precipitates must be retained for disposal. Further, an additional tank is required for resupplying makeup alkali electrolyte to replenish that converted to carbonate and water. Its mileage is approximately 130% better than the acidic-electrolyte DMFC.
- c. DBFC fueled by NaBH₄ liquefied in a stabilizing alkali electrolyte. Although dilution in electrolyte is required, it’s substantially higher energy content per mole produces about the same amount of energy in kilo-watt-hours per net gallon of fuel as the undiluted methanol fuel cell; but, it has no polluting exhaust. While NaBH₄ is an easily-handled powder, it has a higher cost than other fuels. Nevertheless, it may be preferred for special applications.

All of these fuel cells of this invention use Taylor Vortex Flows to achieve enhanced reaction rates by a) reducing mass-transport losses, b) preventing fuel and oxidizer crossover, c) capturing reaction products that can degrade catalysts and electrolytes, d) eliminating those degrading reaction products from the cells, e) increasing temperature to reduce electrode overpotentials and raise reaction rates and f) permitting higher pressures and concentrations to accelerate reactions at both electrodes.

[0339] Electrodes described here use TVF that automatically generate accelerated, high-shear-rate, stable laminar CCF at the electrode surfaces. These laminar flows increase

electrode surface electrical current density while preventing a mixing of fuels and oxidizers that would waste energy and lower conversion efficiency. Recommended electrodes that present high surface area/projected area ratios of catalytic surfaces to reactive chemicals are described in Embodiment C.

[0340] **FIG. 9A** is a cross-sectional view of essential features of a preferred embodiment of an acid electrolyte DRFC **910** of this invention that generates electrical energy from high-hydrogen-content fuels, such as 100% methanol, without need of a fuel reformer to extract H₂ by converting hydrogen and oxygen into electrical energy and water.

[0341] DRFC **910** comprises a fixed cylinder **912** serving as the cell's cathode electrode and having a porous inner catalytic surface layer **914** on its inner wall. The surface is three-dimensional and has depth to accommodate a reaction zone. The cylinder **912** is fixed to metal frame **916** of cell **910** so that it cannot rotate and so that it may conduct electricity to the frame **916**.

[0342] DRFC **910** also comprises a rotating or rotatable cylinder **918** serving as the cell's anode electrode and having a porous outer catalytic surface layer **920** on its outer wall. As for the cathode catalytic surface layer **914**, the anode catalytic surface layer **920** also is three-dimensional and has depth to accommodate a reaction zone. The cylinder **918** is journaled to spin around axis **922** within the fixed cylinder **912**.

[0343] The cylindrical electrodes **912** and **918** are shown in the drawings as right-circular and coaxial; however, these attributes are not a requirement and other cylinder-like geometries (e.g., elliptical, conical, hyperbolic, irregular, different axes) may be employed. Also, it is practical to build DRFC where the inner cylinder **918** is fixed and the outer cylinder **912** rotates or both cylinders rotate at different speeds or directions. All that is required is that one of the cylindrical electrodes **912** and **918** rotates relative to the other so that there is a rotational speed difference between the cylindrical electrodes **912** and **918**.

[0344] The porous inner catalytic cathode surface layer **914** of the fixed cylinder **912** has a radius r_2 . The porous outer catalytic anode surface layer **920** of the rotating or rotatable cylinder **18** has a radius r_1 . An electrolyte chamber **924** having a gap of width $d = r_2 - r_1$ is formed between the catalytic surface layers **914** and **920**.

[0345] The electrolyte chamber **924** is in fluid communication with electrolyte input tube **926** that can be connected to a source (not shown) of electrolyte. An electrolyte exit tube **928** is also provided for draining electrolyte, unreacted fuel or oxidizer, water and carbon, from the electrolyte chamber **924**.

[0346] The cathode electrode fixed cylinder **912** porous inner surface layer **914** is supported by a cylindrical outer porous metal web **930** that provides both structural backing from and electrical conductivity to the metal frame **916**. The outer surface of the porous metal web **930** is in fluid communication with oxidizer manifold **932**. The oxidizer manifold is connected to oxidizer input tube **934** that can be connected to a source (not shown) of oxidizer.

[0347] Preferred oxidizers include purified air or a liquid such as hydrogen peroxide, depending on choice of fuel. The oxidizer penetrates through the porous outer metal web **930** at its outer (first) surface **931** and then moves into porous cathode electrode catalytic (second) surface layer **914**. Multiple catalyst particles embedded within the pores of the cathode electrode layer **914**, disclosed in Embodiment C and below, then participate with the electrolyte in a three-phase (catalyst-oxidizer-electrolyte) reaction with the oxidizer entering the pores to produce hydroxide (OH^- ions) at the cathode electrode's inner surface layer **914**.

[0348] High-hydrogen-content fuel enters the DRFC **910** through fuel input tube **936** and passes into fuel manifold **938**. The fuel manifold **938** is in fluid communication with the rotating or rotatable cylinder **918** anode electrode inner (first) surface metal web **40** that supports the porous outer catalytic surface layer **20**. The fuel penetrates through the porous inner metal web **940** at its inner surface **941** and then moves into porous anode electrode catalytic (second) surface layer **920**. Multiple catalyst particles embedded within the pores of the anode electrode surface layer **920**, disclosed in Embodiment C and below, then participate with the electrolyte in a three-phase (catalyst-fuel-electrolyte) reaction with the fuel, a reducing agent or reductant, entering its pores to produce protons (H^+ ions) at the anode electrode's outer surface layer **920**.

[0349] The inner surface metal web **940** also conducts electrical current to collector ring **942**. The collector ring **942** conducts electrical current to collector brush **944** that is part of electrical terminal **946** insulated from and extending through the metal frame **916** as the

DRFC **910** negative terminal $-$. Electrical terminal **948** is the DRFC **910** positive terminal $+$, which is electrically connected to the cathode inner surface metal web **930** and porous outer catalytic surface layer **920** through the metal frame **916**. The electrical terminals **946** and **948** are connected to an external electrical circuit load **950**.

[0350] The DRFC **910** is operated to produce electricity for transmission to the external electrical circuit load **950** by a process comprising:

1. Pumping electrolyte through electrolyte input tube **926** into electrolyte chamber **924**;
2. Pumping a high-hydrogen-content fuel through the fuel input tube **936** into the fuel manifold **938** and through the anode inner surface metal web **940** and anode porous outer catalytic surface layer **920**;
3. Pumping oxidizer through the oxidizer input tube **934** into the oxidizer manifold **932** and through the cathode outer surface metal web **930** and cathode porous inner catalytic surface layer **914**;
4. Powering electric motor drive **952** to rotate the anode cylinder **918** at a rate sufficient to cause Taylor Vortex Flows **954** and Circular Couette Flows **956** to form over protuberances **958** in the electrolyte chamber **924**; and
5. Draining electrolyte containing H_2O and any CO_2 gas created by the fuel cell **910** acid electrolyte chemical reaction, as well as any unreacted fuel or oxidizer from the electrolyte chamber **924**.

[0351] Creation of the TVF **954** and CCF **956** in the fuel cell electrolyte chamber **924** provides four significant operational advantages, namely:

- ◆ Elimination of a need for PEM to prevent fuel/oxidizer crossover;
- ◆ Exceptionally high-shear-rate laminar electrolyte flow (CCF) **956** at the electrode catalytic surface layers **914** and **920** (see **FIG. 9B**) to facilitate chemical reaction mass transport coupled with accelerated ionic transport

between electrodes, all cooperating to promote faster chemical reactions and high electrical current densities;

- ◆ Elimination of reaction byproducts (e.g., water, heat) with electrolyte circulation; and
- ◆ Direct access of trans-electrode fuel and oxidizer to catalyst surfaces.

These four principal advantages translate into higher power and energy densities in terms of both size and weight over prior art fuel cells.

[0352] Generally, electrode surface layers **914** and **920** are coextensive, both circumferentially and axially. The gap **d** between facing surfaces in the electrolyte chamber **924** may vary somewhat by imparting a slightly cylindrical-conical shape, not shown, to either or both surfaces in order to establish a uniform pressure in axially flowing fluid contained within the chambers **924**.

[0353] In every case, in accordance with the invention, electrolyte, whether or not recirculated for reuse, is contained within the electrolyte chamber, **924**, between one stationary surface layer **914** and one facing spinning surface layer **920**. Rotation of the spinning cylinder **918** imparts energetic, but non-turbulent TVF **954** and CCF **956** in the electrolyte immediately upon entry of the fluid into its chamber **924**.

[0354] The three-phase chemical reaction of catalyst surface layers **914** and **920**, electrolyte and fuel or oxidizer is both temperature-dependent and exothermic. Fuel, electrolyte or oxidizer may be heated initially by balance-of-plant (BOP) or by internal heaters.

DRFC Battery

[0355] The DRFC **910** that has been described with electrodes capable of generating 10 Amperes/cm², will deliver 1,000 Amperes of current from a rotating or rotatable anode electrode catalytic surface layer **920** measuring about 19 mm in diameter by 90 mm long. The voltage under load across terminals **946** and **948** will be about 0.8 to 1.0 volt.

[0356] There are two problems that need to be considered when using high-current DRFC **910**. The first is how to obtain a voltage that will meet requirements of the external electrical circuit load **950**. The second is how to solve problems created by the collector ring **942** and the collector brush **944** that are used to provide a circuit between the rotating or rotatable electrode **918** and the external electrical circuit load. One solution will solve both problems.

[0357] It is obvious to connect a plurality of individual cells in series by sequential connection of the anode of one cell to the cathode of another cell to form a battery or stack having a desired output voltage. This technique will not produce a satisfactory result for DRFC **910** or any other fuel cell that contains a collector ring (e.g., **942**) or a collector brush (e.g., **944**) because of three problems caused by these elements.

[0358] The first problem is that efficient collector rings are made from copper alloys, which are susceptible to attack and corrosion by electrolyte chemicals. Although not shown in **FIG. 9A**, the collector ring **942** requires seals to protect it from exposure to both the electrolyte and the fuel – both of which can increase its surface electrical resistance where the collector brush **944** contacts it.

[0359] The second problem is that a collector brush **944** capable of carrying a 1,000 Ampere current load is physically large – especially when compared to the 19 mm diameter of the rotating or rotatable cylinder **918**. Such a brush will have a face area that is greater than that of a 19 mm diameter cylinder and would require a substantially larger collector ring **942**. Therefore, the size of the collector brush **944** becomes a limiting factor on the electric current capacity of the cell.

[0360] The third problem is that there is a voltage drop across the collector ring **942** and the collector brush **944** of about 0.1 volt under load, which is about 11% of the load voltage. This loss is attributable to contact interface loss of a carbon brush running against a copper alloy ring and to I^2R losses in the carbon brush assembly.

[0361] For these three reasons, it is not practical to simply connect in series DRFC or other fuel cells with a rotating or rotatable electrode to form a battery. However, practical fuel cell (including DRFC) batteries can be built, as shown in **FIG. 10**.

[0362] A fuel cell battery **200**, which may be a DRFC battery or stack, comprises four fuel cells **CELL A - 202A**, **CELL B - 202B**, **CELL C - 202C** and **CELL D - 202D** that may be similar to the DRFC **10** shown in **FIG. 9A**. Each cell contains a rotating or rotatable electrode **204x** where **x** stands for one of the letters **A**, **B**, **C** or **D** that is associated with one of the four cells **202x**. The electrodes **204x** are fixed to a rotating or rotatable shaft **206** that is driven by an electric motor (similar to motor **952**) that is not shown in **FIG. 10**. Each cell also contains a fixed electrode **208x** that is secured to frame **210x**. Each frame **210x** is electrically insulated from adjacent frame(s) **210x**.

[0363] Each of the cells **202x** has a rotating or rotatable electrode manifold **212x** and a fixed electrode manifold **214x**. Fuel duct **216** in rotating or rotatable shaft **206** connects a source of fuel (not shown) to rotating or rotatable electrode manifolds **212A** and **212C**. Similarly, oxidizer duct **218** in rotating or rotatable shaft **206** connects a source of oxidizer (not shown) to rotating or rotatable electrode manifolds **212B** and **212D**. The oxidizer is shown in **FIG. 10** as **O₂**; however, it can be any suitable oxidizer.

[0364] The fixed electrode manifolds **214x** are equipped with input ports **220x**. Fixed electrode manifold input ports **220A** and **220C** connect to a source of oxidizer (not shown). Fixed electrode manifold input ports **220B** and **220D** connect to a source of fuel (not shown).

[0365] Rotating or rotatable electrodes **204A** and **204C** are anodes. Rotating or rotatable electrodes **204B** and **204D** are cathodes. Fixed electrodes **208A** and **208C** are cathodes. Fixed electrodes **208B** and **208D** are anodes.

[0366] As for the DRFC **10** of **FIG. 9A**, this fuel cell **200** is operated by rotating or rotatable the shaft **206** and injecting fuel through duct **216**, port **220A** and port **220D** while also injecting oxidizer through duct **218**, port **220B** and port **220D**. TVF **222** and CCF (not shown) then form in electrolyte chambers **224x** in electrolyte recycled through electrolyte balance of plant (BOP) **226**, as shown in **FIG. 10**.

[0367] An electric circuit – illustrated in part as dashed line **230** – is then formed that starts at battery cathode **e⁺** terminal **228** that is electrically connected to fixed electrode **208A**. The circuit follows near dotted line **230** up fixed electrode **220A**, across electrolyte chamber **224A**, up rotating or rotatable electrode **204A** to copper alloy sleeve busbar **232AB** that provides a low-electrical-impedance connection between anode rotating or rotatable electrode

204A and cathode rotating or rotatable electrode **204B**. The busbar **232AB** is secured to and electrically insulated from the rotating or rotatable shaft **206**. The busbar **232AB** is also insulated (not shown) from electrolyte in chamber **224A** and **224B** to protect it from chemical attack.

[0368] The electric circuit continues up rotating or rotatable electrode **206B**, across electrolyte chamber **224B** and up fixed anode electrode **208B** to copper alloy busbar **234BC**, which is secured to and insulated from frames **210B** and **210C**. The busbar **234BC** provides a low-electrical-impedance connection between anode fixed electrode **208B** and cathode fixed electrode **208C**. The electric circuit continues up electrode **208C**, across electrolyte chamber **224C** to rotating or rotatable anode electrode **204C** and to busbar sleeve **232CD**, which is essentially identical to busbar sleeve **232AB**. The busbar sleeve **232CD** provides a low-electrical-impedance connection between anode rotating or rotatable electrode **204C** and cathode rotating electrode **204D**.

[0369] The electric circuit then continues up rotating or rotatable cathode electrode **204D**, across electrolyte chamber **224D** and up to fixed anode electrode **208D** to battery anode e^- terminal **236**. The circuit is completed by electrical conductors **238** that connect the battery terminals **228** and **236** to external electrical circuit load **240**.

[0370] The arrows adjacent the dashed line **230** show the direction of electricity in the electrodes **204x**, **208x**. Only ions, not electrons, flow across the electrolyte chambers **224x** which may be modeled as voltage sources. The arrows adjacent the electrical conductors **238** show the direction of electric current flow in the external electrical load **240**.

[0371] **FIG. 6** illustrates a four-cell battery in order to show the fixed busbar **234BC**. However, the minimum number of cells required for the fuel cell battery **200** not requiring collector rings or brushes (e.g., **42**, **44**) is only two. Where only two cells are used (e.g., **202A** and **202B**), then an anode terminal similar to anode terminal **236** can be used in place of the fixed busbar **234BC**.

[0372] An important point worthy of emphasis is that this novel fuel cell battery **200** does not contain any collector ring or brush. Thus, there is no need for 1) shaft seals or other mechanisms to protect a collector ring or brush from chemical attack, 2) additional cells or batteries connected in parallel to provide extra current to compensate for a current-limiting

collector ring and brush, or 3) additional cell(s) connected in series to provide extra voltage to compensate for contact interface and I^2R losses in a collector ring - carbon brush assembly. This collector brush-free fuel cell **200** battery configuration makes use of high-current fuels cells, such as the DRFC **10** practical for powering high-energy external electrical circuit loads **240**. Further, it can be built with as many cell pairs as needed to obtain a desired terminal **228 – 236** voltage.

Acid-Electrolyte DRFC Fueled By Methanol

[0373] DRFC fueled by methanol and using an acid electrolyte are called Direct Methanol Fuel Cells (DMFC). The best electrolyte for DMFC is concentrated phosphoric acid, H_3PO_4 that melts at $40^\circ C$; however, it requires heating at start up.

[0374] DMFC have two advantages in mobile applications, such as transportation. First, they can achieve almost complete direct oxidation of CH_3OH to produce only CO_2 and H_2O that are easily exhausted to the atmosphere during TVF electrolyte recirculation. Second, they can operate at a temperature less than $100^\circ C$. However, operation at 250 to $350^\circ C$ will convert 100%-concentration liquid methanol and ethanol at any pressure to a gas and potentially accelerate the activity of cheap catalysts.

[0375] Further, there is no need in DMFC of this invention to dilute methanol to prevent fuel crossover because there is near-total fuel consumption before reaction products reach the electrode-electrolyte interface. Internal pressure greater than 2.7 bar (40 psi) will assure that the fuel remains in concentrated liquid form at $100^\circ C$ within the fuel cell. In such case the lack of a gas phase that must cooperate with the liquid electrolyte in the catalyst surface layer can be an advantage - although this feature is largely mooted by the TVF in DRFC of this invention.

[0376] The chief disadvantage of DMFC is slow reaction times for complete oxidation - even with expensive Pt/Ru catalysts. Anodes constructed as described above and in Embodiment C have effective reaction zone depths that will compensate for inherent reaction delay; but, catalyst cost may not favor DMFC in a particular application.

[0377] Direct reaction of hydrocarbon fuels such as methanol, ethanol, methane and propane in acidic electrolyte can be substantially accelerated with much less expensive

catalysts (e.g., Ni alloy) when higher temperatures and pressures are employed within the fuel cell. Above 240° C and 243° C, respectively, both methanol and ethanol will enter the DRFC as a gas, even though they may be stored in liquid form. If their entry is volumetrically confined, then they will reach pressures in excess of 78.5 and 63 bar (1150 and 925 psi), respectively, at comparable volumetric molar concentrations for these fuels as stored in their liquid form. Any volumetric disadvantage is more than offset by the accelerated reaction rates and use of nanostructured catalysts such as Cu-based cermets or Ni/ceria-doped zirconium on Cu nanoporous supports. Pt also is an economic option at lower loading factors.

[0378] Acid DMFC, even at an elevated temperature, are medium temperature fuel cells as contrasted with a low temperature polymer exchange membrane (PEM) or high temperature solid oxide fuel cells (SOFC). DMFC have many of the advantages of high temperature solid oxide fuel cells (SOFC) and none of the disadvantages of low temperature polymer exchange membrane (PEM) fuel cells.

Alkali-Electrolyte DRFC Fueled By Methanol

[0379] DRFC fueled by methanol and using an alkaline electrolyte are called Direct Methanol Alkaline Fuel Cells (DMAFC). DMAFC use hydroxyl ion electrolytes containing a cation from Group 1 of the Periodic Table of the Elements, such as NaOH, KOH and LiOH.

[0380] The chief advantage of the alkaline electrolytes is that traditional Pt/Ru catalysts oxidize methanol and most hydrocarbon fuels at least 20-times faster than acid electrolytes. Because they also accelerate the cathode oxygen reduction reaction (ORR), less catalyst is required for a given power density. Also, OH⁻ solutions do not require pre-heating, are less corrosive on metal catalysts and electrode structures and are generally more stable than acids other than phosphoric acid.

[0381] DMAFC have an important disadvantage that has made their use impractical. Prior art DMAFC end products from complete oxidation of methanol or any comparable hydrocarbon fuel are water and carbonates, CO₃⁼. The carbonates are formed by the alkaline electrolyte's capture of gaseous CO₂. CO₂ capture depletes the OH⁻ ion concentration in the electrolyte and the ions must be replaced. While this is not a difficult chemical step for this

invention, reconditioning electrolyte to remove carbonates and replace hydroxyl ions adds to the BOP requirement and is an important disadvantage for mobile applications.

[0382] DMAFC of this invention provide one method to mitigate, if not altogether eliminate, the difficulty of reconditioning electrolyte by mixing some electrolyte with the liquid fuel as methanol enters the cell. This mixture will initiate a multi-step chemical reaction within the anode's reaction zone in which the last step is production of CO₂ as a gas at comparatively lower temperatures and pressures of the liquid fuel. CO₂ gas will form at or very near the electrode/electrolyte interface (see **FIG. 2C** and **FIG. 5B**) where it can be quickly sequestered by the TVF as bubbles (e.g., **76**) and expelled from the electrolyte chamber (e.g., **24**) before a significant amount of CO₂ gas goes into solution to appropriate hydroxyl during the formation of carbonates. Rapid recirculation of electrolyte can substantially mitigate CO₂ sequestration.

[0383] An alternative method of operating a DMAFC comprises operation at substantially elevated temperature of at least 250° C, and somewhat less pressure than described for DMFC. In addition to choices from a much wider range of catalyst options, the higher temperatures drive the fuel and reaction products to gasses – not carbonate precipitates. At 250° C and above, CO becomes a fuel in alkaline electrolyte, rather than a catalyst poison, because it is further oxidized to CO₂ which will not dissolve rapidly in the alkaline electrolyte at the elevated temperature. Therefore, the alkaline electrolyte will require less replenishment.

Alkali-Electrolyte DRFC Fueled By Sodium Borohydride

[0384] DRFC fueled by a borohydride containing a cation from Group 1 of the Periodic Table of the Elements, such as sodium borohydride, NaBH₄, or potassium borohydride, KBH₄, and using an alkaline electrolyte are called Direct Borohydride Fuel Cells (DBFC). As with DMAFC, the best electrolytes for DBFC are hydroxyl ion electrolytes containing a cation from Group 1 of the Periodic Table of the Elements, such as KOH, NaOH and LiOH.

[0385] DBFC operate in a fashion similar to that described for the low or elevated temperature DMAFC, except that CO₂ is not produced and there is no hydroxyl ion sequestration. Borohydrides are sold as powders and must be diluted to concentrations of 30

to 50% molar in alkaline electrolyte, generally KOH or NaOH, to be usable in stable solution as fuels. The fuel remains a liquid, even at higher temperatures in the range of 250 to 350° C.

[0386] Complete fuel oxidation produces less-soluble borate, NaBO_2 that will precipitate after reaching about 15% molar concentration in alkaline electrolyte. That borate concentration will not degrade the electrolyte and will not increase as more borate precipitate is produced to be sequestered by TVF and collected in the electrolyte recirculation chamber of BOP.

[0387] As expected, the borohydride fuels are very chemically reactive. Therefore, it is essential to coat or cover the entire fuel path from storage, through the electrode porous metal support structure to, but not including the catalyzed reaction zone, with a suitable dielectric (non-metal) such as carbon or PTFE in order to prevent hydrolysis of the fuel.

[0388] Borohydride fuels cost much more than hydrocarbon fuels. Nevertheless, DBFC are well suited for specialized applications where high-energy or high-power per unit-weight or unit-size requirements are beyond the capabilities of other DRFC.

Embodiment E: *Dynamic Accelerated Reaction Batteries*

[0389] Electrochemical cells and batteries (e.g., stacks, piles) have been studied for two-hundred years with objectives of increasing energy density (e.g. Joules/cm³, Joules/kg), power density (e.g. Watts/cm³, Watts/kg), charge-discharge rate (Amperes/second), terminal voltage, functional operating temperature range and the like. Most improvements in battery technology have been achieved by incremental advances in material selection and fabrication. While these improvements have been important, most of today's cells and batteries structurally resemble the *Voltaic Pile* of 1800 that comprised a stationary anode separated from a stationary cathode by an electrolyte.

[0390] Electrochemists have long understood that battery performance would be improved by causing electrolyte to flow between electrodes. The objectives were either to a) accelerate movement of ions between electrodes, b) prevent formation of metallic dendrites on electrodes that could short-circuit cells, and c) prevent or control flooding of electrodes by electrolytes. Some prior art cells or batteries included moving electrodes (e.g., U.S. Patent No. 4,491,624 to Sarbacher et al, U.S. Patent No. 4,521,498 to Tamminen and U.S. Patent

No. 4,684,585 to Tamminen) to induce electrolyte flows. However, there is no evidence that any of these cells or batteries is capable of discharging at a rate in excess of 1 ampere/ cm² of electrode surface for an extended period.

[0391] Dynamic Accelerated Reaction Batteries (DARB) of this invention comprise one or more electrochemical cells capable of fast and high rates of discharge and, for secondary cells, fast and high rates of charge. These attributes are achieved by incorporating one or more rotating or rotatable electrodes that induce Taylor Vortex Flows (TVF) and Circular Couette Flows (CCF) in electrolytes between anodes and cathodes. Electrodes optimized for use with TVF and CCF and having high current densities and consequent fast charge/discharge rates are described below.

[0392] Taylor Vortex Flows (“TVF” – also known as *Taylor – Couette Flows*), described in Embodiment A, to achieve enhanced reaction rates by a) accelerating electrode surface reaction mass-transport, b) capturing reaction products that can degrade electrode surfaces and electrolytes, c) eliminating those degrading reaction products from the cells, d) increasing operating temperature range to reduce overpotentials at electrodes and raise reaction rates and e) concentrate reacting electrode surface area exposure to electrolyte. Chemical and electrochemical cells – including fuel cells and fuel reformers – utilizing these achievements are described in Embodiment A, Embodiment B and Embodiment D.

[0393] Battery electrodes described here use TVF that automatically generate accelerated, high-shear-rate, stable laminar CCF at the electrode surfaces. These laminar flows increase electrode surface electrical current density by accelerating mass transport of ions and providing means for removing degrading reaction products. Reactive electrodes used in batteries that present high surface area/projected area ratios to electrolytes are described in Embodiment C and below.

[0394] Batteries and cells of this invention comprise different structures and employ TVF in a different manner. For example, cells incorporate porous anode and cathode electrodes separated by electrolyte. In embodiments described below, the electrolyte penetrates each of the electrodes in reversible directions for charge/discharge cycles, respectively, by moving in cross flow through a gap between the electrodes.

[0395] This disclosure describes systems and methods for management of any type of fluid electrolyte in electrochemical cells and batteries. Cells and batteries of this invention have ionic conductivities that are orders of magnitude greater than prior art cells and batteries so that ionic transfer time between electrodes that have been a mass transport limitation of electrical-current-producing chemical reactions now are negligible.

[0396] For cells and batteries incorporating membranes (e.g., lithium cells using LISICON™ membranes to separate an organic anolyte from an aqueous catholyte, such as U.S. Patent No. 5,525,442 to Shuster), the dominant limitation on ionic conductivity is the rate at which ions can migrate through the membrane. This rate can be increased by creating high-shear-rate laminar flow at the surfaces of the membrane. Laminar CCF are in direct contrast with the prior art that teaches that turbulent flow is beneficial in reducing dendrite formation and increasing electrode activity.

[0397] The prior art also teaches that in order to maintain laminar flow, fluid (e.g., electrolyte) velocities must be kept sufficiently low so that the critical turbulent Reynolds Number, Re (not R_c), is not exceeded. The present invention of this disclosure succeeds because its cells have electrolyte velocities that result in much higher circumferential Reynolds Numbers, R_c , and high laminar shear rates stabilized by generated TVF. Because a requirement for laminar flow can be achieved at much higher laminar shear rates using TVF, as taught here, cells and batteries of this invention achieve multiple orders of magnitude higher current densities than non-TVF laminar flow cells and batteries.

[0398] Furthermore, there is a requirement to maintain laminar flow at electrode surfaces while promoting TVF within the electrolyte. Care must be taken to restrict the circumferential Reynolds number, R_c , to non-turbulent values. A set of distinct variables define a particular range of permissible operating parameters. These variables include predetermined ranges of: 1) temperature, 2) kinematic viscosity of the fluids being employed, 3) respective rates of recirculation, 4) angular rotation speed, 5) surface characteristics of the electrodes and 6) physical dimensions of the cell.

[0399] Given appropriate operating parameters, neither gaseous reaction products nor particle precipitates of the redox reaction at the electrodes can penetrate the TVF. Only

redox-product ions in solution can enter the electrolyte and cross rapidly to the opposite electrode, which is an important feature of electrochemical cells utilizing TVF in electrolyte.

[0400] The present invention is a robust electrochemical cell or battery for providing electrical energy containing a fluid electrolyte between relatively rotating or rotatable, coaxial cylindrical electrodes that cause Taylor Vortex Flows (TVF) and Circular Couette Flows (CCF) within the electrolyte. Where a membrane is required for separation of incompatible electrolytes, TVF and CCF enhance ion transport through the membrane.

Dynamic Accelerated Reaction Battery

First Example – Four Cell Stack

[0401] **FIG. 11A** is a fragmentary cross-section view of a Dynamic Accelerated Reaction Battery **B10**. **FIG. 11A** resembles **FIG. 10** of Embodiment D, which is a cross-section view of a TVF/CCF fuel cell. While the battery **B10** and the fuel cell of Embodiment D both convert their potential energies to electrical energy and share many similarities relating to TVF and CCF, they operate differently. DARB and most conventional batteries store potential energy in their electrodes or dual electrolytes while fuel cells store potential energy in their fuels. As a result, batteries and fuel cells have different energy densities, power densities, terminal voltages and currents.

[0402] The battery **10** comprises four cells **CELL A - B12A**, **CELL B - B12B**, **CELL C - B12C** and **CELL D - B12D**. Each cell contains a rotating or rotatable electrode **B14x** where **x** stands for one of the letters **A**, **B**, **C** or **D** that is associated with one of the four cells **B12x**. The electrodes **B14x** are fixed to a shaft **16** that rotates about spin axis **B17** and is driven by an electric motor **B18**. Each cell also contains a fixed electrode **B20x** that is secured to frame **B22x**. The motor **B18** rotates so that so that there is relative motion between one electrode **B14x**, **B20x** of one polarity and another electrode **B20x**, **B14x** of another polarity. In this embodiment, the electrode **B14A** rotates within the electrode **B20A**, the electrode **B14B** rotates with the electrode **B20B**, the electrode **B14C** rotates with the electrode **B20C** and the electrode **B14D** rotates within the electrode **B20D**. Each frame **B22x** is mechanically coupled to and electrically insulated from adjacent frame(s) **B22x**.

[0403] Cylindrical electrodes **B14x** and **B20x** are shown in the drawings as right-circular and coaxial; however, these attributes are not a requirement and other cylinder-like geometries (e.g., elliptical, conical, hyperbolic, irregular, different axes) may be employed. Also, it is practical to build DARB **B10** where the inner electrodes **B14x** are fixed and the outer electrodes **B20x** rotate or both electrodes **B14x**, **B20x** rotate at different speeds or directions. All that is required is that one of the cylinder-like electrodes **B14x** and **B20x** rotates relative to the other so that there is a relative, rotational velocity difference greater than zero between the cylindrical electrodes **B14x** and **B20x**.

[0404] Rotating or rotatable electrodes **B14A** and **B14C** are anodes. Rotating or rotatable electrodes **B14B** and **B14D** are cathodes. In this embodiment all of the electrodes **B14x** are fixed to and rotated by the shaft **B16**, which is common to all for rotating or rotatable the electrodes **B14x**; however a common shaft is not a requirement. Fixed electrodes **B20A** and **B20C** are cathodes. Fixed electrodes **B20B** and **B20D** are anodes. In this embodiment, all of the electrodes **B20x** are fixed to their frames **B22x**, which are mechanically coupled together; however, that is not a requirement. As will be described, the cells **B12x** are connected in an electrical series circuit; but, parallel and combination circuits are also practical.

[0405] Each of the cells **B12x** has a rotating or rotatable electrode manifold **B24x** and a fixed electrode manifold **B26x**. Each of the manifolds **B24x** and **B26x** is connected to electrolyte Balance of Plant (BOP) **28** through first and second electrolyte ducts **B30x** and **B32x** so that during discharge electrolyte can flow through anode electrodes **B14A**, **B20B**, **B14 C** and **B20D** through electrolyte chambers **B38X** and back to BOP **B28** through electrodes **B20A**, **B14B**, **B20C** and **B14D**. The electrodes **B14x** are rotated by the motor **B18** so that there is relative motion between one electrode of one polarity and another electrode of another polarity as well as relative motion of the electrodes **B14x** with respect to the electrolyte.

[0406] An electric circuit – illustrated in part as dashed line **B34** – is then formed that starts at battery cathode e^+ terminal **B36** that is electrically connected to fixed electrode **B20A**. The circuit follows near circuit dashed line **B34** up fixed electrode **B20A**, across electrolyte chamber **B38A**, up rotating or rotatable electrode **B14A** to copper alloy sleeve busbar **B40AB** that provides a low-electrical-impedance connection between anode rotating

or rotatable electrode **B14A** and cathode rotating or rotatable electrode **B20B**. The busbar **B40AB** is secured to and electrically insulated from the rotating or rotatable shaft **B16**. The busbar **B40AB** is also insulated (not shown) from electrolyte in the chambers **B38A** and **B38B** to protect it from chemical attack.

[0407] The electric circuit continues up rotating or rotatable electrode **B14B**, across electrolyte chamber **B38B** and up fixed anode electrode **B20B** to copper alloy busbar **B42BC**, which is secured to and insulated from frames **B22B** and **B22C**. The busbar **B42BC** provides a low-electrical-impedance connection between anode fixed electrode **B20B** and cathode fixed electrode **B20C**. The electric circuit continues up electrode **B20C**, across electrolyte chamber **B38C** to rotating or rotatable anode electrode **B14C** and to busbar sleeve **B40CD**, which is essentially identical to busbar sleeve **B40AB**. The busbar sleeve **B42CD** provides a low-electrical-impedance connection between anode rotating or rotatable electrode **B14C** and cathode rotating or rotatable electrode **B14D**.

[0408] The electric circuit then continues up rotating or rotatable cathode electrode **B14D**, across electrolyte chamber **38D** and up to fixed anode electrode **B20D** to battery anode e^- terminal **B44**. The circuit is completed by electrical conductors **B46** that connect the battery terminals **B36** and **B44** to external electrical circuit **B48**.

[0409] The arrows accompanying the electric circuit dashed line **B34** show the direction of electricity in the electrodes **B14x**, **B20x** for discharge. Only ions, not electrons, flow across the electrolyte chambers **B38x**, which may be modeled as voltage sources. The arrows marked **DISCHARGE** and **CHARGE** adjacent electrical conductors **B46** show the direction of electric current flow for discharging and charging the battery **B10**. Similarly, the arrows marked **DISCHARGE** and **CHARGE** adjacent pipes **B50** show the direction of electrolyte flow for discharging and charging the battery **B10** through the first and second fuel ducts **B30x**, **B32x** connected to the electrolyte chambers **B38x**.

[0410] **FIG. 11A** illustrates a four-cell battery in order to show the fixed busbar **B42BC**. However, the minimum number of cells required for the fuel cell battery **B10** not requiring collector rings or brushes is only two. Where only two cells are used (e.g., **B12A** and **B12B**), then an anode terminal similar to anode terminal **B44** can be used in place of the fixed busbar **B42BC**.

[0411] An important point worthy of emphasis is that this novel battery **B10** does not contain any collector ring or brush. Thus, there is no need for 1) shaft seals or other mechanisms to protect a collector ring or brush from chemical attack, 2) additional cells or batteries connected in parallel to provide extra current to compensate for a current-limiting collector ring and brush, or 3) additional cell(s) connected in series to provide extra voltage to compensate for contact interface and I^2R losses in a collector ring - carbon brush assembly. The collector brush-free configuration makes use of high-current batteries, such as the DARB **B10** practical for powering high-energy external electrical circuits **B48**. Further, it can be built with as many cell pairs as needed to obtain a desired terminal **B36 – B44** voltage.

[0412] Secondary DARB **B10** of **FIG. 11A** can have two operational modes; namely, charge mode at higher than rated voltage and discharge mode at rated voltage or less; both modes being at the same polarity. From an operational perspective, the differences between these two modes are in a) the direction of current in the electric circuit **B34**, **B46** and b) the direction of electrolyte flow in the electrodes **B14x** and **B20x**.

[0413] The battery **B10** is operated by electrically energizing motor **B18** to rotate the shaft **B16** and energizing Electrolyte BOP **B28** to pump electrolyte. As shown for the embodiment of **FIG. 11A**, both the motor **B18** and the Electrolyte BOP **B28** are in a series circuit containing the battery **B10**, the electrical conductors **B46** and the External Electrical Circuit **B48**. This circuit will provide feedback so that the speed of motor **B18** and the flow rate of electrolyte pumped by BOP **B28** will be a function of the magnitude and direction electric current flowing in conductors **B46**. Alternatively, either or both the motor **B18** and the Electrolyte BOP **B28** can be powered from an external source.

[0414] In a battery **B10** discharge cycle, the electrolyte flow – as shown by labeled arrows in **FIG. 11A** – travels the following path:

- Starting at the Electrolyte BOP **B28**;
- Then, through electrolyte ducts **B30a**, **B32b**, **B30c**, **B32d**;
- Then, into anode manifolds **B24a**, **B26b**, **B24c**, **B26d**,
- Then, through the anode electrodes **B14a**, **B20b**, **B14c**, **B20d**;

- Then, into electrolyte chambers **B38a, B38b, B38c, B38d**;
- Then, through cathode electrodes **B20a, B14b, B20c, B14d**;
- Then, into cathode manifolds **B26a, B24b, B26c, B26d**;
- Then, through electrolyte ducts **B32a, B30b, B32c, B30d**; and
- Then, back to electrolyte BOP **B28**.

In a battery **B10** charge cycle, the direction of electrolyte flow is reversed.

[0415] As shown in **FIG. 11B**, the fixed electrode **20A** is located between the fixed electrode manifold **B26A** and the electrolyte chamber **B38A**. Because of pump pressure from the electrolyte BOP **B28**, electrolyte flows from the manifold **B26A** to the chamber **B38A**, as shown by an arrow **B52** in **FIG. 11B**. The rotation at a proper speed of the electrode **B14A** (not shown in **FIG. 11B**) relative to the fixed or stationary electrode **B20A** will cause TVF **B54** to form in the electrolyte chamber **B38A**. When the speed of rotation is properly adjusted, then CCF **B56** will form adjacent to the surfaces of both electrodes **B20A** and **B14A**.

[0416] The surfaces of the electrodes **B20A** and **B14A** may include protuberances **B58** that extend into the CCF **B56**; but, not into the TVF **B54**. The limiting factor for charge and discharge rate or current of the battery **B10** is its internal impedance for an applied voltage which is somewhat higher for charging than its normally rated discharge potential. Internal impedance is a function of transfer rate of anode ions (e.g., Li+) and not electrons in the electrodes **B14x** and **B20x**, which are flooded with electrolyte. The CCF **B56** are high-velocity, high-shear rate laminar flows that provide a dynamic improvement in ionic mass transport within electrolyte and expedite high-speed ion transport between the electrodes **B14x** and **B20x**. The protuberances **B58** also provide a great increase in exposed electrode surface area.

[0417] The relationship between the TVF **B54**, the CCF **B56** and the protuberances **B58** are also shown in **FIG. 2C-3**. The TVF **B54** rotate around axis **B60** that is located on the center **B64** of the electrolyte chamber **B38x**.

[0418] The electrodes **B14x** and **B20x** preferably include electrically conducting isotropic nanoporous chemically active material appropriate to each battery electrode or copper or gold foam nanosponges or nanocarbon filamentary material **86** (**FIG. 2E**) that serve as a scaffold to be speckled, coated or alloyed with chemically active electrode material firmly attached to open cell interconnecting surfaces such as nanoporous copper filamentary material **B70** backed by porous metal grids **B72** that provide both mechanical strength and electrical conductivity. The foam sponges or carbon filamentary material **86** of the protuberances **B58** are further backed and supported by porous metal grids **B72** that also conduct large electrical currents.

[0419] As with the other embodiments, an important feature of the TVF is illustrated in **FIG. 2C-3** where particles from a precipitate, including water attached to the precipitate and bubbles from either electrode surface layers **B14x** or **B20x** introduced into electrolyte chamber **B38x** are drawn into the centers of TVF **B54**. These particles and bubbles **B74** are sometimes formed during operation of the cells **B12x**. The particles and bubbles **B74** are not in actual solution as part of the electrolyte and are therefore subject to the flow dynamics just described. They will experience high pressure gradients caused by the fluid electrolyte TVF **B54**. These high gradients appear in both the high-shear laminar CCF **B56** and within the vortices **B54**. The TVF **B54** quickly drive the particles and bubbles **B74** to the centers of the nearest vortices **B54** where they remain trapped.

[0420] TVF **B54** are individual vortex entities that move in axial flow through the electrolyte chamber **B38x**. The particles and bubbles **B74** trapped within vortices **B54** are forced out of the electrolyte chamber **B38x** along with their host vortex **B54**. Thus, TVF **B54** constitute means for extracting unwanted contaminants **B74** from the electrolyte. These unwanted contaminants **B74** may include reaction precipitates, water, vapor and any gasses exiting either electrode **B14x**, **B20x**; any of which can degrade the electrolyte if allowed to remain within it.

[0421] As shown in **FIG. 2C-3**, one side of the electrolyte chamber **B38x** is the cylinder-like (or slightly conical) rotating or rotatable electrode **B14x** surface at radial distance, r_1 from the spin axis of rotation **B17** about which it spins at an angular rate, Ω_1 . The other side of the electrolyte chamber **B38x** is the cylindrical (or slightly conical) fixed electrode **20x** surface layer, r_2 from cell spin axis of rotation **B17**, which spins at an angular

rate Ω_2 . In this embodiment, the electrode **B20x** surface is fixed and $\Omega_2 = 0$; however, embodiments where $\Omega_2 \neq 0$ are also practical.

[0422] The gap thickness, $d = r_2 - r_1 > 0$ is defined above as the distance between the two surface layers **B20x** and **B14x**. As used herein, the term 'gap' is synonymous with the width, d , of the electrolyte chamber **B38x**.

[0423] Ions are carried convectively by TVF from one electrode to the other in the DARB **B10** at a prodigious rate that is far greater than could ever be achieved in a solid polymer PEM (e.g., NAFION™) or other stationary electrolyte. Once they have arrived near an electrode (e.g., **B14x** or **B20x**) surface, they are subjected to exceptionally energetic shear in laminar CCF **B56** covering the electrode which, for most common electrolyte liquids, will be shown to be somewhat thinner than solid membranes or an otherwise stationary electrolyte.

[0424] It is shear-enhanced diffusion in the laminar boundary layer that transports ions and reaction products to and from the highly porous electrode surfaces. Because roughly-silo-shaped, finger-like protuberances **B58** of chemically reactive porous electrode **B14x** and **B20x** surfaces, illustrated in **FIG. 2C-3**, extend into the laminar CCF **56**, ions have both a shorter path to travel and a faster diffusion rate. The diffusion rate increases rapidly as a function of shear stress in a viscous fluid.

[0425] As stated earlier, the limiting factor for charge and discharge of the battery **B10** is diffusion of anode ions (e.g., Li^+) in the electrodes **B14x** and **B20x**, which are flooded with electrolyte and the creation and delivery of anode ions (e.g., Li^+) and release of electrons to the electrode **B14x** and **B20x** surfaces. The CCF **B56** expedite these reactions and deliveries and enable the DARB **B10** to provide superior charge and discharge rate performance - even with large energy-storing molar loading factors in greatly thickened electrode structures **B14x** and **B20x**.

[0426] Construction of DARB **B10** require mathematical analysis of physical design and operable parameters to select useful values that can be applied to a specific design or embodiment. This has been described in Embodiment A.

[0427] By comparison with DARB **B10**, a high performance Li-ion battery may be able to store as much as 0.22 kW-h per liter of battery volume based on a reported value of 100 a-h/kg, 4 volts and density of 0.534 gm/cc. But, a Li-ion battery's membrane ionic conductivity and static diffusion surface chemistry limit its current density to at most 10 milliamp/cm² or 0.1 kW/liter and requires approximately 2500 cm² of Li electrode surface area. The theoretical maximum energy storage of solid Li at 4 volts is close to 8 kw-h/liter. Such a battery has 27.6 cc of Li per liter of battery so electrodes must be at least 100 microns in thickness. Clearly, the Li battery would require 2.2 hours of charging at substantial overvoltage (not recommended for safety and heating concerns in a sealed battery) to obtain a full charge.

[0428] Because of a much higher current density for both charge and discharge cycles, DARB **B10** reduce recharge time by a factor of 10 or 20 and recirculation venting avoids the explosion hazard. As explained more fully below, these advantages provide greatly increased power density while providing competitive energy storage density.

[0429] Typical CCF **B56** laminar boundary layer shear rates for DARB **B10** result in a "Shear Multiplier", as shown above, of as much as 15 to over 20-times the nominal value of $r_1\Omega_1/d$ for a conventional battery. The value of $1/v$ will be on the order of 100 sec/cm² and the electrolyte chamber gap, d , will be approximately 0.1 cm. R_a will be roughly 10 times the product of the length of a chamber such as manifold **B24** and volumetric exchange rate. If that product is on the order of 10 or 20 (e.g., a meter length can change volume every 5 to 10 seconds, etc.), then it is possible to hold R_a to 200 or less so that a value of $T_c > 10^4$ will be sufficient in nearly all cases to ensure the establishment of effective TVF.

[0430] Boundary layer thickness calculations provide an estimate of ionic conductivity through TVF **54** between electrodes. Clearly, the convective mass transport of the vortices themselves is orders of magnitude beyond relevance and will be ignored. For purposes of this calculation, the value of ionic conductivity in siemens/cm is a primary parameter and is understood to equal (amperes/cm²)/(volts/cm).

[0431] Actual performance of conventional solid-polymer PEM fuel cell and battery plate stacks provides ionic conductivity values that are typically $(0.6)/(0.65/t)$ where t is the thickness of the polymer membrane. Membrane thickness is described in prior art as $0.005 \leq$

$t \leq 0.01$ cm. Therefore, the ionic conductivity of a PEM in a fuel cell or battery for H^+ ions (protons) must be about 4.6×10^{-3} to 9.2×10^{-3} siemens/cm. Values of ionic conductivity for battery liquid electrolytes at low viscous shear are on the order of 20 to 100×10^{-3} siemens/cm. Given the shear stress multiple of the boundary layer as calculated above, it is clear that ionic diffusion driven by concentration gradients and linearly multiplied by shear rate at the electrode surfaces is a further order of magnitude beyond typical battery electrolyte values. For these reasons, ionic conductivity can also be ignored as a limiting factor controlling ionic transport between electrode **B14x** and **B20x** catalytic surfaces in DARB **B10** incorporating TVF **B54** and CCF **B56**.

[0432] The parameters described above for generating TVF **B54** and laminar CCF **B56** apply to both charging and discharging the DARB **B10** in normal operating conditions. However in the case of heavily-used DARB **B10** having worn or corroded electrodes **B14x**, **B20x**, it is sometimes better to charge while spinning the rotating or rotatable electrodes **B14x** at speeds that cause turbulent flows –rather than laminar CCF– at the electrode **B14x**, **B20x** surfaces. Turbulence in these circumstances can accelerate re-plating by opening pores and by dislodging precipitates, which will then be drawn to the centers of TVF **B54** as particles **B74** to be expelled from the electrolyte chamber **B38x** and removed from the electrolyte by BOP **B28**.

Dynamic Accelerated Reaction Battery

Second Example – Interdigitated Electrodes

[0433] **FIG. 12** is a fragmentary cross-sectional view of a second preferred embodiment of a Dynamic Accelerated Reaction Batteries (DARB) **100**. The battery **100** contains two cells **102A** and **102B** (also identified as **102x**, where **x** = **A** or **B**) that are connected in series, as shown for the battery **10** of **FIG. 1A**.

[0434] Each of the cells **102x** contains a pair of interdigitated electrodes **104x** structured as sets of anode **106x** and cathode **108x** concentric, cylinder-like electrodes. The electrodes **106x** and **108x** are interdigitated or nested with each other, as shown in **FIG. 12**. A primary advantage of interdigitated electrodes **102x** is increased energy and power density

per cm³ that is achieved by rotating or rotatable one of the electrodes **106x**, **108x** relative to the other to generate TVF and CCF– as taught above for DARB **B10** of **FIG. 11A**.

[0435] For cell **102A**, the cathode electrodes **108A** are $\cap$ -shaped and secured to fixed electrode plate **109A**, which provides:

- Mechanical support for the cathode electrodes **108A**,
- An electrolyte duct **110A** for connection to Balance Of Plant (BOP) **112**, and
- Electrical conductivity between the electrodes **108A** and e⁺ battery cathode terminal **108''A**.

The interiors of the $\cap$ -shaped cathode electrodes **108A** are electrolyte manifolds **108*A** that are in fluid connection with the electrolyte duct **110A** and BOP **112**.

[0436] In this embodiment, the fixed electrode plate **109A** is secured to cell frame **114A** and does not rotate. Because the plate **109A** is secured to cell frame **114A**, there is no need for a collector ring or brush to be in circuit with the battery cathode terminal **108''A**.

[0437] The anode electrodes **106A** are U-shaped and secured to rotating or rotatable electrode plate **115A**, which provides:

- Mechanical support for the anode electrodes **106A**,
- An electrolyte duct **116A** that extends through a rotating or rotatable shaft **118** for connection to BOP **112**, and
- Electrical conductivity between the electrodes **106A** and a busbar sleeve **120** on rotating or rotatable shaft **118**.

The interiors of the U-shaped anode electrodes are electrolyte manifolds **106*A** that are in fluid connection with the electrolyte duct **116A** and the BOP **112**.

[0438] The rotating or rotatable electrode plate **115A** is secured to the rotating or rotatable shaft **118**, which is free to rotate within the cell frame **114A**. Thus, the anode electrodes **106A** can rotate within the cathode electrodes **108A**.

[0439] The cell **102B** is similar to the cell **102A**; but, the cathode electrodes **108B** rotate within the fixed anode electrodes **106B**. Cell frame **114B** is secured to the cell frame **114A** so that it cannot rotate.

[0440] The cathode electrodes **108B** are secured to rotating or rotatable electrode plate **115B**, which provides:

- Mechanical support for the cathode electrodes **108B**,
- An electrolyte duct **116B** that extends through a rotating or rotatable shaft **118** for connection to BOP **112**, and
- Electrical conductivity between the electrodes **108B** and the rotating or rotatable shaft **118** busbar sleeve **120** that electrically connects the cathode electrodes **108B** to the anode electrodes **106A**.

The interiors of the $\cap$ -shaped cathode electrodes **108B** are electrolyte manifolds **108*B** that are in fluid connection with the electrolyte duct **116B** and BOP **112**.

[0441] The rotating or rotatable electrode plate **115B** is secured to the rotating or rotatable shaft **118**, which is free to rotate within the cell frame **114B**. Thus, the cathode electrodes **108B** can rotate within the anode electrodes **106B**.

[0442] The anode electrodes **106B** are secured to fixed electrode plate **109B** that provides:

- Mechanical support for the anode electrodes **106B**,
- An electrolyte duct **110B** for connection to Balance Of Plant (BOP) **112**, and
- Electrical conductivity between the electrodes **106B** and e^- battery anode terminal **106'B**.

The interiors of the U-shaped anode electrodes **106B** are electrolyte manifolds **106*B** that are in fluid connection with the electrolyte duct **110B** and BOP **112**.

[0443] In this embodiment, the fixed electrode plate **109A** is secured to cell frame **114B** and does not rotate. Because the plate **109B** is secured to cell frame **114B**, there is no need for a collector ring or brush to be in circuit with the battery anode terminal **106''B**.

[0444] Since the relative velocity of the rotating or rotatable electrodes **106A**, **108B** with respect to their fixed electrodes **106B**, **108A** increases as their radii **r** from the rotating or rotatable shaft spin axis **118'** increase, it is necessary to adjust the widths of electrolyte chamber gaps **d** between the electrodes in order to maintain approximately consistent Taylor numbers needed to generate TVF **122** and CCF **124**. As the radii **r** of each successive pair of anodes **106x** and cathodes **108x** increases, the electrolyte chamber **126x** gap **d** between interdigitated or nested electrodes **106x**, **108x** should be decrease by the inverse cube root of the electrode radii **106x**, **108x** in order to preserve a degree of constancy in the Taylor number or in accordance with operating parameters selected from **FIG. 3**. Thus, $d \cdot \sqrt[3]{r} = \text{Constant}$.

[0445] In the embodiment of **FIG. 12**, an electrical series circuit is shown that comprises:

1. Anode e^- terminal **106''B**,
2. Electrical Conductors **128**,
3. Motor **130**,
4. External Electric Circuit **132**
5. Electrolyte BOP **112**, , and
6. Cathode e^+ terminal **108''A**.

The series circuit is used so that the motor **130** and the BOP **112** can sense the magnitude of current required by the External Electric Circuit **132** and react with correct responses (e.g., motor speed, electrolyte flow rate); however, other circuit configurations (e.g., parallel, mixed) are practical.

[0446] The process for operating the battery **100** is the same as the process for operating DARB **B10**, described above. Electric motor **130** is energized to rotate the shaft **118** while BOP **112** pumps electrolyte to and from electrode manifolds **106*x** and **108*x**.

[0447] In a battery **100** discharge cycle, the electrolyte flow travels the following path:

- Starting at the Electrolyte BOP **112**;
- Then, through electrolyte ducts **116A** via rotating or rotatable shaft **118** and **110*B**,
- Then, into anode manifolds **106*A** and **106*B**,
- Then, through anode electrodes **106A** and **106B**;
- Then, into electrolyte chamber **126** gaps **d**;
- Then, through cathode electrodes **108A** and **108B**;
- Then, into cathode manifolds **108*A** and **108*B**;
- Then, through electrolyte ducts **110A** and **116B** via rotating or rotatable shaft **118**;
and
- Then, back to electrolyte BOP **112**.

In the battery **100** charge cycle, the direction of electrolyte flow is reversed.

Dynamic Accelerated Reaction Battery

Third Example – Membrane with Incompatible Electrolytes

[0448] **FIG. 13** is a fragmentary cross-sectional view of a third preferred embodiment of a Dynamic Accelerated Reaction Battery **200**, which may be used where two incompatible electrolytes (e.g., aqueous and organic) are required – such as in a nickel-lithium battery. Prior art cells and batteries use a membrane to separate the two incompatible electrolytes; however, the membrane permits ions to travel from one electrode to the other. These cells must have increased internal resistance because of low ionic permeability of their

membranes. As will be described, cells and batteries of this invention incorporate membranes both to separate incompatible electrolytes and to decrease internal resistance.

[0449] DARB **200** comprise a cell **201** containing a lithium metal anode electrode **202** separated from a nickel-hydroxide, sulphur or other high energy potential cathode **204** by an electrolyte chamber **206** divided by an ion-permeable membrane **208**. The membrane **208** divides the electrolyte chamber **206** into semi-electrolyte-chamber **206A**, adjacent the anode electrode **202**, and semi-electrolyte-chamber **206C**, adjacent the cathode electrode **204**. Examples of suitable membranes are sold under the tradenames NAFION and thio-LISICON.

[0450] Because lithium reacts intensely with water to form explosive hydrogen gas and LiOH, the lithium anode **202** requires a non-aqueous electrolyte, which may be an organic liquid that must not be diluted with water. In this embodiment, each of the semi-chambers **206A**, **206C** contains an electrolyte that is incompatible with the other electrolyte. For example, semi-chamber **206A** can contain an organic electrolyte that is compatible with lithium while semi-chamber **206C** can contain an aqueous electrolyte that is more suitable for the nickel-hydroxide cathode **204**.

[0451] The anode **202**, the cathode **204**, and the ion-permeable membrane **208** are cylinder-like and, in this embodiment, concentric with rotating or rotatable shaft **210**. Motor **212** rotates the shaft **210**, which is mechanically coupled by endplates **211** to the membrane **208** so that the membrane **208** can rotate in the electrolyte chamber **206**. The anode **202** and the cathode **204** are fixed, so neither requires a collector ring or brushes to connect them to an external electrical circuit **214** via electrical conductors **216** connected to e^- anode terminal **218A** and e^+ cathode terminal **218C**.

[0452] The interior of anode **202** is an anode electrolyte manifold **220** that is in fluid connection with anode electrolyte pump **222**, which is attached to the rotating or rotatable shaft **210**. The pump **222** is in fluid connection with the semi-chamber **206A** adjacent the anode **202** so that the pump **222** can pump electrolyte between the manifold **220** and the semi-chamber **206A**.

[0453] The exterior of cathode **204** is a cathode electrolyte manifold **224** that is in fluid connection with cathode electrolyte pump **226**, which is attached to the rotating or rotatable shaft **210**. The pump **226** is in fluid connection with the semi-chamber **206C** adjacent the

cathode **204** so that the pump **226** can pump electrolyte between the manifold **224** and the semi-chamber **206C**.

[0454] A key feature of the battery **200** is its membrane **208** that rotates between and with respect to both the electrodes **202** and **204** to create TVF **228** and CCF **230** in the semi-chambers **206A** and **206C**. The shaft **210** and its pumps **222** and **226** are rotated in one direction for charging and the other direction for discharging in order to control the directions of electrolyte flows.

[0455] The process for operating DARB **200** is the same as the processes for operating DARB **10** and DARB **100**, described above. The electric motor **212** is energized to rotate the shaft **210**, which causes the membrane **208** and the pumps **222** and **226** to rotate.

[0456] Rotation of the pump **222** during discharge causes organic electrolyte to flow between the manifold **220**, through the anode **202** and into the semi-chamber **206A** along a path **232** shown by a dashed line with arrows. Rotation of the pump **226** during discharge causes aqueous electrolyte to flow between the manifold **224**, through the cathode **204** and into the semi-chamber **206C** along a path **234** shown by a dashed line with arrows

[0457] The speed of rotation for the ion-permeable membrane **208** is chosen to generate the TVF **228** and the CCF **230** in both semi-chamber **206A** and semi-chamber **206C**. The high-shear-rate, laminar CCF **230** increase electrode surface electrical current density by accelerating mass transport of ions both at the electrodes **202**, **204** and at the membrane **208**, both of which dramatically lower the internal resistance.

[0458] In the a battery **200** discharge cycle, the electrolytes travel the following paths:

For Anode –

- Starting at the anode manifold **220**;
- Then, through the anode **202**;
- Then, into the semi-chamber **206A** where anions penetrate the membrane **208**;
- Then, into the anode electrolyte pump **222**; and

- Then, returning into the anode manifold **220**,

which follow anode electrolyte flow path **232**.

For Cathode –

- Starting at the semi-chamber **206C** where anions that penetrated the membrane **208** continue to flow toward the cathode **204**;
- Then, through the cathode **204**;
- Then, into the cathode electrolyte manifold **224**;
- Then, into the cathode electrolyte pump **226**; and
- Then, returning into the semi-chamber **206C**,

which follow cathode electrolyte flow path **234**.

In a battery **200** charge cycle, the directions of electrolyte flows **232** and **234** are reversed.

[0459] The battery **200** shown in **FIG. 13** is entirely self-contained as an encapsulated and sealed cell. However, it is practical to add a BOP (not shown), as used for DARB **B10** and DARB **100**. Also, several cells can be mechanically connected together along the rotating or rotatable shaft **210** and electrically connected in a series, parallel or combination circuit to obtain desired voltage and current ratings.

[0460] Electrodes for Dynamic Accelerated Reaction Batteries share some of the characteristics of electrodes for chemical reactors, fuel cells and fuel reformers described in Embodiment A, Embodiment B, Embodiment C and Embodiment D. The main difference between those electrodes and the battery **B10**, **100**, **200** electrodes is that the former are engineered to promote three- phase reactions (e.g., fuel-electrolyte-catalyst) near and at electrode surfaces while promoting intermediate reaction rates; whereas, electrodes for DARB **B10**, **100**, **200** promote two-phase (e.g., electrolyte-metal) reactions within electrodes. Nevertheless, battery electrode surface structures and conditions are important because high-shear-rate, laminar CCF provide high electrolyte and ion transport rates at electrode and

membrane surfaces that accelerate intermediate reactions, lower internal resistance and increase battery energy and power densities.

[0461] DARB **B10, 100, 200** electrodes optimized for high liquid/electrode-surface-area contact per unit of projected electrode area and volume of electrode-electrolyte interface in electrode-electrolyte cross-flow and high-shear-rate laminar CCF generated by TVF. These electrodes produce accelerated mass transport of ions by virtue of intimate contact with a vigorously flowing electrolyte. Mass transport of ions by diffusion through stagnant liquid in conventional batteries is far slower than the movement of ions to (and product from) the electrodes adapted for use with high-shear-rate laminar fluid flows with high rates of viscous shear.

[0462] Typical materials for fabricating DARB electrodes include copper, gold, nickel or perovskite-structure alloy sponges and carbon coated metal foams to shield the metal scaffold acting as a substrate for battery reactive materials from chemical attack if necessary. As used in a NiMH DARB, chemically active maculate deposits or coatings used for the negative electrode or anode commonly comprise a rare earth mixture with nickel, cobalt, manganese or aluminum forming a complex intermetallic compound. Other examples and forms of the metal hydride can use titanium or vanadium with zirconium modified with chromium, cobalt or iron. The positive electrode or cathode may contain a basic nickel oxyhydroxide nanoporous foam as illustrated in **FIG. 2E**.

[0463] Another important DARB application is the lithium-ion secondary battery. Lithium metal, lithium-titanium oxide, or lithium in silicon and germanium coatings or intercalated lithium in carbon nanotubes can serve as nanoporous anode material. Cathodes can be chosen from a variety of lithium/metal-oxides or salts in a single compatible organic electrolyte. Neither these batteries nor the NiMH batteries described above require any type of membrane or separator. Nickel oxyhydroxide cathodes of **FIG. 2E** can be used in lithium batteries with an appropriate rotating or rotatable membrane in the dual electrolyte of DARB **200**, presented above. Alternatively, sulphur cathodes can be used to obtain higher voltage and greater power density. The use of sparse mesh makes the protuberances **332** porous to electrolytes.

[0464] Referring to **FIG 7F**, there is a successive hierarchy of structures that form the protuberances **332**. **FIG. 7F** shows a magnification of the protuberances **332** that displays mesoporosity. There is sufficient width and breadth to permit moderate interstitial laminar flow of fluid through mesopores **338**. In addition, capillary action through the interstices contributes to the amount of electrolyte available for reaction. The degree of interstitial wetting will depend upon electrolyte viscosity and wetting angle, both of which are very high for electrolytes such as organic solvents and simple hydroxides.

[0465] The diameters (widths, if non-circular) of the protuberances **332** are nominally 12.5 μm . Therefore, there each protuberance **332** will contain approximately 12 to 15 mesopores **338** across its diameter (width).

[0466] The protuberances **58**, **332** provide an approximate 4-fold increase in electrode/interface area ratio. That, combined with a 250% increase in metal or particle surface **336** loading, contributes to 10-times the metal surface area available to electrode reactions over present practice and an expected 10-fold increase in current performance. The actual operating current increase under load will be less due to ohmic and other losses; but, these losses can be minimized by using thicker materials.

[0467] Metal or metal alloy particles or coatings **336** may be attached to the filaments **334** in a manner similar to that shown in **FIG. 7F**. The metal particles **336** are of about 2 to 7 nm in size for best surface area dispersion and surface chemical reaction activity. For DARB **B10**, **100**, **200**, lithium, nickel, iron, metal salts, oxides and metals selected from the Transition Metals Group and their alloys are preferred metals for the particles **336**.

[0468] A metal foam sponge **86** (**FIG. 2E**), even with an open pore volume of 75%, is more effective for the mass transport exposure of metal to TVF and CCF than supported particles **336**. Even with scaffold pore **87** diameters of 25 nm, the active metal area ratio for a 100 micron thick metal layer is an unprecedented 8,750 cm^2 to 1 cm^2 of projected electrode area. It is useful to calculate how much battery volume would be required in state of the art cells containing the same active electrode surface area. Because of these attributes, DARB attributes include low impedance, high current density and fast charge/discharge cycle capacity.

[0469] For DARB **B10**, **100**, **200** anodes, the nanoporous metal foam sponges **86** can be produced from an alloy having face-centered cubic geometry with a Miller Index of (1,1,1) and can be loaded with reactive electrode particles **336** or coatings made from a colloidal suspension of the appropriate salts or otherwise deposited as taught in the prior art. The foam sponges **86**, containing reactive electrode particles **336**, can be heat-treated so that the particles **336** are absorbed into copper struts **87** to form highly conductive DARB **B10**, **100**, **200** electrode coatings. Alternatively, a 5 to 15 nm metal porous foam sponge **86** can be thermally coated by heat sputtering to the struts **87**.

[0470] The micro or nano open porosity of the electrodes **B14x**, **B20x**, **106x**, **108x**, **202** or **204** provides greatly increased electrode surface areas for the chemical reactions. Forced convection of an incompressible liquid electrolyte will transport ions created by some battery chemistries at one electrode directly into the electrolyte chamber where the ion concentration becomes greatly increased at the electrode-chamber boundaries. TVF will quickly transport those ions to the opposite porous electrode where forced convective flow will cause them to enter the electrode.

[0471] Conventional battery electrodes provide 5, to at most, 10 cm² of active electrode area per cm² of projected surface. In available nano porous Ni where:

ρ_v = fraction open pore volume, and

A_r = active area factor per unit projected area;

it can be shown that if:

$f(\rho_v)$ = a function of pore fraction, such that

$A_r = f(\rho_v)(T/P_D)$,

T = the depth thickness of the electrolyte flow permeated electrode, and

P_D = the nominal pore diameter that is considered to include both struts and holes.;

then, a solution of the following equation for x can be used in an expression for A_r as follows:

$$(1 - \rho_v) = (0.75\pi x^2 + x^3)/(1 + x)^3$$

$$A_r = [3\pi x/(1 + x)^2](T/P_D) = f(\rho_v)(T/P_D)$$

[0472] Maximum effective surface is obtained at porosities of 50 to 65% open pore fraction. For a 1.0 mm thick electrode with the stated range of open pore volume and 25 nm pores, the area multiplication factor is approximately 92,800 cm² of exposed reactive electrode surface area per cm² of projected electrode.

[0473] For rechargeable Ni-Li batteries, the amount of exposed reactive surface area of the cathode material determines the total cell energy capacity in terms of mAh/g. The electrodes in this example have reactive surface areas far greater than those used in conventional batteries and therefore can provide greater discharge and charge rate parameters per unit weight or size than conventional batteries. Further, TVF and CCF enhance transient current changes by accelerating ions to, across and from the membranes.

Dynamic Accelerated Reaction Battery

Fourth Example – Incorporating A Fuel Cell

[0474] While DARB are capable of high transient discharge currents, their energy is stored in their electrodes and therefore is limited to the amount of anions that can be plated or removed from their anodes. By contrast, fuel cells, such as those taught in Embodiment A and Embodiment D, derived their energy from continuously replaceable fuels; but, have limited transient current capacity. While combining batteries with fuel cells is taught in the prior art as an aggregation of two distinct technologies, the combination of DARB with Direct Reaction Fuel Cells (DRFC) of Embodiment D or the fuel cells of Embodiment A provides synergies not available in existing products.

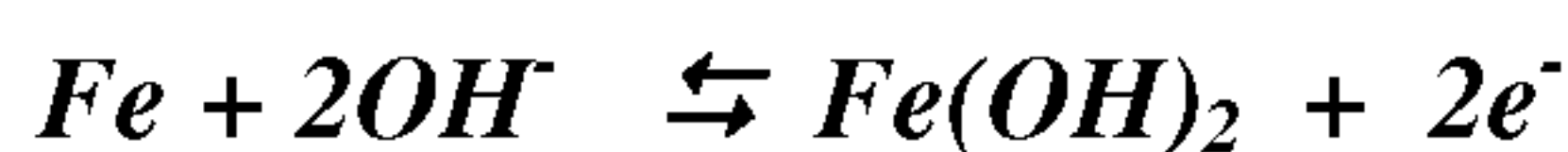
[0475] One of the most durable batteries ever built was invented by Thomas Edison and claimed in US Patent No. 852,424. Modern Edison Cells are Ni-Fe alkaline cells that have about five times the energy storage capacity of Pb/acid batteries and last 10 to 20 times longer. Edison cells are built with environmentally "clean" materials and are fully recyclable.

[0476] The chief disadvantage of current Edison Cells with their static electrolytes is their very low charge/discharge current. However, Ni-Fe alkaline electrolyte DARB have

increased active electrode surface area and accelerated ionic and electrolyte mass transport that surpass the conventional Edison Cell's low current limitations. Because the electrodes do not perceptibly dissolve and need not be re-plated – as required by other battery chemistries, the Ni-Fe batteries endure many discharge-charge cycles of use.

[0477] The relevant chemical reactions for the Edison battery are:

Anode:



Cathode:



The reaction sum is:



[0478] Cadmium (Cd) can be substituted for Fe in the above chemical equations to obtain equations for NiCd batteries using the same electrolyte. NiCd batteries are popular because they have excellent energy storage capacities and can be made in accordance with this invention. The stability of Cd, Fe and Ni electrode materials and the improved and extremely high surface area to volume ratios, taught above, make these electrodes very desirable for DARB.

[0479] One limitation of the FeNi and NiCd DARB, that is disclosed in their chemical equations, is that water is consumed from an ever more alkaline aqueous KOH/LiOH solution. Water - or the lack of it - becomes the limiting factor during discharge. Although the electrolyte is rediluted when charging the batteries, repeated cycles make it difficult to hold the volume of water required to match electrode storage capacity.

[0480] In this invention, synergy is achieved by combining water-producing alkaline fuel cells as described in Embodiments A and D (e.g., DRFC) with water consuming batteries. Water management becomes a simple matter of power balance that can be regulated with microprocessor controllers because the batteries and the fuel cells can use the same electrolyte and common alkalinity. Consequently, it is possible to stoichiometrically

match or offset water produced in the fuel cell with water consumed in the battery by circulating the same electrolyte through each device while both are producing electrical power.

[0481] These systems circulate electrolyte through small, shared reservoirs in BOP that maintain pH by releasing excess water at a temperature exceeding 100 °C. Heat is provided by fuel cell exothermic reactions. When a fuel cell is charging the battery, both the battery and the fuel cell add water to their shared electrolyte. As the battery discharges, water produced by the fuel cell replaces water lost by the battery. The system is self-starting because these batteries are capable of delivering sufficient power in their quiescent mode to energize rotation and circulation. At shutdown, the system uses heat to vaporize excess water that would otherwise freeze in cold weather. The electrolyte is natural antifreeze at proper pH.

[0482] **FIG. 14** is a fragmentary cross-sectional view of a Dynamic Accelerated Reaction Battery **400**, as described above, incorporating a Direct Reaction Fuel Cell, as described in Embodiment D. The battery **400** is similar in appearance to the Dynamic Accelerated Reaction Battery **10** of **FIG. 1A**; however, there are important structural and operational differences.

[0483] The battery **400** comprises four cells **CELL A - 412A**, **CELL B - 412B**, **CELL C - 412C** and **CELL D - 412D**. **CELL A - 412A** and **CELL B - 412B** are battery cells. **CELL C - 412C** and **CELL D - 412D** are fuel cell cells.

[0484] Each cell contains a rotating or rotatable electrode **414x** where **x** stands for one of the letters **A**, **B**, **C** or **D** that is associated with one of the four cells **412x**. The electrodes **414x** are fixed to a shaft **416** that rotates about spin axis **417** and is driven by an electric motor **418**. Each cell also contains a fixed electrode **420x** that is secured to frame **422x**. The motor **418** rotates so that so that there is relative motion between one electrode **414x**, **420x** of one polarity and another electrode **420x**, **414x** of another polarity. In this embodiment, the electrode **414A** rotates within the electrode **420A**, the electrode **414B** rotates with the electrode **420B**, the electrode **414C** rotates with the electrode **420C** and the electrode **414D** rotates within the electrode **420D**. Each frame **422x** is mechanically coupled to and electrically insulated from adjacent frame(s) **422x**.

[0485] Cylindrical electrodes **414x** and **420x** are shown in the drawings as right-circular and coaxial; however, these attributes are not a requirement and other cylinder-like geometries (e.g., elliptical, conical, hyperbolic, irregular, different axes) may be employed. Also, it is practical to build batteries **400** where the inner electrodes **414x** are fixed and the outer electrodes **420x** rotate or both electrodes **414x**, **420x** rotate at different speeds or directions. All that is required is that one of the cylinder-like electrodes **414x** and **420x** rotates relative to the other so that there is a relative, rotational velocity difference greater than zero between the cylindrical electrodes **414x** and **420x**.

[0486] Rotating or rotatable electrodes **414A** and **414D** are anodes. Rotating or rotatable electrodes **414B** and **414C** are cathodes. In this embodiment all of the electrodes **414x** are fixed to and rotated by the shaft **416**, which is common to all for rotating or rotatable the electrodes **414x**; however a common shaft is not a requirement. Fixed electrodes **420A** and **420D** are cathodes. Fixed electrodes **420B** and **420C** are anodes. In this embodiment, all of the electrodes **420x** are fixed to their frames **422x**, which are mechanically coupled together; however, that is not a requirement.

[0487] The electrodes **414x** are rotated by the motor **418** so that there is relative motion between one electrode **414x** of one polarity and an adjacent electrode **420x** of another polarity. There is also relative motion of the electrodes **414x** with respect to the electrolyte in all of the cells **412x**.

[0488] Each of the cells **412x** has a rotating or rotatable electrode manifold **424x** and a fixed electrode manifold **426x**. Each of the battery manifolds **424A**, **424B**, **426B** and **426D** is connected to electrolyte Balance of Plant (BOP) **428** through first and second electrolyte ducts **430x** and **432x**. Fuel cell electrolyte chambers **438C** and **438D** are also connected to the BOP **428** through their first and second electrolyte ducts **430x** and **432x**.

[0489] During discharge of battery cells **412A**, **412B**, electrolyte flows, as shown by arrows, through the battery anode electrodes **414A** and **420B**, then through electrolyte chambers **438X** and back to BOP **428** through battery cathode electrodes **420A** and **414B**. During charge of battery cells **412A**, **412B**, the electrolyte flows in the opposite direction. Electrolyte can flow through the fuel cell electrolyte chambers **438C** and **438D** in either direction.

[0490] Operation of the fuel cell cells **412C** and **412D** is explained in Embodiment A and Embodiment D. The cells **412C** and **412D** may be powered by H_2 as their fuel, as described in Embodiment A; however, Direct Reaction Fuel Cells can be fueled by methane, methanol and sodium borohydride and similar fuels, as described in Embodiment D.

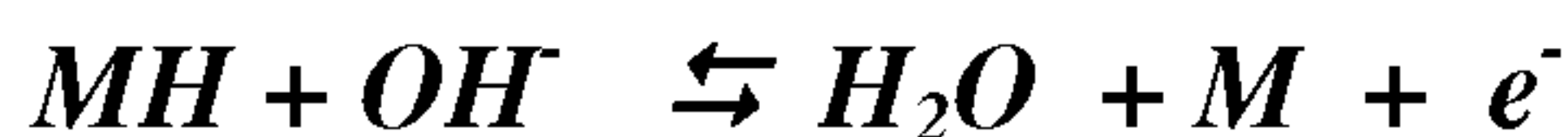
[0491] Fuel is introduced into the cells **412C** and **412D** through fuel port **460**, which enters the anode manifold **426C** and connects to anode manifold **424D** through fuel duct **462**. An oxidizer, such as O_2 , is introduced into the cells **412C** and **412D** through oxidizer port **464**, which enters the cathode manifold **426D** and connects to cathode manifold **424C** through oxidizer duct **466**.

[0492] Fuel penetrates the anode electrodes **420C** and **414D** to reach their surfaces where the fuel participates in a three-phase reaction (fuel – anode catalyst – electrolyte) that yields electrons that provide electrical energy to External Electrical Circuit **448**. The reaction also provides protons (H^+) that combine with (OH^-) ions entering anode electrodes **420C** and **414D** from the electrolyte chambers **438C** and **438D**. That reaction yields H_2O that flows through means for sequestering water from the fuel cells **412C** and **412D** to provide make-up water to the electrolyte in the battery cells **412A** and **412B**, which include electrolyte chambers **438C** and **438D**, the electrolyte pipes **450**, the electrolyte BOP **428** and electrolyte ducts **430x** and **432x**.

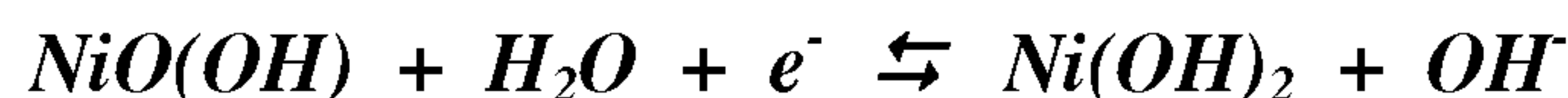
[0493] Oxidizer penetrates the cathode electrodes **414C** and **420D** to reach their surfaces where the oxidizer participates in a three-phase reaction (oxidizer- cathode catalyst – electrolyte) that receives electrons from the External Electrical Circuit **448** which produces (OH^-) ions that enter the electrolyte chambers **438C** and **438D**. These redox reactions are consistent with alkaline electrolyte commonly used in batteries. Acid electrolyte would simply reverse the direction of (H^+) ion transfer and water would be produced within cathode electrodes **414C** and **420D**.

[0494] An important battery, widely used by the automobile industry for all-electric cars, is the nickel-metal hydride usually written as NiMH where the M in the negative electrode or anode actually stands for a complex intermetallic compound of a proprietary nature with several manufacturers. The relevant chemical reactions closely parallel those for the Edison cell and take place in relation to the same aqueous solution of KOH:

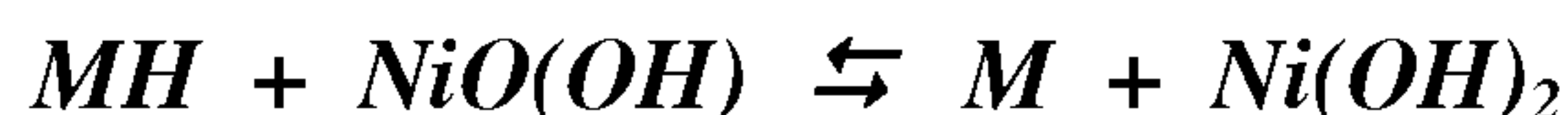
Anode:



Cathode:



The reaction sum is:



In this case it is important to note that the net reaction in either direction potentially does nothing to the electrolyte. Consequent limited electrolyte volume permits sealed, internal closed circuit, repetitive recirculation of the electrolyte through a collective assembly of a bank of cells made in accordance with **FIG. 11A** or **FIG. 12** in the absence of an external BOP. Nevertheless, repetitive charge cycles may cause loss of water from electrolyte, which is common to other battery types. Water replacement as described below with reference to **FIG. 14** solves that problem.

[0495] The fuel cell cells **412C** and **412D** are connected in an electrical series circuit. Similarly, the battery cells **412A** and **412B** are connected in an electrical series circuit. These two circuits are connected in a parallel electrical circuit that will now be described.

[0496] The battery **400** electric circuit – illustrated in part as dashed line **434** – is then formed that starts at fixed busbar **442BC**. The fixed busbar **442BC** is connected to the battery anode **420B**, the fuel cell anode **420C** and external anode (e^-) terminal **436** by anode busbar **437**.

[0497] The battery branch of the parallel circuit follows near the dashed line **434** down through fixed anode electrode **420B**, across electrolyte gap **438B**, down through rotating or rotatable cathode electrode **414B**, down through rotating or rotatable copper sleeve busbar **440AB** on the rotating or rotatable shaft **416**, down through rotating or rotatable anode electrode **414A**, across electrolyte gap **438A** and down through fixed cathode electrode **420A** and up to external cathode (e^+) terminal **444** by cathode busbar **445**.

[0498] The fuel cell branch of the parallel circuit follows near the dashed line **434** up through fixed anode electrode **420C**, across the electrolyte gap **438C**, up through rotating or rotatable cathode electrode **414C**, up through rotating or rotatable copper sleeve busbar **440CD** on the rotating or rotatable shaft **416** up through rotating or rotatable anode electrode **414D**, across electrolyte gap **438D** and up through fixed cathode electrode **420D** to the busbar **445** that is connected to external cathode (e^+) terminal **444**.

[0499] The arrows accompanying the electric circuit dashed line **434** show the direction of electricity in the electrodes **414x**, **420x** for discharge. Only ions, not electrons, flow across the electrolyte chambers **438x**, which may be modeled as voltage sources. The arrows marked **DISCHARGE** and **CHARGE** adjacent electrical conductors **446** show the direction of electric current flow for discharging and charging the battery **400**. Similarly, the arrows marked **DISCHARGE** and **CHARGE** adjacent electrolyte pipes **450** show the direction of electrolyte flow for discharging and charging the battery cells **412A** and **412B** through the first and second fuel ducts **430A**, **430B**, **432A** and **432B** that are connected to the electrolyte chambers **438A** and **438B**.

[0500] As is the case for the DARB **B10** shown in **FIG. 11A**, this novel fuel cell - battery **400** does not contain any collector ring or brush. Thus, there is no need for 1) shaft seals or other mechanisms to protect a collector ring or brush from chemical attack, 2) additional cells or batteries connected in parallel to provide extra current to compensate for a current-limiting collector ring and brush, or 3) additional cell(s) connected in series to provide extra voltage to compensate for contact interface and I^2R losses in a collector ring - carbon brush assembly.

[0501] The battery **400** is operated by electrically energizing motor **418** to rotate the shaft **416** and energizing Electrolyte BOP **28** to pump electrolyte. As shown for the embodiment of **FIG. 7**, both the motor **418** and the Electrolyte BOP **428** are in a series circuit containing the battery **400**, the electrical conductors **446** and the External Electrical Circuit **448**. This circuit will provide feedback so that the speed of motor **418** and the flow rate of electrolyte pumped by BOP **428** will be a function of the magnitude and direction electric current flowing in conductors **446**. As will be described below, the BOP **428** also includes means for using exothermic heat energy and water from the fuel cells **412C**, **412D** to maintain optimum battery cell **412A**, **412B** temperature and electrolyte pH. Alternatively,

either or both the motor **418** and the Electrolyte BOP **428** can be powered from an external source.

[0502] As described above for DARB **B10**, the rotation at a proper speed of the rotating or rotatable electrodes **414x** (**FIG. 14**) relative to the fixed or stationary electrodes **420x** will cause TVF **454** to form in the electrolyte chambers **438x**. When the speed of rotation is properly adjusted, then CCF will form adjacent to the surfaces of both electrodes **420x** and **414x**. The CCF are high-velocity, high-shear rate laminar flows that provide a dynamic improvement in ionic mass transport within electrolyte and expedite high-speed ion transport between the electrodes **414x** and **420x** in both the battery cells **412A**, **412B** and the fuel cell cells **412C**, **412D**. In this embodiment, both the battery cells **412A**, **412B** and the fuel cell cells **412C**, **412D** share means, including the rotating or rotatable shaft **416** and the motor **418**, in common for rotating both battery **412A**, **412B** electrodes **414A**, **420A**, **414B**, **420B** and fuel cell **412C**, **412D** electrodes **414C**, **420C**, **414D**, **420D** to create TVF **454** and CCF **56** in both the battery cell **412A**, **412B** electrolyte chambers **438A**, **438B** and the fuel cell **412C**, **412D** electrolyte chambers **438C**, **438D**.

[0503] An essential feature of DARB combined with TVF fuel cells is heat and water balance. The embodiment just described comprises NiFe or NiCd electrodes and alkaline electrolyte that consume water during discharge. NiMH electrodes also consume water or outgas during recharge. Water loss is replaced by the fuel cell. The feature is also useful for other battery chemistries.

[0504] For example, heat and water balance also increase performance of Pb/acid batteries. Those batteries make water that must be removed to prevent dilution of the electrolyte. The fuel cell's exothermic reaction generates energy that can heat the battery's electrolyte to boil off water as the battery's electrolyte becomes more diluted during discharge. When the Pb/acid battery requires replacement of water during the battery's charge cycle, the water can be retrieved from a common reservoir that also receives water produced by the fuel cell.

[0505] Therefore irrespective of battery type, a fuel cell can provide water or heat energy through the BOP **428** to retain or dispose of water as needed by the battery in order to maintain optimum pH. The pressure and temperature of the battery can be controlled to keep

its electrolyte pH constant. Higher operating temperature and pressure in an incompressible electrolyte at optimum pH increases battery efficiency, energy density and power density.

[0506] As shown here, there are several synergies that the battery **400** provides that are not found when aggregating prior art fuel cells and batteries. One benefit of incorporating TVF/CCF fuel cells in DARB is exceptionally high volumetric energy storage density that is achieved as a consequence of the fuel associated with the fuel cell and the energy density of electrodes of the battery with a reduced electrolyte volume. A second benefit is the fast response of the battery transient power demand while the fuel cell supports average current demand. A third benefit is that the fuel cells need only be sized to average load, rather than peak load, and the batteries can be sized to transient load rather than average load, thus achieving a smaller and lighter electrical energy supply. All of these contribute to an electrical energy source that has some of the best characteristics of both batteries and fuel cells.

Battery Charging And Discharging

[0507] Aqueous electrolyte battery cells require safe handling of H₂ and O₂ because they can form an explosive mixture explosion during charging. Because battery cell charging requires the application of a voltage somewhat higher than the natural fully charged open circuit voltage (OCV) of the cell, special provision may be required to prevent or compensate for electrolysis of aqueous electrolyte. Even 'intelligent chargers', which adjust applied voltage in response to battery reaction voltage, may permit charger voltage to exceed the dissociation potential of water. This can cause hydrolysis and release of a hazardous gas mixture.

[0508] Under standard conditions (STP), the free energy voltage of water formation in a fuel cell is 1.23 volts. This represents 83% of the energy of formation or enthalpy. About 0.25 volts of overvoltage represents energy that is lost to heat. Therefore, at least 1.5 volts is required to charge a cell and split its water molecules. However, electrolysis at any appreciable rate is no more efficient than the opposite fuel cell reaction and produces a similar overvoltage of approximately 0.5 to 0.6 volt. Consequently, a charging voltage greater than 2.0 to 2.1 volt is likely to release appreciable amounts of hydrogen and oxygen gasses.

[0509] During charging, electrode polarity remains unchanged; but, charge current flows in a direction opposite to that of discharge current (e.g, charging electrons flow into the battery's anode rather than out of the anode – as during discharge). Battery terminology is retained here in order to avoid confusion with electrolyzers where the electrodes have opposite labels or polarities.

[0510] Normally, charging electrons reduce the battery anode metal-oxide or complex intermetallic compound in order to restore them to their pure metallic or hydride form. As a cell's full charge voltage is approached, charging current should be reduced. If excessive voltage is applied, then extra current can cause hydrolysis in a process similar to an alkaline electrolyzer where electrons combine with water to produce four OH⁻ ions and two H₂ gas molecules within the cell's anode. Conversely, O₂ gas is produced within the cell's cathode where four 4OH⁻ ions yield two H₂O molecules. The net reaction not only fails to restore needed water; but, it consumes water to further concentrate alkalinity. The synergistic combination of a battery with a fuel cell, as described above for DARB 400 of FIG. 14, can offset this water loss; but, the discharge of potentially explosive gasses must, nevertheless, be prevented.

[0511] The four battery embodiments described above are best charged (or recharged) with a method comprising continuous circulation (or recirculation) of electrolyte by forced convection through the electrodes along a path commencing at the cathode (e.g., B20A, 108A, 204, 420A) then continuing through the cathode into the electrolyte chamber or gap (e.g., B38A, 126A, 206, 438A, d) and then through the anode (e.g., B14A, 106A, 202, 414A). Recirculation may or may not include an electrolyte BOP (e.g., B28, 112, 428).

[0512] The fuel cell and battery embodiment 400 of FIG. 14 contains an electrolyte BOP 428 comprising means for cycling H₂ and O₂ gases produced by the battery cells 412A and 412B into fuel and O₂ consumed by the fuel cells 412C and 412D. During battery cell 412A and 412B charging, O₂ from the cathodes 420A and 414B enter the adjacent electrolyte chambers 438A and 438B. The oxygen gas forms bubbles that are drawn into the TVF 454A and 454B, where they are trapped – just as particles and bubbles B74 are shown in FIG. 2C-3.

[0513] The TVF **454** in the battery cells **412A** and **412B** are subjected to axial flow, as previously explained, and exit the electrolyte chambers **438A** and **438B** through electrolyte chamber ducts **470A** and **470B**. The electrolyte chamber ducts **470A** and **470B** are connected by the electrolyte pipes **450** to the electrolyte BOP **428** where the O₂ is separated from the electrolyte and fed to the oxidizer port **464** by oxidizer duct **474**.

[0514] Simultaneously, H₂ that is produced at the anodes **414A** and **420B** during the charge cycle bubbles into the electrolyte flowing into the rotating or rotatable electrode manifold **424A** and the fixed electrode manifold **426B**. The electrolyte containing the hydrogen gas is then returned to the BOP **428** through first electrolyte duct **430A** and second electrolyte duct **432B**, which are both connected to the BOP **428** by the electrolyte pipes **450**. The H₂ that is separated from the returned electrolyte in the BOP **428** is fed to the fuel port **460** by fuel duct **476**.

[0515] The synergy of coupling the fuel cell cells **412C**, **412D** to the battery cells **412A**, **412B** includes their ability to exchange H₂, O₂ and H₂O and reduces the need to provide additional supplies of gasses and water. It also provides practical means for transferring heat energy from the fuel cell cells **412C**, **412D** that are exothermic reactors to the battery cells **412A**, **412B** and the BOP **428** that are endothermic reactors because the water exhausted by the fuel cell cells is heated. This improves the overall fuel efficiency beyond the level that could be achieved if the fuel cell cells **412C**, **412D** and the battery cells **412A**, **412B** operated independently of each other.

[0516] Recirculation may not require an electrolyte BOP (e.g., **428**). Because gas will not penetrate TVF, O₂ gas from the cathode can be trapped in the electrolyte chamber (e.g., **438A**, **438B**) where it can mix with H₂ gas from the anode to form an explosive mixture. One method of preventing this is to provide means for admixing catalyst nanoparticles (e.g., Pt, Pd) with the electrolyte to promote the formation of H₂O molecules. These means can be included in the BOP.

[0517] The catalytic particles will remain suspended in the liquid electrolyte and become trapped within the TVF (e.g., **454**) where they are most needed to catalyze the production of water from any combustible gasses that are produced during the charge cycle. The particles have little effect during discharge and can readily permeate the electrode pores

(338, 344) without clogging them. The amount of catalyst needed is far less than the amount required for a catalytic electrode.

[0518] If a battery (10, 100, 200) is constructed independently of a companion fuel cell and its electrolyte is recirculated through a BOP, then the simple expedient of intermittently and momentarily halting TVF generation by slowing or stopping rotation will allow gas to be driven into the BOP (48, 112, 214) where it can be burned off using a hot glow coil. The gas purge frequency depends upon the sophistication of the charging apparatus, which can be optimized to minimize gas production.

[0519] The Dynamic Acceleration Reaction Batteries taught here use:

- High-shear-rate, laminar CCF that are generated by TVF,
- Electrodes with high ratios of active surface area to projected surface areas, and
- Dynamic circulation of electrolyte directly through highly dispersed porous electrodes

that provide unprecedented high charge and discharge rates, as well as high energy and power densities per cm³ and per gram.

[0520] DARB will work with all types of liquid electrolytes – including Ni(OH)₂ – Li cells that incorporate membranes for separation of incompatible electrolytes. Whereas membranes in prior art cells increase battery internal resistance, membranes 208 in DARB 200 can be operated to reduce internal resistance.

[0521] Not only do TVF and CCF dramatically increase mass transport of electrolyte and ions through electrodes; but, they lower electrode overpotentials by reducing or eliminating adverse intermediate reactions either by eliminating a constituent chemical or by accelerating the reaction. Thus, battery energy efficiency is improved.

[0522] DARB can be configured as completely sealed systems or for use with BOP. Where BOP is used, electrolyte can be refreshed and reaction products (e.g., precipitates sequestered by TVF) can be removed before they can damage electrodes. This is a very important advantage for increasing battery life when used with cell chemistries that create compounds that are incompatible with electrodes (e.g., PbSO₄).

[0523] Because CCF provide high shear rates, they can move ions from one electrode to the other in very short times. This feature makes DARB well suited for satisfying high transient current demands.

[0524] While DARB can provide very high transient currents, they lack the energy capacity of TVF-CCF fuel cells taught in Embodiment A, Embodiment B, Embodiment C and Embodiment D. By contrast, fuel cells have high energy ratings; but, are slower to respond to high transient current requirements. Because they share similar structural characteristics and complementary operating characteristics, DARB and TVF-CCF fuel cells can be combined to produce unique electric power supplies. For example, they can provide both high energy and high power with high transient discharge rates that can accommodate sudden demands for power for automotive applications.

[0525] The terms ‘DARB’, ‘battery’ and ‘batteries’ have been used above to describe battery embodiments containing multiple cells. Those terms will also be used in claims that follow where they are now defined to include electrical energy sources having a single cell or multiple cells, unless otherwise described.

Conclusion

[0526] The present disclosure has been presented above with respect to the described and illustrated embodiments of chemical cells, fuel cells and batteries using TVF and CCF, electrodes with high ratios of active surface area to projected surface areas, and dynamic circulation of electrolyte directly through highly dispersed porous electrodes. The fuel cells and batteries are electrochemical energy conversion systems that far exceed performances of prior art devices – including the long-standing 1-Ampere/cm² fuel cell electrode performance barrier of the prior art.

[0527] All applications and patents identified in this disclosure are hereby incorporated herein by reference.

[0528] It is to be understood that the disclosure is not to be limited to the described embodiments and examples. Accordingly, reference should be made primarily to the following claims to determine the scope of this invention.

CLAIMS

I claim:

1. In a chemical cell (10) containing a fluid, an improvement comprising:
means (18, 24, 34, 36) for creating Taylor Vortex Flows (28, 50) in the fluid.
2. In the chemical cell (10) of claim 1, a further improvement comprising:
means (18, 24, 34, 36, 50) for creating Circular Couette Flows (58) in the fluid.
3. In the chemical cell (10) of Claim 1 wherein the chemical cell is a fuel cell (12), a further improvement comprising:
one cylinder-like electrode (34) rotatable relative to and separated by a fluid chamber (40) from another cylinder-like electrode (36).
4. In the fuel cell (12) of Claim 3, the improvement further comprising:
means (34, 36) for creating Taylor Vortex Flows (50) in the fluid chamber (40).
5. In the fuel cell (12) of Claim 4, the improvement further comprising:
means (34, 36, 50) for creating Circular Couette Flows (58) in the fluid chamber (40).
6. In the fuel cell (12) of Claim 5, the improvement further comprising:
a fluid that is an electrolyte in the fluid chamber (40).

7. In the fuel cell (12) of Claim 6, the improvement further comprising:
- protuberances (60) that extend from a surface layer (34', 36') of an electrode (34, 36) into the Circular Couette Flows (58).
8. In the fuel cell (12) of Claim 4 in which the means (34, 36) for creating Taylor Vortex Flows (50) includes a first cylindrical-like electrode (36) enclosing a second cylindrical-like electrode (34) separated from the first by an electrolyte chamber (40) of gap distance d and length L and means for rotating one electrode with respect to the other at Ω radians per second, the improvement further comprising:
- a. means for pumping electrolyte into and out of the chamber (40) at a total volumetric exchange rate of $\dot{U}/U$ where U is the volume of electrolyte in the chamber and $\dot{U}$ is the volumetric rate of flow into and out of the chamber; and
 - b. means for regulating the volumetric exchange rate of axial flow and Taylor Number T_c of vortex flow (50) in the electrolyte so that –
 - i. $T_c = 2 r_2 \Omega^2 d^3 / \nu^2 (1 + \{ r_1 / r_2 \}) > 1,715 (f\{R_a\})$, and;
 - ii. $R_c = \{ \Omega r_1 d / \nu \} \leq 10^4$

where:

 1. $f\{R_a\} = 1.0 + (0.297)(\log_{10} R_a)^{4.04342}$ for $R_a \geq 1.0$
 $f\{R_a\} = 1.0$ for $0 \leq R_a \leq 1.0$,
 2. r_1 = radius of the first electrode (36),
 3. r_2 = radius of the second electrode (34),
 4. $d = r_1 - r_2$,
 5. ν = kinematic viscosity of electrolyte = $\mu(\text{poise})/\rho(\text{grams/cc.})$,
 6. $R_a = (dL/\nu)(\dot{U}/U)$, and
 7. $\dot{U}/U \geq 0$.

9. In the fuel cell (12) of Claim 8 wherein $RPM = 30 \Omega/\pi$, coordinates of d and RPM are within a Zone of Operable Parameters (70).
10. In the fuel cell (12) of Claim 3 in which the improvement further comprises:
- The first electrode (36) is reactive with a first chemical entering its pores from its first surface (44) to produce a first ion at its second surface layer (36'); and
 - The second electrode (34) is reactive with a second chemical entering its pores from its first surface (32) to produce a second ion at its second surface layer (34') having a charge different from that of the first ion.
11. In the fuel cell (12) of Claim 10, the improvement further comprises:
- means for controlling entry of a chemical into pores of an electrode surface layer (34' or 36') so that reaction-time:residence-time (t_a/t_r) $\leq 1/10$.
12. A fuel cell (12) containing first and second cylinder-like electrodes (34, 36) separated by a fluid electrolyte gap (d, 40) between the electrodes (34 and 36), comprising:
- means (50) for extracting unwanted contaminants (66) from the electrolyte.
13. The fuel cell (12) of Claim 12, wherein the means for extracting unwanted contaminants (66) from the electrolyte include:
- means (34, 36) for creating Taylor Vortex Flows (50) in electrolyte.
14. In the fuel cell (12) of Claim 10 in which the means (34, 36) for creating Taylor vortex flows (50) includes a first cylinder-like electrode (36) adjacent a second cylinder-like electrode (34) separated from the first by an electrolyte chamber (40) with –

- i. gap distance d,
- ii. gap length L, and
- iii. means for rotating one electrode (36 or 34) with respect to the other electrode (34 or 36) at Ω radians per second,

the improvement further comprising:

- a. means for pumping electrolyte into and out of the chamber (40) at a total volumetric exchange rate of $\dot{U}/U$ where U is the volume of electrolyte in the chamber and $\dot{U}$ is the volumetric rate of flow into and out of the chamber (40); and
- b. means for regulating the volumetric exchange rate of axial flow and Taylor Number T_c of vortex flow in the electrolyte so that –

$$T_c = 2 r_2 \Omega^2 d^3 / \nu^2 (1 + \{ r_1 / r_2 \}) > 1,715(f\{R_a\}), \text{ and};$$

$$R_c = \{ \Omega r_1 d / \nu \} \leq 10^4$$

where:

1. $f\{R_a\} = 1.0 + (0.297)(\log_{10} R_a)^{4.04342}$ for $R_a \geq 1.0$
 $f\{R_a\} = 1.0$ for $0 \leq R_a \leq 1.0$
2. r_1 = the largest radius of the first electrode,
3. r_2 = the smallest radius of the second electrode,
4. ν = kinematic viscosity of electrolyte = $\mu(\text{poise})/\rho(\text{grams/cc.})$,
5. $R_a = (dL/\nu)(\dot{U}/U)$, and
6. $\dot{U}/U \geq 0$.

15. An electrochemical cell (10) comprising:

- a. a first electrode (36) that is –
 - i. reactive with a first chemical entering its pores from its first surface (44) to produce a first ion at its second surface layer(36');
- b. a second electrode (34) that is –
 - i. reactive with a second chemical entering its pores from its first surface (32) to produce a second ion at its second surface (34) having a charge different from that of the first ion, and

ii. within the first electrode (36) so that a chamber (40) is created between the second surface layers (36' and 34') of the two electrodes (36 and 34);

c. a fluid electrolyte in the chamber (40); and

d. means for moving one electrode (36 or 34) with respect to the other electrode (34 or 36) to create flows (50) in the fluid electrolyte

so as to generate a voltage across the electrodes (36, 34) that are adapted to be connected to an external electrical circuit.

16. The electrochemical cell (10) of Claim 15 wherein:

Taylor Vortex Flows (50) are created in the fluid electrolyte.

17. The electrochemical cell (10) of Claim 15 wherein:

Circular Couette Flows (58) are created in the fluid electrolyte.

18. The electrochemical cell (10) of Claim 15 wherein:

a. the first electrode (36) is cylinder-like and its second surface layer is its inner surface layer (36'); and

b. the second electrode (34) is cylinder-like and its second surface layer is its outer surface layer (34') that is located substantially parallel to and within the first cylinder-like electrode (36) so as to create the chamber (40) for the electrolyte between the electrodes (36 and 34).

19. The electrochemical cell (10) of Claim 15 comprising in addition:
means for controlling entry of a chemical into pores of an electrode layer
(34' or 36') so that reaction-time:residence-time (t_a/t_r) $\leq 1/10$.
20. The electrochemical cell (10) of Claim 15 wherein:
one chemical is a reductant and the other chemical is an oxidizer.
21. The electrochemical cell (10) of Claim 15 wherein:
the flows include Taylor Vortex Flows (50).
22. The electrochemical cell (10) of Claim 21 wherein:
the flows include Circular Couette Flows (58).
23. The electrochemical cell (10) of Claim 22 wherein one of the electrodes (34, 36)
comprises:
a. a catalytic surface layer (34', 36'), and
b. protuberances (60) that extend from the surface layer (34', 36') into the
Circular Couette Flows (58).
24. The electrochemical cell (10) of Claim 23 wherein one of the electrode catalytic
surface layers (34', 36') comprises:
nanoporous metal foam (86).
25. The electrochemical cell (10) of Claim 24 wherein the nanoporous metal foam (86)
comprises:
pores (87) surrounded by scaffold struts (88).

26. The electrochemical cell (10) of Claim 25 wherein the nanoporous metal foam (86) comprises:

organic catalyst particles that decorate the scaffold struts (88).

27. The electrochemical cell (10) of Claim 25 wherein the nanoporous metal foam (86) comprises:

metal catalyst particles that decorate the scaffold struts (88).

28. The electrochemical cell (10) of Claim 24 wherein the metal is selected from the:

Table of the Elements Platinum Group Metals.

29. The electrochemical cell (10) of Claim 28 wherein the metal comprises:

an alloy selected from the Platinum Group Metals.

30. The electrochemical cell (10) of Claim 29 wherein the alloy comprises:

platinum.

31. The electrochemical cell (10) of Claim 29 wherein the alloy comprises:

ruthenium.

32. The electrochemical cell (10) of Claim 18 comprising in addition:

a fuel reformer (14) located with the second electrode (34) that generates hydrogen gas, which enters into fuel cell (12) by penetrating the second electrode (34).

33. A process for operating an electrochemical cell (10) to produce electricity for transmission to an external load comprising:

a. pumping a reductant through an anode electrode (34) of the cell (10);

- b. pumping an oxidizer through a cathode electrode (36) of the cell (10);
- c. pumping electrolyte into an electrolyte chamber (40) of the cell (10) that is located between the electrodes (34 and 36); and
- d. rotating one electrode (34 or 36) with respect to the other electrode (36 or 34) at a rate sufficient to cause Taylor Vortex Flows (50) in the electrolyte chamber (40).

34. The process of Claim 33 wherein:

the rotation of one electrode (34 or 36) with respect to the other electrode (34 or 36) is at a rate sufficient to cause electrolyte Circular Couette Flows (58) in the electrolyte chamber (40).

35. The process of Claim 34 wherein the reductant is:

hydrogen.

36. The process of Claim 33 in which the cell (10) contains a fuel reformer chamber (26) between a fixed catalytic surface (18) and a rotating catalytic surface (24) and the process comprises an additional steps of:

- a. pumping a fuel containing hydrogen atoms into the fuel reformer chamber (26); and
- b. rotating the reformer relative to the rotating catalytic surface (24) at a speed sufficient to cause –
 - i. fuel reformer Taylor Vortex Flows (28) in reformer chamber (26),
 - ii. fuel cell Taylor Vortex Flows (50) in the fuel cell electrolyte chamber (40), and
 - iii. H_2 from the fuel to penetrate through anode electrode (34) to creates H^+ ions that pass into the electrolyte chamber (40).

37. The process of Claim 36 wherein:

rotation of one electrode(34 or 36) with respect to the other electrode (36 or 34) is at a rate sufficient to cause Circular Couette Flows (58) in the electrolyte chamber (40).

38. A system for enhancing catalyzed reaction rates at porous catalytic surfaces (34', 36') of an electrochemical cell (10), the system comprising:

- a. a first electrode (34) having a first porous catalytic surface layer (34');
- b. a second electrode (36) having a second porous catalytic surface layer (36');
- c. the first electrode (34) and the second electrode (36) defining an electrolyte chamber (40) between the first porous catalytic surface layer (34') of the first electrode (34) and the second porous catalytic surface layer (36') of the second electrode (36), the electrolyte chamber (40) including an electrolyte input tube (42) configured so that a liquid electrolyte passing through the electrolyte chamber (40) from the electrolyte input tube (42) passes adjacent the first and second electrodes (34, 36); and,
- d. the electrolyte chamber (40) being dimensioned, and at least one of the first electrode (34) or the second electrode (36) being configured to rotate relative to the other of the first electrode (34) or the second electrode (36) at a rate of rotation adequate to produce Taylor Vortex Flows (50) within the liquid electrolyte flowing from the electrolyte input tube (42) through the electrolyte chamber (40).

39. The system of claim 38, wherein the electrochemical cell (10) comprises:
- a fuel reformer (14) located within the first electrode (34) and having a reformer fuel chamber (26) on the side of the first electrode (34) that is opposite that of the electrolyte chamber (40)
- wherein, during operation, hydrogen from the reformer fuel chamber (26) penetrates the first electrode (34).
40. The system of Claim 39 wherein:
- the first electrode (34) is rotated a rate of rotation adequate to produce Taylor Vortex Flows (28) within the reformer fuel chamber (26).
41. The system of Claim 40 wherein:
- the first electrode (34) is rotated at a rate of rotation adequate to produce Circular Couette Flows (28, 50) in the reformer fuel chamber (26) and the fuel cell (12) electrolyte chamber (40).

42. The system of claim 38, wherein the electrochemical cell (10) is a fuel cell (12) and wherein the electrodes (34, 36) are separated by an electrolyte chamber (40) to permit one electrode (34) to rotate within the other electrode (36) and the electrolyte chamber (40) has a gap distance d , and gap length L , and further comprising:

- a. means for rotating one electrode (36, 34) with respect to the other electrode (34, 36) at Ω radians per second;
- b. means for pumping electrolyte into and out of the chamber (40) at a total volumetric exchange rate of $\dot{U}/U$ where U is the volume of electrolyte in the chamber and $\dot{U}$ is the volumetric rate of flow into and out of the chamber (40); and
- c. means for regulating the volumetric exchange rate of axial flow and Taylor Number T_c of vortex flow in the electrolyte so that –

$$T_c = 2 r_2 \Omega^2 d^3 / \nu^2 (1 + \{ r_1 / r_2 \}) > 1,715(f\{R_a\}), \text{ and};$$

$$R_c = \{ \Omega r_1 d / \nu \} \leq 10^4$$

where:

1. $f\{R_a\} = 1.0 + (0.297)(\log_{10} R_a)^{4.04342}$ for $R_a \geq 1.0$
 $f\{R_a\} = 1.0$ for $0 \leq R_a \leq 1.0$
2. r_1 = the largest radius of the first electrode,
3. r_2 = the smallest radius of the second electrode,
4. ν = kinematic viscosity of electrolyte = $\mu(\text{poise})/\rho(\text{grams/cc.})$,
5. $R_a = (dL/\nu)(\dot{U}/U)$, and
6. $\dot{U}/U \geq 0$.

43. The system of Claim 38, wherein a chemical reactant passing through the cell (10) has a reaction time (t_a) within the first or second electrode (36, 34) and comprising in addition:

means for causing the chemical reactant to pass through a reaction zone of the first or second electrode (36, 34) zone in a length of time (t_r) that is at least 10 times a chemical conversion reaction time (t_a) for the chemical reactant within the first or second electrode (36, 34).

44. An electrochemical cell (10) comprising:
- a first surface (34') that contains a catalyst,
 - a second surface,
 - a fluid between the surfaces (34'36'), and
 - means (34, 36) for generating a vortex (50) in the fluid that is enveloped by a laminar shear boundary (58) adjacent to one of the surfaces (34', 36').
45. A fuel cell (12) comprising:
- a cathode electrode (36, 36'),
 - an anode electrode (34, 34'),
 - a fluid electrolyte between the electrodes (36, 36' 34, 34'), and
 - means (34, 36) for generating a vortex (50) in the electrolyte that is enveloped by a laminar shear boundary (58) adjacent one of the electrodes (36, 36' 34, 34').
46. In a fuel reformer (14, 90), an improvement comprising:
- means (18', 24' or 92, 96) for creating Taylor Vortex Flows (28, 98) in fuel.

47. In the fuel reformer (14, 90) of Claim 46, an improvement comprising:
means (18', 24' or 92, 96) for creating Circular Couette Flows (58, 99) in the fuel.
48. In the fuel reformer (14, 90) of Claim 46 having a catalyst surface layer (18', 24', 92), an improvement comprising:
means (108, 110, 102) for extracting carbon buildup from the catalyst surface layer (18', 24', 92) for capture and disposal by Taylor Vortex Flows (98).
49. In the fuel reformer (14, 90) of Claim 48 having a catalyst surface layer (18', 24', 92) and utilizing makeup gas, an improvement comprising:
means (108, 110, 102) for introducing oxidizing gas into the make-up gas to oxidize any carbon adhering to the catalyst surface (18', 24', 92).
50. In the fuel reformer (14, 90) of Claim 48, an improvement comprising:
a vibrating transducer (122) that is mechanically coupled to the catalytic surface layer (92).
51. In the fuel reformer (14, 90) of Claim 46 in which the means (18, 24 or 92, 96) for creating Taylor Vortex Flows (28 or 98) includes a first cylindrical surface layer (24' or 92) enclosing a second cylindrical surface layer (18' or 96) separated from the first by a fuel chamber (26 or 94) of gap distance d and length L and means (116) for rotating one electrode with respect to the other at Ω radians per second, further comprising:
a. means for pumping fuel into and out of the chamber (26 or 94) at a total volumetric exchange rate of $\dot{U}/U$ where U is the volume of electrolyte in the chamber and $\dot{U}$ is the volumetric rate of flow into and out of the chamber; and

b. means for regulating the volumetric exchange rate of axial flow and Taylor Number T_c of vortex flow (28 or 98) in the electrolyte so that –

i. $T_c = 2 r_2 \Omega^2 d^3 / \nu^2 (1 + \{ r_1 / r_2 \}) > 1,715(f\{R_a\})$, and;

ii. $R_c = \{ \Omega r_1 d / \nu \} \leq 10^4$

where:

1. $f\{R_a\} = 1.0 + (0.297)(\log_{10} R_a)^{4.04342}$ for $R_a \geq 1.0$
 $f\{R_a\} = 1.0$ for $0 \leq R_a \leq 1.0$,
2. r_1 = radius of the first surface layer (18' or 92),
3. r_2 = radius of the second surface layer (24' or 96),
4. $d = r_1 - r_2$,
5. ν = kinematic viscosity of electrolyte = $\mu(\text{poise})/\rho(\text{grams/cc.})$,
6. $R_a = (dL/\nu)(\dot{U}/U)$, and
7. $\dot{U}/U \geq 0$.

52. In the fuel reformer (14 or 90) of Claim 51 wherein:

$RPM = 30 \Omega / \pi$, coordinates of d and RPM are within a Zone of Operable Parameters (118a or 118b).

53. In the fuel reformer (14 or 90) of Claim 51 wherein:

the first surface layer (24' or 92) is reactive with the fuel to create hydrogen.

54. A fuel reformer (14 or 90) comprising:

- a. first and second surface layers (18', 24', or 92, 96) separated by a fluid chamber (26 or 94); and
- b. means (18', 24' or 92, 96, 114) for extracting unwanted contaminants (66) from the fuel.

55. The fuel reformer (14 or 90) of Claim 54, wherein the means for extracting unwanted contaminants (66) from the fuel include:

means (18', 24' or 92, 96) for creating Taylor Vortex Flows (28 or 98) in the fuel.

56. The fuel reformer (14 or 90) of Claim 51, comprising:

means (18', 24' or 92, 96) for creating Circular Couette Flows (58, 99) in the fuel.

57. In the fuel reformer (14 or 90) of Claim 53 in which the means (18', 24' or 92, 96) for creating Taylor Vortex Flows (26 or 98) includes a first surface layer (18' or 92) adjacent a second surface layer (24' or 96) and separated from the first surface layer by a fuel chamber (26 or 94) with –

- i. gap distance d (d or d''),
- ii. gap length L , and
- iii. means (116) for rotating one surface (24' or 96) with respect to the other surface layer (18' or 92) at Ω radians per second,

further comprising:

- a. means for pumping fuel into and out of the chamber (26 or 94) at a total volumetric exchange rate of $\dot{U}/U$ where U is the volume of fuel in the chamber and $\dot{U}$ is the volumetric rate of flow into and out of the chamber (26 or 94); and
- b. means for regulating the volumetric exchange rate of axial flow and Taylor Number T_c of vortex flow in the electrolyte so that –

$$T_c = 2 r_2 \Omega^2 d^3 / \nu^2 (1 + \{ r_1 / r_2 \}) > 1,715(f\{R_a\}), \text{ and};$$

$$R_c = \{ \Omega r_1 d / \nu \} \leq 10^4$$

where:

- 1. $f\{R_a\} = 1.0 + (0.297)(\log_{10} R_a)^{4.04342}$ for $R_a \geq 1.0$
 $f\{R_a\} = 1.0$ for $0 \leq R_a \leq 1.0$
- 2. r_1 = the smallest radius of the first surface layer (18', 96),
- 3. r_2 = the largest radius of the second surface layer (24', 92),

4. ν = kinematic viscosity of fuel = $\mu(\text{poise})/\rho(\text{grams/cc.})$,
5. $R_a = (dL/\nu)(\dot{U}/U)$, and
6. $\dot{U}/U \geq 0$.

58. A chemical cell (14 or 90) comprising:

- a. a first surface layer (24' or 92) that is –
 - i. reactive with a first chemical entering its pores (68) to produce hydrogen;
- b. a second surface (18' or 96) that is –
 - i. permeable to hydrogen, and
 - ii. adjacent the first surface layer (24' or 92) so that a chamber (26 or 94) is created between the surface layers (18', 24' or 92, 96);
- c. a chemical containing hydrogen in the chamber (26 or 94); and
- d. means (116) for moving one surface layer (24' or 96) with respect to the other surface (18' or 92) to create flows (28, 58, 59 or 98, 99) in the chemical in the chamber (26 or 94)

so the chemical can be reformed to produce hydrogen.

59. The chemical cell (14 or 90) of Claim 58 wherein:

- a. the first surface layer (24' or 92) is cylinder-like; and
- b. the second electrode (18' or 96) is cylinder-like and located substantially parallel to and within the first surface layer (24' or 92) so as to create the chamber (26 or 94) for the chemical between the surface layers (18', 24' or 92, 96).

60. The chemical cell (14 or 90) of Claim 58 wherein the flows (28 or 98) the in the chemical in the chamber (26 or 94) comprise:

Taylor Vortex Flows (28, 50, 98).

61. The chemical cell (14 or 90) of Claim 58 wherein the flows the in the chemical in the chamber (26 or 94) comprise:

Circular Couette Flows (58, 99) surrounding Taylor Vortex Flows (28, 50 or 98).

62. The chemical cell (14 or 90) of Claim 58 wherein the chemical is selected from a group comprising:

methane (CH_4), methanol (CH_3OH), ethanol ($\text{C}_2\text{H}_5\text{OH}$), propane (C_3H_8), butane (C_4H_{10}), octane (C_8H_{18}), kerosene ($\text{C}_{12}\text{H}_{26}$), gasoline, ammonia (NH_3) and sodium borohydride (NaBH_4).

63. A process for operating a chemical cell (14 or 90) to produce hydrogen comprising:

- a. pumping a chemical into a chamber (26 or 94) having an inner cylindrical surface layer (18' or 96) and an outer cylindrical surface layer (24' or 96); and
- b. rotating one of the surface layers (24' or 96) with respect to the other surface (18' or 92) at a rate sufficient to form Taylor Vortex Flows (28, 50 or 98) in the chemical in the chamber (26 or 94).

64. The process of operating a chemical cell (14 or 90) of Claim 63 wherein:

Circular Couette Flows (58, 99) surround the Taylor Vortex Flows (28, 50, 98).

65. The process for operating a chemical cell (14 or 90) of Claim 63 wherein the fuel is selected from a group comprising:

methane (CH_4), methanol (CH_3OH), ethanol ($\text{C}_2\text{H}_5\text{OH}$), propane (C_3H_8), butane (C_4H_{10}), octane (C_8H_{18}), kerosene ($\text{C}_{12}\text{H}_{26}$), gasoline, ammonia (NH_3) and sodium borohydride (NaBH_4).

66. The process for operating a chemical cell (14 or 90) Claim 63 in which the cell (10) contains a fuel reformer chamber (26) between a fixed surface layer (18', 92) and a rotating surface layer (24', 96) and the process comprises an additional step of:

- a. pumping a fuel containing hydrogen atoms into the fuel reformer chamber (26, 94); and
- b. rotating the reformer rotating surface layer (24) at a speed sufficient to cause –
 - i. fuel reformer Taylor Vortex Flows (28, 50, 98) in reformer chamber (26), and
 - ii. H_2 from the fuel to pass through one of the surface layers (18', 24', 92, 96)

67. The process for operating a chemical cell (14 or 90) Claim 66 wherein:

Circular Couette Flows (59, 99) surround the Taylor Vortex Flows (28, 50, 98) in the reformer chamber (26, 94).

68. A chemical cell (14 or 90) comprising:

- a. a first surface layer (24' or 92) containing porous catalyst;
- b. a second surface layer (18' or 96);

- c. the first surface layer (24' or 92) and the second surface layer (18' or 96) defining a chamber (26 or 94) between the surface layers (18', 24', 92, 96) and the chamber (26 or 94) including an input tube (22 or 98) configured so that a fluid passing through the chamber (26 or 94) from the input tube (22 or 104) passes adjacent the first and second surface layers (18', 24' or 92, 96); and,
- d. the chamber (26 or 94) being dimensioned, and at least one of the surfaces (24' or 96) being configured to rotate relative to the other surface layer (18' or 92) at an adequate rate of rotation to produce Taylor Vortex Flows (28 or 98) within the fluid flowing from the input tube (22 or 104) through the chamber (26 or 94).

69. The chemical cell of Claim 68 comprising in addition:

Circular Couette Flows (58, 99) surrounding the Taylor Vortex Flows (28, 98) in the reformer chamber (26, 94).

70. The chemical cell of Claim 69 comprising in addition:

protuberances (60) that extend from the first surface layer (18', 24', 92, 96) into the Circular Couette Flows (59,99).

71. The chemical cell of Claim 68 wherein the porous catalyst comprises:

nanoporous metal foam scaffold (86) having pores (87) surrounded by struts (88).

72. The chemical cell of Claim 71 where the struts (88) are:

decorated by catalyst particles.

73. The chemical cell of Claim 71 wherein the foam scaffold (86) includes a metal selected from:

the Table of the Elements Platinum Group Metals.

74. The chemical cell of Claim 71 wherein the foam scaffold (86) includes a metal selected from:

the Table of the Elements Group 10.

75. A chemical cell (10) comprising:

- a. a fuel reformer (14) containing a catalytic shell surface layer (18') and a second surface layer (24') that are separated by a fuel chamber (26) to permit one layer to rotate within the other layer and the fuel chamber having a gap distance d_1 and a gap length L_1 ;
- b. fuel cell (12) containing electrodes (34, 36) that are separated by an electrolyte chamber (40) to permit one electrode (34) to rotate within the other electrode (36) and the electrolyte chamber (40) having a gap distance d_2 , and gap length L_2 ;
- c. means for rotating one surface layer (18', 24') with respect to the other surface layer (24', 18') at Ω_1 radians per second;
- d. means for rotating one electrode (36, 34) with respect to the other electrode (34, 36) at Ω_2 radians per second;
- e. means for pumping fuel into and out of the reformer chamber (26) at a total volumetric exchange rate of $\dot{U}_1/U_1$ where U is the volume of fuel in the chamber (26) and $\dot{U}_1$ is the volumetric rate of flow into and out of the chamber (26);
- f. means for pumping electrolyte into and out of the electrolyte chamber (40) at a total volumetric exchange rate of $\dot{U}_2/U_2$ where U_2 is the volume of electrolyte in the chamber (40) and $\dot{U}_2$ is the volumetric rate of flow into and out of the chamber (40); and
- g. means for extracting hydrogen from the fuel reformer (14) and passing it through the fuel cell electrode (34) for a reduction reaction.

76. The chemical cell (10) of Claim 75 comprising in addition:

means for regulating the volumetric exchange rate of axial flow and Taylor Number T_c of vortex flow in the electrolyte chamber (40) and fuel chamber (26) so that for $x = 1$ or 2 –

$$T_c = 2 r_2 \Omega^2 d_x^3 / \nu^2 (1 + \{ r_1 / r_2 \}) > 1,715(f\{R_a\}), \text{ and};$$

$$R_c = \{ \Omega r_1 d / \nu \} \leq 10^4$$

where:

$$1. \quad f\{R_a\} = 1.0 + (0.297)(\log_{10} R_a)^{4.04342} \quad \text{for } R_a \geq 1.0$$

$$f\{R_a\} = 1.0 \quad \text{for } 0 \leq R_a \leq 1.0$$

2. r_1 = the largest radius of the first electrode or layer,

3. r_2 = the smallest radius of the second electrode or layer,

4. ν = kinematic viscosity of electrolyte or fuel =
 $\mu(\text{poise})/\rho(\text{grams/cc.}),$

5. $R_a = (dL_x/\nu)(\dot{U}/U),$ and

6. $\dot{U}/U \geq 0.$

77. An chemical cell (14, 90) comprising:

a. a first surface (24', 92) that contains a catalyst,

b. a second surface (18', 96),

c. a fluid between the surfaces (18' 92 and 24', 96), and

d. means (18' 92 or 24', 96 and 116) for generating a vortex (28, 50, 98)

in the fluid that is enveloped by a laminar shear boundary (58, 59, 99)

adjacent to one of the surfaces (18', 24', 92, 96).

78. A chemical process accelerator system in a chemical cell (10) comprising:
- viscid fluid Taylor Vortex Flows (28, 50, 50c, 98); and
 - a catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) supported in laminar Circular Couette Flows (58, 59, 99) generated by the Taylor Vortex Flows (28, 50, 50c, 98).
79. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein:
- the catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) is a cylinder-like surface layer (36',92) adjacent a second cylinder-like surface layer (34', 96), and
 - one of the cylinder-like surfaces (36' 92, 34' 96) is rotatable to produce the Taylor Vortex Flows (28, 50, 50c, 98) between the two cylinder-like surfaces.
80. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein the catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) comprises:
- a metal alloy containing an element selected from the Periodic Table of the Elements Platinum Group Metals.
81. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein the catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) comprises:
- a metal alloy containing an element selected from the Periodic Table of the Elements Group 10.

82. The chemical process accelerator system in a chemical cell (10) of Claim 81

wherein the metal comprises:

nickel.

83. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein

the viscid fluid comprises:

a hydrogen-rich fuel.

84. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein

the viscid fluid comprises:

an electrolyte.

85. The chemical process accelerator system in a chemical cell (10) of Claim 84 wherein

the electrolyte comprises:

an alkaline.

86. The chemical process accelerator system in a chemical cell (10) of Claim 84 wherein

the electrolyte comprises:

an acid.

87. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein

the catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) is a surface layer comprising:

protuberances (60, 90, 132, 132f, 132g) that extend into Circular Couette

Flows (58, 59, 99).

88. The chemical process accelerator system in a chemical cell (10) of Claim 87 wherein the protuberances (60, 90, 132, 132f, 132g):

do not extend into the Taylor Vortex Flows (28, 50, 50c, 98).

89. The chemical process accelerator system in a chemical cell (10) of Claim 87 wherein the protuberances (60, 90, 132, 132f) are in:

a hexagonal close packed array (140a, 140c).

90. The chemical process accelerator system in a chemical cell (10) of Claim 87 wherein the protuberances (132f) are:

streamlined.

91. The chemical process accelerator system in a chemical cell (10) of Claim 87 wherein the protuberances (60, 90, 132, 132f) comprise:

aggregate clumps (139) of carbon balls (138) decorated with Table of the Elements Platinum Metals Group catalyst particles (136) adhered to the carbon balls (138, 139).

92. The chemical process accelerator system in a chemical cell (10) of Claim 87 wherein the protuberances (60, 90, 132, 132f, 132g) comprise :

a nanoporous metal foam sponge (86).

93. The chemical process accelerator system in a chemical cell (10) of Claim 92 wherein the nanoporous metal foam sponge is :

loaded with catalytic particles (136).

94. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein the catalyst (132g) comprises: multiple layers(144, 145, 146, 147, 148) of different types of catalyst materials.

95. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein the catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) comprises:

a metal selected from the Periodic Table of the Elements Platinum Metals Group.

96. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein the catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) comprises:

a metal selected from the Periodic Table of the Elements Group 10.

97. The chemical process accelerator system in a chemical cell (10) of Claim 78 comprising in addition:

means (18', 24' 28, 34', 36' 50, 50c, 60, 92, 96, 98, 116) for extracting unwanted contaminants (66) from the system.

98. The chemical process accelerator system in a chemical cell (10) of Claim 78 comprising in addition:

means for using exothermic energy to heat the catalysts (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148).

99. The chemical process accelerator system in a chemical cell (10) of Claim 78 comprising in addition:

means (100) for raising thermal excitation in the catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) to increase its D-band energy level to near the Fermi level in order to reduce significantly energy of activation for catalysis.

100. The chemical process accelerator system in a chemical cell (10) of Claim 99 wherein the means (100) for raising thermal excitation in the catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) raise catalyst temperatures to:

at least 500° C.

101. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein the catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) comprises:

a metal alloy in which one element has been removed by selective dissolution.

102. The chemical process accelerator system in a chemical cell (10) of Claim 101 wherein the metal alloy comprises:

face-centered-cubic structural geometry.

103. The chemical process accelerator system in a chemical cell (10) of Claim 101 wherein the face-centered-cubic structural geometry of the metal alloy has:

a Miller Index of (1,1,1).

104. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein the catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) comprises:

a metal alloy having a perovskite structure.

105. The chemical process accelerator system in a chemical cell (10) of Claim 78 wherein the catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) comprises:

a metal alloy containing ruthenium.

106. A chemical process accelerator system in a chemical cell (10) comprising:

- a. viscid fluid vortex flows (28, 50, 50c, 98); and
- b. a catalyst (14, 18', 20, 24', 34' , 36, 86, 92, 130, 132, 132f, 132g, 136, 144,145, 146,147,148) supported in high-shear-rate laminar flows (58, 59, 99) generated by the vortex flows (28, 50, 50c, 98).

107. A fuel cell (910) containing electrolyte between its cathode (912) and anode (918) electrodes comprising: means (912, 918, 952) for creating Taylor Vortex Flows (954) in the electrolyte.

108. The fuel cell (910) of Claim 107, configured as a direct reaction fuel cell, and comprising in addition: means (936, 938) for pumping high-hydrogen-content fuel through the anode (918).

109. The fuel cell (910) of Claim 107 comprising in addition:

means (912, 918, 952, 954) for creating Circular Couette Flows (956) in the electrolyte.

110. The fuel cell (910) of Claim 109, configured as a direct reaction fuel cell, and comprising in addition:

means (936, 938) for pumping high-hydrogen-content fuel through the anode (918).

111. The fuel cell (910) of Claim 107 wherein:

one electrode (912 or 918) is rotatable relative to the other electrode (918 or 912).

112. The fuel cell (910) of Claim 111, configured as a direct reaction fuel cell, and comprising in addition:

means (936, 938) for pumping high-hydrogen-content fuel through one of the electrodes (912 or 918).

113. The fuel cell (910) of Claim 111 wherein:

the Taylor Vortex Flows (954) flow in an axial direction with respect to the rotation of the rotating electrode (912 or 918).

114. The fuel cell (910) of Claim 111 wherein:

one of the electrodes (912 or 918) rotates within the other.

115. The fuel cell (910) of Claim 114, configured as a direct reaction fuel cell, and comprising in addition:

means (936, 938) for pumping high-hydrogen-content fuel through one of the electrodes (912 or 918).

116. The fuel cell (910) of Claim 111 wherein:

one of the electrodes (912 or 918) has a cylinder-like geometry.

117. The fuel cell (910) of Claim 116, configured as a direct reaction fuel cell, and comprising in addition:

means (936, 938) for pumping high-hydrogen-content fuel through one of the electrodes (912 or 918).

118. The fuel cell (910) of Claim 107 in which the means (912, 918, 952) for creating Taylor Vortex Flows (954) includes a first cylindrical electrode surface layer (914 or 920) enclosing a second cylindrical electrode surface layer (920 or 914) separated from the first cylindrical electrode surface layer (914 or 920) by an electrolyte chamber (924) of gap distance d and length L and means for rotating one electrode surface with respect to the other at Ω radians per second, further comprising:

a. means for pumping electrolyte into and out of the chamber (924) at a total volumetric exchange rate of $\dot{U}/U$ where U is the volume of electrolyte in the chamber and $\dot{U}$ is the volumetric rate of flow into and out of the chamber; and

b. means for regulating the volumetric exchange rate of axial flow and Taylor Number T_c of vortex flow (954) in the electrolyte so that –

i. $T_c = 2 r_2 \Omega^2 d^3 / \nu^2 (1 + \{ r_1 / r_2 \}) > 1,715(f\{R_a\})$, and;

ii. $R_c = \{ \Omega r_1 d / \nu \} \leq 10^4$

where:

1. $f\{R_a\} = 1.0 + (0.297)(\log_{10} R_a)^{4.04342}$ for $R_a \geq 1.0$
 $f\{R_a\} = 1.0$ for $0 \leq R_a \leq 1.0$,
2. r_1 = radius of the first electrode (36),
3. r_2 = radius of the second electrode (34),
4. $d = r_1 - r_2$,
5. ν = kinematic viscosity of electrolyte = $\mu(\text{poise})/\rho(\text{grams/cc.})$,
6. $R_a = (dL/\nu)(\dot{U}/U)$, and
7. $\dot{U}/U \geq 0$.

119. The fuel cell (910) of Claim 118, configured as a direct reaction fuel cell, and comprising in addition:

means (936, 938) for pumping high-hydrogen-content fuel through one of the surface layers (914, 920).

120. The fuel cell (910) of Claim 118 wherein:

- a. $RPM = 30 \Omega/\pi$, and
- b. coordinates of d and RPM are within a Zone of Operable Parameters (80).

121. The fuel cell (910) of Claim 111 in which:

- a. one electrode (912 or 918) is reactive with a first chemical entering its pores from its first surface (931 or 941) to produce a first ion at its second surface layer (914 or 920); and
- b. the other electrode (918 or 912) is reactive with a second chemical entering its pores from its first surface (941 or 931) to produce a second ion at its second surface layer (920 or 914) having a charge different from that of the first ion.

122. The fuel cell (910) of Claim 121 comprising:

means for controlling entry of a chemical into pores of an electrode (912 or 918) so that reaction-time:residence-time $(t_a/t_r) \leq 1/10$.

123. The fuel cell (910) of Claim 121, configured as a direct reaction fuel cell, wherein:

one of the chemicals is a high-hydrogen-content fuel.

124. A fuel cell (910) containing first and second electrodes (912, 918) separated by a fluid electrolyte in a gap (d) between the electrodes (912, 918), comprising:

means (954) for extracting unwanted contaminants (66) from the electrolyte.

125. The fuel cell (10) of Claim 124, wherein the means for extracting unwanted contaminants (66) from the electrolyte include:

means (912, 918, 952) for creating Taylor Vortex Flows (954) in the electrolyte.

126. The fuel cell (910) of Claim 124, configured as a direct reaction fuel cell, and comprising in addition:

means (936, 938) for pumping high-hydrogen-content fuel through one of the electrodes (912 or 918).

127. The fuel cell (910) of Claim 125 in which the means (912, 918, 952) for creating Taylor Vortex Flows (954) includes a first electrode (912) adjacent a second electrode (918) separated from the first by an electrolyte chamber (924) with –

- i. gap distance d,
- ii. gap length L, and
- iii. means for rotating one electrode (912 or 918) with respect to the other electrode (918 or 912) at Ω radians per second,

further comprising:

- a. means for pumping electrolyte into and out of the chamber (924) at a total volumetric exchange rate of $\dot{U}/U$ where U is the volume of electrolyte in the chamber and $\dot{U}$ is the volumetric rate of flow into and out of the chamber (940); and
- b. means for regulating the volumetric exchange rate of axial flow and Taylor Number T_c of vortex flow in the electrolyte so that –

$$T_c = 2 r_2 \Omega^2 d^3 / \nu^2 (1 + \{ r_1 / r_2 \}) > 1,715(f\{R_a\}), \text{ and};$$

$$R_c = \{ \Omega r_1 d / \nu \} \leq 10^4$$

where:

- 1. $f\{R_a\} = 1.0 + (0.297)(\log_{10} R_a)^{4.04342}$ for $R_a \geq 1.0$
 $f\{R_a\} = 1.0$ for $0 \leq R_a \leq 1.0$
- 2. r_1 = the largest radius of the first electrode,
- 3. r_2 = the smallest radius of the second electrode,
- 4. ν = kinematic viscosity of electrolyte = $\mu(\text{poise})/\rho(\text{grams/cc.})$,
- 5. $R_a = (dL/\nu)(\dot{U}/U)$, and
- 6. $\dot{U}/U \geq 0$.

128. The fuel cell (910) of Claim 127, configured as a direct reaction fuel cell, and comprising in addition:

means (36, 38) for pumping high-hydrogen-content fuel through one of the electrodes (912, 918).

129. A fuel cell (910) comprising:

- a. a first electrode (912) that is –
 - i. reactive with a first chemical entering its pores from its first surface (931) to produce a first ion at its second surface layer (914);
- b. a second electrode (918) that is –
 - i. reactive with a second chemical entering its pores from its first surface (941) to produce a second ion at its second surface layer (920) having a charge different from that of the first ion, and
 - ii. adjacent the first electrode (912) so that a chamber (924) is created between the second surface layers (914 and 921) of the two electrodes (912 and 918);
- c. a fluid electrolyte in the chamber (924); and
- d. means for moving one electrode (912 or 918) with respect to the other electrode (918 or 920) to create flow (954) in the fluid electrolyte

so as to generate a voltage across the electrodes (912, 918) that are adapted to be connected to an external electrical circuit load (950).

130. The fuel cell (910) of Claim 129, configured as a direct reaction fuel cell, and comprising in addition:

- means (936, 938) for pumping high-hydrogen-content fuel through one of the electrodes (912, 918).

131. The fuel cell (910) of Claim 129 wherein:
- a. the first electrode (912) is cylinder-like and its second surface is its inner surface layer (914); and
 - b. the second electrode (918) is cylinder-like and its second surface is its outer surface layer (920) that is located substantially parallel to and within the first cylinder-like electrode (912) so as to create the chamber (924) for the electrolyte between the electrode surface layers (914 and 920).
132. A fuel cell (910) comprising:
- a. A first cylinder-like electrode (912) that is –
 - i. reactive with a first chemical within its pores to produce a first ion at its inner surface layer (914), and
 - ii. adapted to be connected to one electrical terminal (46 or 48) of an electrical circuit load (950);
 - b. A second cylinder-like electrode (918) that is –
 - i. reactive with a second chemical within its pores to produce a second ion at its outer surface layer (920) having a charge different from that of the first ion,
 - ii. smaller in diameter than the first electrode inner surface (914) and having an axis substantially parallel to that of the first electrode (912),
 - iii. within the first electrode inner surface (914) so that a chamber (924) is created between facing surface layers (914 and 920) of the two electrodes (12 and 18), and

- iv. adapted to be connected to another electrical terminal (946 or 948) of the electrical circuit load (950);
 - c. a fluid electrolyte in the chamber (924); and
 - d. means for axially rotating one electrode (912 or 918) with respect to the other electrode (918 or 920) to create Taylor Vortex Flows (954) in the fluid electrolyte
- so as to generate a voltage across the electrodes (912 and 918).

133. The fuel cell (910) of Claim 132 in which one chemical is an oxidizer and the other is a reductant.

134. The fuel cell (910) of Claim 132 wherein a chemical has a reaction time (t_a) within its electrode (912 or 918) pores and comprising in addition:

means for causing the chemical to pass through its electrode (912 or 918) reaction zone in a length of time (t_r) that is at least 10 times the chemical conversion reaction time (t_a) within its electrode (912 or 918).

135. A process for operating a fuel cell (910) to produce electricity for transmission to an external electrical circuit load comprising:

- a. pumping a high-hydrogen-content fuel through an anode electrode (918) of the fuel cell (910);
- b. pumping an oxidizer through a cathode electrode (912) of the fuel cell (910);
- c. pumping electrolyte into an electrolyte chamber (924) of the fuel cell (910) that is located between the electrodes (912 and 918); and
- d. rotating one electrode (912 or 918) with respect to the other electrode (918 or 912) at a rate sufficient to cause electrolyte Taylor Vortex Flows (954) in the electrolyte chamber (924).

136. A fuel cell (910) containing electrolyte between its electrodes (912, 918) and comprising:

- a. viscous fluid Taylor Vortex Flows (954) in the electrolyte; and
- b. an electrode (912, 918) catalyst surface layer (914 or 920) supported in a laminar flow (956) generated by the Taylor Vortex Flows (954).

137. The fuel cell (910) of Claim 136 wherein:

- a. the catalyst surface layer (914 or 920) is cylindrical-like and is adjacent a second cylindrical-like surface (918 or 912), and
- b. one of the cylindrical-like surfaces (912, 914 or 918, 920) is rotated to produce the Taylor Vortex Flows (954) between the two cylindrical-like surfaces (912, 914, 918, 920).

138. The fuel cell (910) of Claim 136 wherein:

the catalyst surface layer (14 or 20) comprises an element selected from the Platinum Metals Group.

139. The fuel cell (910) of Claim 136 wherein:

the viscous fluid is an electrolyte.

140. The fuel cell (910) of Claim 139 wherein:

the electrolyte is alkaline.

141. The fuel cell (910) of Claim 140 wherein the alkaline electrolyte contains:

an element from Group 1 of the Periodic Table of Elements.

142. The fuel cell (910) of Claim 140 wherein:

the electrolyte is acidic.

143. The fuel cell (910) of Claim 136, configured as a direct reaction fuel cell, and comprising in addition:

means (936, 938) for pumping high-hydrogen-content fuel through the catalyst surface layer (920).

144. The fuel cell (910) of Claim 143 wherein:

the fuel is a hydrocarbon.

145. The fuel cell (910) of Claim 144 wherein:

the hydrocarbon contains an alkane.

146. The fuel cell (910) of Claim 144 wherein:

the hydrocarbon contains an alcohol.

147. The fuel cell (910) of Claim 144 wherein:

the hydrocarbon contains kerosene.

148. The fuel cell (910) of Claim 143 wherein:

the fuel is a borohydride.

149. The fuel cell (910) of Claim 148 wherein:

the borohydride contains a cation from Group 1 of The Periodic Table of the Elements.

150. The fuel cell (910) of Claim 149 wherein the cation from Group 1 of The Periodic Table of the Elements is:

sodium.

151. The fuel cell (910) of Claim 136 wherein the catalyst surface layer (914 or 920) comprises:

protuberances (958) extending from catalyst surface layer (914 or 920) into the laminar flow (956).

152. The fuel cell (910) of Claim 151 wherein:

the protuberances (958, 132f) are streamlined.

153. The fuel cell (910) of Claim 151 wherein the catalyst surface layer (914 or 920) comprises:

a plurality of catalyst layers (144, 145, 146, 147, 148).

154. The fuel cell (910) of Claim 151 wherein the protuberances (132) comprise:

a sparse mesh of fine filaments (134).

155. The fuel cell (910) of Claim 154 wherein the sparse mesh of fine filaments (134) contains:

aggregate carbon balls (138, 139).

156. The fuel cell (910) of Claim 155 wherein the aggregate carbon balls (138, 139) are decorated by:

particles (136) of a metal selected from the Periodic Table of the Elements
Platinum Metals Group.

157. The fuel cell (910) of Claim 155 wherein the aggregate carbon balls (138, 139) are decorated by:

particles (136) of a metal selected from the Periodic Table of the Elements
Group 10.

158. The fuel cell (910) of Claim 154 wherein the sparse mesh of fine filaments (134) is decorated by:

particles (136) of a metal selected from the Periodic Table of the Elements
Platinum Group Metals.

159. The fuel cell (910) of Claim 154 wherein the sparse mesh of fine filaments (134) is decorated by:

particles (136) of a metal selected from the Periodic Table of the Elements
Group 10.

160. The fuel cell (910) of Claim 136 wherein the catalyst surface layer (914 or 920) comprises:

a nanoporous metal foam sponge (86).

161. The fuel cell (910) of Claim 160 wherein the nanoporous metal foam sponge (86) comprises:

a metal alloy in which one element has been removed by selective
dissolution.

162. The fuel cell (910) of Claim 161 wherein the metal alloy comprises:

face-centered-cubic structural geometry.

163. The fuel cell (910) of Claim 162 wherein the face-centered-cubic structural geometry of the metal alloy has:

a Miller Index of (1,1,1).

164. The fuel cell (910) of Claim 161 wherein the metal alloy comprises:

a perovskite structure.

165. The fuel cell (910) of Claim 160 wherein the nanoporous metal foam sponge (86) is:

decorated with catalytic particles (136) of metal selected from the Platinum Metals Group.

166. The fuel cell (910) of Claim 160 wherein the nanoporous metal foam sponge (86) is:

decorated organic catalytic particles (136).

167. The fuel cell (10) of Claim 160 wherein the nanoporous metal foam sponge (86) contains:

a metal from the Platinum Group Metals.

168. The fuel cell (910) of Claim 167 wherein the metal is:

a platinum alloy.

169. The fuel cell (910) of Claim 168 wherein the platinum alloy contains:

ruthenium.

170. The fuel cell (910) of Claim 160 wherein:

the nanoporous metal foam sponge (86) is secured to a copper substrate.

171. The fuel cell (910) of Claim 160 wherein:

the nanoporous metal foam sponge (86) is coated with a high-molecular-weight compound.

172. A fuel cell (910) comprising:

- a. a cathode electrode (912),
- b. an anode electrode (918),
- c. a fluid electrolyte between the electrodes (912, 918), and
- d. means (952, 912, 914, 918, 920) for generating a vortex (954) in the electrolyte that is enveloped by a laminar shear boundary (956) adjacent one of the electrodes (912, 918).

173. A fuel cell battery (200) comprising:

- a. a rotating shaft (206);
- b. at least two fuel cells (202x) each having a rotating electrode (204x) that is fixed to the rotating shaft (206),
 - i. the rotating electrode (204x) of the first cell (202A) being an anode (204A), and
 - ii. the rotating electrode of the second cell (202B) being a cathode (204B) and
- c. a busbar (232AB) providing an electrical connection (230) between the anode (204A) and the cathode (204B).

174. The fuel cell battery (200) of Claim 173, configured as a direct reaction fuel cell battery, wherein the two fuel cells (202A, 202B) are direct reaction fuel cells and comprising in addition:

- a. an anode (208B) in the second cell (202B) that is separated from the second cell cathode (204B) by an electrolyte chamber (224B); and
- b. means (216, 212A, 220B, 214B) for pumping high-hydrogen-content fuel through the anode (204A, 208B) of each cell fuel cell (202A, 202B).

175. The fuel cell battery (200) of Claim 174 comprising in addition:

- a. a cathode electrode (208A) in the first cell (202A);
- b. a battery terminal (228) electrically connected (230) to the cathode electrode (208A);
- c. an anode electrode (208B) in the second cell (202B);
- d. a battery terminal (236) electrically connected (230) to the anode electrode (208B).

176. The fuel cell battery (200) of Claim 175 comprising in addition:

- a. a first electrolyte chamber (224A) having one side adjacent the first cell (202A) anode (204A)
- b. a cathode (208A) adjacent the opposite side of the first electrolyte chamber (224A);
- c. a second electrolyte chamber (224B) having one side adjacent the second cell (202B) cathode (204B);

- d. an anode (208B) adjacent the opposite side of the second electrolyte chamber (224B); and
- e. means (204A, 204B, 208A, 208B, 206, 52) for creating Taylor Vortex Flows (54) within an electrolyte in the electrolyte chambers (224A, 224B).

177. A fuel cell battery (200) of comprising:

- a. a rotatable shaft (206);
- b. two fuel cells (202A, 202D) each having a rotatable electrode (204A, 204D) that is fixed to the rotatable shaft (206), the rotatable electrode (204A) of the first cell (202A) being an anode (204A) and the rotatable electrode of the second cell (202D) being a cathode (204D);
- c. a cathode electrode (208A) in the first cell (202A) separated from a first cell anode (204A) by an electrolyte chamber (224A);
- d. a battery terminal (228) electrically connected (230) to the cathode electrode (208A);
- e. an anode electrode (208D) in the second cell (202D) separated from a second cell cathode (204D) by an electrolyte chamber (224D);
- f. a battery terminal (236) electrically connected (230) to the anode electrode (208D); and
- g. an electrical circuit (230) connection between the rotatable anode (204A) and the rotatable cathode (204D).

178. The fuel cell battery (200) of Claim 177, configured as a direct reaction fuel cell battery, wherein the two fuel cells (202A, 202D) are direct reaction fuel cells and comprising in addition:

means (216, 212A, 220D, 214D) for pumping high-hydrogen-content fuel through the anode (204A, 208D) of each cell fuel cell (202A, 202D).

179. A dynamic accelerated reaction battery (10, 100, 200, 400) comprising:

- a. a battery cell (B12x, 102x, 201, 412A, 412B);
- b. electrodes of a first polarity (B14x, 106x, 202, 414x) and a second polarity (B20x, 108x, 204, 420x) located with the cell (B12x, 102x, 201, 412x);
- c. an electrolyte chamber (B38x, 126x, 206, 438x) for flowing electrolyte between the cell's electrodes of a first polarity (B14x, 106x, 202, 412x) and the cell's electrodes of a second polarity (B20x, 108x, 204, 420x);
- d. means (B28, 112, 222, 428) for pumping electrolyte through the electrodes (B14x, 20x, 106x, 108x, 202, 204, 226, 414A, 414B, 420A, 420B); and
- e. means (B14x, B16, B18, B20x, 106x, 108x, 115, 118, 122, 202, 204, 208, 210, 212, 414x, 416, 418, 420x) for creating Taylor Vortex Flows (B54, 124, 228, 454) in the electrolyte chamber (B38x, 126x, 206, 438x) electrolyte .

180. The battery (B10, 100, 200, 400) of Claim 179 wherein:

the electrodes (14x, 20x, 106x, 108x, 202, 204, 414x, 420x) are cylinder-like.

181. The battery (B10, 100, 200, 400) of Claim 180 wherein:
- one electrode (B14x, 106x, 202, 414x) of one polarity is located within one electrode (B20x, 108x, 204, 420x) of another polarity.
182. The battery (B10, 100, 400) of Claim 180 wherein:
- the electrode (B14x, 106x, 414x) of one polarity rotates relatively within the electrode (B20x, 108x, 420x) of another polarity.
183. The battery (10, 100, 200, 400) of Claim 180 wherein:
- the electrolyte flows into the electrolyte chamber (B38x, 126x, 206, 438x) after flowing through an anode electrode (B14x, 106x, 202, 414x) when the cell is in a discharge cycle.
184. The battery (B10, 100, 200) of Claim 179, comprising in addition:
- means (B14x, B16, B18, B20x, B54, 106x, 108x, 115, 118, 122, 124, 202, 204, 208, 210, 212, 228, 414x, 416, 418, 420x) for creating Circular Couette Flows (B56, 124, 230) in the electrolyte chamber (38x, 126x, 206, 438x) electrolyte.
185. The battery (10, 100, 200) of Claim 179, comprising in addition:
- means (B16, B18, 118, 122, 208, 210, 212, 416, 418) for providing relative motion between an electrode (B14x, B20x, 106x, 108x, 202, 204, 414x, 420x) and the electrolyte chamber (B38x, 126x, 206, 438x) electrolyte.

186. The battery (B10, 100, 400) of Claim 179, comprising in addition:
- means (B16, B18, 118, 416, 418) for providing relative motion between one electrode of one polarity (B14x, 106x, 414x) separated from another electrode of another polarity (B20x, 108x, 420x) by the electrolyte chamber (B38x, 126x, 206, 438x).
187. The battery (B10, 100, 400) of Claim 186 wherein:
- each of the electrodes (B14x, B20x, 106x, 108x, 414x, 420x) is cylinder-like; and
 - an electrode (B14x, 106x, 414x) of one polarity is rotatable within an electrode (B20x, 108x, 420x) of another polarity.
188. The battery (B10, 100, 400) of Claim 179, comprise in addition:
- a second cell (B12B, 102B, 412B) containing an electrode (B20B, 108B, 420B) of one polarity separated by an electrolyte chamber (B38B, 126B, 438B) from another electrode (B14B, 106B, 414B) of another polarity; and
 - means (B40xx, B42xx, 120, 440xx, 442xx) for electrically connecting one of the electrodes (B14A, B20B, 414A) in the first cell (B12x, 102x, 412x) to one of the electrodes (B14B, 20A, 414B) that is of the opposite polarity in the second cell (B12B, 102B, 412B).
189. The battery (B10, 100, 400) of Claim 188 comprising in addition:
- means (B16, B18, 118, 130, 416, 418) for spinning a first electrode (B14x, 106x, 414x) of the first cell (B12A, 106A, 412A) within another electrode

(B20A, 108A, 420A) of the first cell (B12A, 102A, 412A) and spinning an electrode (B14B, 20B, 414B) of the opposite polarity to that of the first electrode (B14x, 106x, 414x) of the first cell (B12A, 102A, 412A) within and relative to another electrode (20B) of the second cell (B12B).

190. The battery (B10, 100, 400) of Claim 189 wherein:

the electrolyte flows into the electrolyte chamber (B38B, 126B, 438B) after flowing through an anode electrode (B20B, 108B, 420B) when the cell is in a discharge cycle.
191. The battery (100) of Claim 189, wherein its electrodes (106x, 108x) are:

interdigitated, one electrode (106x) within the other (108x).
192. The battery (100) of Claim 191, wherein its electrodes (106x, 108x) are:

cylinder-like.
193. The battery (100) of Claim 191, wherein:

one interdigitated, electrode (106x) rotates within the other interdigitated electrode (108x).
194. The battery (100) of Claim 193, wherein:

the interdigitated electrodes (106x, 108x) are separated by an electrolyte chamber (126x).
195. The battery (100) of Claim 194 wherein:

the electrolyte flows into the electrolyte chamber (126x,) after flowing through an anode electrode (106x, 108x) when the cell is in a discharge cycle.

196. The battery (100) of Claim 194, comprising:

- a. a first cell (102A) containing an electrode (106A) of a first polarity that is interdigitated with an electrode (108A) of a second polarity;
- b. a second cell (102B) containing an electrode (106B) of a first polarity that is interdigitated with an electrode (108B) of a second polarity; and
- c. means (120) for electrically connecting one electrode (106A, 108A) having one polarity in the first cell (102A) to one electrode (106B, 108B) of another polarity in the second cell (102B).

197. The battery (200) of Claim 179, comprising in addition:

- a. a membrane (208) dividing the electrolyte chamber (206) into a first semi-electrolyte-chamber (206A) adjacent the first electrode (202) and a second semi-electrolyte-chamber (206C) adjacent the second electrode (204); and
- b. means (202, 204, 210, 212) for providing relative motion between the membrane (208) and the electrodes (202, 204).

198. The battery (200) of Claim 197 wherein:

- a. the first electrode (202) is an anode; and

b. electrolyte flows through the anode (202) into the semi-electrolyte chamber (206A) adjacent the anode (202) when the cell is in a discharge cycle.

199. The battery (200) of Claim 197 wherein the electrode of a first polarity is an anode (202) and comprising in addition:

- a. means (214) for discharging the cell (201); and
- b. means (220, 222) for pumping electrolyte through the anode electrode (202) during the cell (201) discharge cycle.

200. The battery (400) of Claim 179 comprising in addition:

- a. a fuel cell (412C);
- b. electrodes of a first polarity (420C) and a second polarity (414C) located with the fuel cell (412C);
- c. an electrolyte chamber (438C) for flowing electrolyte between the cell's electrodes of a first polarity (420C) and the cell's electrodes of a second polarity (412C);
- d. means (428) for pumping electrolyte through the electrolyte chamber (438C);
- e. means (414C, 416, 418, 420C) for creating Taylor Vortex Flows (454) in the electrolyte chamber (438x) electrolyte; and
- f. means (442BC) for electrically connecting a battery cell (412B) electrode of one polarity (420B) to a fuel cell (412C) electrode of the same polarity(420C).

201. The battery (400) of Claim 200 comprising in addition:
- means (445) for electrically connecting another battery cell (412A) electrode of another polarity (420A) to another fuel cell (412D) electrode of the same polarity(420D).
202. The battery (400) of Claim 200 comprising in addition:
- a Balance Of Plant (428) that includes means for using exothermic heat energy and water from the fuel cells (412C, 412D) to maintain optimum battery cell (412A, 412B) temperature.
203. The battery (400) of Claim 200 comprising in addition:
- a Balance Of Plant (428) that includes means for using exothermic heat energy from the fuel cells (412C, 412D) to maintain optimum battery cell (412A, 412B) electrolyte pH.
204. The battery (400) of Claim 200 comprising in addition:
- a Balance Of Plant (428) that includes means for using water from the fuel cells (412C, 412D) to maintain optimum battery cell (412A, 412B) electrolyte pH.
205. The battery (400) of Claim 200 comprising in addition:
- means (438C, 450, 428, 430C, 432C) for sequestering water from the fuel cell (412C) to provide make-up water to the electrolyte in the battery cell (412A).

206. The battery (400) of Claim 200 comprising in addition:
means (414C, 416, 418, 420C) for creating Circular Couette Flows (56) in the electrolyte chamber (438x) electrolyte.
207. The battery (400) of Claim 200 comprising in addition:
means for rotating both the battery (412A, 412B) electrode (414A, 420A, 414B, 420B) and the fuel cell (412C, 412D) electrode (414C, 420C, 414D, 420D) to create TVF (454) and Circular Couette Flows (56) in both the battery cell (412A, 412B) electrolyte chamber (438A, 438B) and the fuel cell (412C, 412D) electrolyte chamber (438C, 438D).
208. The battery (400) of Claim 200 comprising in addition:
means (438x, 470A, 470B, 450, 428, 474, 476, 460, 464) for cycling H₂ and O₂ gases produced by the battery cell (412A, 412B) into fuel and O₂ consumed by the fuel cell (412C, 412D).
209. The battery (B10, 100, 200) of Claim 179 wherein one of the electrodes (12x, 14x, 106x, 108x, 202, 204) comprises:
an isotropic 3-dimensional open-pore-structure foam sponge (340) with nanometer-diameter pores (344) and somewhat smaller diameter scaffold struts (342) made by a process in which one metal element was removed from an alloy of that metal by selective dissolution to yield the nanoporous metal foam sponge (340) that will absorb electrolyte.

210. The battery (B10, 100, 200) of Claim 209 comprising in addition:
- a. means (14x, 16, 18, 20x, 54, 106x, 108x, 115, 118, 122, 124, 202, 204, 208, 210, 212, 228) for creating laminar Circular Couette Flows (56, 124, 230) in the electrolyte chamber (38x, 126x, 206) electrolyte; and
 - b. protuberances (58) extending from one of the electrodes (12x, 14x, 106x, 108x, 202, 204) into the laminar Circular Couette Flows (56, 124, 230) in the electrolyte chamber (38x, 126x, 206) electrolyte.
211. The battery (B10, 100, 200) of Claim 209 wherein the nanoporous metal foam sponges (340) comprise:
- an alloy having face-centered cubic geometry with a Miller Index of (1,1,1).
212. The battery (B10, 100, 200) of Claim 209 wherein the nanoporous metal foam sponges (340) comprise:
- an alloy having a perovskite structure.
213. The battery (B10,100, 200,400) of Claim 179 comprising in addition:
- means for admixing catalyst nanoparticles with the electrolyte to promote the formation of H₂O molecules from O₂ and H₂ gas in the electrolyte..
214. The battery (B10, 100) of Claim 179 in which the means (14x, 16, 18, 20x, 106x, 108x, 115, 118, 122) for creating Taylor Vortex Flows (54, 124) includes a first cylinder-like electrode (14x, 106x) enclosing a second cylinder-like electrode (20x, 108x) separated from the first cylinder-like electrode by an electrolyte chamber (38x, 126x) of gap distance d and

length L and means for rotating one electrode surface with respect to the other at Ω radians per second, further comprising:

- a. means (28, 112) for pumping electrolyte into and out of the chamber (38x, 126x, 206) at a total volumetric exchange rate of $\dot{U}/U$ where U is the volume of electrolyte in the chamber and $\dot{U}$ is the volumetric rate of flow into and out of the chamber; and
- b. means for regulating the volumetric exchange rate of axial flow and Taylor Number T_c of vortex flow (54, 128) in the electrolyte so that –
 - i. $T_c = 2 r_2 \Omega^2 d^3 / \nu^2 (1 + \{ r_1 / r_2 \}) > 1,715(f\{R_a\})$, and;
 - ii. $R_c = \{ \Omega r_1 d / \nu \} \leq 10^4$

where:

1. $f\{R_a\} = 1.0 + (0.297)(\log_{10} R_a)^{4.04342}$ for $R_a \geq 1.0$
 $f\{R_a\} = 1.0$ for $0 \leq R_a \leq 1.0$,
2. r_1 = radius of the electrode of the first polarity (14x, 106x),
3. r_2 = radius of the electrode of the second polarity (20x, 108x),
4. $d = r_1 - r_2$,
5. ν = kinematic viscosity of electrolyte = $\mu(\text{poise})/\rho(\text{grams/cc.})$,
6. $R_a = (dL/\nu)(\dot{U}/U)$, and
7. $\dot{U}/U \geq 0$.

215. The battery (B10, 100) of Claim 214 wherein:

- a. $\text{RPM} = 30 \Omega / \pi$, and
- b. coordinates of d and RPM are within a Zone of Operable Parameters (80).

FIG. 2A

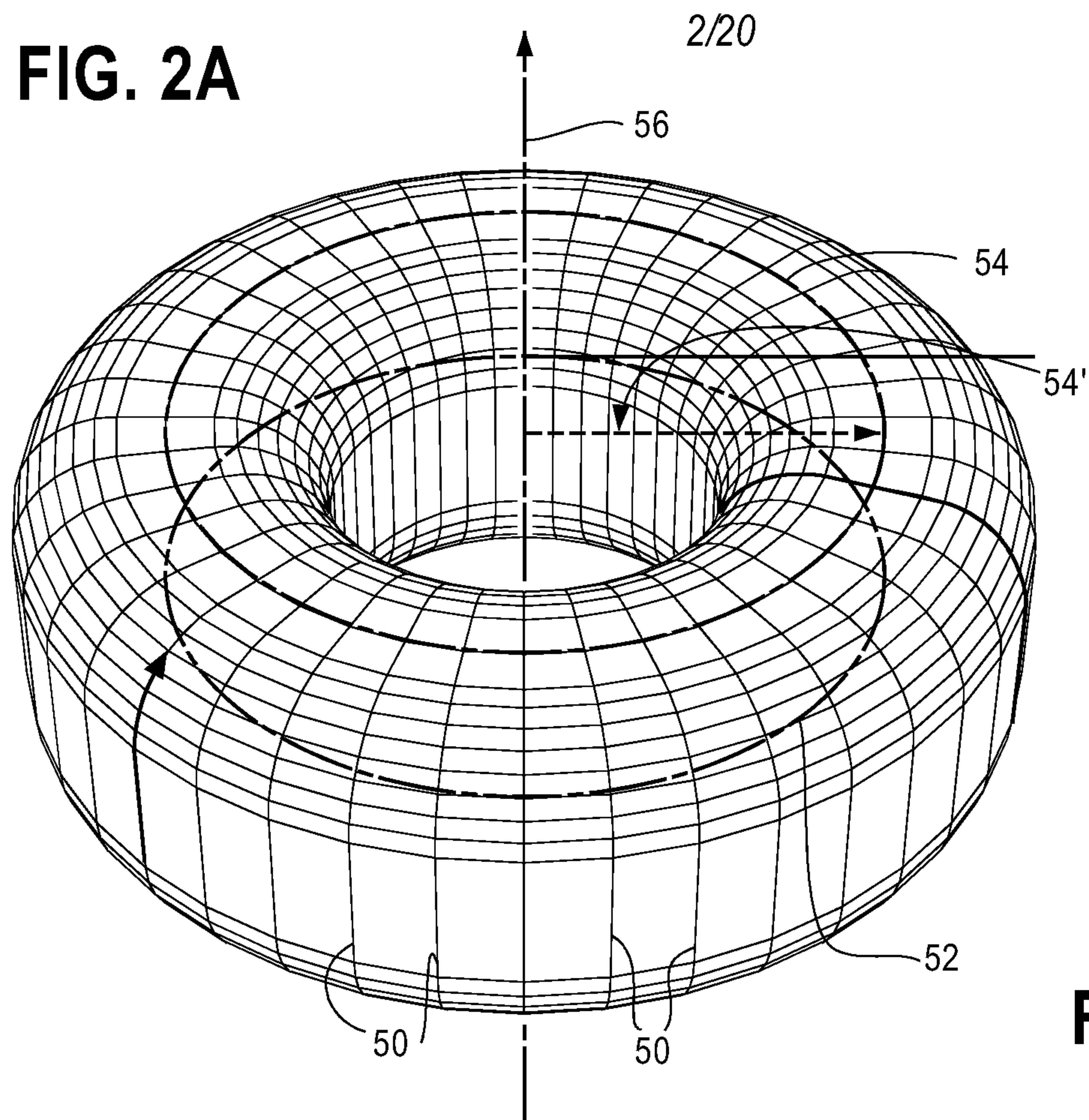


FIG. 2B

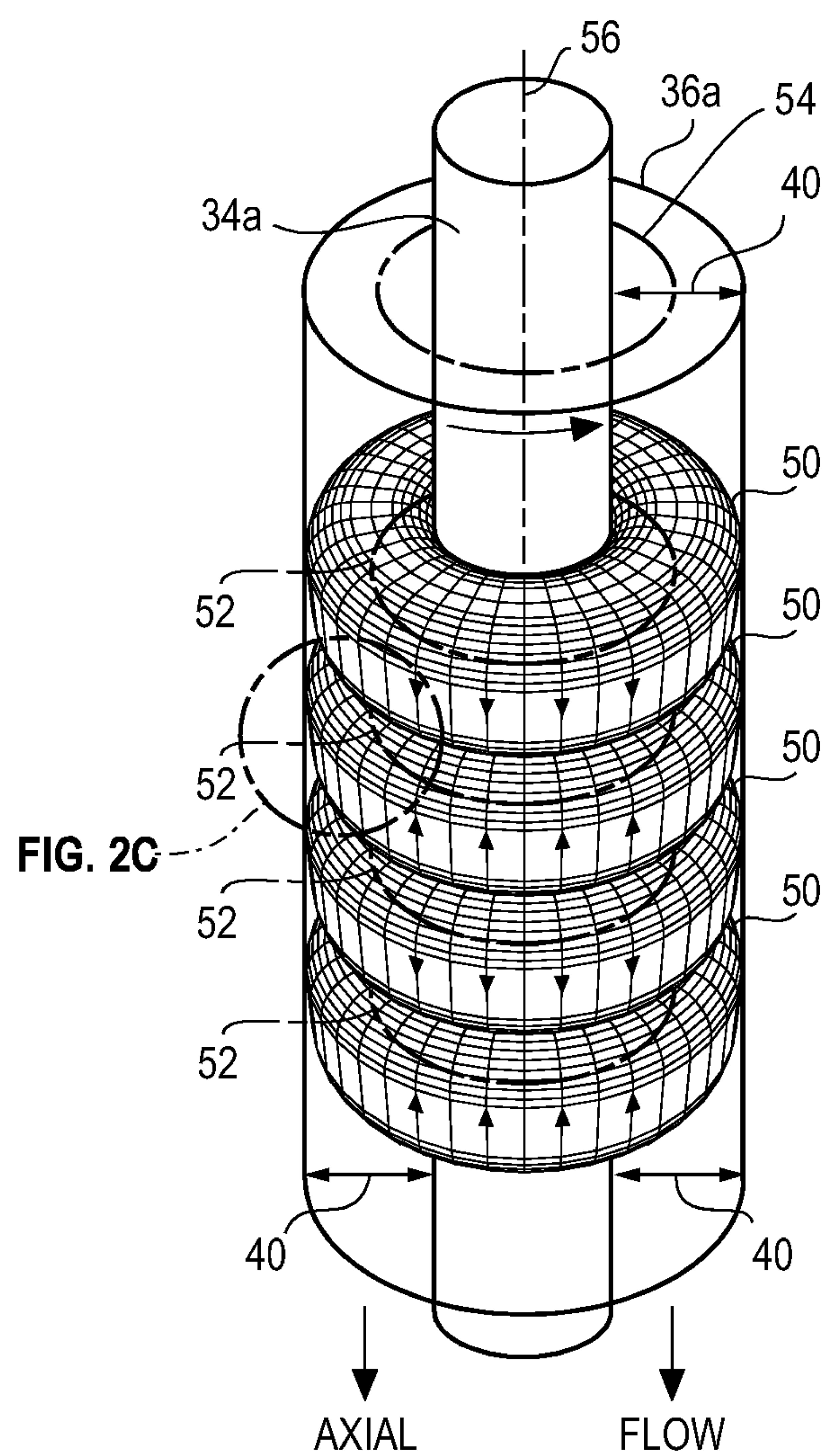


FIG. 2C

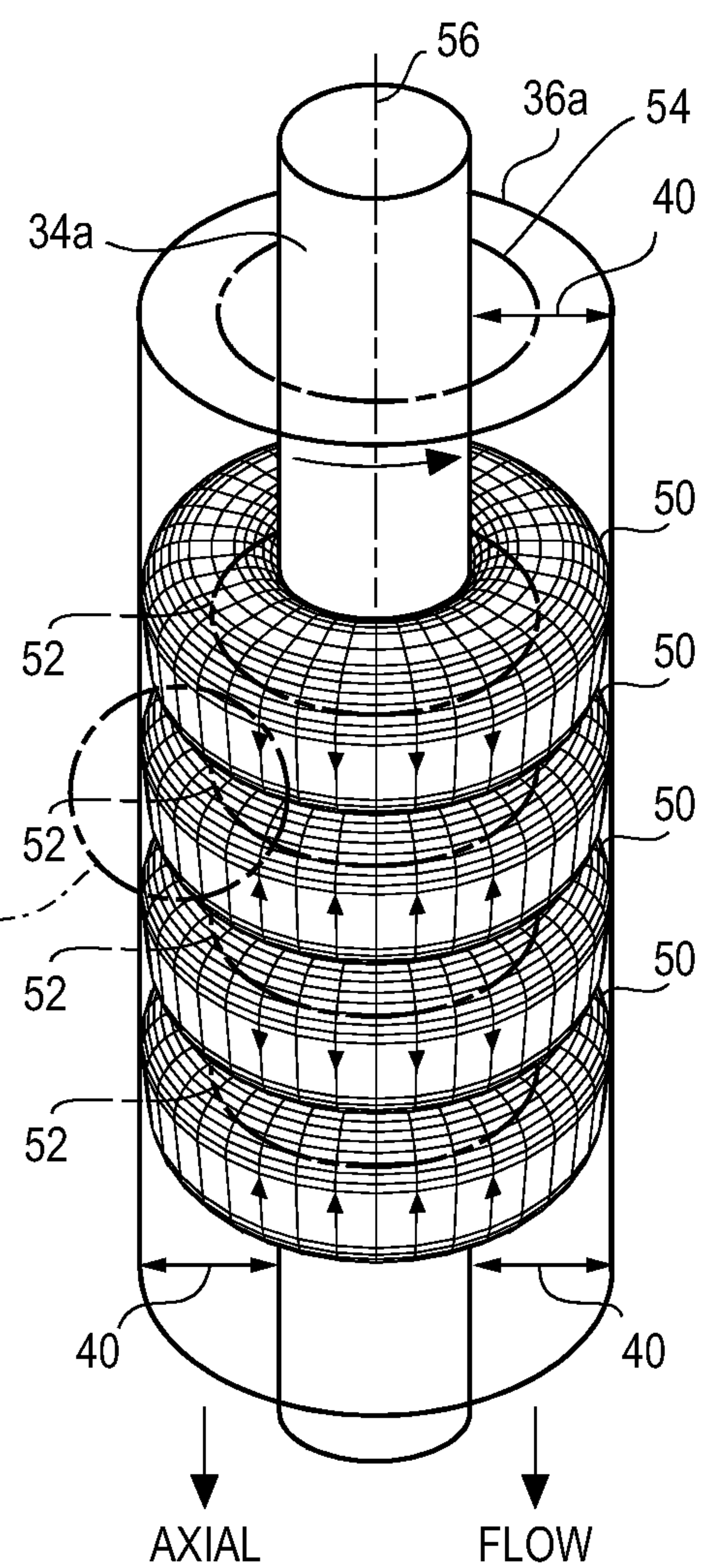


FIG. 2C-1

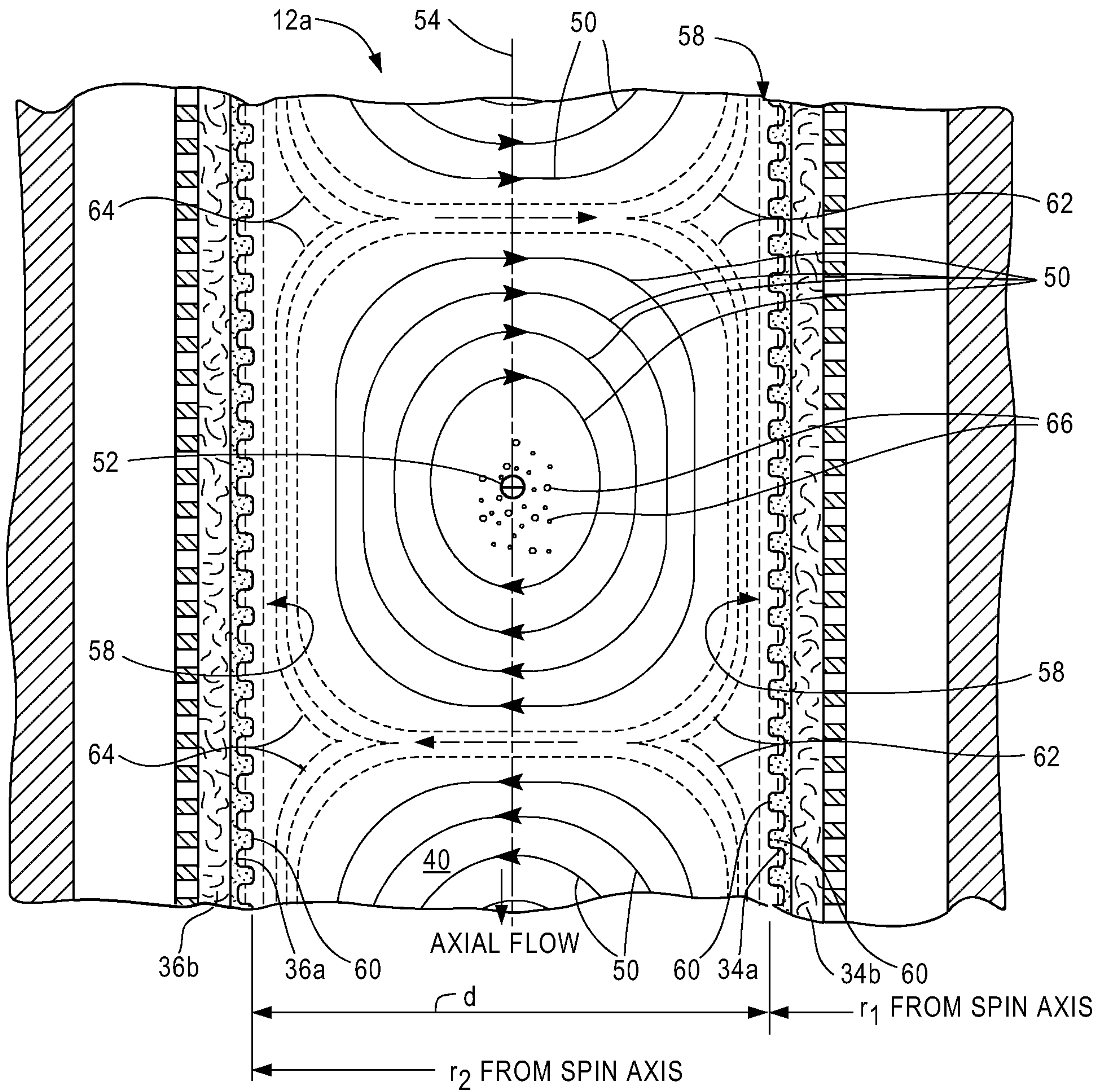
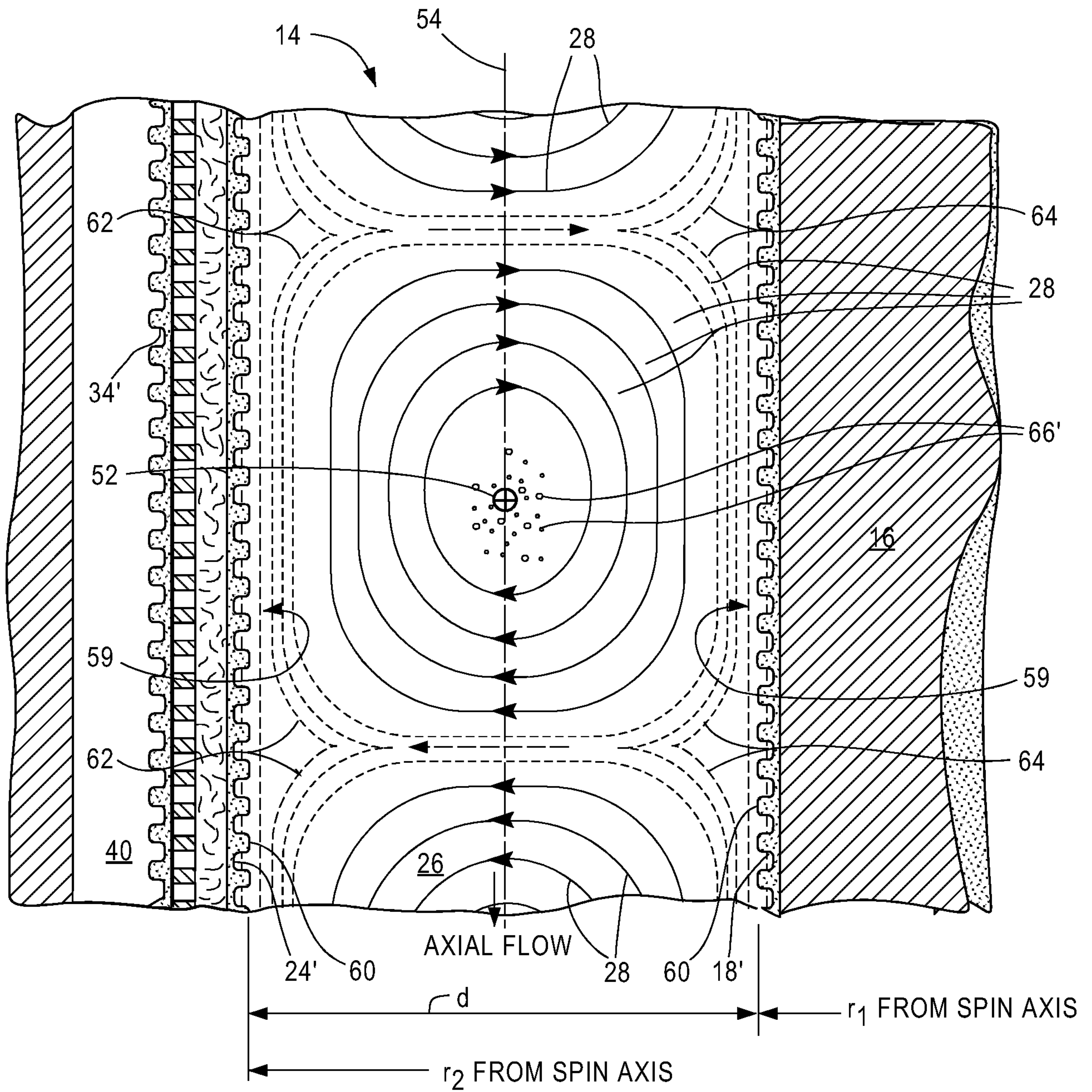


FIG. 2C-2



5/20

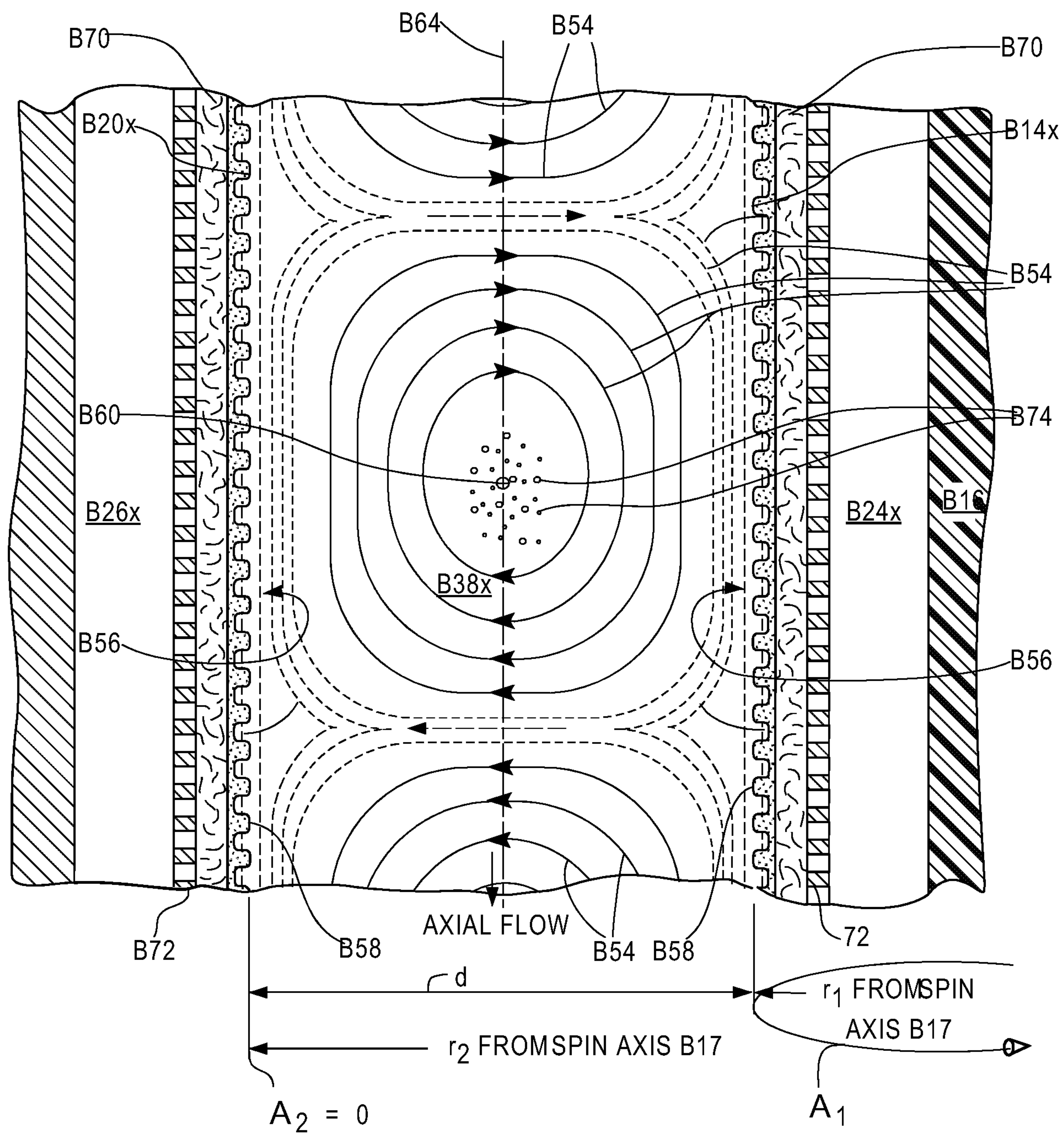
FIG. 2C-3

Fig. 2D

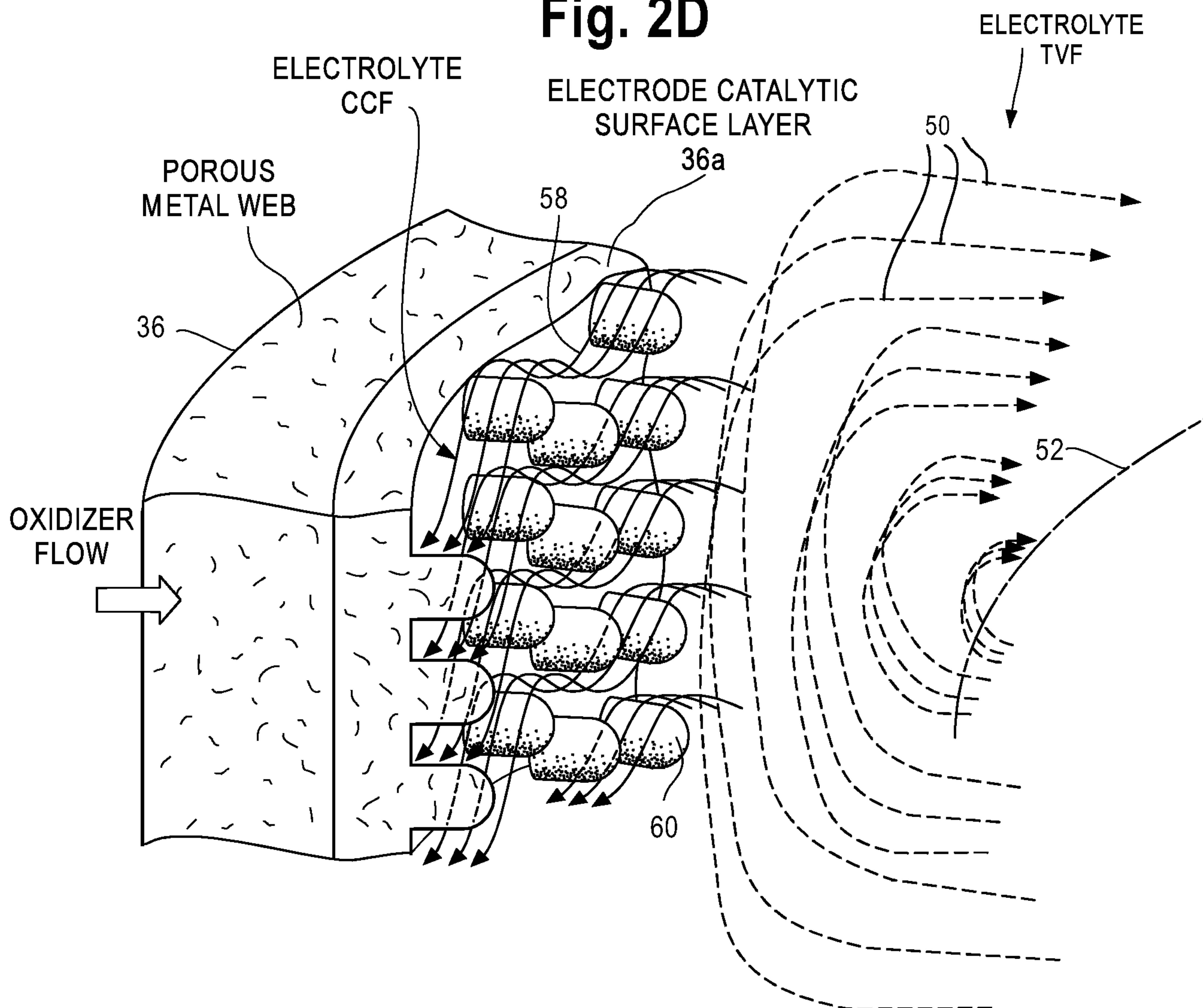


Fig. 2E

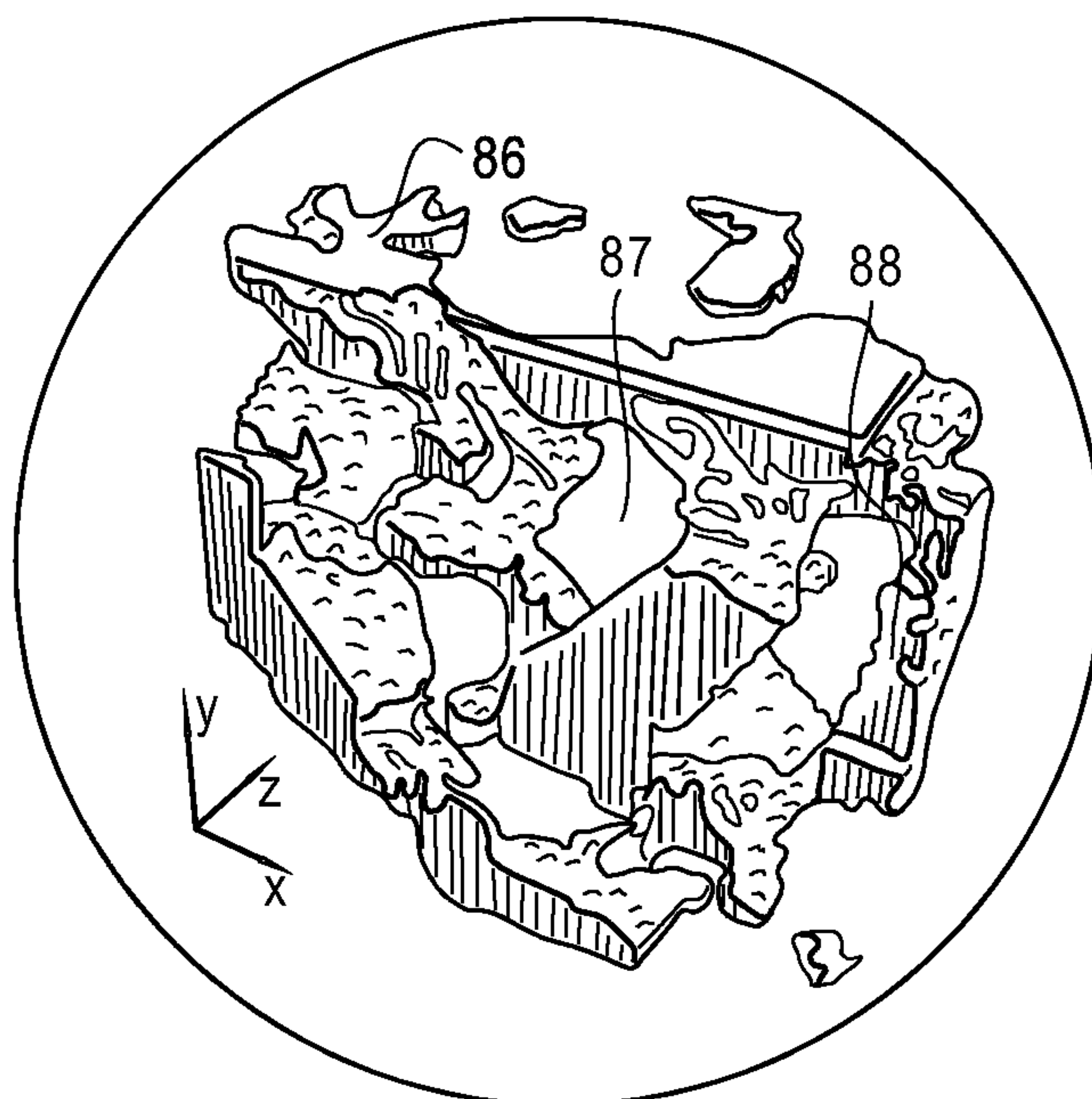
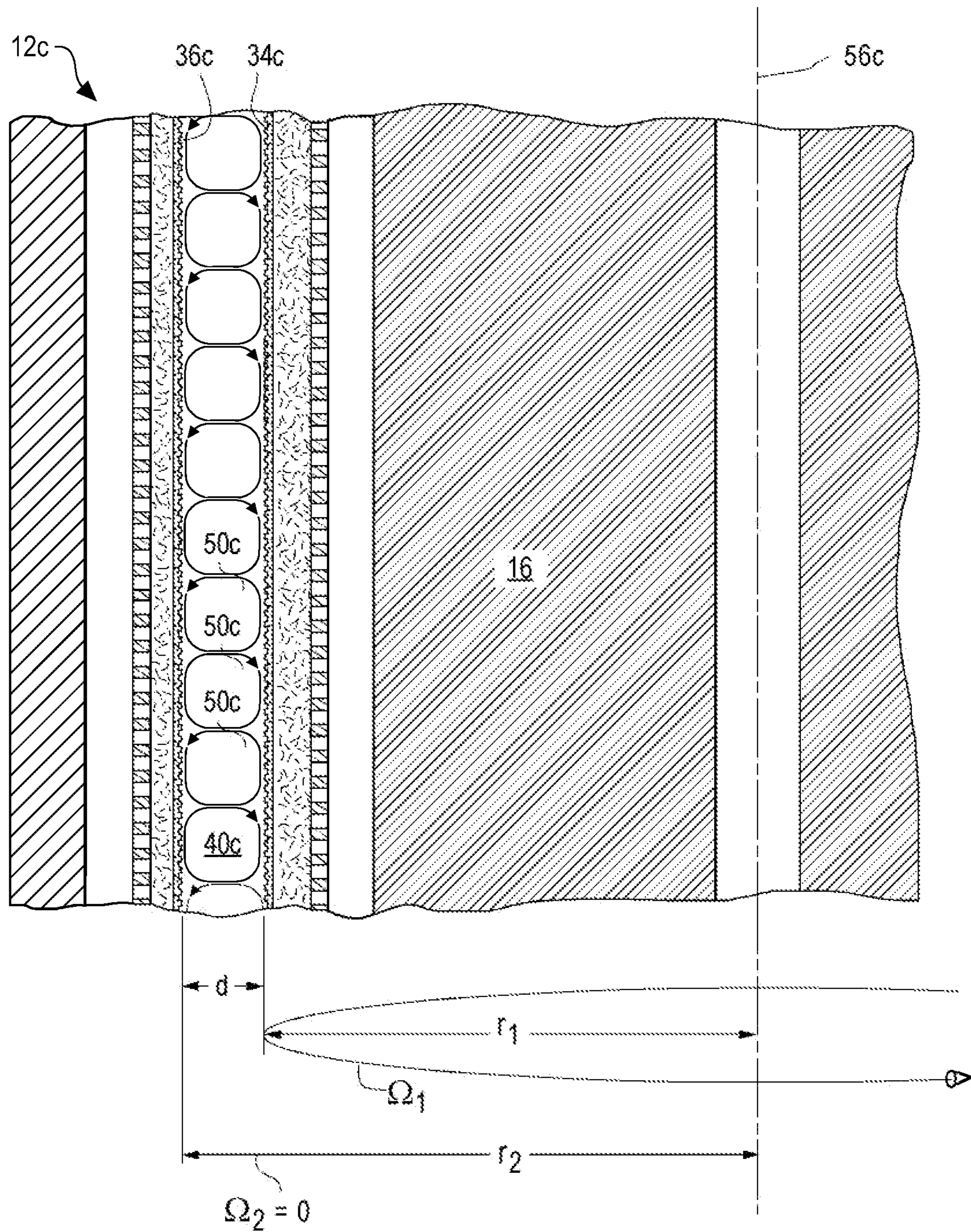
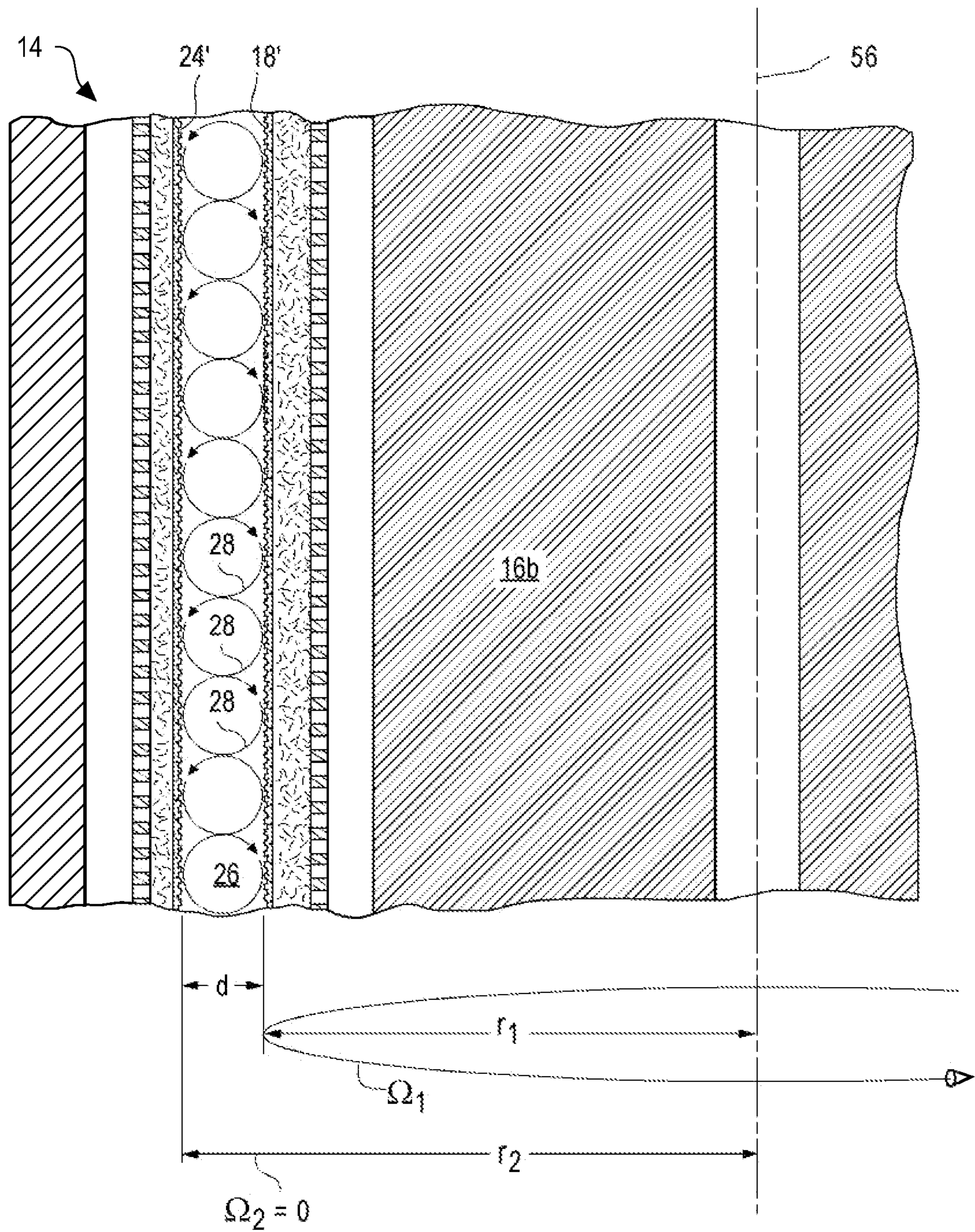


FIG. 3-1



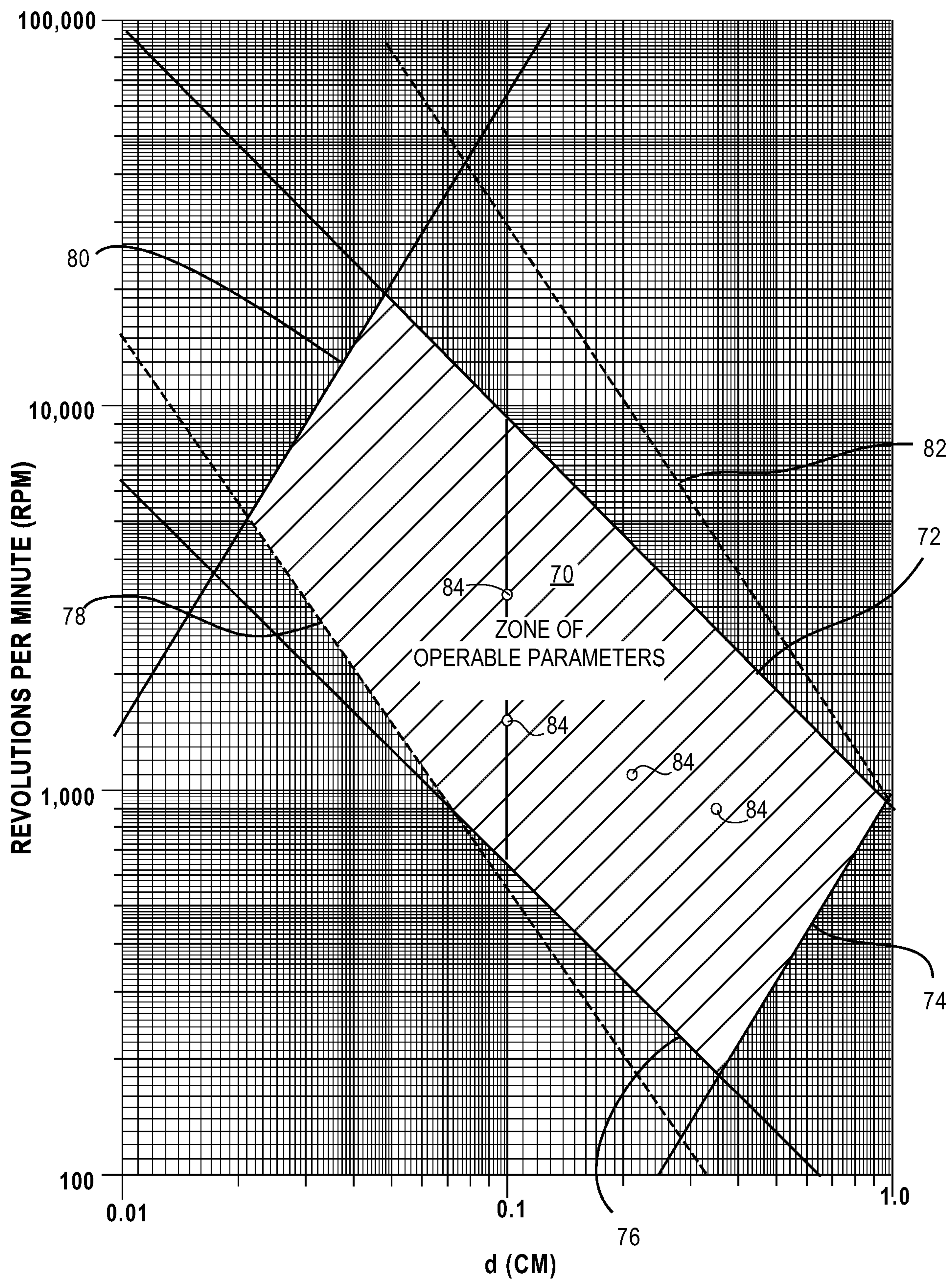
8/20

FIG. 3-2

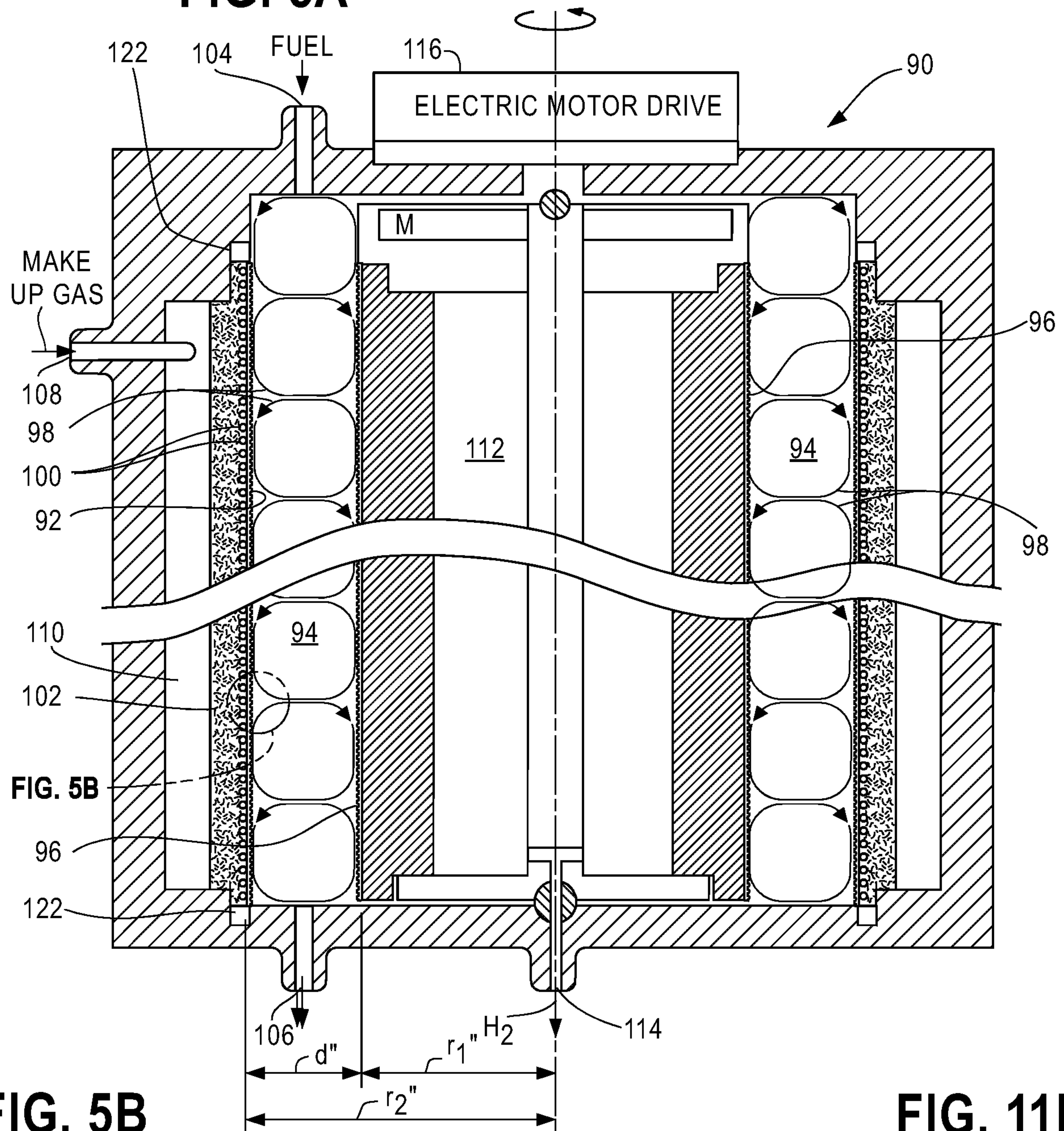
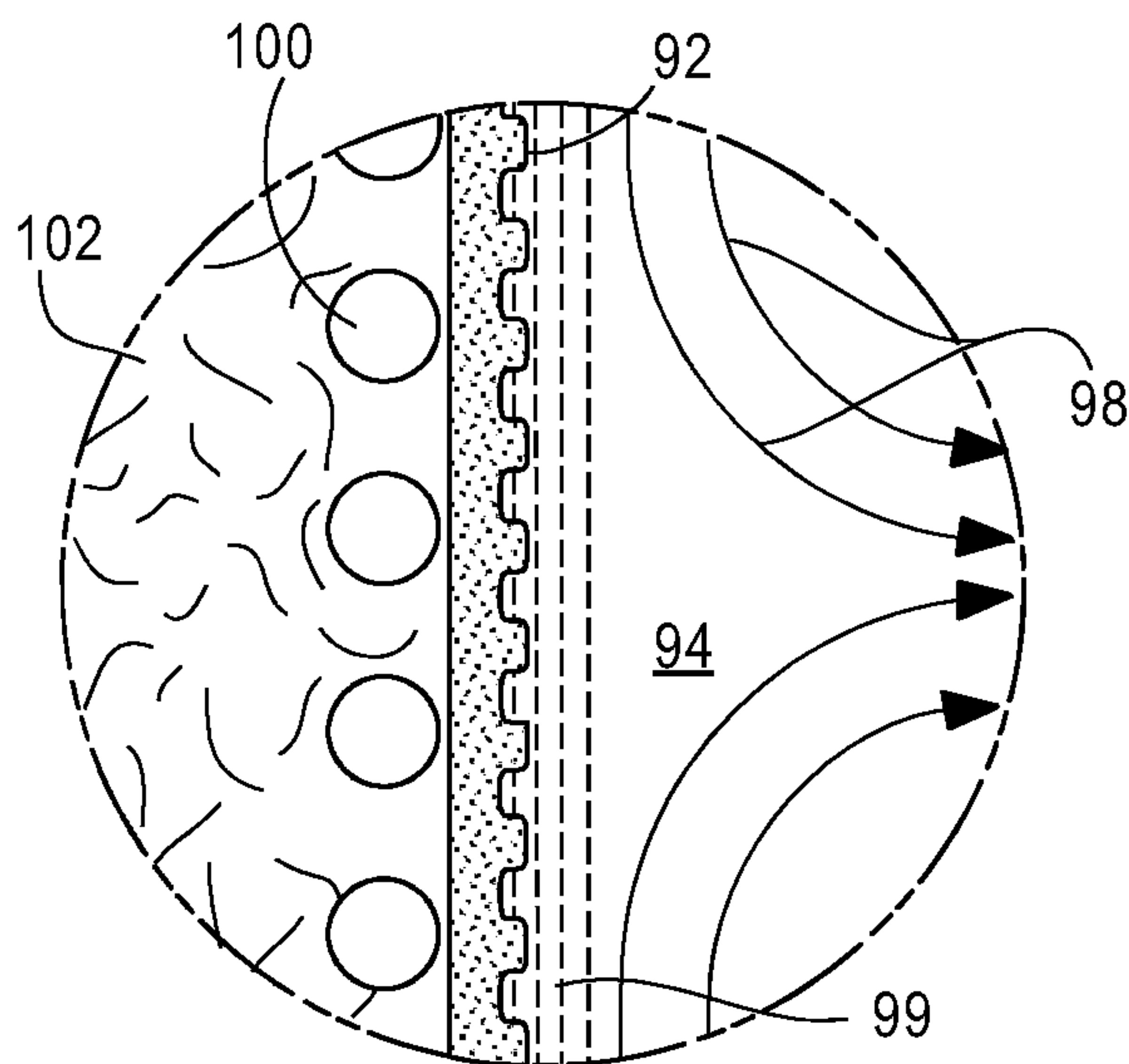
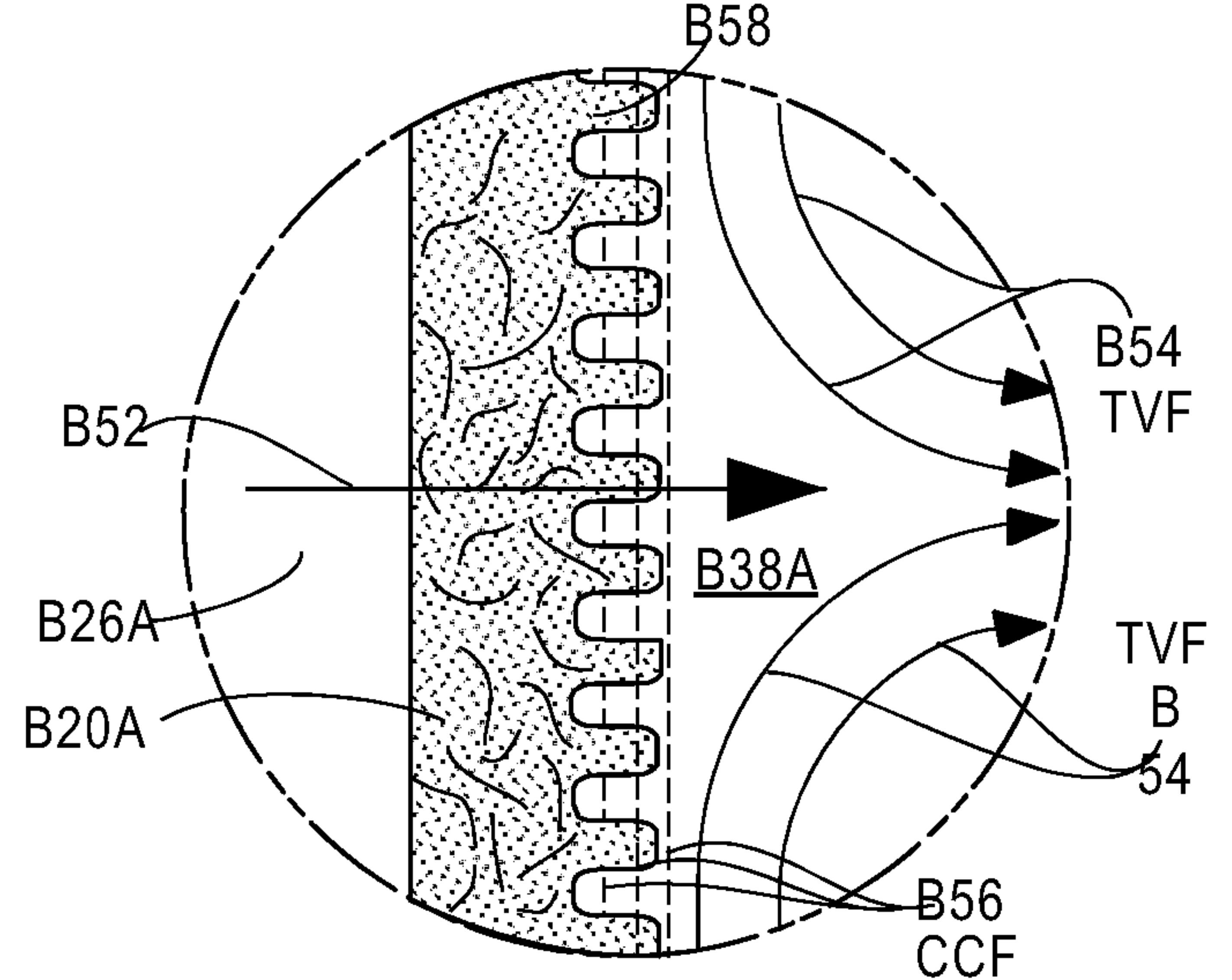


9/20

FIG. 4

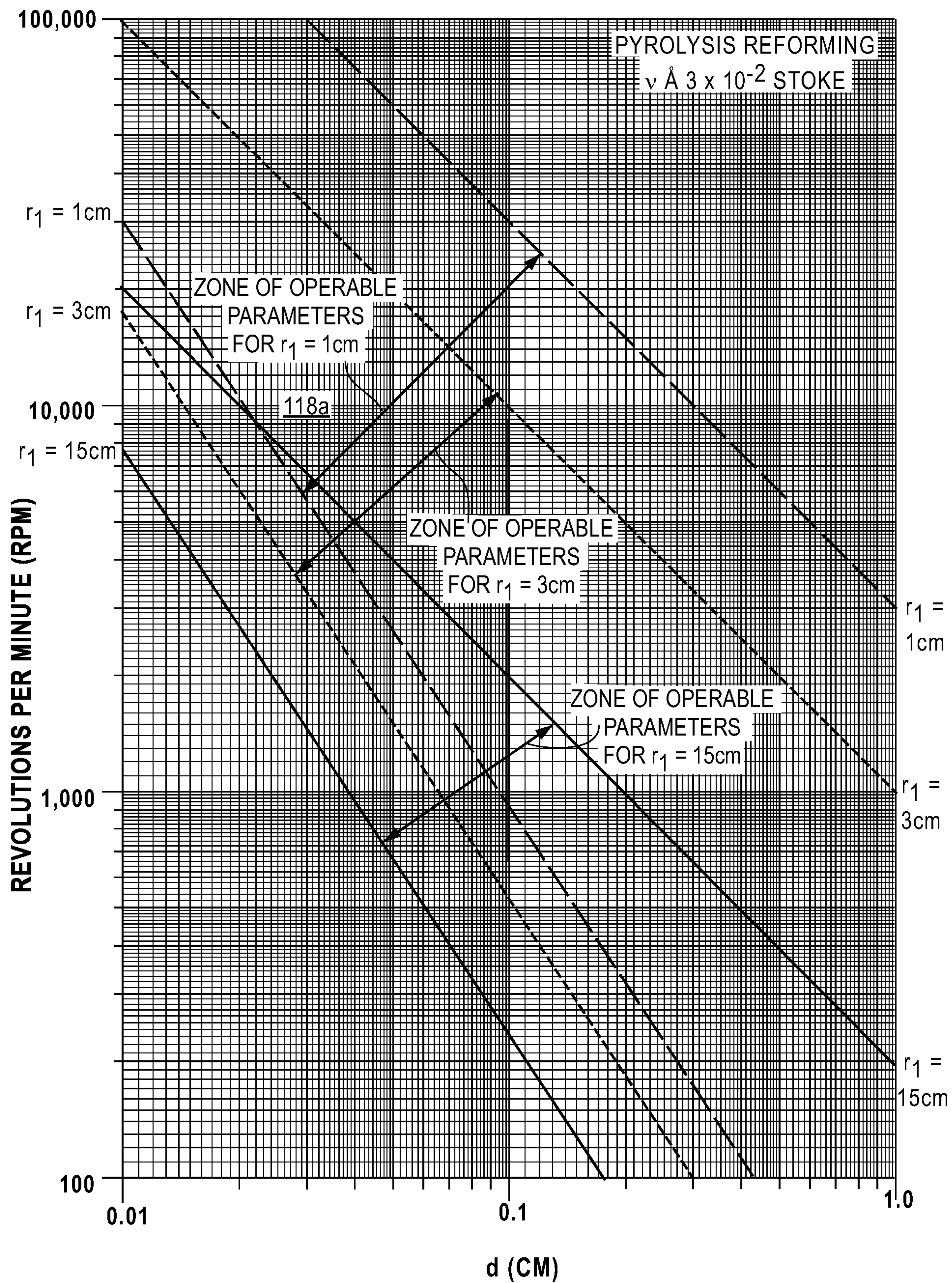


10/20

FIG. 5A**FIG. 5B****FIG. 11B**

11/20

FIG. 6A



12/20

FIG. 6B

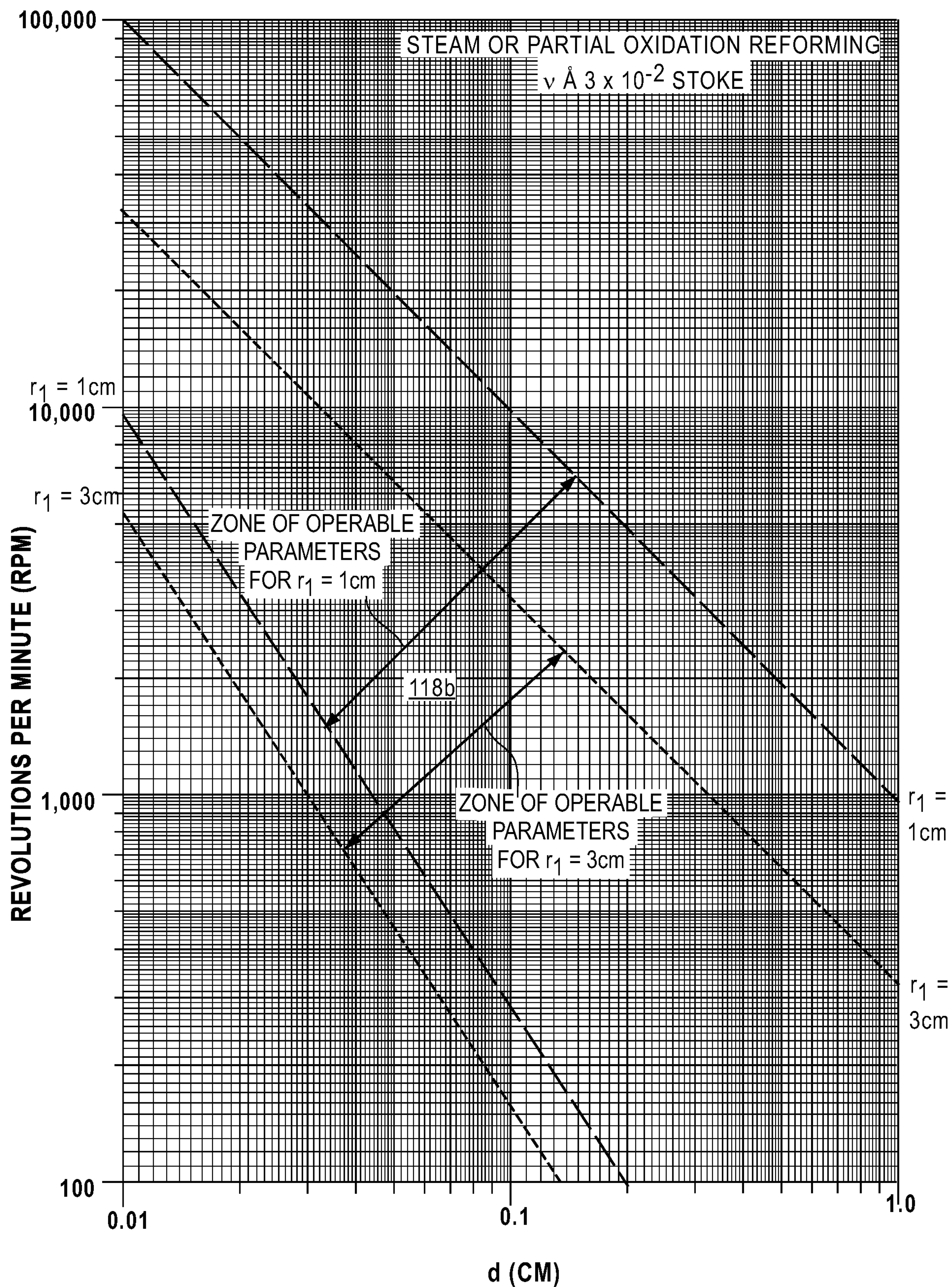
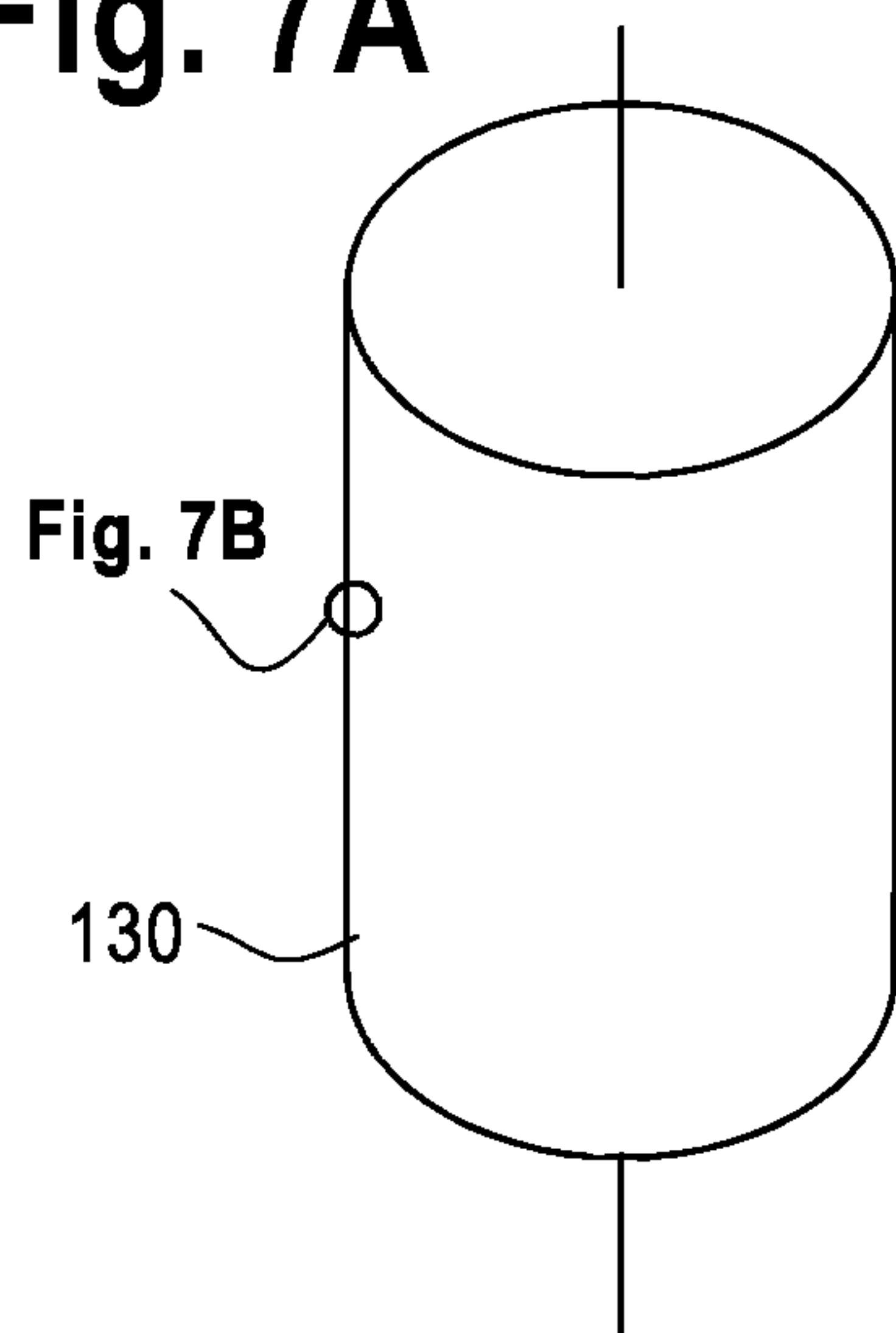


Fig. 7A

13/20

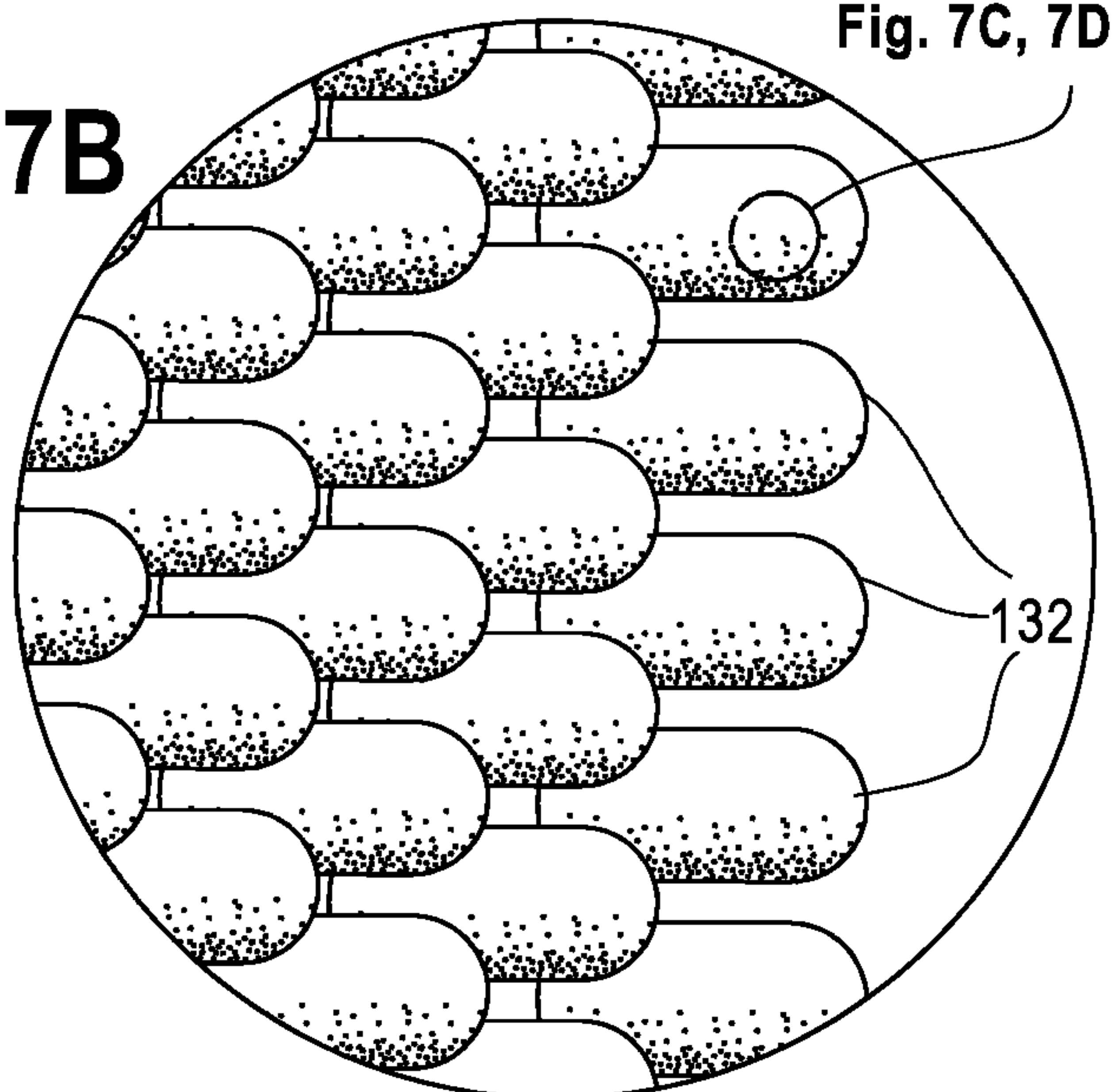
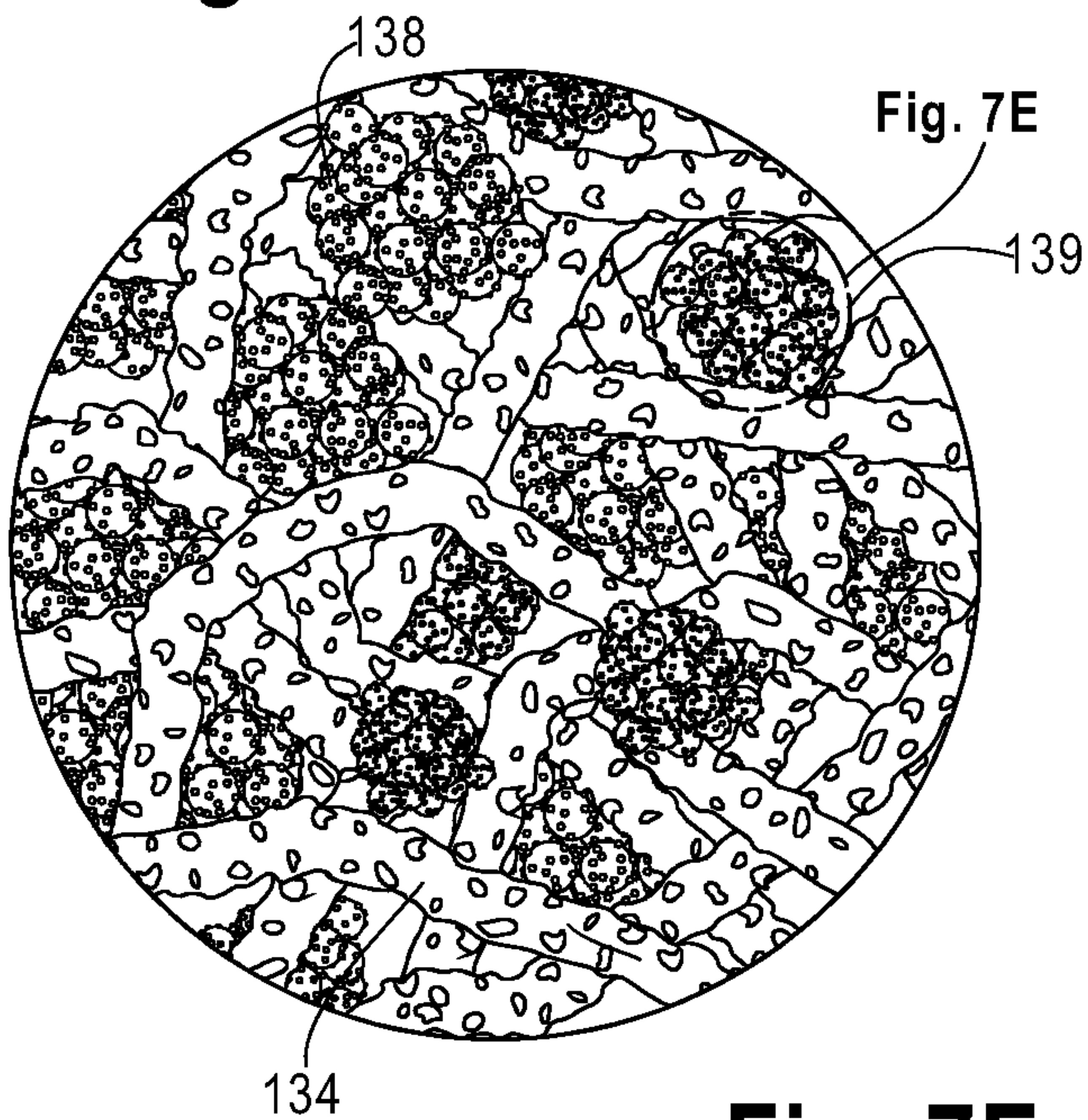
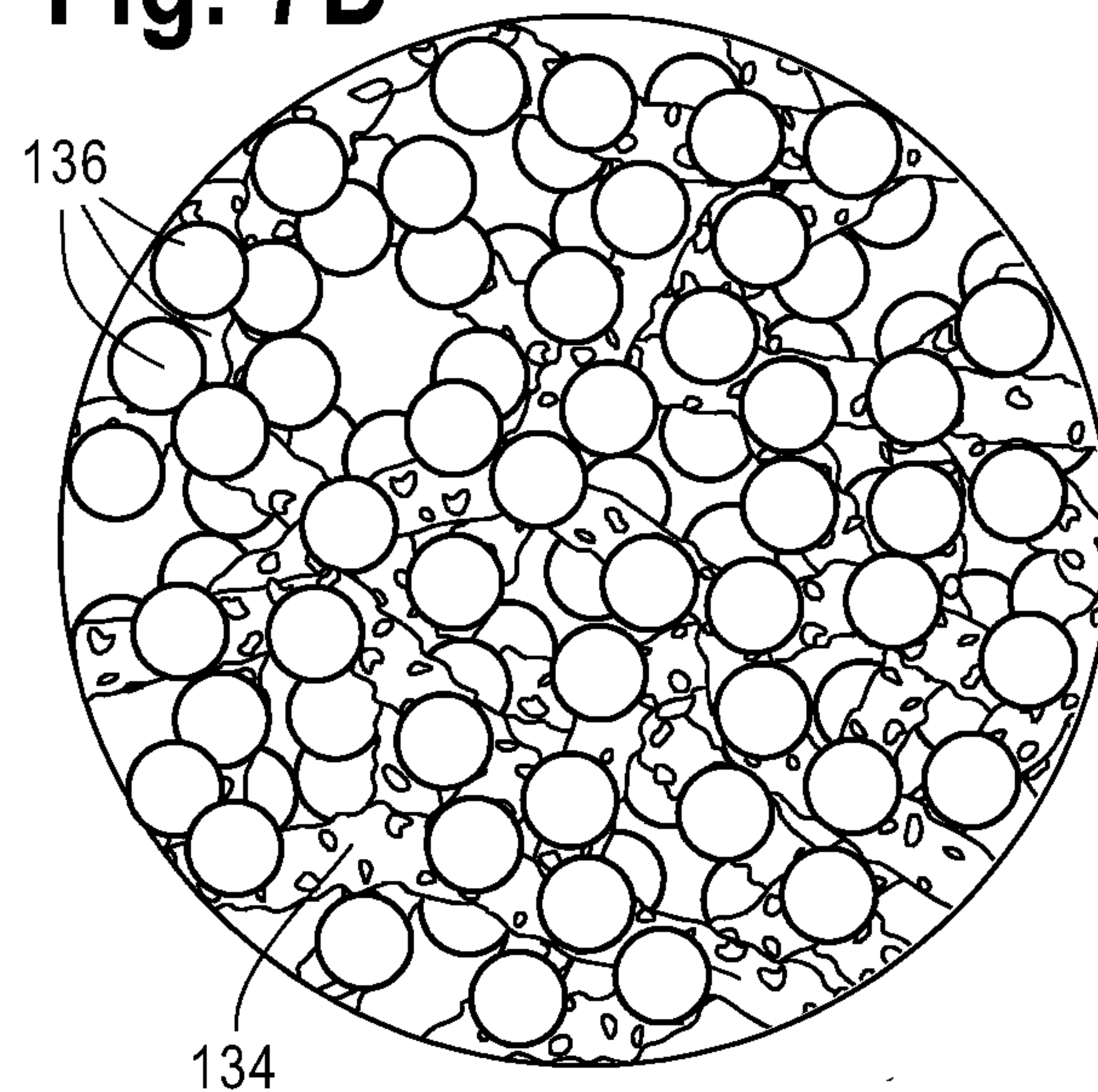
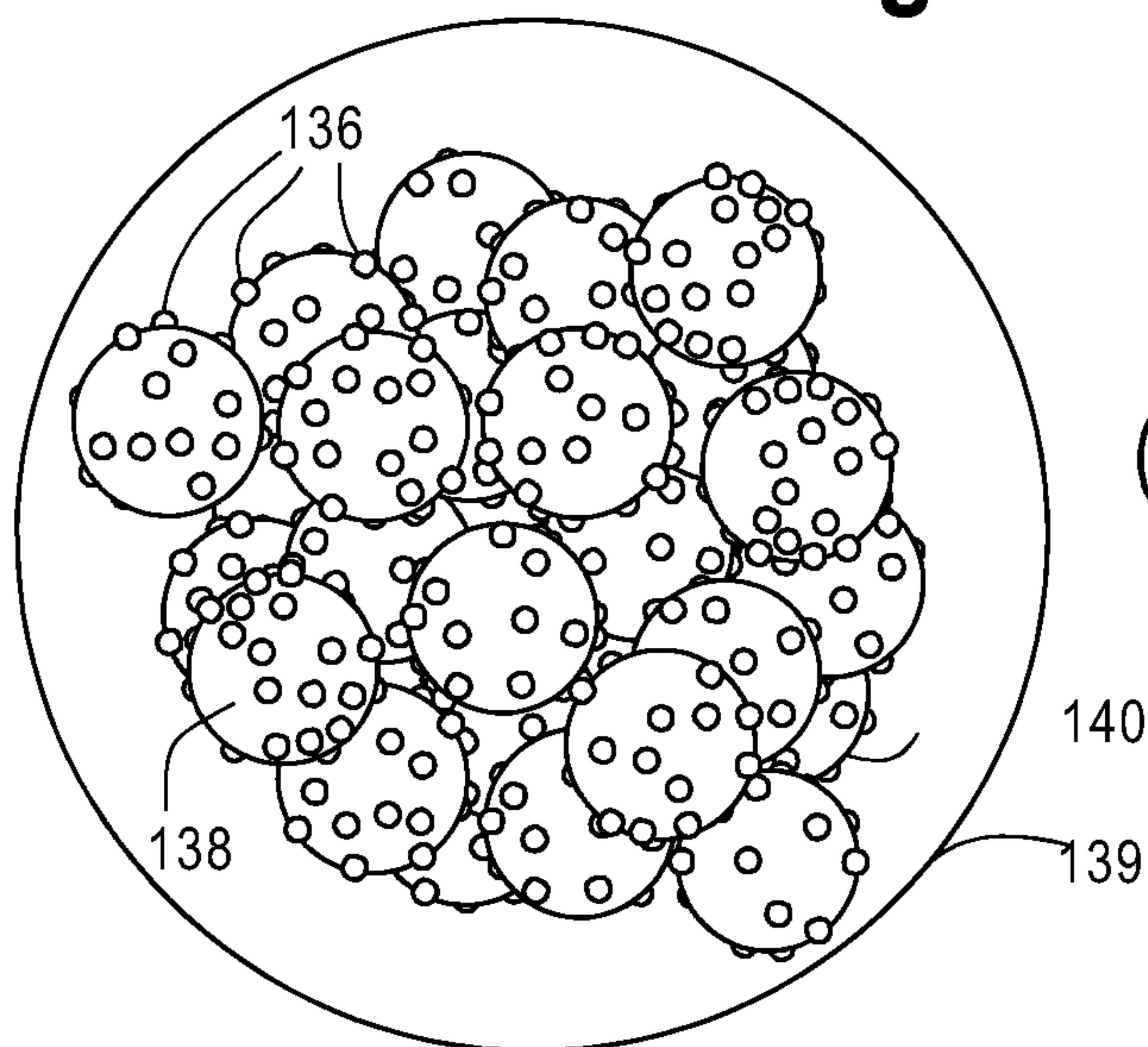
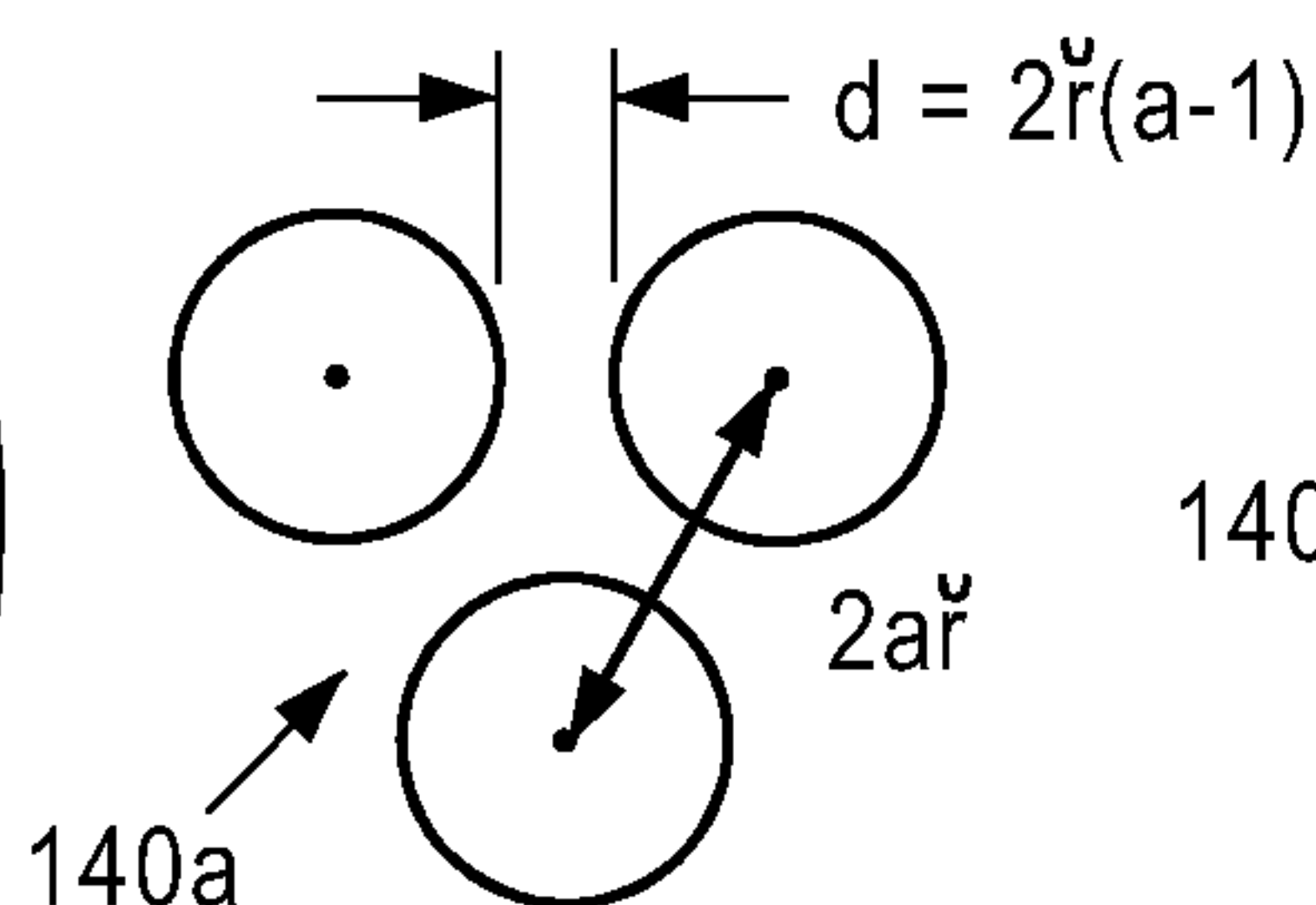
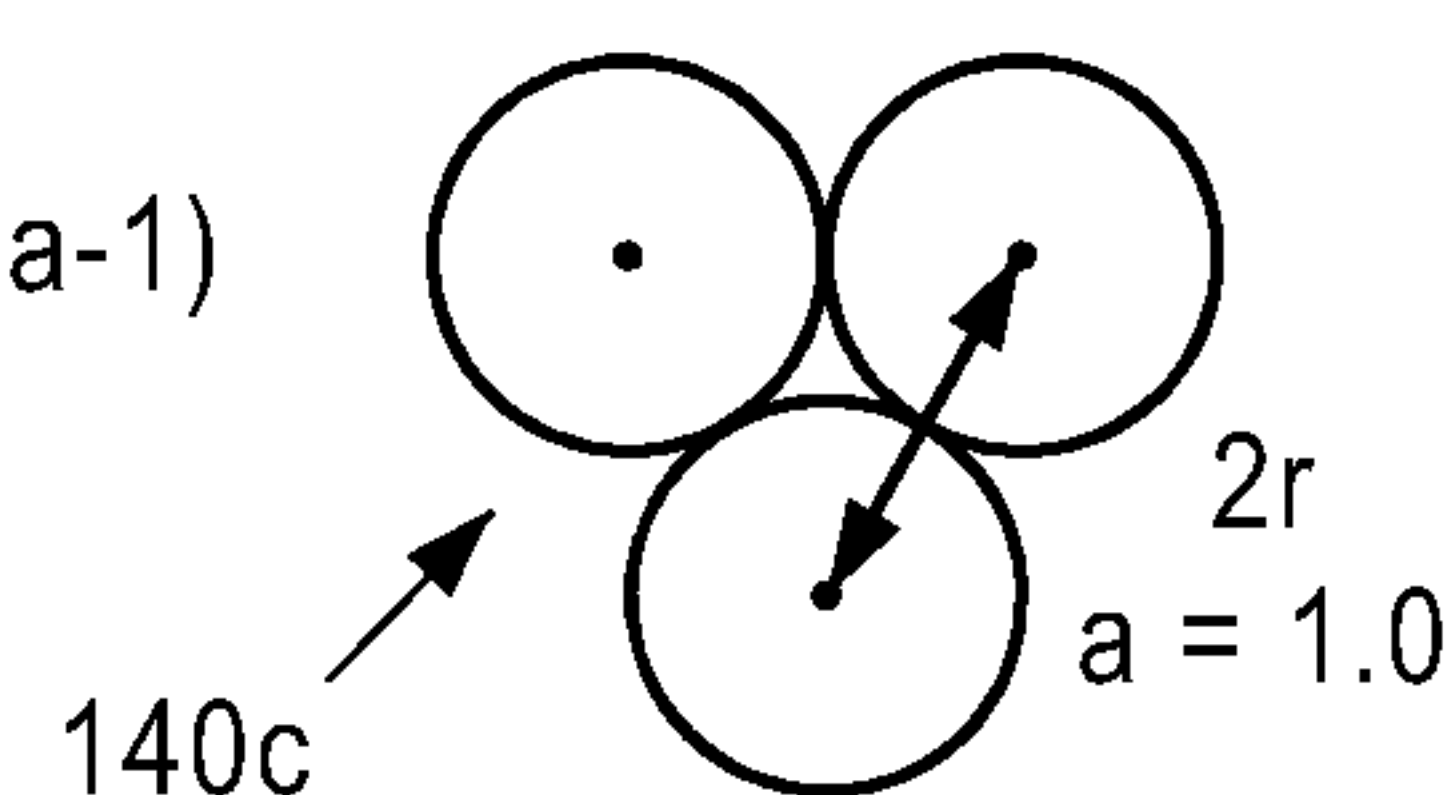
Fig. 7B**Fig. 7C****Fig. 7D****Fig. 7E****Fig. 8A****Fig. 8C****Fig. 8B**
Null

Fig. 8D

14/20

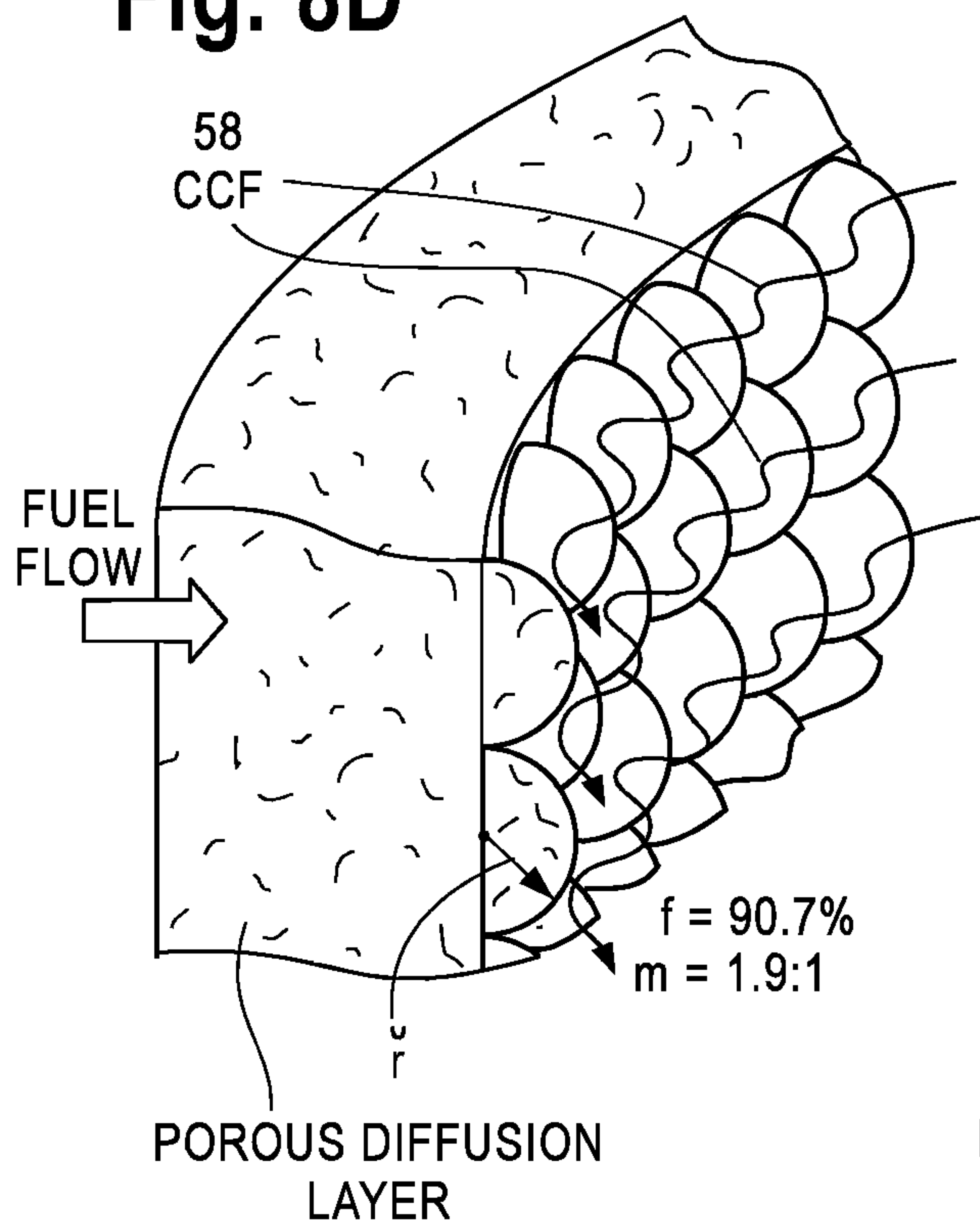


Fig. 8E

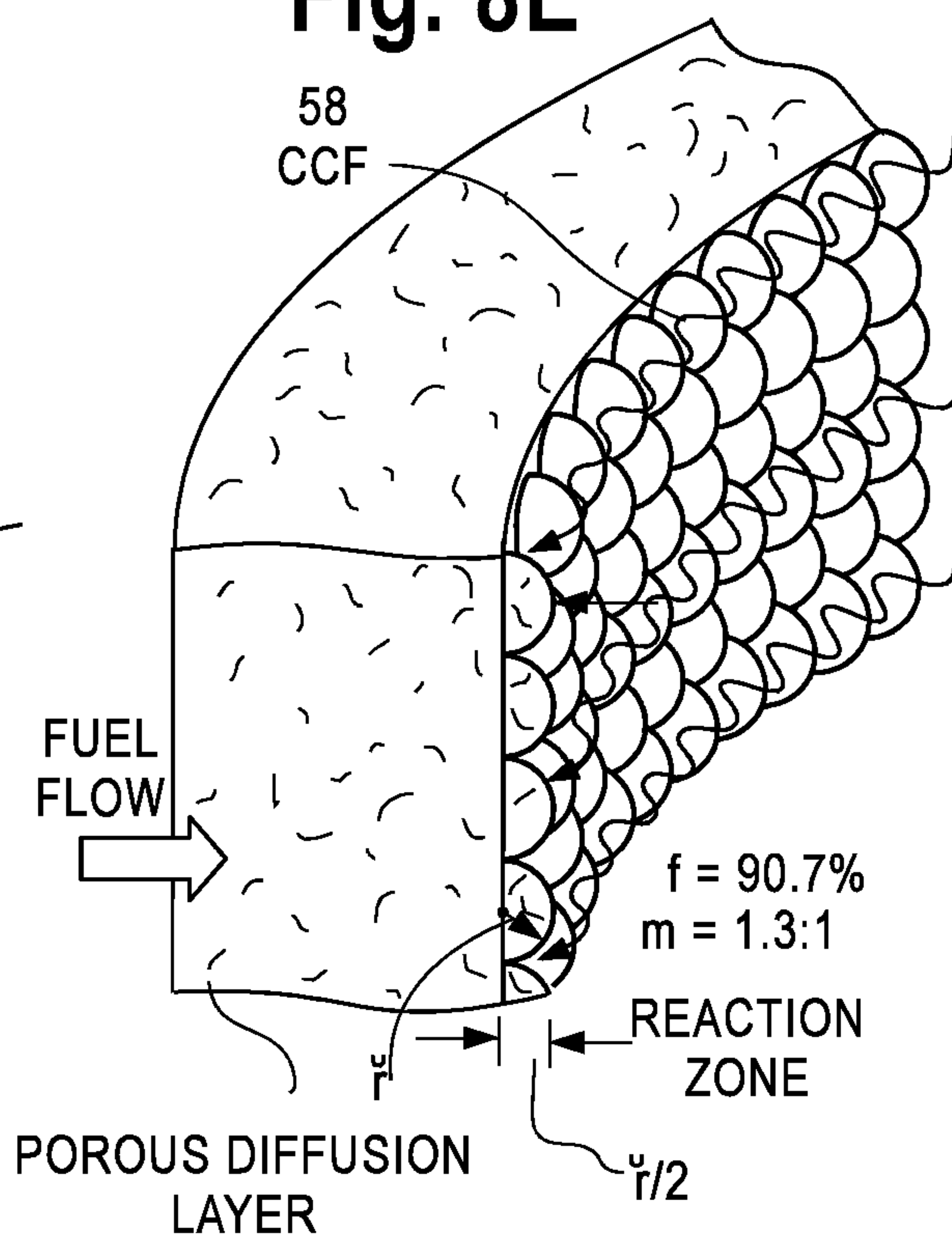


Fig. 8F

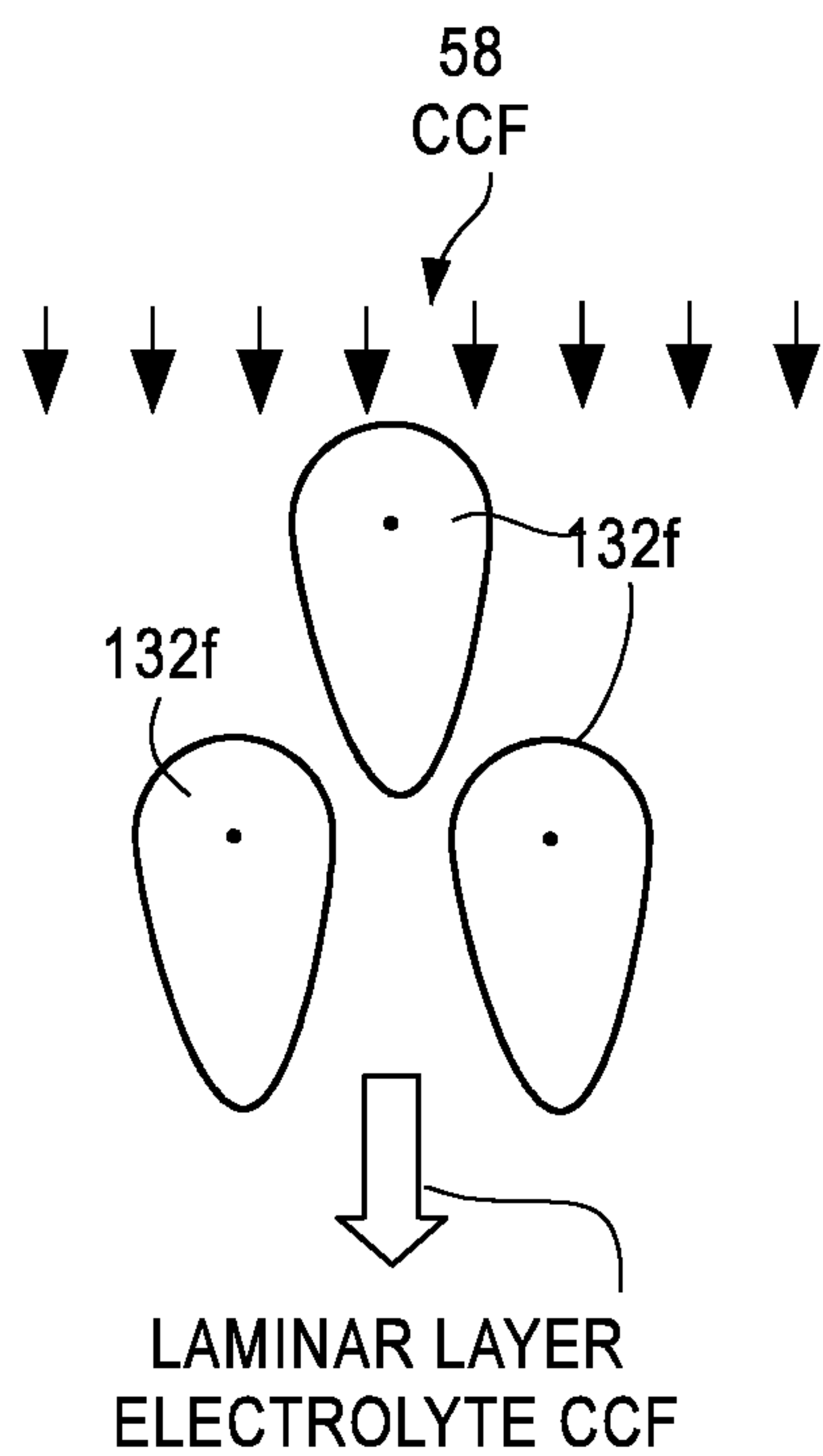
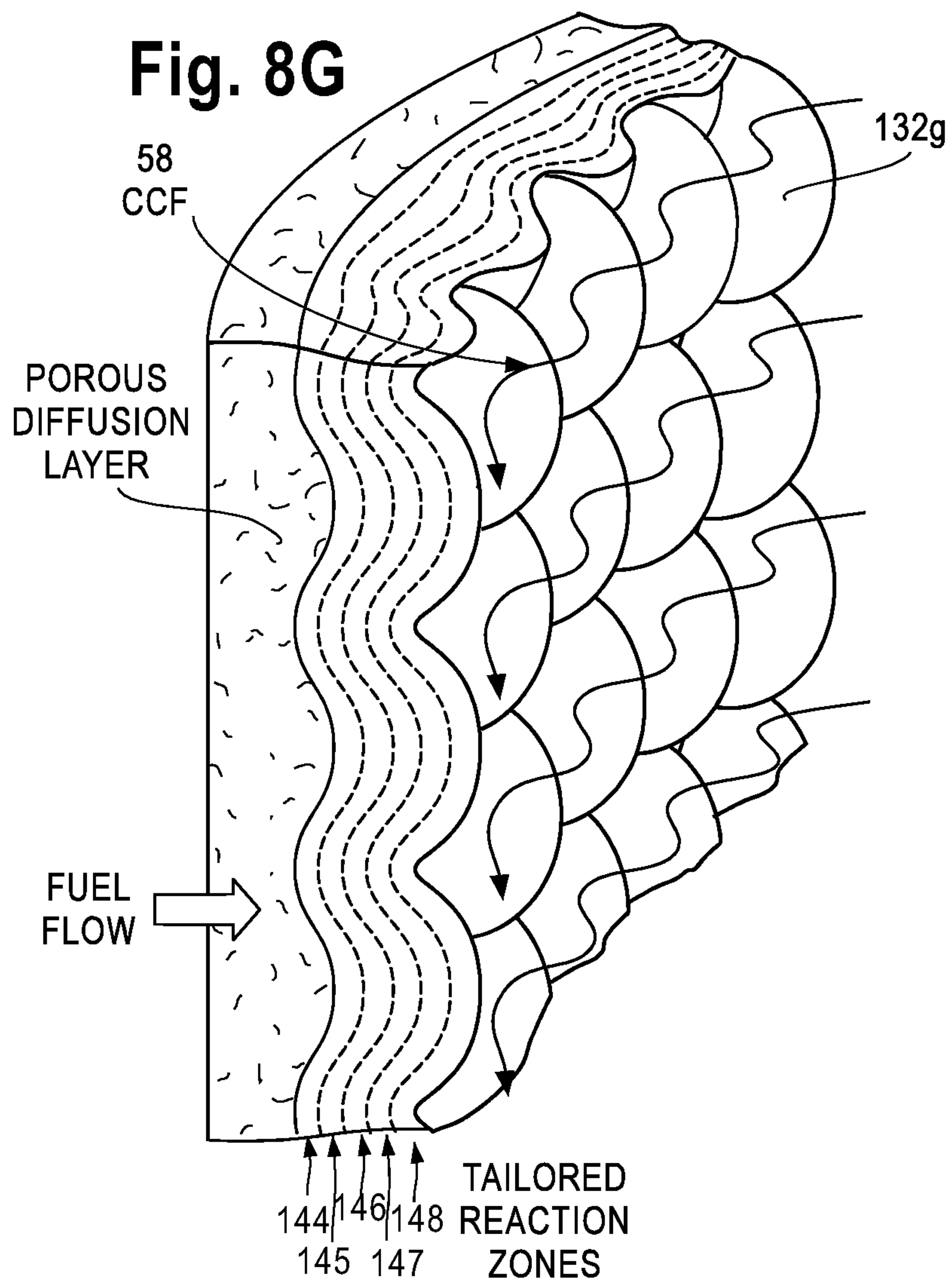


Fig. 8G



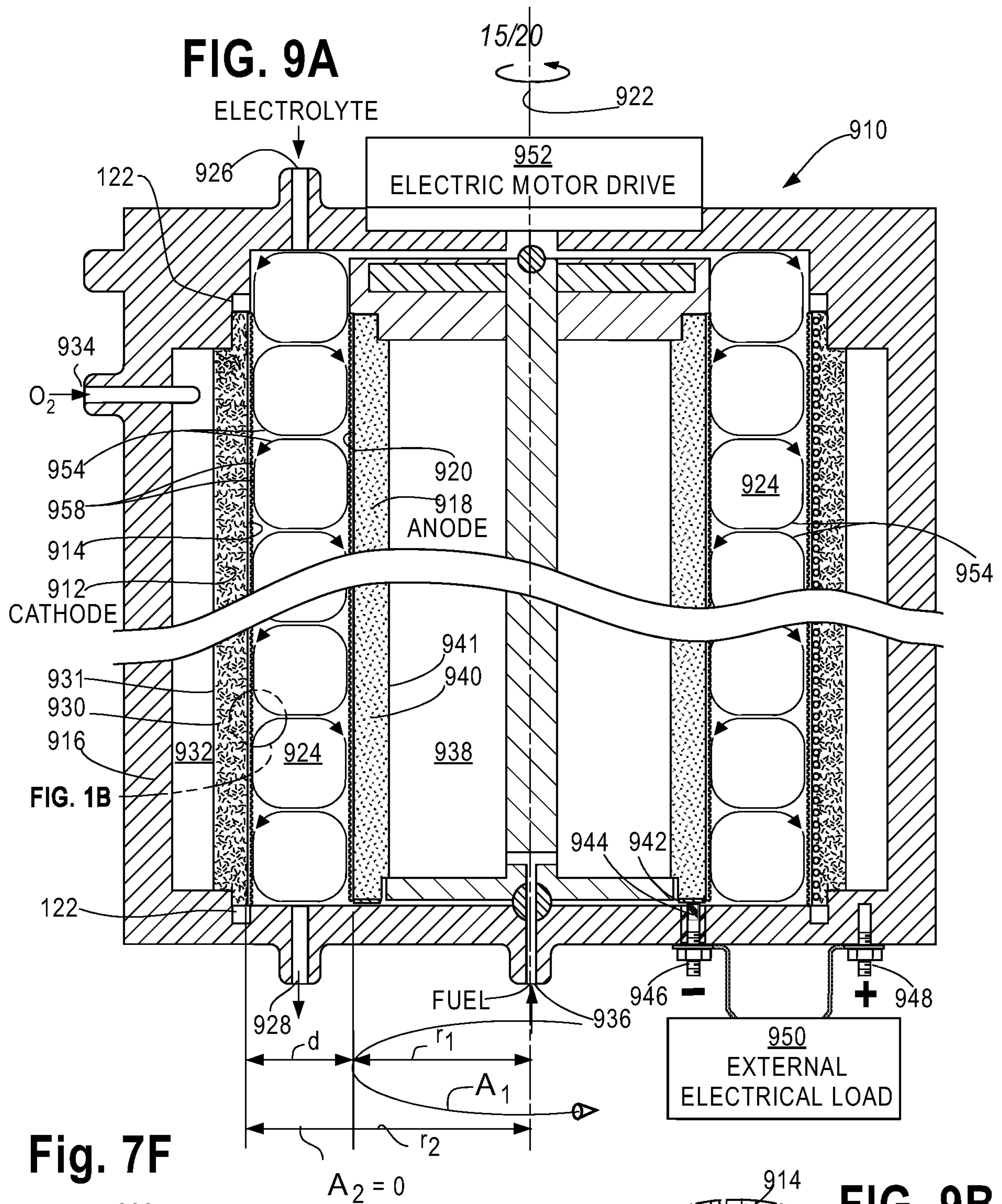


Fig. 7F

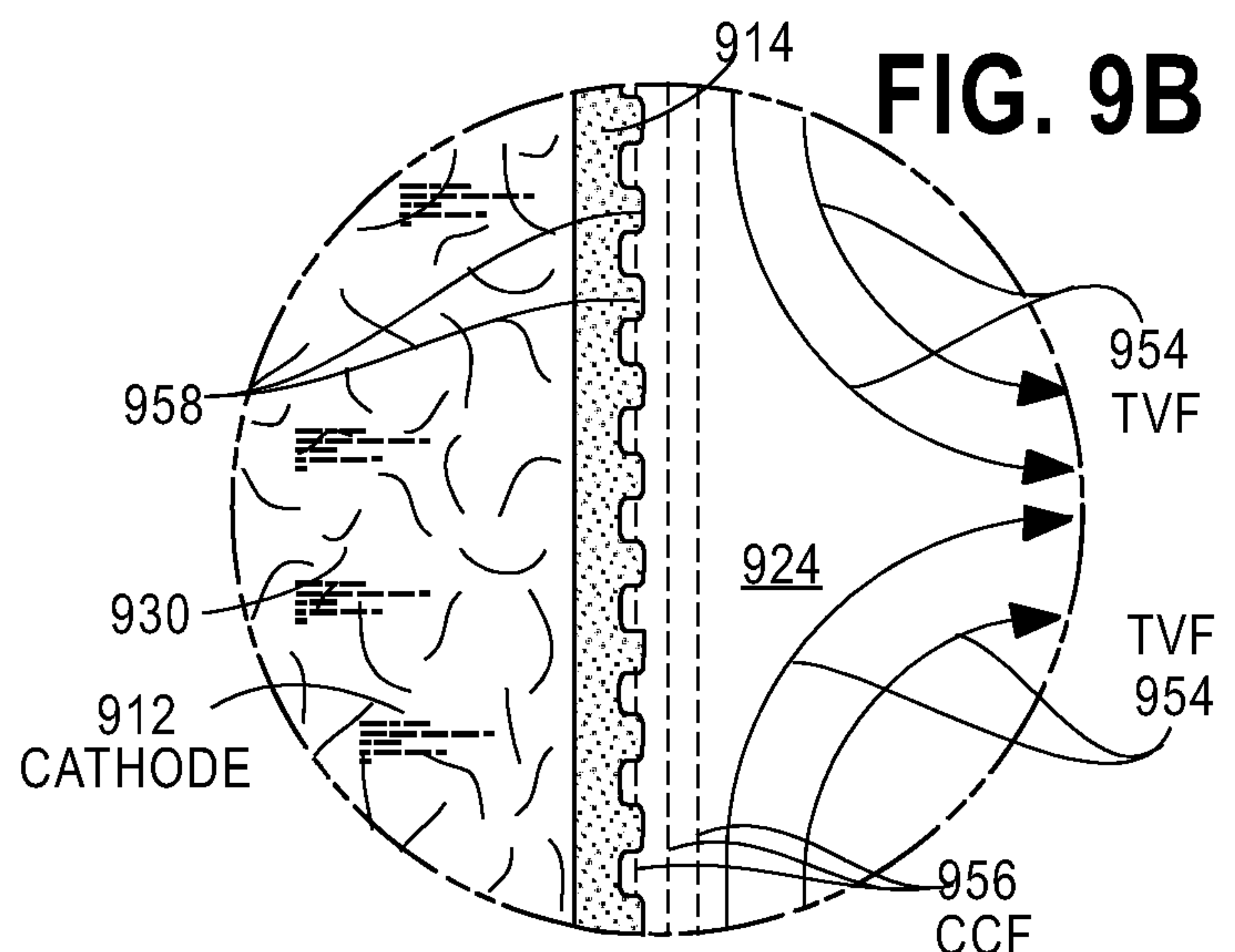
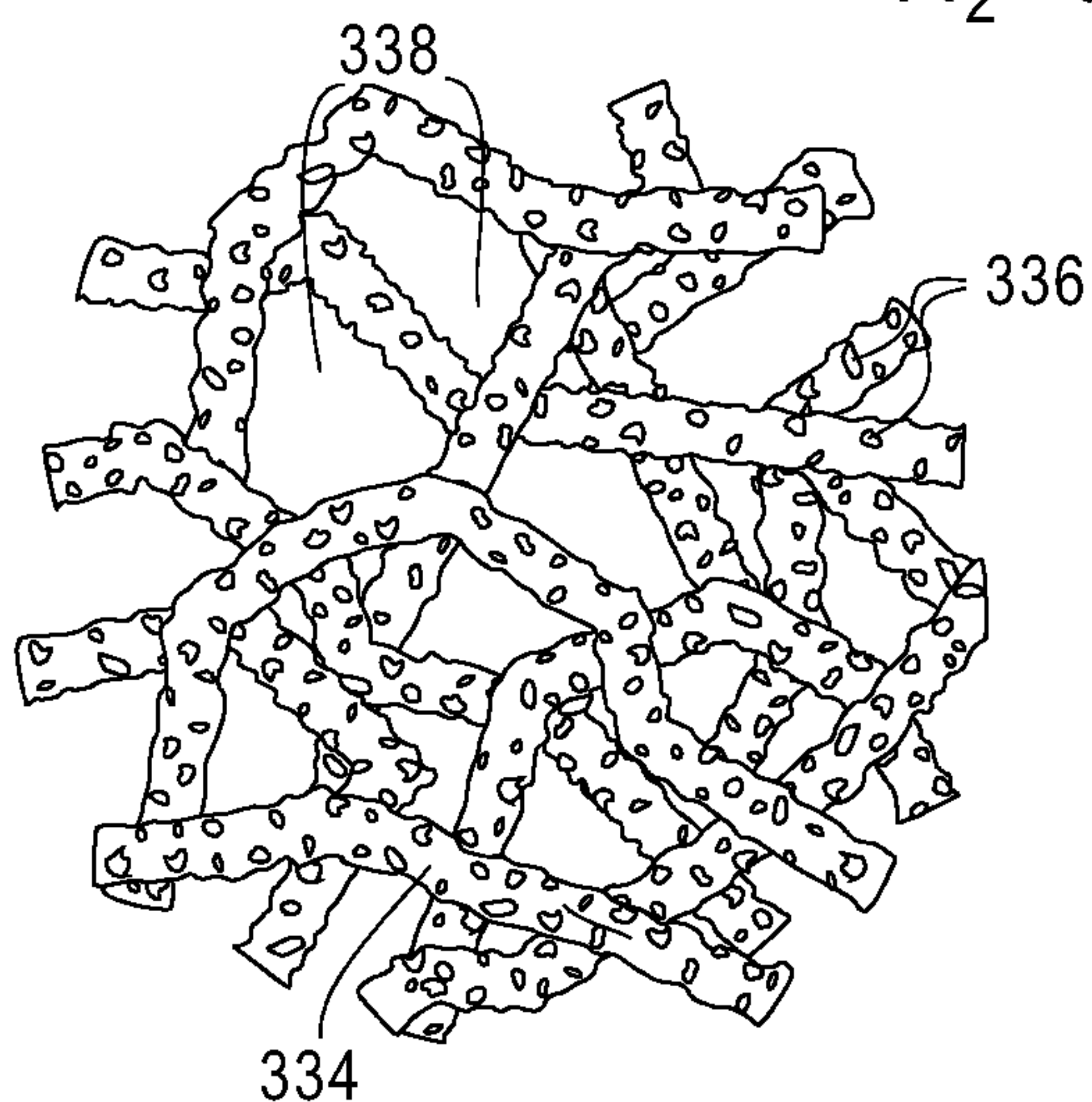
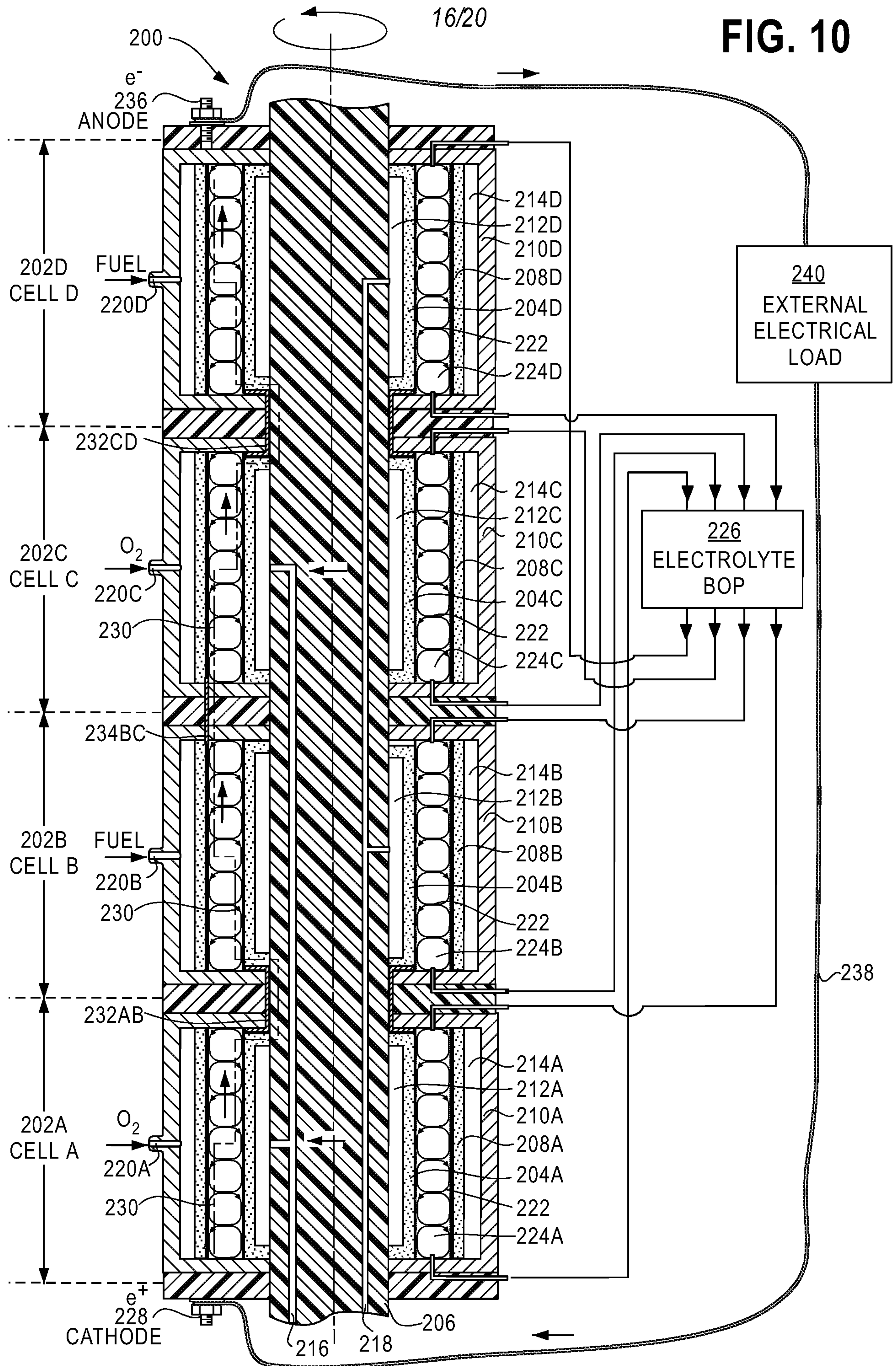
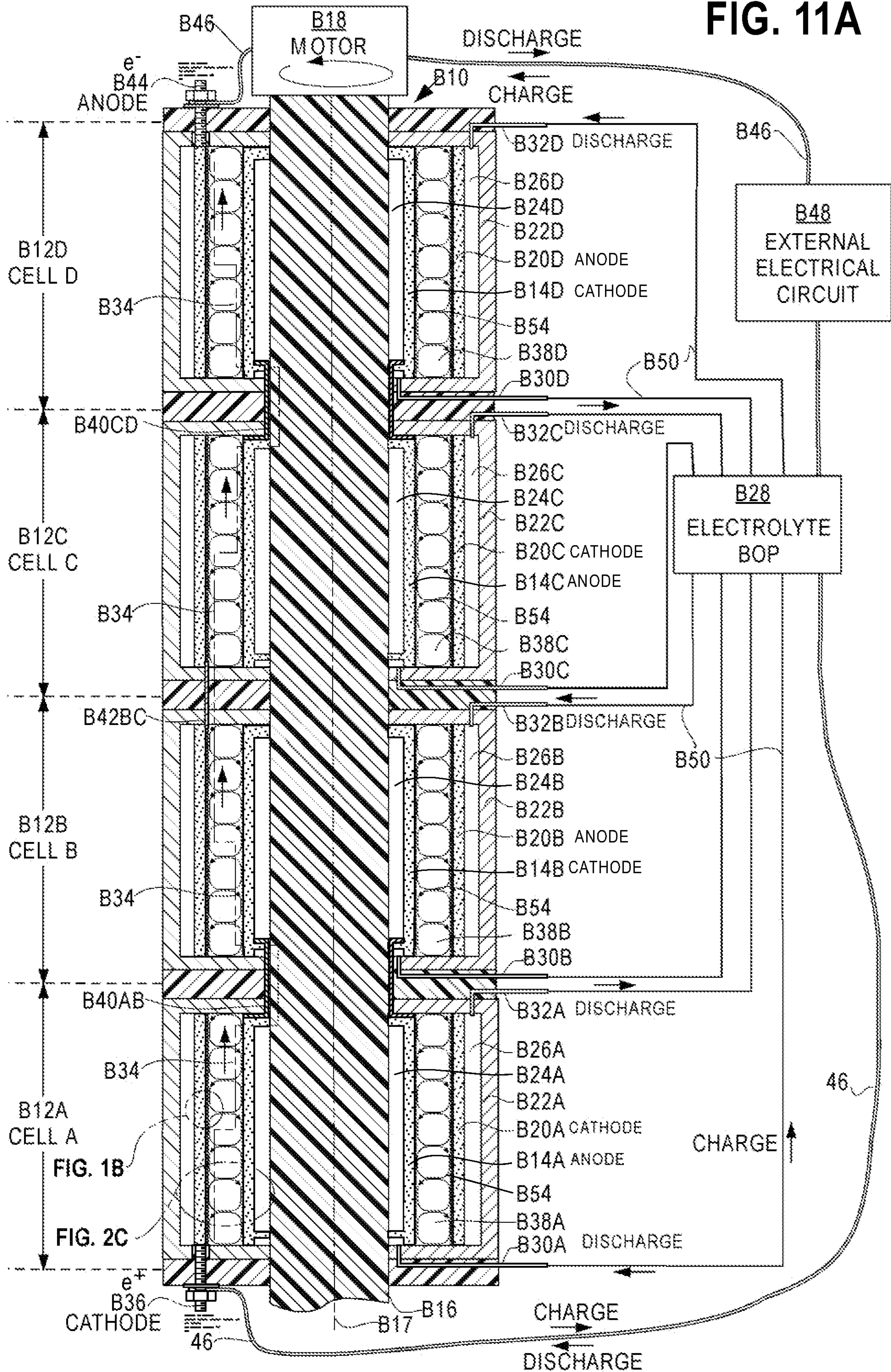


FIG. 10



17/20

FIG. 11A



18/20

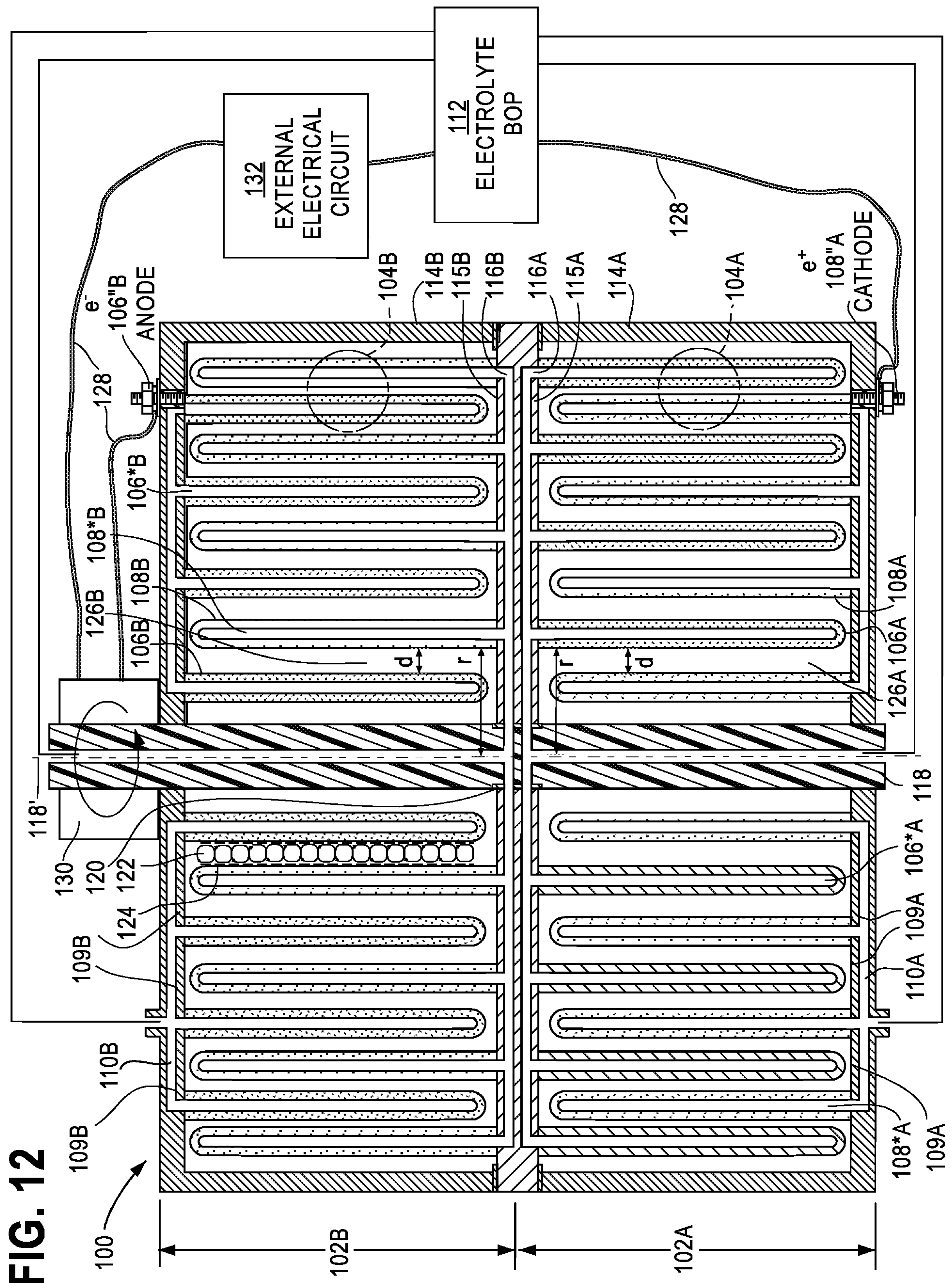
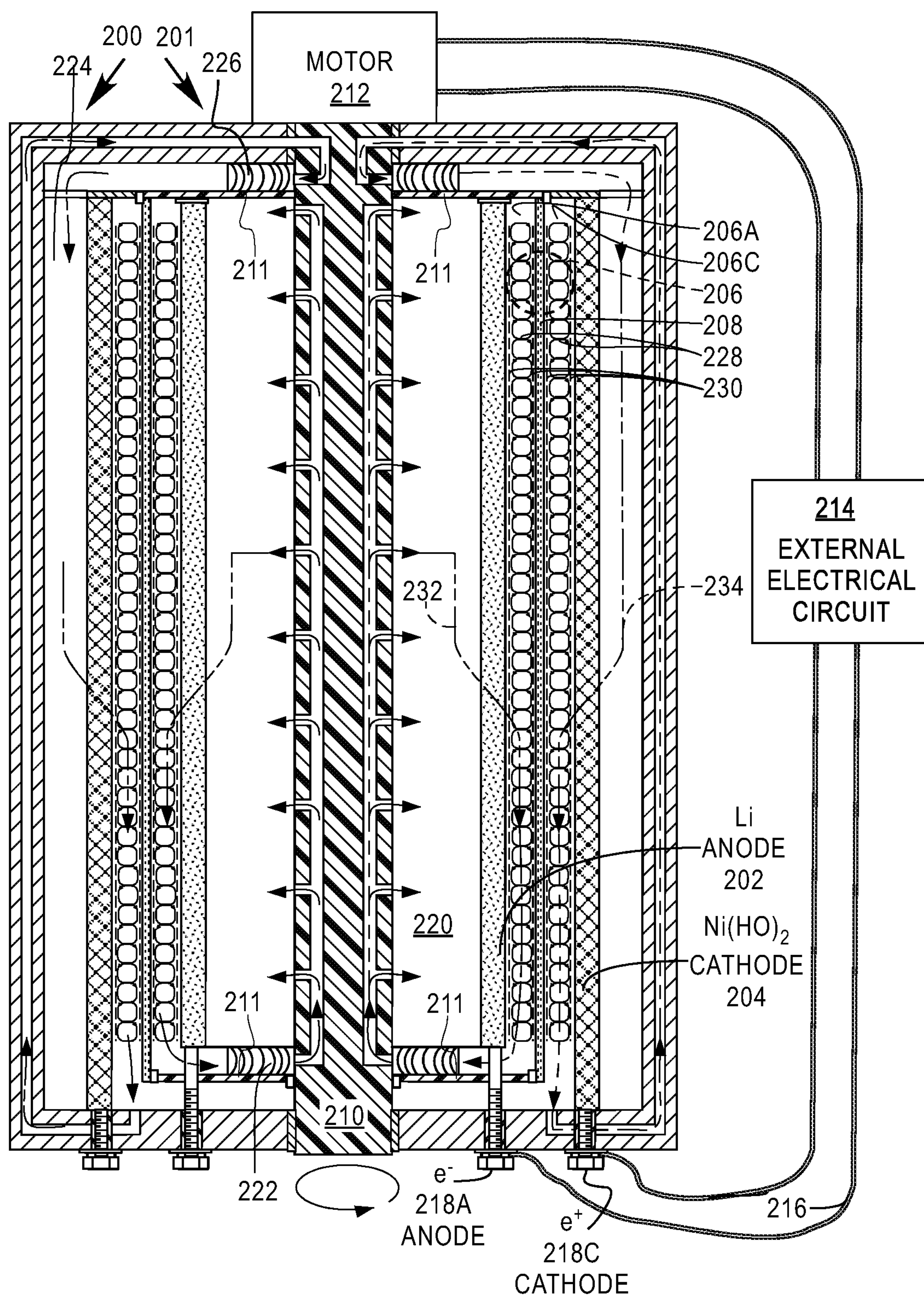


FIG. 13



20/20

FIG. 14

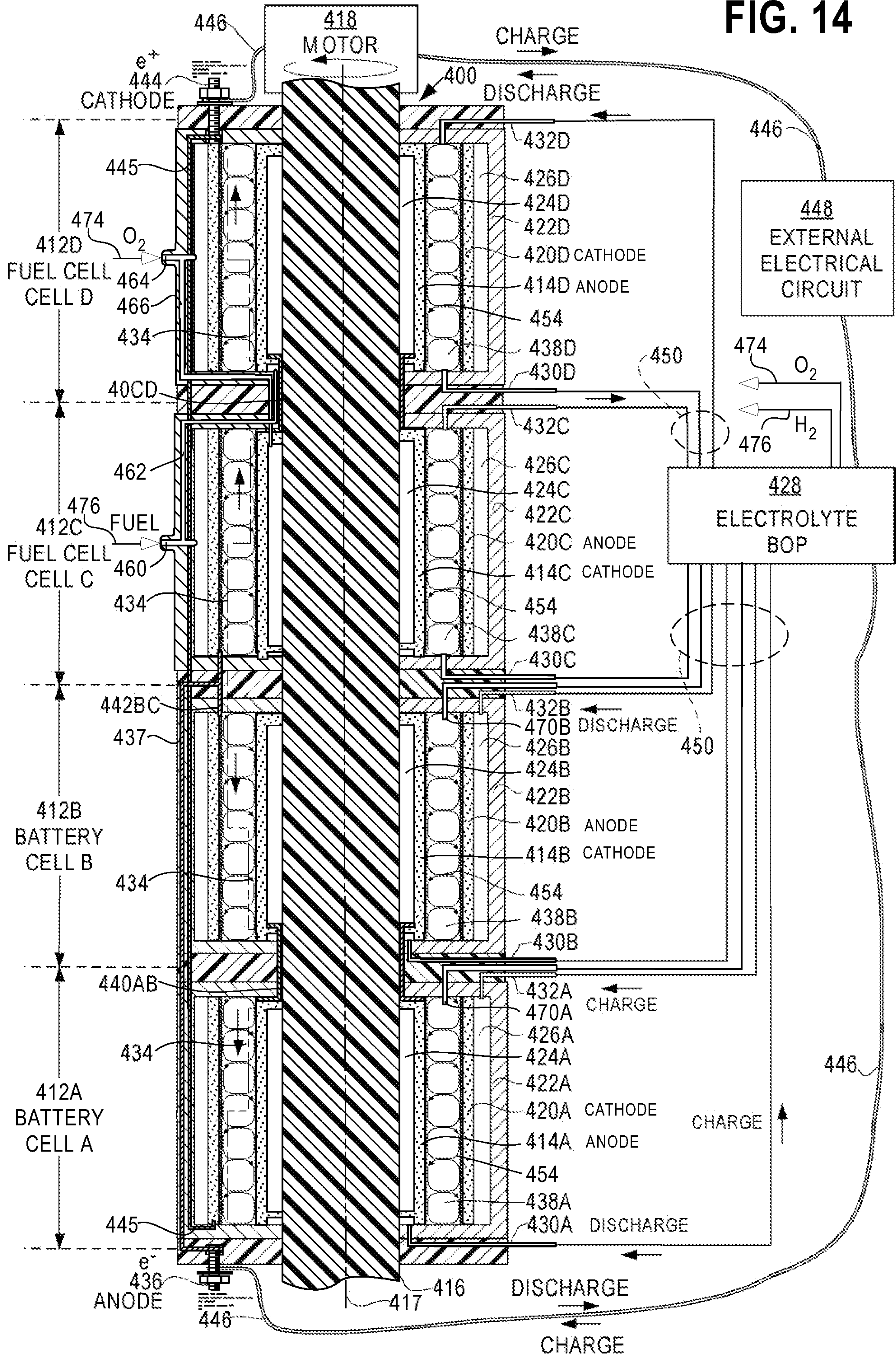


FIG. 2C-1

