

NOVEL MODULAR ELECTROCHEMICAL CELL AND STACK DESIGN

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Non-Provisional Application Serial No. 15/447,536, filed March 2, 2017. The entire contents are incorporated by reference in this disclosure.

BACKGROUND

[0002] The present disclosure relates generally to an electrochemical cell and more particularly to an electrochemical cell constructed to improved serviceability and scalability attributes.

[0001] Electrochemical cells such as fuel cells convert a fuel into usable energy via electrochemical reactions rather than by combustion. As such—and in addition to having fewer failure-prone mechanical parts—electrochemical cells have several environmental advantages over internal combustions engines (ICEs) and related power-generating sources. In one common form, when configured as a fuel cell—such as a proton exchange membrane or polymer ion-exchange membrane (in either event, PEM) fuel cell—defines a generally thin two dimensional structure that includes a pair of generally planar catalyzed electrodes that are separated by a generally planar ion-transmissive medium (such as those made with a perfluorosulfonic acid, a commercial version of which is NafionTM) in what is commonly referred to as a membrane electrode assembly (MEA). Generally planar plates with serpentine reactant flow channels formed on one or both opposing major surfaces are disposed against the electrodes; in this way, the electrochemical reaction occurs when a first reactant in the form of a gaseous reducing agent (such as hydrogen, H₂) is introduced through the channels to be ionized at the anode and then made to pass through the porous electrodes and ion-transmissive medium such that it combines with a second reactant in the form of a gaseous oxidizing agent (such as oxygen, O₂) that has been introduced through the channel of another plate that is placed facingly adjacent the other electrode (the cathode); this combination of reactants form water as a byproduct. The electrons that

were liberated in the ionization of the hydrogen proceed in the form of direct current (DC) to the cathode via external circuit that typically includes a load (such as an electric motor) where useful work may be performed. The power generation produced by this flow of DC electricity is typically increased by combining numerous such cells into a larger current-producing assembly. In one such construction, the fuel cells are connected in series along a common stacking dimension in the assembly—much like a deck of cards—to form a fuel cell stack. Depending on the power output required, such stacks may include a large number (often between about two hundred and three hundred) of individual stacked cells.

[0002] Similarly, in flow batteries, stored chemical energy is converted to power during battery discharging, while chemical species are electrochemically produced and stored during charging. Tanks are used to store the electrolyte solutions, namely, the anolyte and the catholyte that are pumped in order to circulate between the tanks and the electrochemical cell. During discharging of the battery, the anolyte is pumped between its tank and the electrochemical cell anode where it undergoes electrochemical oxidation, while the catholyte is pumped between its tank and the cathode where it undergoes electrochemical reduction. The two electrodes of the cell are separated by an ion exchange membrane that allows the selective diffusion of specific ionic species, like protons or hydroxyl ions. As in the case of the fuel cell, the stack in the flow battery includes multiple elemental units (that is to say, the electrochemical cells) electrically connected in series (for example, through bipolar plates) and hydraulically connected in parallel to form a stack of cells.

[0003] Such a stack of fuel cells or flow batteries is ordinarily assembled under compression in order to seal the cells or batteries and to secure and maintain a low interfacial electrical contact resistance between the reactant plates, the gas diffusion media, and the catalyst electrodes. A desired compression load on the fuel cell stack typically ranges from about fifty to about two hundred psi (and sometimes more), and is maintained by a compression retention enclosure housing the fuel cell stack. In one common form, the enclosure includes tie rods that extend through or around the end plates in order to maintain the cells in the compressed state.

[0004] A problem with this approach is that the power output of the as-assembled stack is fixed by the number of cells within the stack and the relatively precise, ordered way these cells are compressed and retained. Thus, a use-versus-supply mismatch arises if there is a need for an incremental increase in power that is greater than a single stack can provide, yet far less than that provided by the inclusion of an additional stack; such a situation leads to an inefficient use of the available power. Moreover, should one of the cells within the stack require repair or replacement, disassembly becomes a cumbersome process, as the various structural connections that span the substantial entirety of the stack must be carefully removed in order to ensure that the relatively thin-profiled cells aren't damaged during such disassembly and individual cell removal. Such serviceability concerns are especially prevalent with the thin bipolar plate structures that are used to convey the reactant to the respective electrode assemblies within the cell.

[0005] Additional sealing may be achieved through the use of numerous gaskets or related seals, often including at least one seal for each exposed surface of the reactant plates, as well as at other locations in and around the MEA. This too presents problems in that the large number of seals makes cell assembly more difficult and expensive. Furthermore, the use of the compression loads placed on the assembled stack has a tendency to cause these seals or gaskets to become either misaligned or overly compressed, either of which can compromise seal integrity.

SUMMARY

[0006] According to one embodiment of the present disclosure, an electrochemical cell is disclosed. The cell includes a pair of current collectors that when joined together form an electrode assembly, and an ion-exchange membrane disposed between the electrodes of the assembly. In addition, reactant flowpaths are included to convey a respective reactant to the electrode assembly and ion-exchange membrane. The construction of the inner (i.e., first) of the current collectors is such that the electrode structure has a three-dimensional volumetric form that can nest within a compatibly-sized and shaped volume formed within the outer (i.e., second) current collector by inserting the volume defined by the first current collector through an opening that is formed in the second current collector. In this way,

once the two current collectors are joined in the nesting fashion, the respective three-dimensional volumes form an electrode assembly with the ion-exchange membrane being disposed between them. Facingly adjacent mounting surfaces of the joined collectors promote a sealed contact around the perimeter of the opening. The ion-exchange membrane is constructed such that when one of the reactants is ionized at the electrode associated with one of the current collectors, it flows through the membrane prior to being electrochemically joined to the other reactant that is ionized at the electrode of the other current collector.

[0007] Within the present context, while much of the present disclosure may be construed as describing the inner current collector as functioning as an anode to receive a reactant to be oxidized (for example, hydrogen, H_2) and the outer current collector as functioning as a cathode to receive a reactant to be reduced (for example, oxygen, O_2), it will be appreciated that an oppositely-configured electrochemical cell where the reactant being oxidized is conveyed to the outer current collector while the reactant being reduced is conveyed to the inner current collector is also contemplated. Likewise, whether the reactants being delivered to the electrochemical cell correspond to the fuel and oxygen supply or conversely the oxygen and fuel supply (for a fuel cell), or for a first electrolyte and a second electrolyte (in the case of a flow battery) is a matter of the electrode configurations, and that which reactant or electrolyte correlates to which electrode and corresponding current collector will be understood from the context. As such, both variants are deemed to be within the scope of the present disclosure.

[0008] Further within the present context, the three-dimensional volume attributes of the inner and outer current collectors is meant to distinguish from those cell configurations where one of the cell dimensions is substantially less than that of the other two in a conventional Cartesian coordinate system. For example, when the through-the-thickness dimension of a cell with otherwise planar attributes is more than an order of magnitude thinner than the length or width dimension (such as that associated with a conventional PEM fuel cell), it is deemed to define a substantially two dimensional structure, while that of the inner and outer current collectors of the disclosed cells define a substantially three-dimensional structure.

[0009] According to another embodiment of the present disclosure, an electrochemical cell assembly made up of reactant delivery conduit and a plurality of electrochemical cells. The reactant delivery conduit includes a first portion and a second portion each of which are configured to convey a different reactant than the other, while the flowpaths of the electrochemical cells are fluidly coupled to the delivery conduit to convey respective reactants to and from the electrodes in the manner set forth in the previous embodiment.

[0010] According to yet another embodiment of the present disclosure, a method of assembling an electrochemical cell assembly is disclosed. The method includes providing numerous electrochemical cells each of which includes an inner current collector, an outer current collector and an ion-exchange membrane. Each of the current collectors includes one more electrodes that are dimensionally configured to create a respective three-dimensional volume. In this way, the electrode that corresponds to the inner current collector may be made to pass through an opening formed in the outer current collector so that upon placement of the ion-exchange membrane between the electrodes of the inner and outer current collectors, at least a portion of the interior three-dimensional volume of the inner current collector is nested within the three-dimensional volume of the outer current collector. In addition, by securing the inner and outer current collectors of each electrochemical cell within the assembly to one another, opposing mounting faces from each current collector form a releasable seal around a perimeter of the opening. Furthermore, fluid coupling is established between the inner current collector of each electrochemical cell within the assembly to a first portion of a reactant delivery conduit through an inner reactant flowpath that comprises an inner reactant inlet and an inner reactant outlet that is in turn in fluid communication with the inner reactant chamber. Likewise, fluid coupling is established between the outer current collector of each electrochemical cell within the assembly to a second portion of a reactant delivery conduit through an outer reactant flowpath that comprises an outer reactant inlet and an outer reactant outlet that is in fluid communication with an interstitial space that is formed around the outer electrode.

[0011] In a comparable manner, such an assembled electrochemical cell may be operated by introducing at least a portion of one of the first and second reactants into the inner current collector from the first portion of the reactant delivery conduit and the first flowpath, while introducing at least a portion of the other of the first and second reactants into the outer current collector from the second portion of the reactant delivery conduit and the second flowpath. Subsequently, the reactants are ionized at the electrodes such that at least some of the ionized portion of the one of the introduced first or second reactants passes through the ion-exchange membrane in order to be later electrochemically combined with an ionized portion of the other of the introduced first or second reactants. An electric current generated by the ionizing of the introduced first or second reactant can be then used to perform useful work.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0012] The following detailed description of specific embodiments of the present disclosure can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

FIG. 1 illustrates a simplified partially exploded, sectional view of a portion of a planar fuel cell with surrounding bipolar plates according to the prior art;

FIG. 2A illustrates a simplified exploded isometric view of an electrochemical cell configured as a fuel cell in accordance with one or more embodiments shown or described herein;

FIG. 2B illustrates a different simplified exploded isometric view of the fuel cell of FIG. 2A;

FIG. 3 illustrates a pair of the fuel cells of FIGS. 2A and 2B in their fluid connection to reactant-conveying conduit in accordance with one or more embodiments shown or described herein; and

FIGS. 4A and 4B illustrate respectively plan and horizontal edge views of a notional two dimensional cell array and a linear cell array.

DETAILED DESCRIPTION

[0013] Embodiments disclosed herein include a source of electrical power that uses a repeating array of generally three-dimensional electrochemical cells in such a way that ease of power output scalability and individual cell maintenance is improved. Such a cell includes a pair of electrodes contained within respective housing such that the cell defines a three-dimensional structure. In this way, the flowpath that is used to introduce the reactants into the cell for subsequent ionization and electrochemical combination is not limited to a single planar surface, but may instead define a three-dimensional volumetric region. For example, if the electrodes are part of a cubic, box-like structure, there are five such generally planar surfaces per cell all of which are in fluid communication with the reactant supply. In one form, an assembly made from numerous such cells could be used for ground-based (that is to say, stationary) power units for electric power generation, combined heat and power (CHP) or the like.

[0014] Referring first to FIG. 1, a single fuel cell **10** of a conventional fuel cell stack is shown in schematic cross-sectional view. The fuel cell **10** includes a substantially planar PEM **12**, anode catalyst layer **14** in facing contact with one surface of the PEM **12**, and cathode catalyst layer **16** in facing contact with the other surface. Collectively, the PEM **12** and catalyst layers **14** and **16** are referred to as the MEA **18**. An anode diffusion layer **20** is arranged in facing contact with the anode catalyst layer **14**, while a cathode diffusion layer **22** is arranged in facing contact with the cathode catalyst layer **16**. Each of diffusion layers **20** and **22** are made with a generally porous construction to facilitate the passage of gaseous reactants to the catalyst layers **14** and **16**. Collectively, anode catalyst layer **14** and cathode catalyst layer **16** are referred to as electrodes, and can be formed as separate distinct layers as shown, or in the alternate (as mentioned above), as embedded at least partially in diffusion layers **20** or **22** respectively, as well as embedded partially in opposite faces of the PEM **12**; it will be appreciated that all such variants are within the scope of the present disclosure.

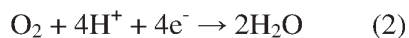
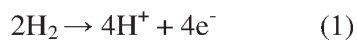
[0015] In addition to providing a substantially porous flowpath for reactant gases to reach the appropriate side of the polymer ion-exchange membrane **12**, the diffusion layers

20 and **22** may be used to establish electrical contact between the electrode catalyst layers **14**, **16** and respective electrically conductive plates **24**, **26** that in turn may be used to permit an electric current flow to an outside circuit. Moreover, by its generally porous nature, the diffusion layers **20** and **22** also form a conduit for removal of product gases generated at the catalyst layers **14**, **16**. Furthermore, the cathode diffusion layer **22** generates significant quantities of water vapor due to the electrochemical combination (or joining) of the ionized hydrogen and the ionized oxygen that takes place either in or on its surface; it will be appreciated that within the present context, such surface may also include the facingly-adjacent cathode catalyst layer **16**. Such moisture-generating feature may be useful in keeping the PEM **12** suitably hydrated, while water management apparatus—such as hydrophobic coatings, conduit, valves, pumps or the like (none of which are shown)—may also be used to ensure that water levels in and around the cell **10** aren't excessive.

[0016] Although shown notionally as having a thick-walled structure for ease of visualization, FIG. 1 should not be used to infer that the relatively planar conventional fuel cell **10** has a significant three-dimensional structure, such as when the through-the-thickness dimension along the Y-axis of the Cartesian coordinates of the cell **10** is on the same order of magnitude as that of the length or width dimensions of the respective X or Z axes. In fact, while the in-plane dimensions tend to be relatively large (for example, measuring several inches along both the width and height dimensions for a total cell surface area of about one hundred square inches), the through-the-thickness dimension tends to be relatively small (for example, no more than about one one-hundredth of an inch). To the extent that there is a major surface-to-major surface thickness, it is significantly the result of reactant channels **24A**, **26B** and the corresponding plate structure **24**, **26** that gives definition to such channels, where such thickness is significantly less than an order of magnitude of the length and width dimensions. Within the present context, such thin, planar cells **10** are deemed to have a two-dimensional structure. In one form, the plates **24**, **26** are stamped or otherwise formed from metal sheet or foil into bipolar plates where the channels **24A**, **26A** are defined on the opposing major surfaces of each plate. Regardless of whether the plates **24**, **26** are configured with bipolar attributes, they provide separation between facingly-adjacent MEAs **18** and accompanying diffusion

layers **20**, **22** from adjacent MEAs and layers (neither of which are shown) in a stack. One plate **24** engages the anode diffusion layer **20** while a second plate **26** engages the cathode diffusion layer **22**. The channels **24A**, **26A** separate adjacent sections of the reactant gas flow channels (shown by the arrows) by projecting toward and making direct contact with the respective diffusion layers **20**, **22**. Moreover, while the plates **24**, **26** are presently shown (for stylized purposes) defining purely rectangular reactant gas flow channels **24A**, **26A** and related structure, it will be appreciated by those skilled in the art that a more accurate embodiment will be those that define generally serpentine-shaped channels as is known in the art.

[0017] In operation, a first gaseous reactant, such as hydrogen (H_2), is delivered to the anode catalyst layer **14** side of the MEA **18** through the channel **24A** from plate **24**, while a second gaseous reactant, such as oxygen (O_2 , typically in the form of air) is delivered to the cathode catalyst layer **16** side of the MEA **18** through the channels **26A** from plate **26**. Catalytic reactions occur at the anode catalyst layer **14** and the cathode catalyst layer **16** respectively, producing protons that migrate through the proton-conductive PEM **12** and electrons that result in an electric current that may be transmitted through the diffusion layers **20** and **22** and bipolar plates **24**, **26** by virtue of contact between the lands between the channels **24A**, **26A** and the respective layers **20** and **22**. At the cathode catalyst layer **16**, the electrons and positively charged hydrogen ions combine with oxygen to form water, which flows out of the cell **10**. These reactions are represented formulaically as follows:



where a theoretical voltage of about 1.2 volts per cell is reduced in a PEM fuel cell to about 0.7 volts in actual (i.e., “real-world”) situations, where losses (such as activation losses, ohmic losses, fuel crossover losses and so-called Nerstian losses) account for the drop.

[0018] Referring next to FIGS. 2A and 2B, instead of using a stack of generally planar fuel cells **10**, the electrochemical cell **100** according to the present disclosure employs simple unit cells in a two-part nested construction. Although shown as having a cubic structure, cell **100** may also define other shapes (such as hemispherical, triangular or the like) depending on how many surfaces are formed by the electrodes, so long as such surface or surfaces provide a three-dimensional volumetric reactant chamber. Thus, in one embodiment of an electrochemical cell **100** according to the present disclosure, each half-cell is made up of an inner current collector **200** and an outer current collector **300** with primary structures in the form of a frame **240** and housing **340**, respectively. Unlike conventional fuel cell configurations—where numerous thin individual planar cells each with an anode, cathode and intermediate electrolyte are arranged in a stack or related construction to achieve higher power outputs—a complete electrochemical cell **100** within the context of the present disclosure is formed from the combination of the inner current collector **200** with an electrode **210** that extends a significant direction along all three Cartesian coordinate axes to define a three-dimensional structure. Such electrode **210** is made up of major surfaces **210A**, **210B**, **210C**, **210D** and **210E**. A sixth surface associated with the frame **240** cooperates with these major surfaces **210A**, **210B**, **210C**, **210D** and **210E** to define an interior three-dimensional volume **220** that corresponds to an inner reactant chamber **530** that acts as an enclosure for the introduction of one of the reactants. The sixth surface functions to provide a wall through which reactant-bearing inlet and outlet flowpaths **510**, **520** pass, as well as for power connectivity and other ancillary infrastructure. Likewise, a comparable electrode **310** is formed by the major surfaces **310A**, **310B**, **310C**, **310D** and **310E** of the outer current collector **300** that also extend a significant direction along all three Cartesian coordinate axes. The volume **310** defined by the electrode **310** is situated within the surrounding housing **340** in such a way that an at least partially hollow interstitial volume (not shown) is formed between the generally cubic electrode **310** and the inner surface of the housing **340**. As shown, both electrodes **210**, **310** define a generally cubic structure where all of the various electrode surfaces associated with each respective current collector **200**, **300** are constructed of generally contiguous members of substantially equal length and width dimensions of right-angle construction relative to one another. As discussed above, it will be appreciated by

those skilled in the art that other three-dimensional shapes may also be employed so long as they promote a three-dimensional construction of cell **100**, as well as the relatively unobstructed insertion and removal between the first and outer current collectors **200**, **300**. Significantly, the interior three-dimensional volume **220** defined by electrode **210** within the inner current collector **200** is sized and shaped to be insertable through an opening **330** and into the volume defined by electrode **310** within the outer current collector **300**.

[0019] The surfaces that make up the electrode **210** form a substantially continuous three-dimensional fluid boundary for the receipt of one of the reactants; in this way, when sealingly secured on a mounting surface **250** that is defined on frame **205**, the electrode **210** and its respective surfaces **210A**, **210B**, **210C**, **210D** and **210E** form a fluid-tight container so that the only substantial ingress and egress for the non-ionized reactant contained therein is through flowpath **500** and its respective inlet **510** and outlet **520**. In a similar manner, the contiguous edgewise connection of the various surfaces **310A**, **310B**, **310C**, **310D** and **310E** of electrode **310** ensures that they form a substantially continuous three-dimensional fluid boundary for the receipt of the other of the reactants; in this way, when sealingly secured within housing **340**, these surfaces **310A**, **310B**, **310C**, **310D** and **310E** form a fluid-tight container so that the only substantial ingress and egress path for the non-ionized reactant contained therein is through flowpath **600** and its respective inlet **610** and outlet **620**.

[0020] In one form, the contiguous electrode surfaces **210A**, **210B**, **210C**, **210D** and **210E** or **310A**, **310B**, **310C**, **310D** and **310E** of the respective inner and outer current collectors **200**, **300** attain their electrode status through having an electrocatalyst (such as platinum or the like) be disposed on a fluidly porous and electrically conductive media that is exposed to the as-introduced reactant. For example, if the catalyst is dispersed directly onto the ion-exchange membrane **400** and the ion-exchange membrane **400** is in the form of a PEM, then the combination may be referred to as a catalyst coated membrane (CCM). Any suitable porous media—such as carbon in either woven or finely divided powder form—known in the art may be used as support for the electrocatalyst.

[0021] An ion-exchange membrane **400** is disposed between the electrodes **210**, **310**. The ion-exchange membrane **400** is constructed such that when a first reactant is ionized at the numerous contiguous electrode surfaces **210A**, **210B**, **210C**, **210D** and **210E** or **310A**, **310B**, **310C**, **310D** and **310E** (depending on which of the current collectors **200**, **300** is configured to receive the reactant being oxidized), it flows through the ion-exchange membrane **400** prior to being electrochemically joined to a second reactant that is ionized at the plurality of contiguous electrode surfaces **310A**, **310B**, **310C**, **310D** and **310E** or **210A**, **210B**, **210C**, **210D** and **210E** of the other of current collectors **300**, **200**.

[0022] In one form, the frame **240** of the inner current collector **200** defines a generally rectangular shape with which to provide the planar mounting surface **250** for the secure attachment of the edges of electrode surfaces **210A**, **210B**, **210C** and **210D**. Similarly, the housing **340** of the outer current collector **300** forms a rigid attachment with an exposed planar mounting surface **350** at one end that can be seated on the planar mounting surface **250** of the frame **240** of the inner current collector **200**. Gaskets **700** may be secured or otherwise mounted onto one or the other of the planar mounting surfaces **250**, **350**. In one form, only one of the gaskets **700** are formed on a corresponding one of the planar mating surfaces **250**, **350**, while in another form, they can be formed on each respective planar mounting surfaces **250**, **350**. The use of a single gasket **700** ensures that a reactant that is introduced into the inner volume **220** of the electrode **210** will not prematurely or inadvertently combine with a reactant being introduced to the electrode **310**.

[0023] Significantly, the proposed gasket **700** configuration permits a single peripheral gasket, thereby significantly simplifying sealing construction relative to that of the planar fuel cell design discussed in conjunction with FIG. 1. Not only does this reduce the chances for reactant or byproduct leakage, it makes it easier (and less expensive) in cell **100** configurations where otherwise numerous gaskets within each planar fuel cell would be required. Furthermore, threaded bolts or other fastening members **360** can be made to project outwardly from the planar mating surface **350** of the outer current collector **300** in order to fit within apertures **260** formed in the inner current collector **200** as way to compress the gaskets **700** and provide tight, secure attachment between the mating planar

mounting surfaces **250, 350**. Similarly, in situations where acid electrolytes are used (such as for the electrolysis of water or the reverse recombination of H_2 and O_2 into water), the overall cost may be significantly reduced, as the far fewer number of required gaskets takes on greater significance in such circumstances where the gaskets must be made from an acid-resistant—and therefore much more expensive—material. One example of an assembly as discussed herein that could use an acidic electrolyte is one where the individual cells **100** are configured as phosphoric acid fuel cells (PAFCs). Although the electrolyte is different, the reliance on both on H_2 and O_2 means that their electrode reactions as depicted in Equations (1) and (2) are identical. Likewise, the construction of the electrodes and catalysts tend to be very similar between PEM and PAFC constructions. In situations where the assembly discussed herein is made from PAFC (rather than PEM) cells **100**, the electrolyte may be distributed in a porous layer (for example, one made from silicon carbide or the like). As with PEM-based configurations, the use of water management conduit may be beneficially employed.

[0024] Flowpath **500** is formed to provide fluid access to the inner current collector **200**. One of a first and second reactant is introduced through an inlet flowpath **510** into the inner reactant chamber **530** of the inner current collector **200**, while excess is taken out through an outlet flowpath **520**. A comparable flowpath **600** with inlet flowpath **610** and outlet flowpath **620** is used to convey the other of a first and second reactant through the interstitial volume **V** that resides between the housing **340** and the electrode **310** of the outer current collector **300**. Quick-connect fluid couplings (not shown) may be formed on the outward-directing ends of flowpaths **500, 600** to promote ease of connecting and disconnecting of each cell **100** from reactant delivery conduit **800** that will be discussed in more detail below. Such couplings or related fluid fittings may be operated by hand to give tool-free connecting and disconnecting without the need for a wrench or related instrument. In addition, such couplings may be equipped with self-sealing valves as a way to minimize spillage for residual reactant. It will be appreciated that the placement of the flowpaths **500, 600** on the respective inner and outer current collectors **200, 300** depicted in FIGS 2A, 2B and 3 is merely shown for visualization convenience, and that their preferred placement is that location on the cell **100** that promotes ease of manufacture, assembly or disassembly in the manner consistent with the present disclosure.

[0025] With particular regard to the three-dimensional geometric features, the protruding hollow cube that makes up the inner current collector **200** projects along the insertion (or nesting) direction along the Cartesian Y-axis with lateral projections along the corresponding X-axis and Z-axis. This hollow cube forms one of the electrodes **210** with five generally planar exposed surfaces **210A**, **210B**, **210C**, **210D** and **210E**, while the receiving hollow cube that makes up the outer current collector **300** forms the other electrode **310**, also with five generally planar exposed surfaces **310A**, **310B**, **310C**, **310D** and **310E**. In this way, each cell **100** forms the electrical conversion capability of five similarly-sized traditional planar fuel cells **10** of FIG. 1. By having simple geometric shapes, coupled with quick-connect fluid coupling and compressed, secure connection between the first and outer current collectors **200**, **300**, autonomy of each cell **100** is promoted. This is furthered by having the assembly and fluid connection of each cell **100** not depend on the assembly and fluid coupling of any adjacent cells **100** in order to have each cell **100** perform its current-generating function. Likewise, the ease with which each cell **100** may be disassembled, removed, repaired, reassembled and reconnected to the reactant delivery conduit **800** (that is shown in FIG. 3 and discussed below) provides an enhanced degree of serviceability that is not available in the compressed stack cells **10** of FIG. 1, while the multi-surfaced electrode configuration of each cell **100** allows for incremental increases in electric current and related power output without having to attach an entirely separate stack. Moreover, the fluid communication between the flowpaths **500**, **600** and the respective volumes **220**, **320** within the corresponding current collectors **200**, **300** is configured such that each of the plurality of contiguous electrode surfaces **210A**, **210B**, **210C**, **210D** and **210E** or **310A**, **310B**, **310C**, **310D** and **310E** receives the respective first or second reactant substantially equally and substantially simultaneously with all other surfaces, thereby promoting minimum pressure drop of the reactant as it flows from the reactant delivery conduit **800** discussed below and toward the ion-exchange membrane **400**.

[0026] As mentioned above, while FIGS. 2A and 2B disclose an electrochemical cell **100** where the inner current collector **200** acts as an anode such as to receive H_2 or a related reactant being oxidized and the outer current collector **300** acts as a cathode such as to receive O_2 or a related reactant being reduced, it will be appreciated that the choice

of anode versus cathode for the current collectors **200**, **300** is arbitrary, and that with suitable modifications to the construction of and introduction of reactant into the electrodes formed within each such current collectors **200**, **300**, an oppositely-configured cell **100** where the outer current collector **300** acts as an anode such as to receive the reactant being oxidized and the inner current collector **200** acts as a cathode such as to receive the reactant being reduced is also within the scope of the present disclosure.

[0027] Referring with particularity to FIG. 2B, where the ion-exchange membrane **400** and gasket **700** of FIG. 2A have been omitted for clarity, a first reactant flowpath **500** is shown in the form of an inlet **510** and an outlet **520** extending through the wall of the frame **240** with mating surface **250** that acts as a closure surface when secured against the corresponding mating surface **350** of the housing **340** that provides structure and containment for the outer current collector **300**. By having all of the flowpaths **500**, **600** (and their associated quick-connect couplings) be located on one surface of the cell **100** promotes ease of scalability and maintenance by permitting direct plugging and unplugging of the cell **100** along a common pair of reactant-conveying fluid conduit, such as that shown and discussed in conjunction with FIG. 3 below.

[0028] In situations where the electrode assembly and the intervening ion-exchange membrane **400** are structured to have the present cubic or related three-dimensional attributes, the resulting MEA and surrounding current collectors **200**, **300** may benefit from a balanced water level to ensure proper operation. In particular, a water management conduit (not shown) may be fluidly connected to each cell **100** to ensure that an adequate level of hydration is present to promote the conductivity of the ion-transmissive ion-exchange membrane **400** that is disposed between catalyzed electrodes. This is particularly useful when the ion-exchange membrane **400** is a PEM, as selective locations within such a cell require excess water removal to avoid flooding or related blockage of the reactant flowpaths **500**, **600**. It will be understood that when used to remove excess water in configurations where the ion-exchange membrane **400** is configured to have a proton migration path therethrough, such a water management conduit is preferably connected to the fluid side of the MEA where the O₂ is being introduced. In other locations within the cell **100**, it would be beneficial to provide additional hydration. In

one form, the water management conduit is preferably placed fluidly adjacent the location where the combining of the two ionized reactants takes place, and that all such variants are deemed to be within the scope of the present disclosure. Such water management conduit may be used in conjunction with one or more water vapor transfer (WVT) units or devices (also referred to as a cathode humidifier unit, membrane humidifier, fuel cell humidifier or the like). In such a WVT unit configuration, wet-side and dry-side reactant flowpaths (for example, a cathode exhaust and a cathode inlet) may be placed in moisture-exchange communication with one another through a membrane media in the WVT unit such that excess moisture leaving the cathode exhaust may diffuse through the media to the drier flowpath on the cathode inlet.

[0029] Referring next to FIGS. 3 along with 4A and 4B, an assembly made up of numerous cells **100** (two of which are presently shown) that are aligned along the reactant delivery conduit **800** that is divided into first and second portions **810**, **820**. In one example, the first reactant **R1** (such as H_2 or related fuel) may be conveyed through the first reactant delivery conduit portion **810** so that it can be introduced into the three-dimensional inner surface profile of the inner current collector **200** via inlet flowpath **510** while the excess can be removed from the same through the outlet flowpath **520**. Likewise, the second reactant **R2** (such as air or a related O_2 supply) may be conveyed through the second reactant delivery conduit portion **820** so that it can be introduced into the interstitial space between the three-dimensional electrode and the housing **340** of the outer current collector **300** via inlet flowpath **610** while the excess can be removed from the same through the outlet flowpath **620**. Although shown presently with the division between the first and outer current collectors **200**, **300** as taking place along the vertical (i.e., Y-axis) direction, it will be appreciated that the orientation of the cells **100** and their corresponding direction of movement in order to effect connection and disconnection between the current collectors **200**, **300** from one another—as well as fluidly decoupling of each cell **100** from the reactant delivery conduit **500**—may be a matter of design choice to take into consideration ease of serviceability and scalability, and that all such variants are deemed to be within the scope of the present disclosure.

[0030] A cross-interconnect **900** may be placed between adjacent cells **100** in order to provide one or the other of series and parallel electrical connection between them, where series connectivity may be used to increase voltage output and parallel connectivity may be used to increase current output. In this way, the desired voltage and current output from an assembly of numerous cells **100** can be tailored to meet the needs of a load being powered. As can be seen, in one form, a small amount of spacing is reserved between adjacent cells **100**; in addition to creating space for the optional cross-interconnect **900**, such spacing helps to avoid disturbing an adjacent cell **100** when one is being taken apart for servicing, as well as when a new one is being added to the assembly. The relative autonomy enjoyed by each of the individual cells **100** means that the difficulties associated with traditional stack-based designs—including pre-assembly compression and alignment of cells, as well as the subsequent reverse steps required when attempting to remove or replace one or more such cells—is reduced or eliminated.

[0031] In operation, the first reactant **R1** is conveyed longitudinally along the axial of the first reactant delivery conduit portion **810**. For each cell **100**, the first flowpath **510**—which may be fluidly connected to the first reactant delivery conduit portion **810** through a quick-connect coupling (not shown)—acts like a side-branch **815** off of the first reactant delivery conduit portion **810** in order to serve as an inlet into the cell **100** in general and the generally hollow volumetric space that is defined by the three-dimensional inner volume **220** in particular. The multi-surface exposure of the reactant **R1** that is introduced to the electrode **210** of the three-dimensional inner volume **220** and subsequent catalytic reaction (such as that depicted in Equation (1) above) causes the ionized reactant **R1** to pass through the conductive ion-exchange membrane **400**. In one form, the ion-exchange membrane **400** forms an enveloping glove-like (or bag-like) surrounding of the electrode **210** that is made up of the major surfaces **210A**, **210B**, **210C**, **210D** and **210E**, while in another form, the ion-exchange membrane **400** forms a wallpaper-like covering of the electrode **310** that is made up of major surfaces **310A**, **310B**, **310C**, **310D** and **310E**. From there, the ionized first reactant **R1** can combine with ionized second reactant **R2** that is delivered from the inlet flowpath **610** that may be fluidly connected to the second reactant delivery conduit portion **820** through a similar quick-connect coupling. In a similar manner to that of the first reactant **R1**, the exposure of the reactant **R2** that is

introduced into the electrode **310** and subsequent catalytic reaction (such as that depicted in Equation (2) above) causes the ionized second reactant **R2** (which cannot pass through the conductive ion-exchange membrane **400** in the same manner as reactant **R1**) to combine with reactant **R1** at the electrode **310** major surfaces **310A**, **310B**, **310C**, **310D** and **310E**. As mentioned above, in situations where the first reactant **R1** is H_2 and the second reactant **R2** is O_2 , the water generated by the combination of these two reactants may be managed (including removal and hydration, both as needed) by a water management conduit. Any unconsumed excess of the reactants **R1**, **R2** may be conveyed away from the respective first and outer current collectors **200**, **300** through the corresponding outlet flowpaths **520**, **620** and back into the respective streams that flow within the first and second reactant delivery conduit portions **810**, **820**. As with the inlet flowpaths **510**, **610**, the outlet flowpaths **520**, **620** may be equipped with quick-connect couplings.

[0032] As shown with particularity in FIG. 4A, the individual cells **100** may be arranged in a modular two-dimensional array or matrix such that they form a larger assembly. In such construction, the two reactant delivery conduit portions **810**, **820** may act as manifolds so that numerous side-branches **815**, **825** may extend from the respective manifold so that the various cells **100** may be arranged in the matrix-like manner shown. Likewise, the various cross-interconnects **900** may be used to establish the desired level of series and parallel electrical coupling between some of all of the individual cells **100**. Although depicted in exemplary way as having a seventeen-by-eighteen array of 350 cells that should be capable of generating a high voltage output (for example, around 300 volts) by virtue of each of the seventeen cells **100** within each row being electrically connected in a negative-to-positive series followed by the last cell **100** in each row being connected to the first cell **100** in an adjacent row, it will be appreciated that other arrays and other forms of the cross-interconnects **900** may be used as needed.

[0033] As shown with particularity in FIG. 4B, the individual cells **100** may be arranged as part of a modular linear array of individual cells **100**. As shown, the various cells **100** may straddle the elongate reactant delivery conduit portions **810**, **820**. As with the two-dimensional array or matrix that is depicted in FIG. 4A, the two reactant delivery

conduit portions **810**, **820** may act as manifolds so that numerous side-branches **815**, **825** (such as shown in FIG. 4A) may extend toward the various cells **100** for ease of fluid connecting and disconnecting. Also as with the two-dimensional array or matrix that is depicted in FIG. 4A, the modular construction made possible by the autonomous individual cells **100** means that the electric power output of the linear array may be made as large or small as needed, merely by adding to or removing from the reactant delivery conduit portions **810**, **820** one or more of cells **100**. It will also be appreciated that a combination of the embodiments of FIGS. 4A and 4B may be constructed in order to give the assembly a two-deep construction. In such case, the structure can be further expanded to three-dimensional stack.

[0034] While the present disclosure is particularly suited to fuel cells, it is also useful as a power source in a flow battery (also referred to herein as a secondary battery, not shown). Instead of generating electrical energy through the reduction-oxidation reactions associated with the MEA-based structure discussed herein for a fuel cell, the flow battery stores chemical energy in the form of electroactive materials that can be conveniently stored and subsequently used as part of a negative electrode reaction and positive electrode reaction discharging process for the creation of electric current. A pair of tanks may be used to store the electroactive materials. These active materials form the equivalent of ion-exchange membrane **400** (albeit in liquid form) from each of the tanks by corresponding pumps for delivery into one or the other of the inner and outer current collectors **200**, **300**. In one form, the electrolyte solutions include one or more transition metals that can be oxidized or reduced, which in turn leads to generating a corresponding electromotive force. As such, a battery made in conjunction with the present disclosure differs from traditional batteries in that the storage of the electrolytes in the external tanks. In this way, the energy being stored need not be contained within the bulk electrode materials and the attendant mechanical and thermal stresses associated with battery operation. This helps promote overall assembly modularity and its related serviceability and scalability attributes. When configured as a battery, the electrolyte contained within the tanks and pumped to the cell **100** from pumps is still deemed to be disposed between the two electrode assemblies (such as those associated with the electrodes **210**, **310**) once introduced into the cell **100**, even if in a liquid form instead of the membrane form

associated with PEM-based configurations, in that such electrolyte still is used for ion transport.

[0035] Although not shown, the present disclosure may also be configured as an electrolyzer that uses electricity and catalytically-active electrodes in order to promote an otherwise non-spontaneous chemical reaction. In one exemplary form, the electrolyzer may be used to transform water (H_2O) into H_2 and oxygen O_2 . In one exemplary form, such an electrolyzer cell may use a PEM such that it along with the anode and cathode form the MEA discussed herein. Thus, to obtain H_2 , the cell **100** configured as an electrolyzer could use a conventional water source (such as sea water or the like) so that the electrode is made from a material that can withstand high current density and high voltages. In one form, the water being supplied is acidic or alkaline, while in another form, the water is relatively free of salinity, acidity or alkalinity such that is relatively pure. Such an electrolyzer may also be used for electrochemical machining, rust removal, electroplating, the production of metals from metallic compounds, as well as the generation of chlorine, sodium hydroxide, electrolyzed water or the like.

[0036] It is noted that for the purposes of describing and defining features discussed in the present disclosure, it is noted that reference herein to a variable being a function of a parameter or another variable is not intended to denote that the variable is exclusively a function of the listed parameter or variable. Rather, reference herein to a variable that is a function of a listed parameter is intended to be open-ended such that the variable may be a function of a single parameter or numerous parameters. It is likewise noted that recitations herein of a component of the present disclosure being configured or programmed in a particular way, to embody a particular property, or function in a particular manner, are structural recitations, as opposed to recitations of intended use. More specifically, the references herein to the manner in which a component is programmed or configured denotes an existing physical condition of the component and, as such, is to be taken as a definite recitation of the structural characteristics of the component.

[0037] It is noted that one or more of the following claims utilize the term “wherein” as a transitional phrase. For the purposes of defining features discussed in the present

disclosure, it is noted that this term is introduced in the claims as an open-ended transitional phrase that is used to introduce a recitation of a series of characteristics of the structure and should be interpreted in like manner as the more commonly used open-ended preamble term “comprising”.

[0038] It is noted that terms like “preferably”, “generally” and “typically” are not utilized herein to limit the scope of the claims or to imply that certain features are critical, essential, or even important to the structures or functions disclosed herein. Rather, these terms are merely intended to highlight alternative or additional features that may or may not be utilized in a particular embodiment of the disclosed subject matter. Likewise, it is noted that the terms “substantially” and “approximately” and their variants are utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement or other representation. As such, use of these terms represent the degree by which a quantitative representation may vary from a stated reference without resulting in a change in the basic function of the subject matter at issue.

[0039] It will be apparent to those skilled in the art that various modifications and variations can be made to the embodiments described herein without departing from the spirit and scope of the claimed subject matter. Thus it is intended that the specification cover the modifications and variations of the various embodiments described herein provided such modification and variations come within the scope of the appended claims and their equivalents.

CLAIMS

1. An electrochemical cell comprising:
 - an inner current collector;
 - 5 an inner reactant flowpath;
 - an outer current collector;
 - an outer reactant flowpath; and
 - an ion-exchange membrane, wherein
 - the inner reactant flowpath comprises an inner reactant inlet, an inner
 - 10 reactant outlet, and an inner reactant chamber in fluid communication with the inner reactant inlet and the inner reactant outlet,
 - the inner current collector comprises one or more inner electrodes that are dimensionally configured to create an interior three-dimensional volume forming at least a portion of the inner reactant chamber,
 - 15 the outer current collector comprises one or more outer electrodes that are dimensionally configured to create an interior three-dimensional volume forming an opening therein,
 - the inner current collector and the interior three-dimensional volume of the inner current collector are nested through the opening and within the three-
 - 20 dimensional volume of the outer current collector such that the interior three-dimensional volume of the inner current collector resides within both the inner current collector and the outer current collector,
 - the inner electrodes of the inner current collector oppose the outer electrodes of the outer current collector across the ion-exchange membrane,
 - 25 the outer reactant flowpath is separated from the ion-exchange membrane by the outer electrodes, and
 - the inner current collector and the outer current collector comprise opposing mounting faces that form a releasable seal around a perimeter of the opening.
- 30 2. The electrochemical cell of claim 1, wherein the electrode of each of the inner and outer current collectors comprises a single continuous surface.

3. The electrochemical cell of claim 1, wherein the electrode of each of the inner and outer current collectors comprises a plurality of distinct electrode surfaces.
- 5 4. The electrochemical cell of claim 3, wherein the electrode of each of the inner and outer current collectors comprises at least three distinct electrode surfaces.
5. The electrochemical cell of claim 3, wherein the electrode of each of the inner and outer current collectors comprises at least four distinct electrode surfaces.
- 10 6. The electrochemical cell of claim 3, wherein the electrode of each of the inner and outer current collectors comprises at least five distinct electrode surfaces that define a substantially cubic structure.
- 15 7. The electrochemical cell of claim 3, wherein each of the plurality of distinct electrode surfaces of the inner collector receives a reactant substantially equally and substantially simultaneously with all of the other surfaces of the plurality of distinct electrode surfaces of the inner collector, while each of the plurality of distinct electrode surfaces of the outer collector receives a reactant substantially equally and substantially simultaneously with all of the other surfaces of the plurality of distinct electrode surfaces of the outer collector.
- 20 8. The electrochemical cell of claim 1, wherein the electrodes of each of the first and outer current collectors comprise an electrocatalyst disposed on a fluidly porous and electrically conductive media.
- 25 9. The electrochemical cell of claim 1, wherein the ion-exchange membrane comprises a polymer ion-exchange membrane such that it along with the electrodes of the inner and outer current collectors forms a membrane electrode assembly.
- 30 10. The electrochemical cell of claim 9, wherein the ion-exchange membrane substantially envelops the inner reactant chamber.

11. The electrochemical cell of claim 9, wherein the ion-exchange membrane covers the substantially entirety of the interior three-dimensional volume of the outer current collector.
- 5
12. The electrochemical cell of claim 9, wherein the ion-exchange membrane extends laterally over at least a portion of at least one of the mounting faces.
13. The electrochemical cell of claim 1, wherein the electrochemical cell comprises
- 10 a battery.
14. The electrochemical cell of claim 1, wherein the electrochemical cell comprises a fuel cell.
- 15
15. The electrochemical cell of claim 14, further comprising a water management conduit that is in fluid communication with a membrane electrode assembly that is formed by the ion-exchange membrane and the electrodes of the inner and outer current collectors.
- 20
16. The electrochemical cell of claim 1, further comprising a gasket disposed on at least one of the mounting faces.
17. The electrochemical cell of claim 1, wherein both of the inner reactant inlet and the inner reactant outlet are located in one surface of the inner current collector.
- 25
18. An electrochemical cell assembly comprising:
- reactant delivery conduit defining a first portion and a second portion each of which are configured to convey a different reactant than the other; and
- a plurality of electrochemical cells each comprising:
- 30 an inner current collector;
- an inner reactant flowpath;
- an outer current collector;

an outer reactant flowpath; and
an ion-exchange membrane, wherein

the inner reactant flowpath comprises an inner reactant inlet, an
inner reactant outlet, and an inner reactant chamber in fluid
communication with the inner reactant inlet and the inner reactant outlet,

the inner current collector comprises one or more inner electrodes
that are dimensionally configured to create an interior three-dimensional
volume forming at least a portion of the inner reactant chamber,

the outer current collector comprises one or more outer electrodes
that are dimensionally configured to create an interior three-dimensional
volume forming an opening therein,

the inner current collector and the interior three-dimensional
volume of the inner current collector are nested through the opening and
within the three-dimensional volume of the outer current collector such
that the interior three-dimensional volume of the inner current collector
resides within both the inner current collector and the outer current
collector,

the inner electrodes of the inner current collector oppose the outer
electrodes of the outer current collector across the ion-exchange
membrane,

the outer reactant flowpath is separated from the ion-exchange
membrane by the outer electrodes, and

the inner current collector and the outer current collector
comprise opposing mounting faces that form a releasable seal around a
perimeter of the opening.

19. The electrochemical cell assembly of claim 18, wherein each of the portions of
the reactant delivery conduit comprises a manifold with a plurality of branches that
extend substantially parallel with one another and substantially orthogonal to a flow of
reactant contained within the manifold.

20. The electrochemical cell assembly of claim 19, wherein the plurality of electrochemical cells is coupled to the parallel-extending branches of the reactant delivery conduit in such a way that they define a substantially two-dimensional cell array.

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21. The electrochemical cell assembly of claim 20, wherein the manifolds of the reactant delivery conduit are spaced apart from one another in a parallel manner on substantially opposing edges of the two-dimensional cell array.

10 22. The electrochemical cell assembly of claim 18, further comprising a cross-interconnect to provide one or the other of series and parallel electrical connection between adjacent electrochemical cells.

15 23. A method of forming an electrochemical cell assembly, the method comprising:
providing a plurality of electrochemical cells each of which comprise:

an inner current collector with one or more inner electrodes that are dimensionally configured to create an interior three-dimensional volume that forms at least a portion of an inner reactant chamber;

20 an outer current collector with one or more outer electrodes that are dimensionally configured to create an interior three-dimensional volume with an opening therein;

an ion-exchange membrane disposed between the electrodes of the inner and outer current collectors;

25 inserting, for each electrochemical cell within the assembly, the inner current collector through the opening in the outer current collector such that at least a portion of the interior three-dimensional volume of the inner current collector is nested within the three-dimensional volume of the outer current collector;

30 securing the inner and outer current collectors of each electrochemical cell within the assembly to one another such that opposing mounting faces from each current collector form a releasable seal around a perimeter of the opening;

fluidly coupling the inner current collector of each electrochemical cell within the assembly to a first portion of a reactant delivery conduit through an inner reactant

flowpath that comprises an inner reactant inlet and an inner reactant outlet that is in fluid communication with the inner reactant chamber; and

fluidly coupling the outer current collector of each electrochemical cell within the assembly to a second portion of a reactant delivery conduit through an outer reactant
5 flowpath that comprises an outer reactant inlet and an outer reactant outlet that is in fluid communication with an interstitial space that is formed around the outer electrodes.

24. The method of claim 23, further comprising servicing the assembly by removing one of the electrochemical cells from the assembly without disturbing any other of the
10 electrochemical cells within the assembly.

25. The method of claim 23, further comprising increasing a power out capability of the assembly by adding one of the electrochemical cells to the assembly without disturbing any other of the electrochemical cells within the assembly.

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26. The method of claim 25, further comprising placing a cross-interconnect to provide one or the other of series and parallel electrical connection between adjacent electrochemical cells.