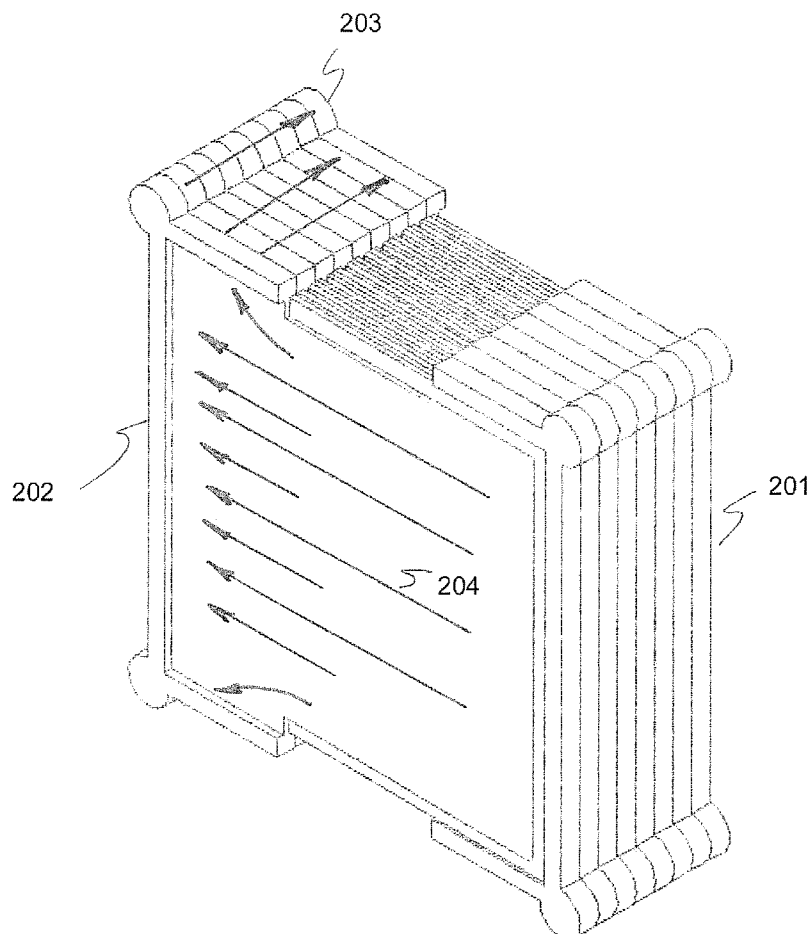




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(19) **United States**(12) **Patent Application Publication****Swan**(10) **Pub. No.: US 2007/0111089 A1**(43) **Pub. Date: May 17, 2007**(54) **ELECTROCHEMICAL CELL FOR HYBRID
ELECTRIC VEHICLE APPLICATIONS****Publication Classification**(75) Inventor: **David Herman Swan**, Lawrencetown
(CA)(51) **Int. Cl.**
H01M 2/24 (2006.01)(52) **U.S. Cl.** **429/160**; 429/162; 29/623.1Correspondence Address:
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DENVER, CO 80202(57) **ABSTRACT**(73) Assignee: **Railpower Technologies Corp.**, Bros-
sard (CA)(21) Appl. No.: **11/468,235**(22) Filed: **Aug. 29, 2006****Related U.S. Application Data**(60) Provisional application No. 60/712,762, filed on Aug.
30, 2005.

Embodiments of the present invention are directed an electrochemical energy storage device, such as a cell or a battery, that includes segmented stackable bus bars for stacking electrodes, the bus bar segments extending a substantial length of an edge of the electrodes to provide proper inter-electrode spacing, substantially uniform electrochemical potential and current density between electrodes, efficient internal heat dissipation and desired electrode structural rigidity, and, optionally, a compression member, separate from the case, to compress the stacked electrodes.



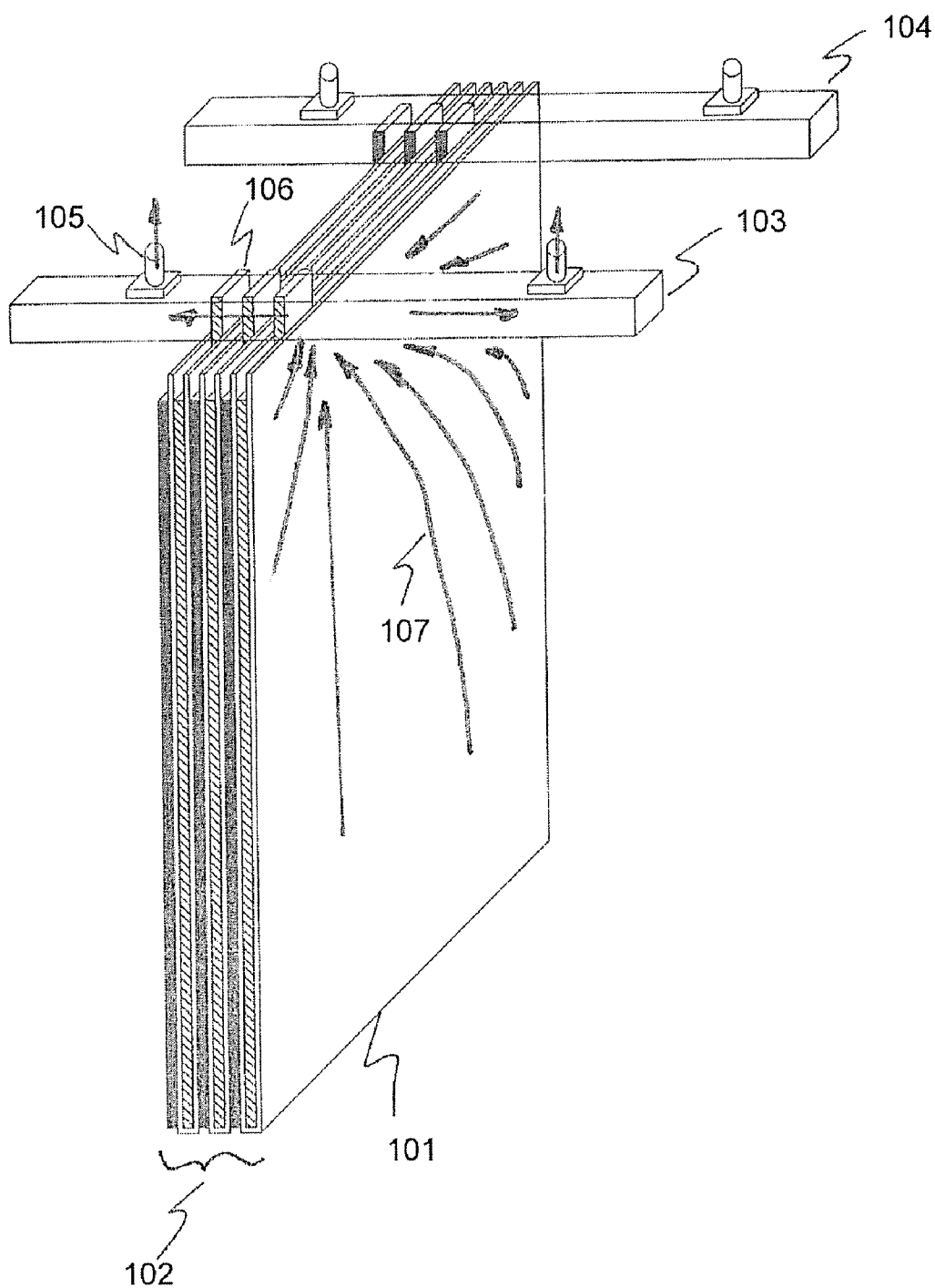


Figure 1
Prior Art

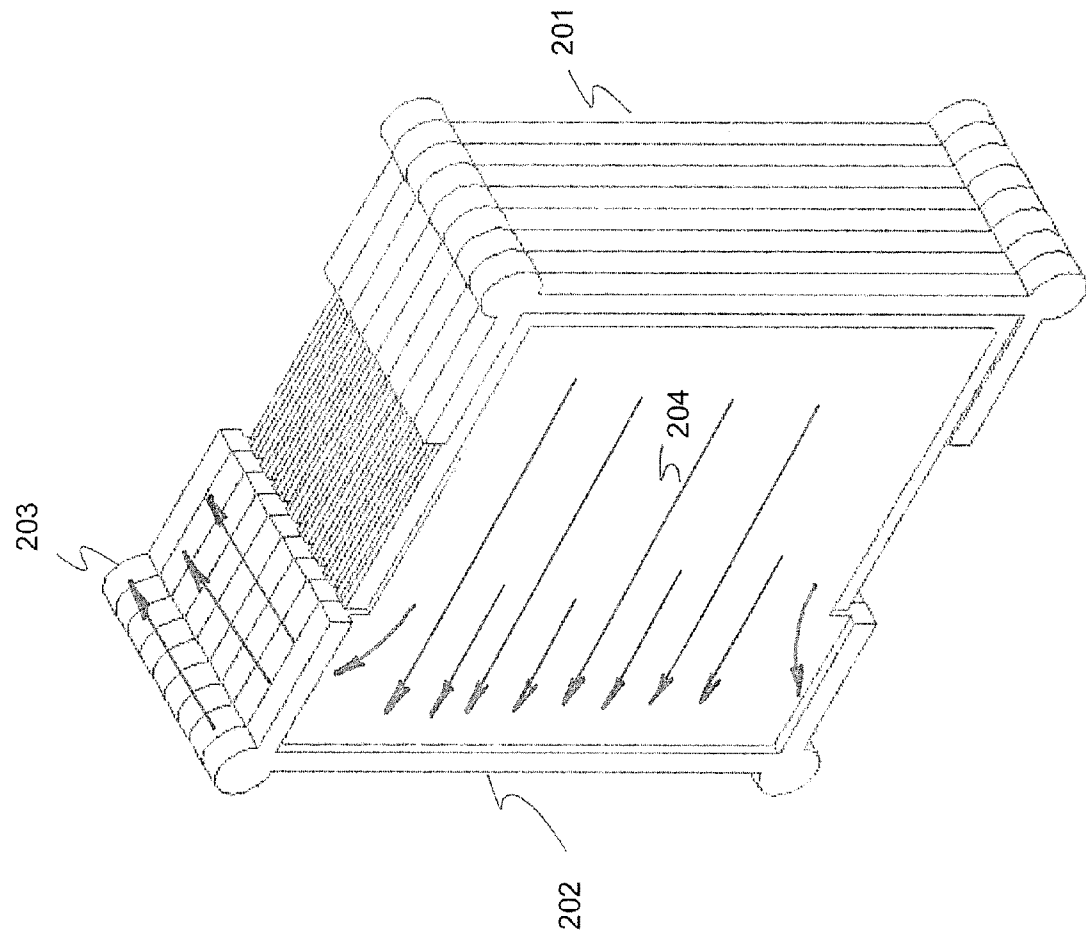


Figure 2

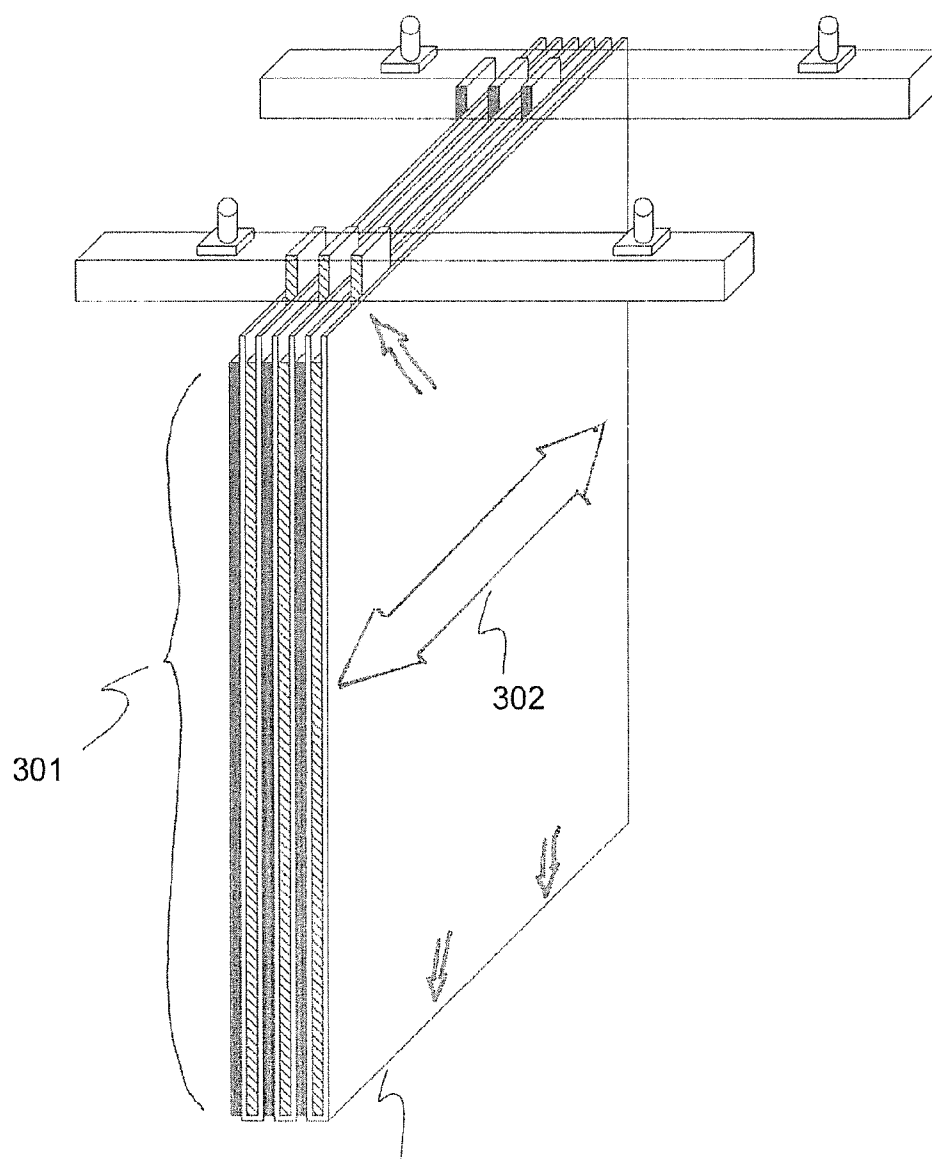


Figure 3
Prior Art

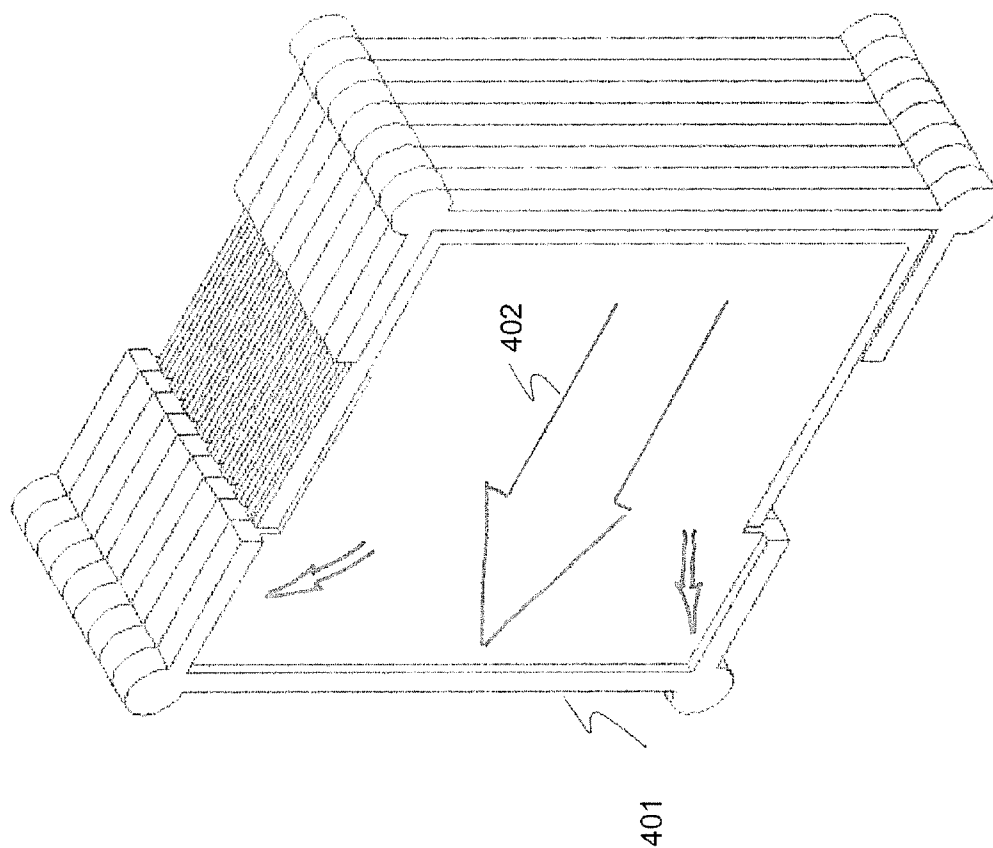


Figure 4

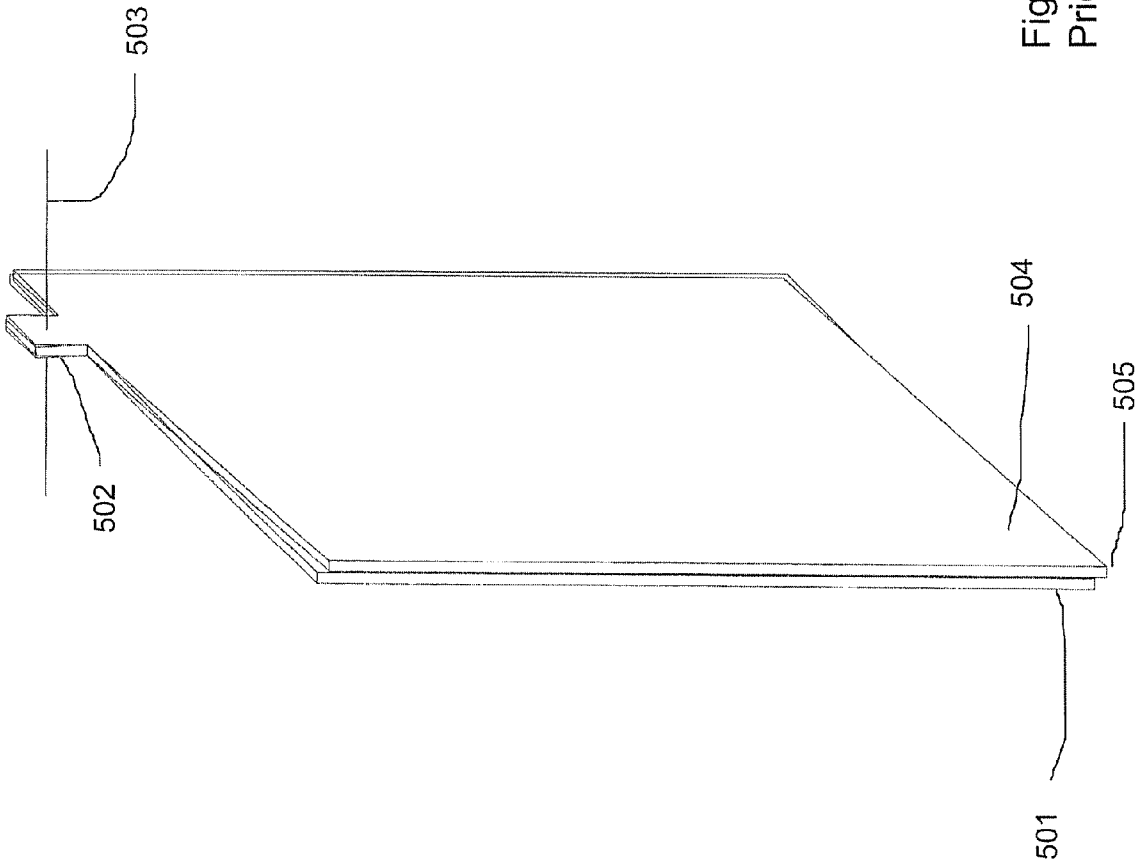


Figure 5
Prior Art

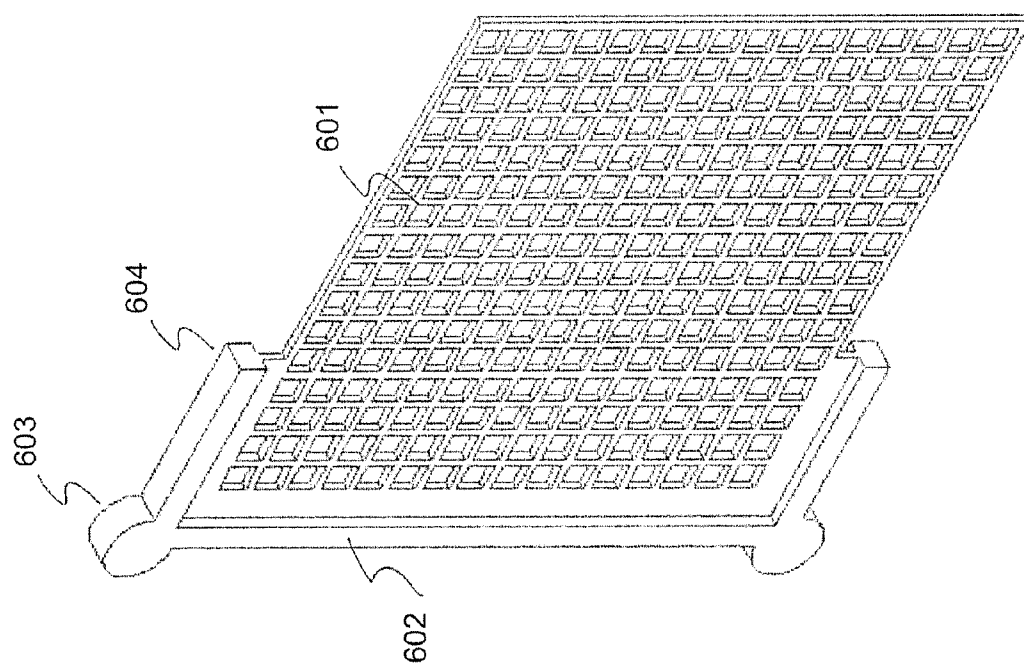


Figure 6

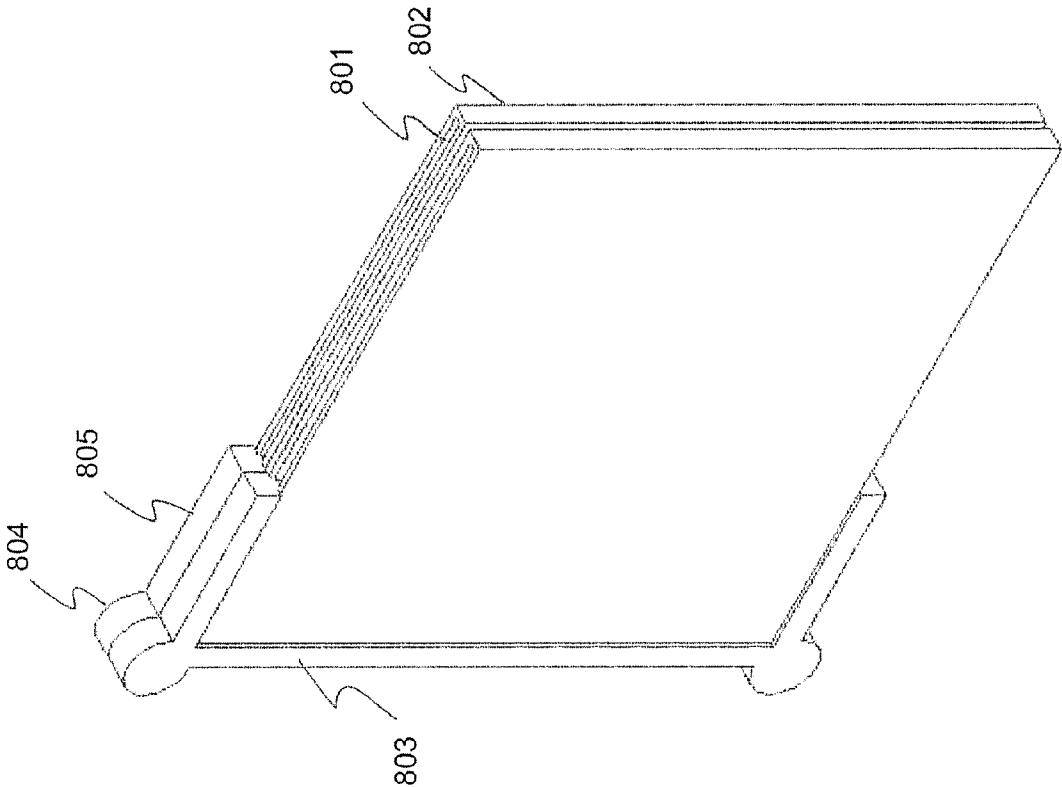


Figure 8

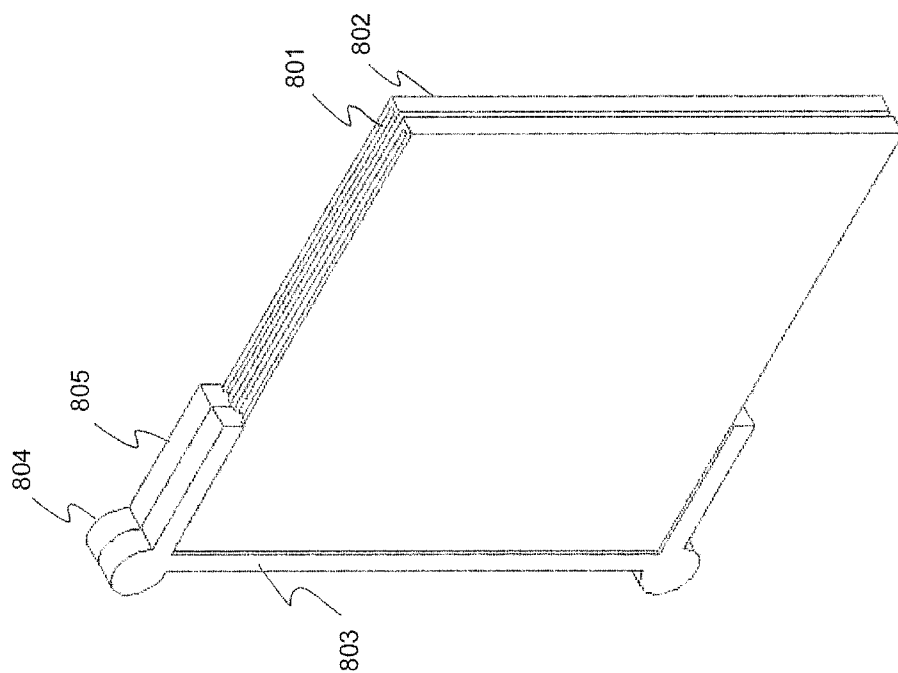


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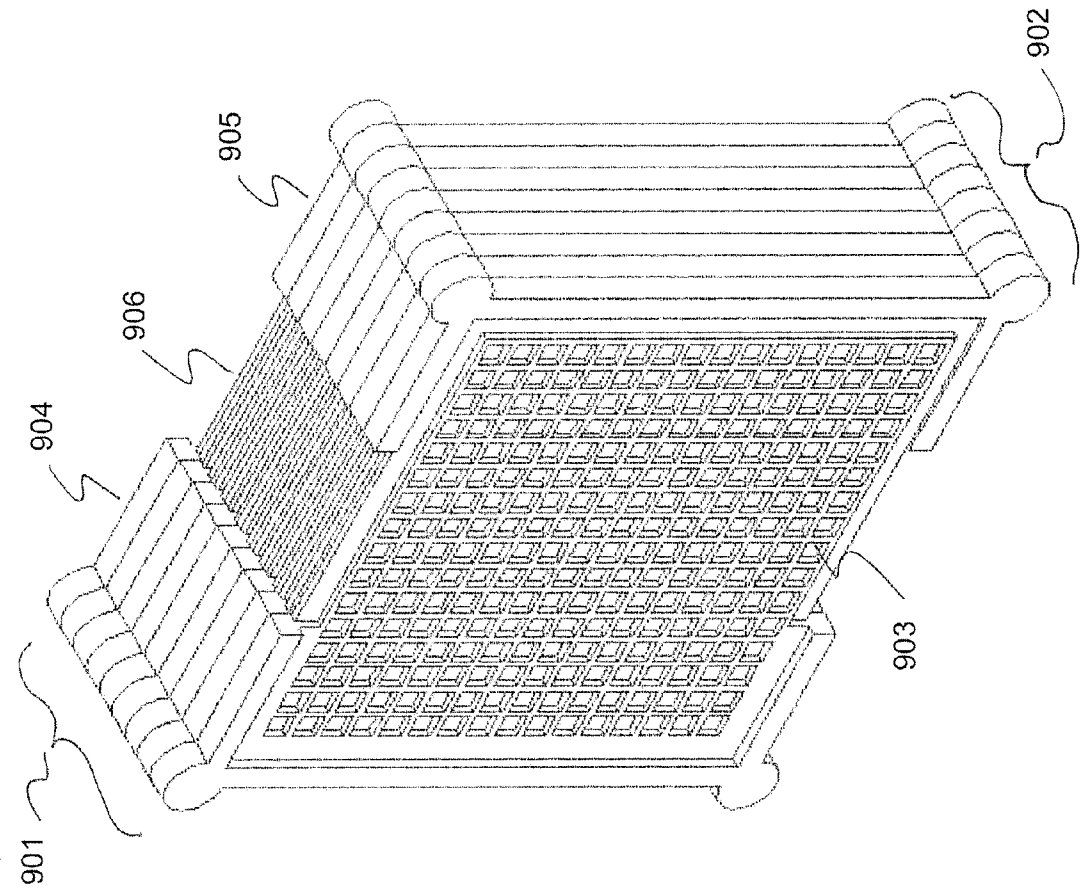


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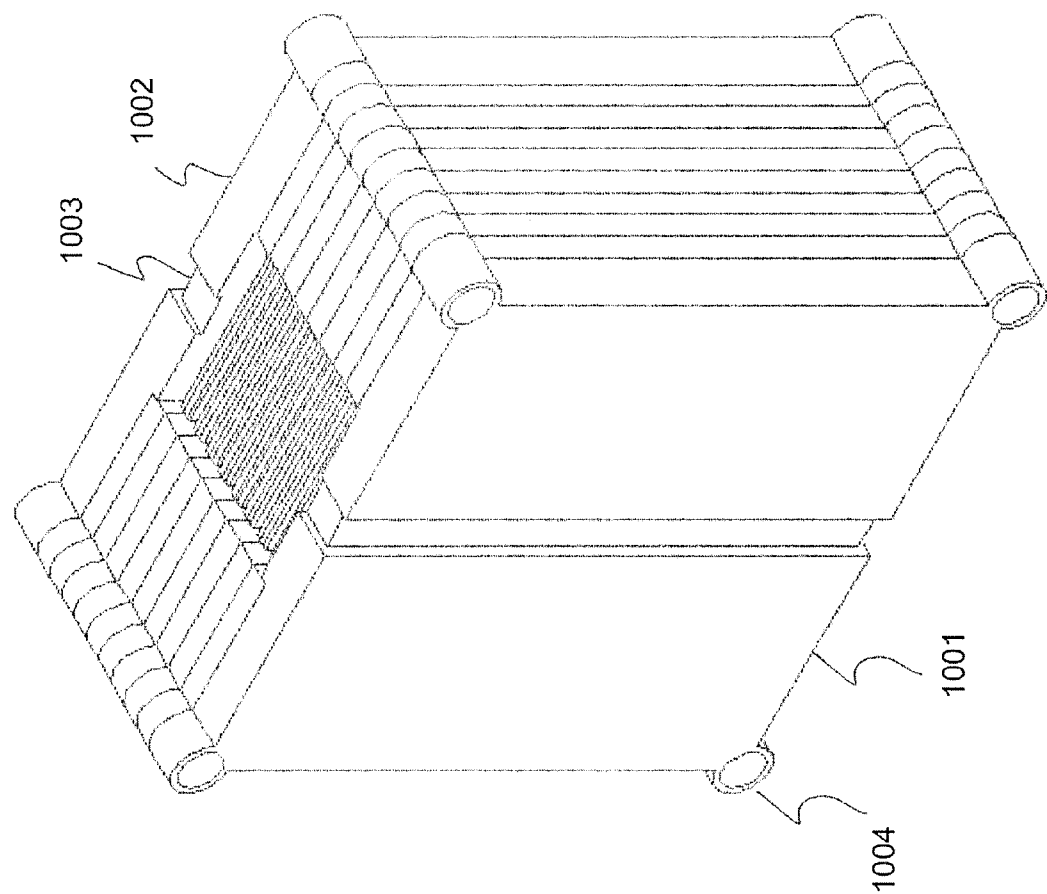


Figure 10

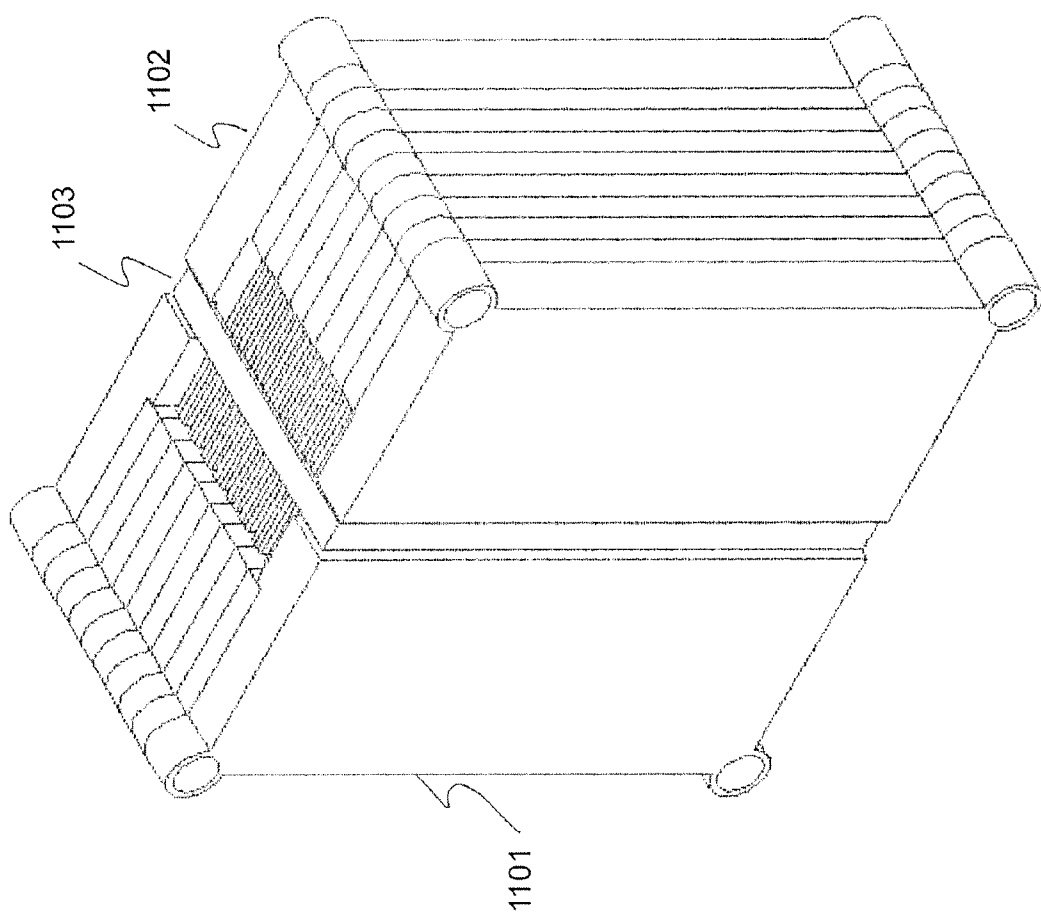


Figure 11

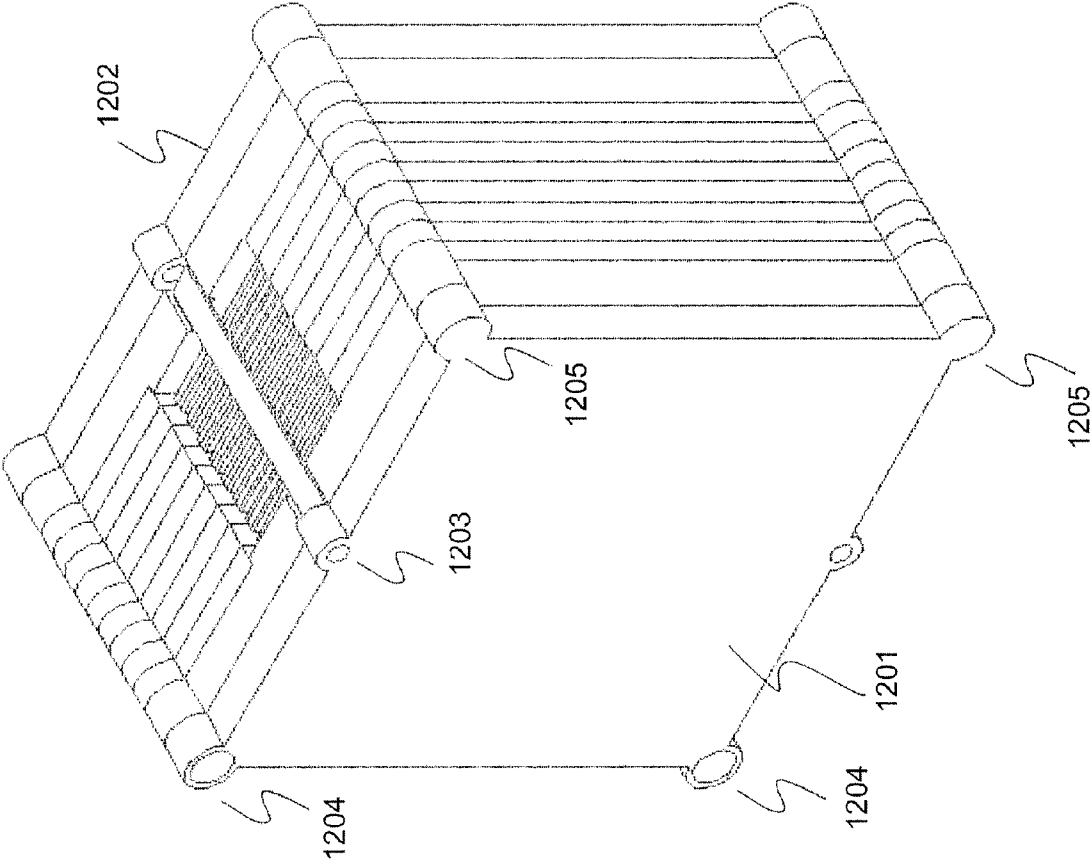


Figure 12

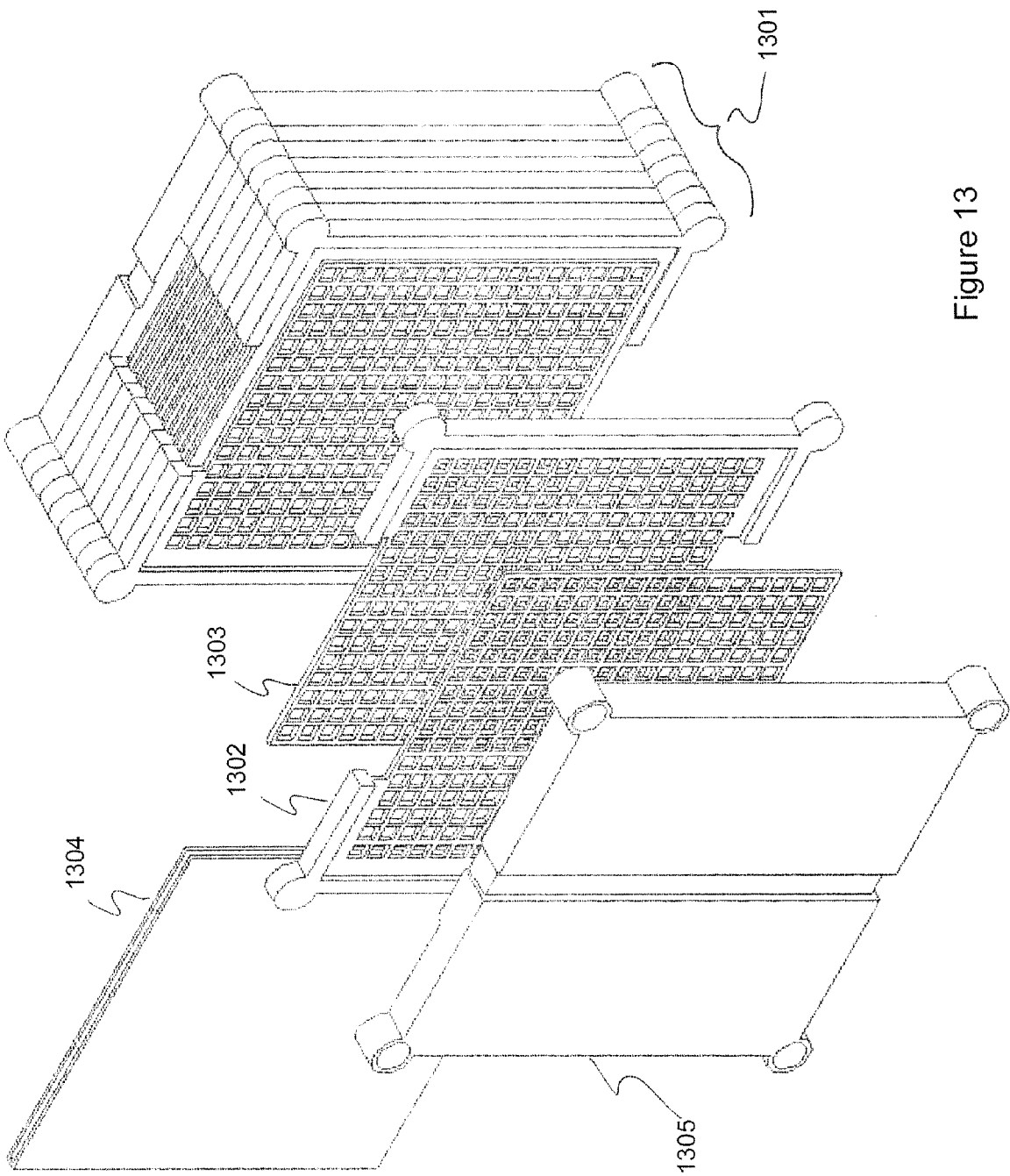


Figure 13

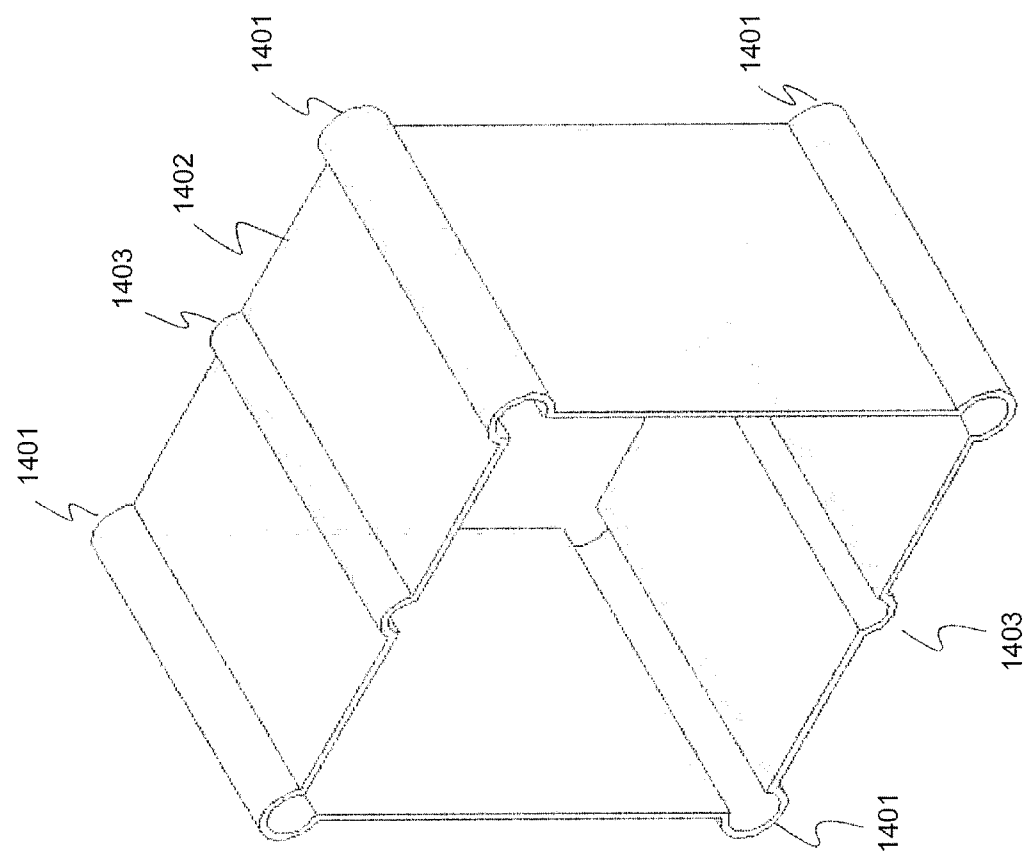


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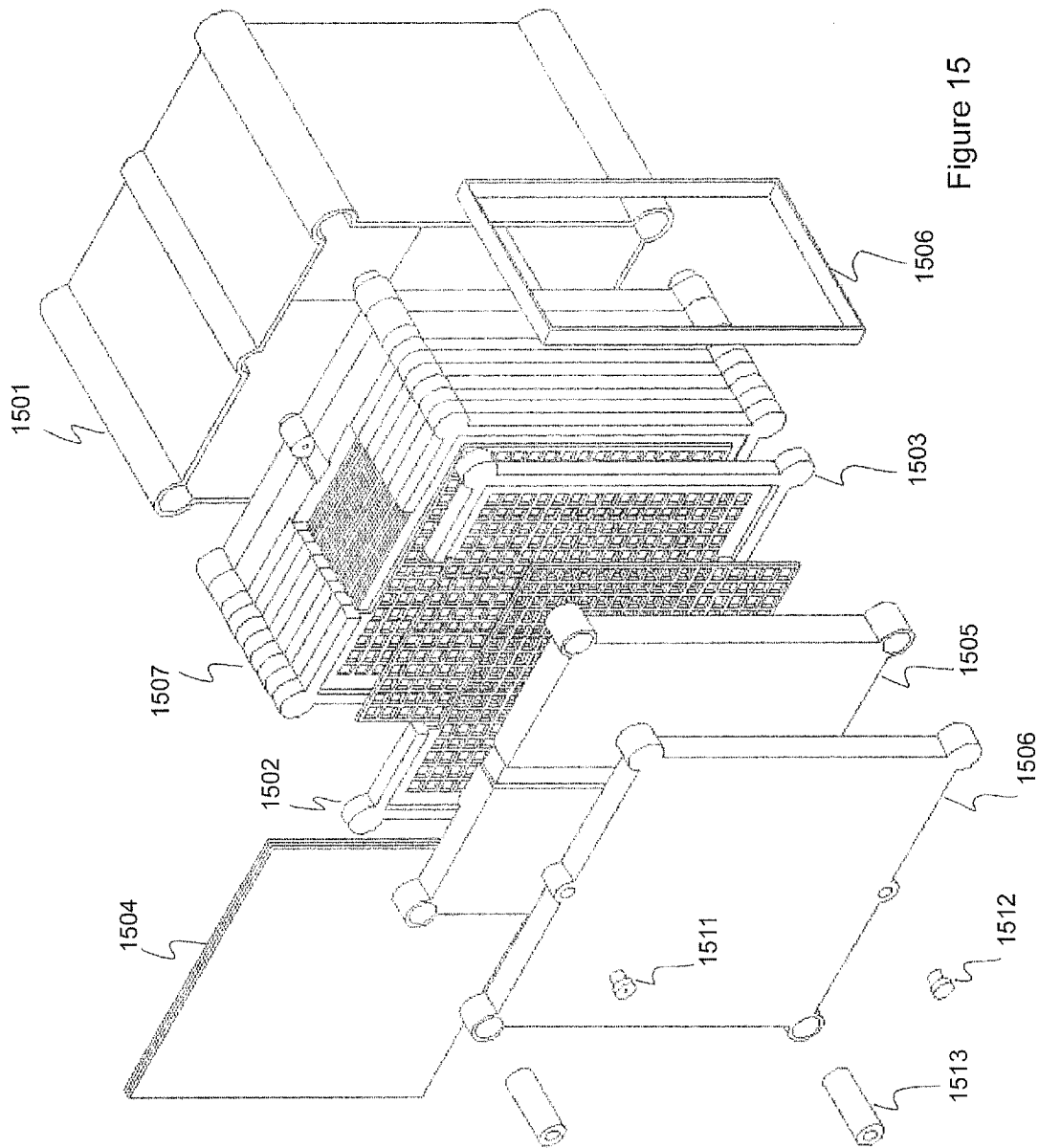
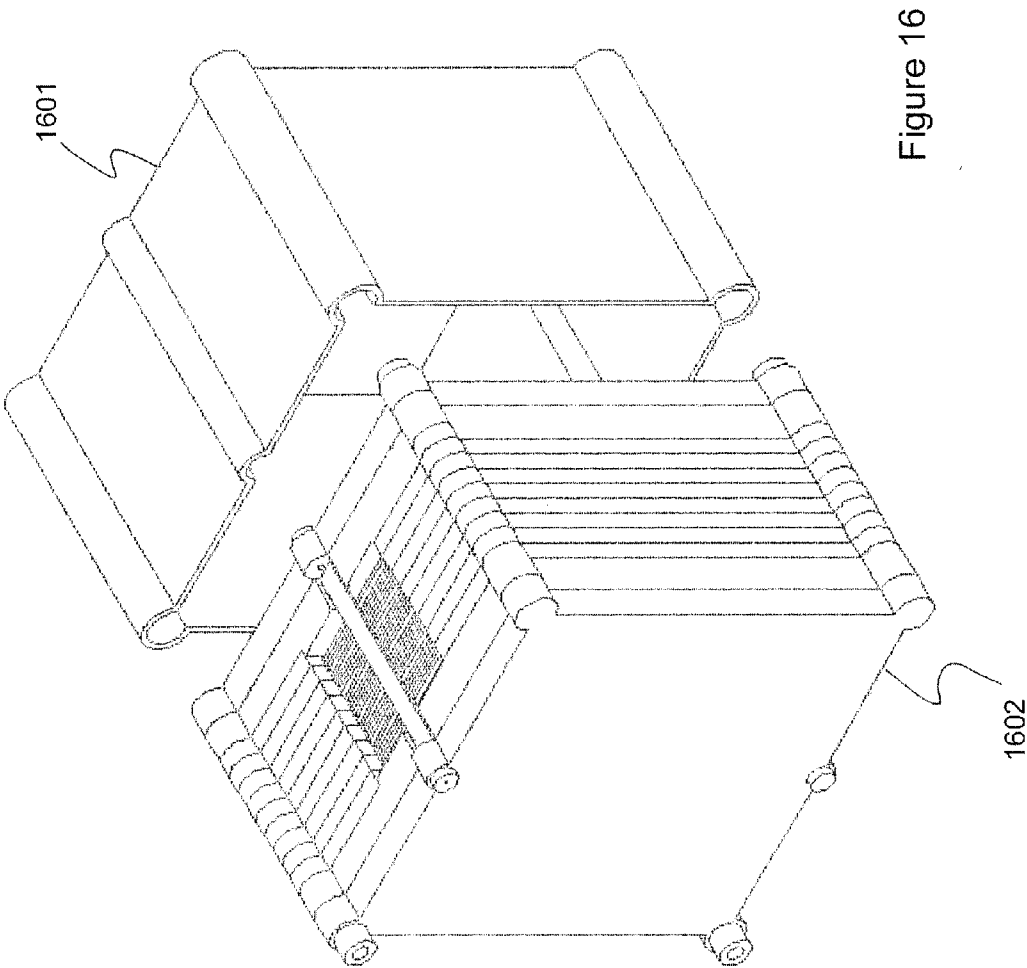


Figure 15



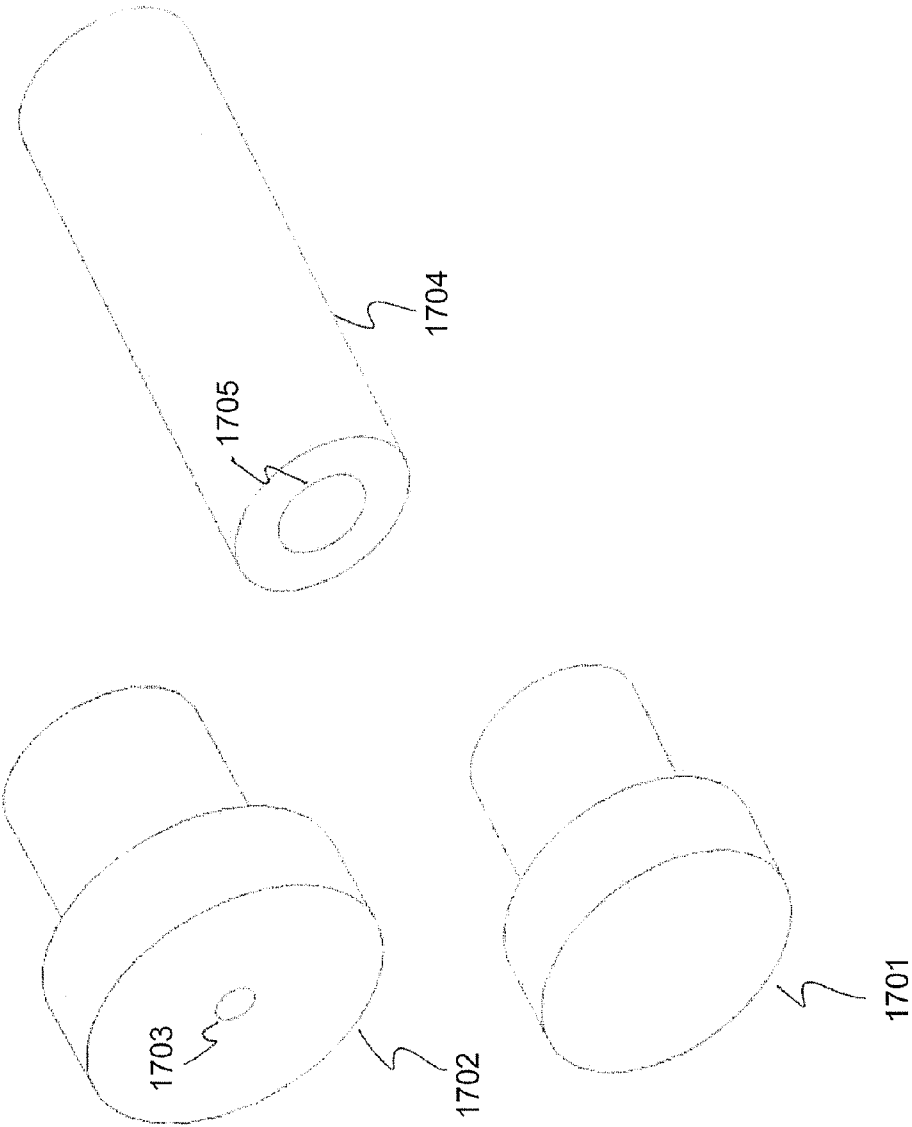


Figure 17

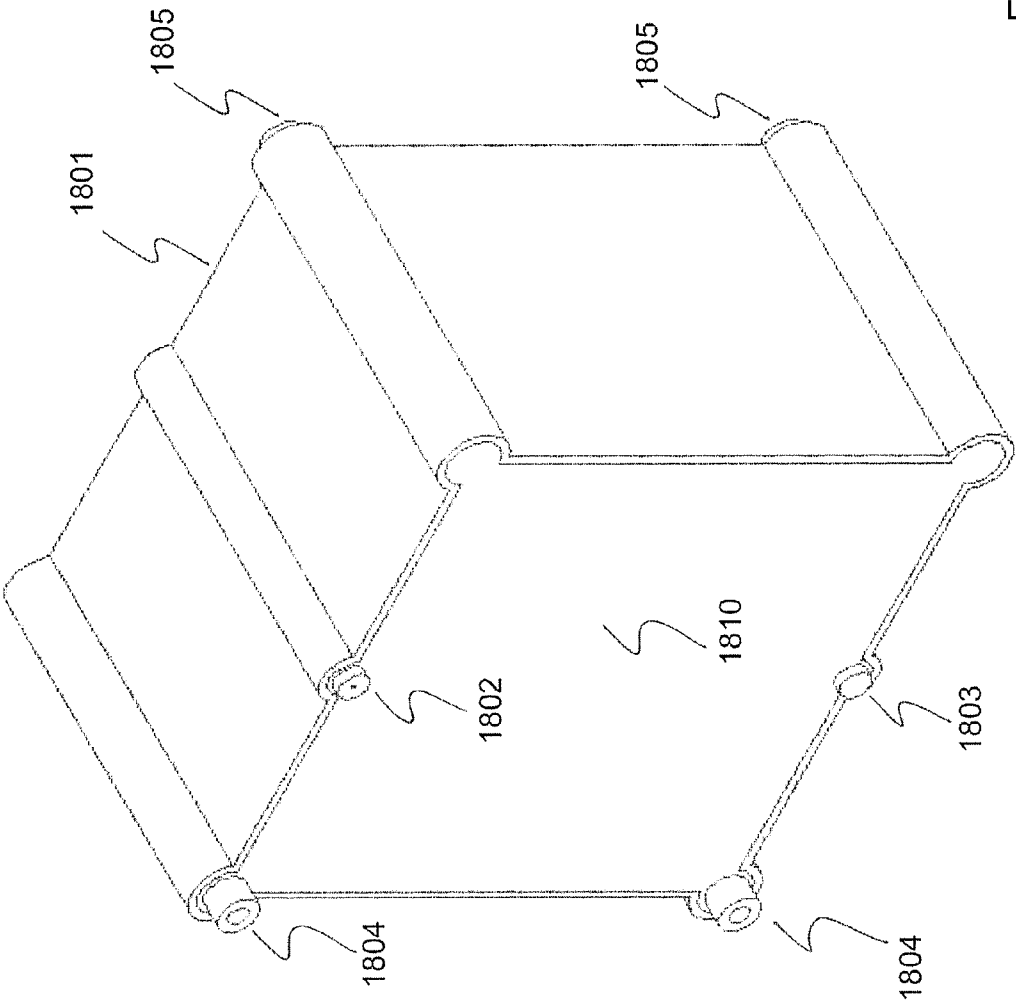


Figure 18

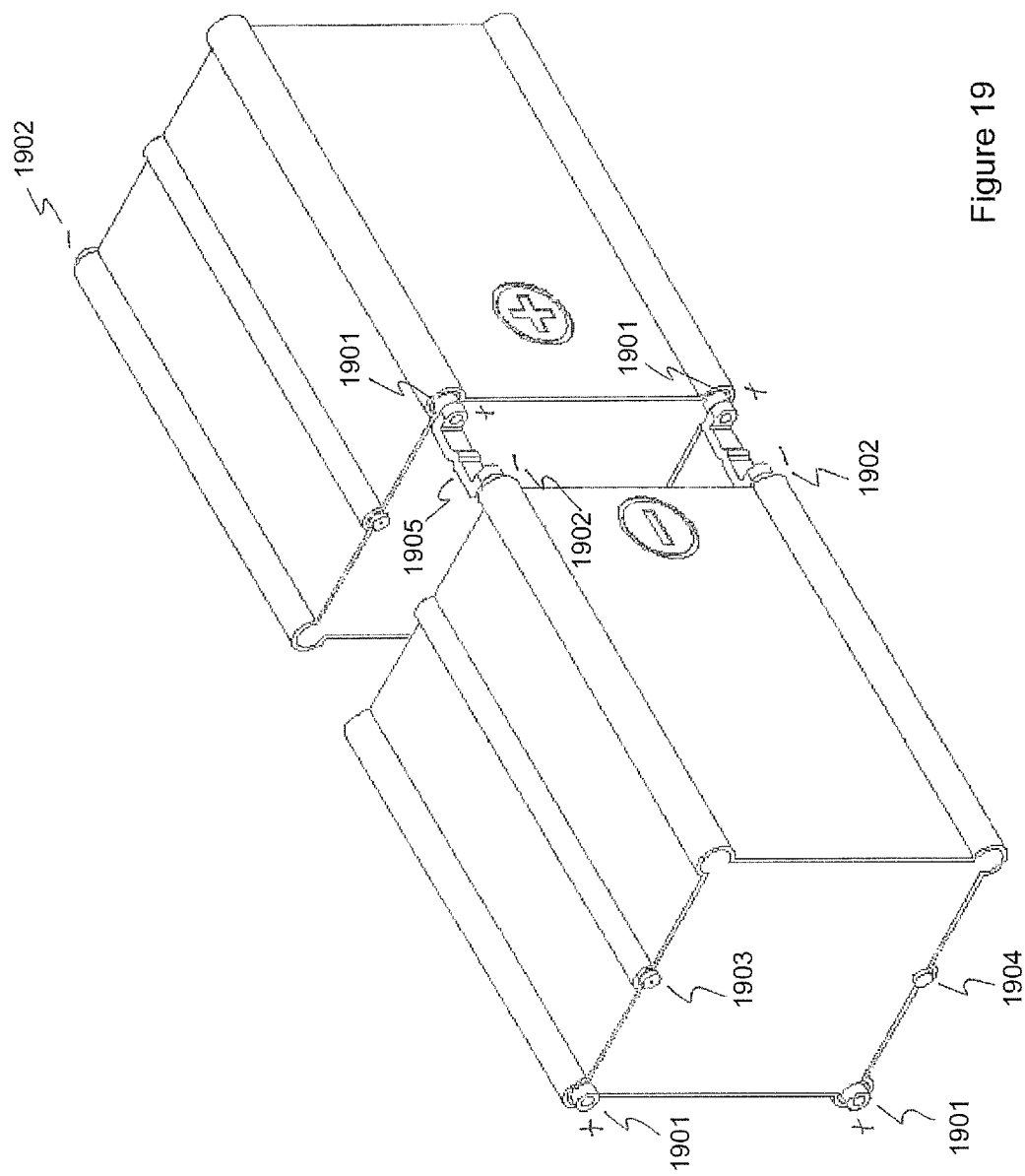


Figure 19

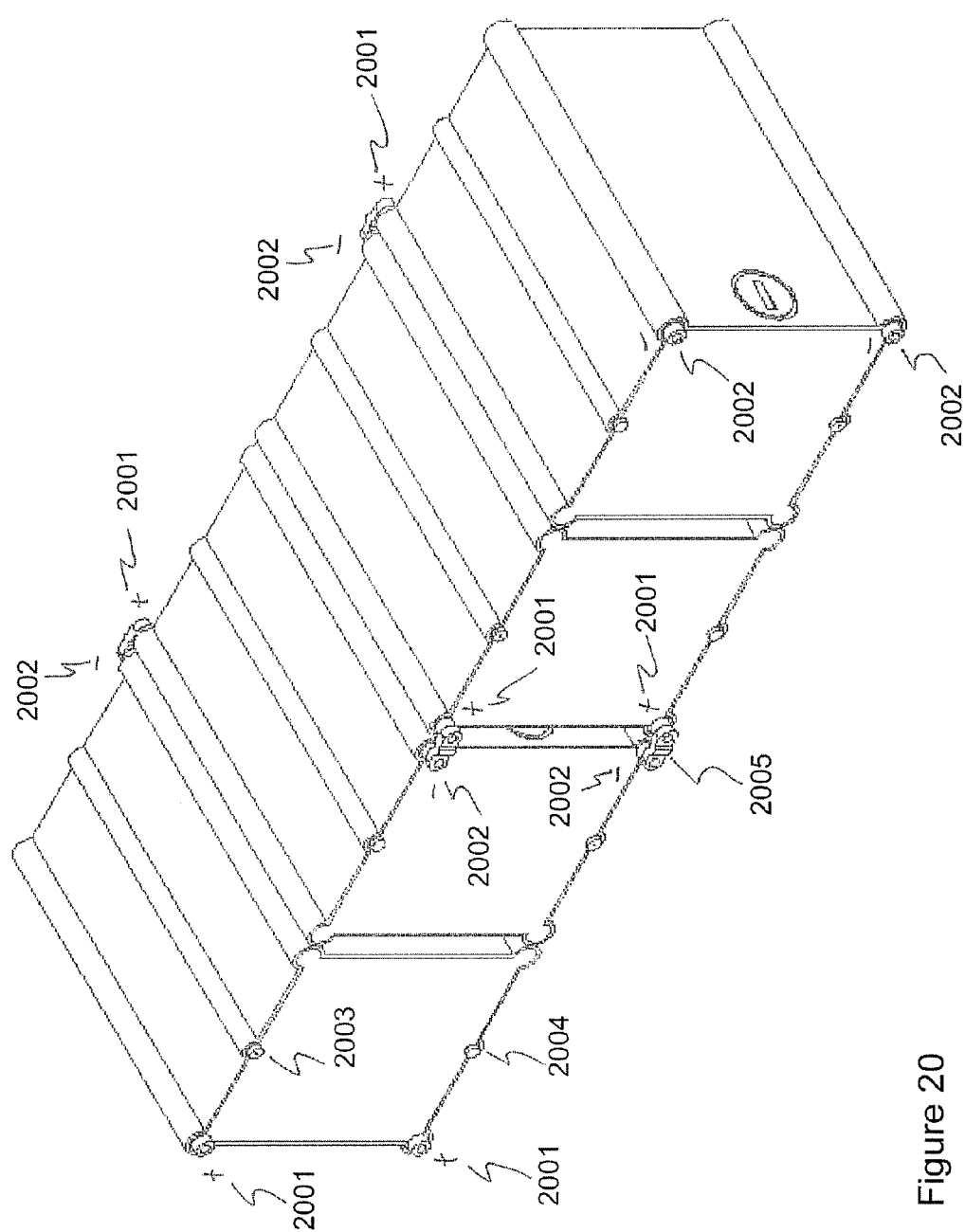


Figure 20

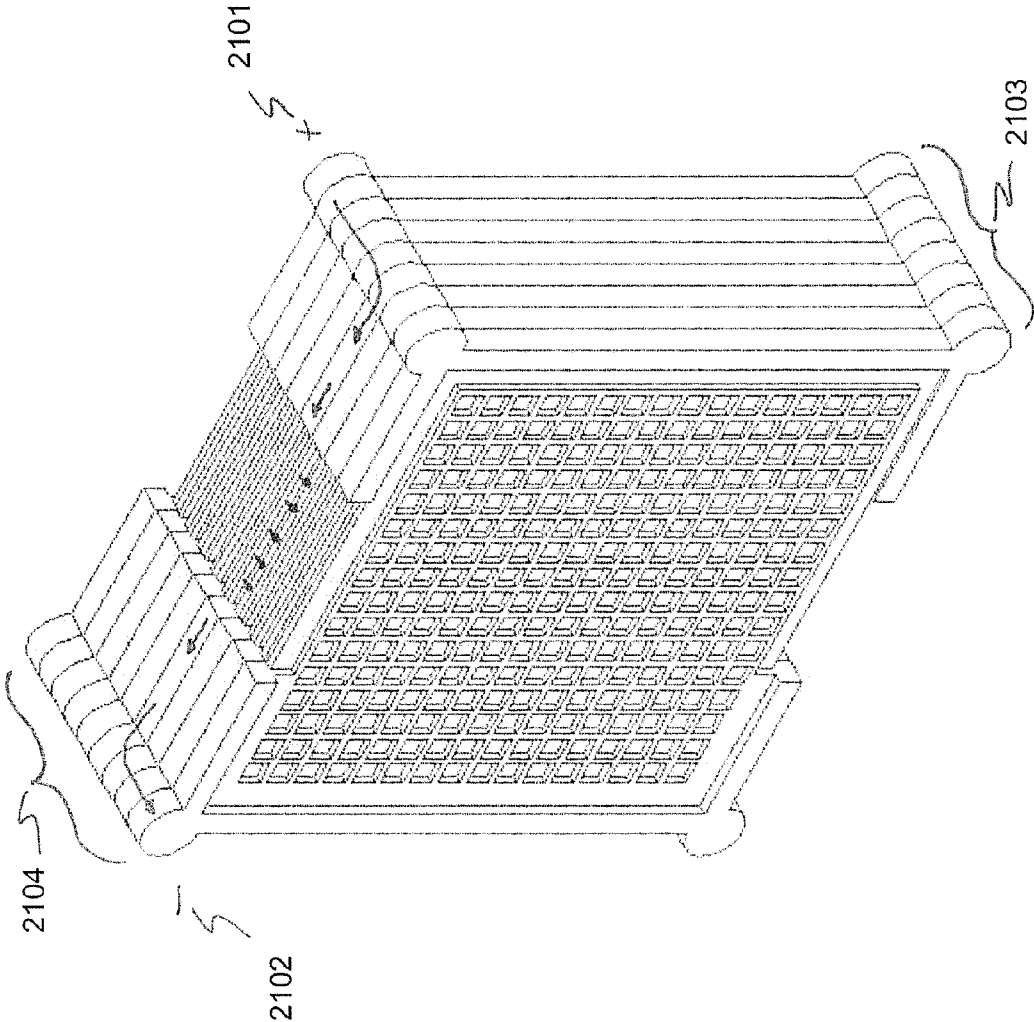


Figure 21

ELECTROCHEMICAL CELL FOR HYBRID ELECTRIC VEHICLE APPLICATIONS

CROSS REFERENCE TO RELATED APPLICATION

[0001] The present application claims the benefits, under 35 U.S.C. §119(e), of U.S. Provisional Application Ser. No. 60/712,762, filed Aug. 29, 2005, entitled "Electrochemical Cell for Hybrid Electric Vehicle Applications" to Swan and which is incorporated herein by this reference.

FIELD

[0002] The present invention relates generally to a method of constructing electrochemical energy storage devices for improved lifetime under partial state-of-charge operation, enhanced dissipation of internally generated heat and improved stability to shock and vibration loads.

BACKGROUND

[0003] Large energy storage battery systems are known, for example, from diesel submarines. In this application, a pack of large energy storage batteries are used to provide all-electric power. These are designed to provide high energy storage capacity for extended underwater operations during which the battery pack cannot be recharged. Battery pack cost and lifetime are generally not major concerns.

[0004] Large energy storage battery systems have also been used as standby power sources and for power regulation in a number of applications. As an example, a large stationary battery system was installed at the island village of Metlakatla, Alaska in the late 1990s. The 1.4 megawatt-hour, 756 volt battery system was designed to stabilize the island's power grid providing instantaneous power into the grid when demand was high and absorbing excess power from the grid to allow its hydroelectric generating units to operate under steady-state conditions. Because the battery pack is required to randomly accept power as well as to deliver power on demand to the utility grid, it is continuously operated at between 70 and 90% state-of-charge. Equalization charges are conducted during maintenance periods scheduled only twice each year.

[0005] It has been possible to assess aging and performance capabilities over time in this controlled cycling type of service by detailed monitoring. Data has been generated to demonstrate the long-term viability of cells in this type of use, performing functions such as load leveling, peak shaving and power quality enhancement. Detailed examination of the cells plates and separators have shown little wear indicating that controlled operation such as described above can result in battery lifetimes that can approach design lifetimes associated with float service.

[0006] Large capacity (over about 400 A-hrs) lead-acid cells, for example, are typically designed for standby use applications characterized by:

- [0007] 1. maintaining close to a full state of charge (float charge condition);
- [0008] 2. low discharge rates (typically about C/20);
- [0009] 3. lifetime limited by calendar life where the cell life is terminated by internal corrosion, water loss;

[0010] 4. lifetime not limited by ampere-hour throughput; and

[0011] 5. short cell string length (24 to 36 cells electrically connected in series).

[0012] It has long been thought that to achieve optimum life and performance from a lead-acid battery, it is necessary to float the battery under rigid voltage conditions to overcome self-discharge reactions while minimizing overcharge and corrosion of the cell's positive grid. This has resulted in batteries being used primarily in a standby mode.

[0013] The use of energy storage batteries in combination with a generator is known for automobiles, buses and other road and highway vehicles. Electric batteries have been used to store electric power to drive electric locomotives as, for example, disclosed by Manns in U.S. Pat. No. 1,377,087 which is incorporated herein by reference. Donnelly has disclosed the use of a battery-dominant hybrid locomotive in U.S. Pat. No. 6,308,639 which is also incorporated herein by reference.

[0014] One of the principal objectives of hybrid locomotive design is to operate the locomotive in such a way as to maximize the lifetime of its energy storage unit. This is because the cost structure of an energy storage unit such as for example a battery pack or capacitor bank is primarily one of capital cost and secondarily of operating costs. It is known, for example, that operating a lead-acid battery pack in a preferred state-of-charge ("SOC") range or with a preferred charging algorithm or with both tends to extend serviceable lifetime of cells in cyclical service towards that of float service. However, this mode of operation limits the effectiveness of a hybrid vehicle such as a locomotive that has high power demands, requires large storage capacity and often requires large reductions in state-of-charge at intermediate or high power.

[0015] A hybrid electric vehicle ("HEV") application is typically characterized by:

- [0016] 1. maintaining a variable partial state of charge during operation;
- [0017] 2. high discharge rates from C/5 to 2 C;
- [0018] 3. lifetime limited by amp-hour throughput;
- [0019] 4. lifetime not limited by calendar life; and
- [0020] 5. very long cell strings (several hundred cells electrically connected in series).

[0021] Operation of large series strings of electrically series-connected lead-acid batteries under hybrid locomotive operating conditions has resulted in substantially shorter cell lifetimes due to premature capacity loss. Premature capacity loss can result from, for example:

[0022] high resistance at the interface of the active material and grid surface of the positive plate;

[0023] expansion and contraction of body of active material on the positive plate causing a progressive loss of cohesion at the interface of the active material and grid surface;

[0024] sulfation on the negative plate.

[0025] When any of these conditions lead to premature capacity loss, it generally signals the end of the useful

lifetime of a cell or cells in a series string. Even the onset of any of these conditions can upset the balance of other cells in a string and accelerate premature capacity loss in the entire pack as a result of thermal and chemical imbalances. In a hybrid locomotive, for example, cells are subjected to shock and vibration loadings and are operated in widely varying ambient thermal environments. These can lead to cell failure because of, for example, shorting due to active particles being dislodged and moving around; ground faults from acid mist venting and/or case cracking; and large temperature variation amongst the cells in the pack.

[0026] Another problem with, for example, large energy storage lead-acid cells is stratification of the electrolyte when the cells are oriented with their plates in a vertical position. This is often a problem with sulphuric acid electrolytes in a separator matrix at high charging or discharging rates causing local hot spots to develop and change the concentration of the electrolyte. This problem can be overcome by using a gel electrolyte. The disadvantage of gel electrolyte cells is that the gel electrolyte tends to have a high internal resistance and so may limit the power output of a large energy storage cell, especially in a HEV application. Alkaline cells typically do not have an electrolyte stratification problem because the alkaline salt in the solution does not participate in the cell reaction.

[0027] High capacity, high power cells for use in large hybrid vehicle applications, such as hybrid locomotives, have the following needs for improvement to enable them to meet performance expectations:

- [0028] significantly improve hybrid cycle-life as measured by ampere-hour throughput;
- [0029] reduce internal ohmic resistance;
- [0030] eliminate electrolyte stratification
- [0031] maintain homogeneity of the electrochemistry across the surface of the plates
- [0032] significantly improve heat transfer from the plates to case walls where it can be efficiently removed; and
- [0033] significantly improve grid structural support for high vibration/shock applications.

[0034] There thus remains a need for a large, high capacity electrochemical energy storage device that significantly reduces the base electrochemical, electrical, thermal, and mechanical conditions that lead to premature capacity loss and abbreviated cell lifetime.

SUMMARY

[0035] These and other needs are addressed by the various embodiments and configurations of the present invention which are directed generally to electrochemical energy storage devices and particularly to a large capacity electrochemical cell that is substantially optimized for a duty cycle typical of hybrid locomotives in yard and/or road switching service and other hybrid vehicles.

[0036] In a first embodiment of the present invention, an electrochemical energy storage device is provided that includes:

[0037] (a) stacked electrodes arranged in electrode pairs, each electrode pair including an adjacent positive and negative electrode plates separated by a layer or separator matrix of electrolyte and the electrode plate pairs being arranged such that adjacent electrodes have opposing polarities;

[0038] (b) a positive bus bar interconnecting the positive electrodes; and

[0039] (c) a negative bus bar interconnecting the negative electrodes.

[0040] In the device, one or more of the following is true at charging or discharging rates between about 0.5 C and 2 C;

[0041] (c1) at least one of the positive and negative bus bars contacts the corresponding positive and negative electrodes, respectively, to provide a substantially uniform current density between each of the corresponding contacted electrodes (e.g., the current flow between the corresponding positive and negative electrodes preferably varies no more than about 20%, more preferably no more than about 15%, and even more preferably no more than about 10%);

[0042] (c2) at least one of the positive and negative bus bars contacts physically at least half a length of a peripheral edge of each of the corresponding positive and negative electrode plates, respectively, to maintain a relative orientation of the bus bar and corresponding electrodes substantially constant over time;

[0043] (c3) for each electrode plate pair, an electron travels an electrical current path of a substantially constant electrical resistance, the current path extending from the positive bus bar, through the positive electrode, traversing the electrolyte and through negative electrode, and to the negative bus bar;

[0044] (c4) a substantial length of a peripheral edge of at least one of the positive and negative bus bars contacts physically a case enclosing the electrode pairs to remove thermal energy generated by the flow of electricity;

[0045] (c5) for each electrode plate pair, a substantially constant electrical potential gradient normal to the bus bars exists across any grid structure on the surface of the electrodes (e.g., the electrical potential gradient normal to the bus bars preferably varies no more than about 20%, more preferably no more than about 15%, and even more preferably no more than about 10%);

[0046] (c6) at any point along the lengths of the positive and negative bus bars, a substantially constant electrical potential exists between opposing points on the bus bars (e.g., the electrical potential between opposite points on the bus bars preferably varies no more than about 20%, more preferably no more than about 15%, and even more preferably no more than about 10%);

[0047] (c7) for each electrode plate pair, a substantially constant electrochemical potential exists between any opposing points on the electrode pair; and

[0048] (c8) at any point in an enclosed volume of the device, a substantially constant electrochemical reaction exists. The above properties of the present invention hold true preferably at charging or discharging rates between about 0.5 C and 2 C but, as can be appreciated, can also hold true at charging or discharging rates outside this range.

[0049] In another embodiment, an electrochemical energy storage device is provided that includes one or more of the following features:

[0050] (1) the positive and negative bus bars are segmented, each segment physically contacting a corresponding electrode, the positive bus bar segments being stacked to define a plurality of spaced apart positive electrodes and the negative bus bar segments to define a plurality of spaced apart negative electrodes, each of the negative electrodes being received in a corresponding inter-electrode space between adjacent positive electrodes and each of the positive electrodes being received in a corresponding inter-electrode space between adjacent negative electrodes;

[0051] (2) the positive and negative bus bars are segmented, each segment physically contacting most, if not all, of a selected peripheral edge of a corresponding electrode, the adjacent segments being stacked one on top of the other to form the respectively polarized bus bar;

[0052] (3) the positive and negative bus bars define one or more gas venting spaces positioned between the positive and negative bus bars, the case forming an interference fit along the peripheral edges of the bus bars;

[0053] (4) the stacked electrodes are compressed and maintained in compression by a compression member separate from the case; and

[0054] (5) the case includes one or more offset member to define a channel between adjacent cases when the cases are positioned side-by-side.

[0055] According to an aspect of the present invention, the energy storage device, or cell, of the present invention is designed for partial state-of-charge use and for a large ampere-hour capacity cell with improved power, heat transfer and life characteristics compared to conventional cells. The cell cross-section can be any shape with square or rectangular being preferred. The length can be changed to provide a scalable capacity (400 to 2,500 ampere-hours) using the same parts. More specifically, the present invention may be designed for:

[0056] uniform use of cell electrochemistry (long HEV life);

[0057] improved heat transfer from plates to case wall;

[0058] high power output due to lower ohmic resistance;

[0059] terminal designed and positioned to minimize longitudinal or lateral cell interconnect pattern;

[0060] high vibration/shock capability (direct grid to case wall support, electrode compression independent of case);

[0061] number of unique parts, independent of size scale of the cell;

[0062] 200 to 4,500 amp hour capacity, scalable by a change in length;

[0063] unique geometry using extruded case and internal electrode compression plates;

[0064] terminals at opposite ends for reduced interconnect length;

[0065] compression of electrodes by internal compression plates and tension band; and/or

[0066] unique grid, bus bar and terminal arrangement.

[0067] In the following descriptions, lead-acid chemistry will be used to illustrate the invention. However, the principles illustrated are applicable to other electrochemical cell chemistries such as for example, nickel-metal hydride; nickel-zinc; and lithium ion.

[0068] The present invention can be an HEV specific cell design and a scalable cell that has been designed to improve power, heat transfer and life characteristics compared to other large capacity lead-acid cells.

[0069] In a preferred embodiment, a cell is fabricated by stacking a number of positive and negative plate elements where the positive and/or negative plate elements have a separator material between them. The positive plate elements include a grid which is intimately connected to a side structure which forms a portion of the positive electrode (integral enlarged perimeter current collector) and a portion of the cell sidewall. The negative plate elements include a grid which is intimately connected to a mirror image side structure which forms a portion of the negative electrode and a portion of the opposite cell sidewall.

[0070] The cell of the present invention can be used with a separator material impregnated with a liquid electrolyte or it can utilize a gel electrolyte.

[0071] The cell can have a number of advantages. By way of example, in the cell current can flow in a substantially identical pattern across each plate at approximately a uniform current density to a low resistance electrode/terminal. This minimizes internal plate resistance and maintains a substantial uniformity of current flow for all plates in the stack. The cell geometry can also allow heat energy to be generated uniformly by each plate, no matter where it is in the stack, and a major portion of the internally generated heat directed to a side plate which is in intimate contact with the inside of the plastic case. Additionally, the integral perimeter current collector structure along with active compression of the plate stack can impart to the cell a structural rigidity that resists damage caused by shock and vibration.

[0072] These and other advantages will be apparent from the disclosure of the invention(s) contained herein.

[0073] The above-described embodiments and configurations are neither complete nor exhaustive. As will be appreciated, other embodiments of the invention are possible utilizing, alone or in combination, one or more of the features set forth above or described in detail below.

[0074] The following definitions are used herein:

[0075] An electrochemical cell as used herein is a device that converts energy from an electrochemical reaction to useable electrical energy and in which the electrolyte is substantially stationary with respect to the positive and negative electrode plate pairs.

[0076] A cell as used herein is an individual valve-regulated unit comprised of one or more internal plate assemblies, each plate assembly including a negative plate, a separator material containing an electrolyte and a positive plate. The plate assemblies are all electrically connected in parallel such that the open-circuit voltage of the cell is

substantially the same as the open-circuit voltage across any of the plate assemblies. The cell may have one or more external negative and positive terminals.

[0077] A battery as used herein is an individual electrochemical unit comprised of two or more cells where the cells are electrically connected in series or combinations of series and parallel. The battery may have one or more external negative and positive terminals.

[0078] A valve regulated cell or battery is one in which internally generated gas pressure causes a vent to open when a selected internal pressure is reached but does not allow reverse flow of gas into the cell or battery from the outside.

[0079] A flow battery is a battery where the electrolyte is allowed to flow from a first storage container, between the plates of the cell and to a second storage container. Since the electrolyte is in motion with respect to the positive and negative electrode plate pairs when the cell is being charged or discharged, it is not an electrochemical cell as used herein.

[0080] A fuel cell is an electrochemical energy conversion device differing from an electrochemical cell as used herein in that it is designed for continuous replenishment of the reactants consumed. It produces electricity from an external supply of fuel and oxygen as opposed to the self-contained electrolyte of an electrochemical cell. Additionally, the electrodes within an electrochemical cell react and change as the cell is charged or discharged, whereas the electrodes of a fuel cell are catalytic and relatively stable.

[0081] A capacitor is an electrical energy storage device that stores energy in the electric field between a pair of closely spaced conductor plates.

[0082] C-rate: The charge and discharge current of a battery is measured in C-rate. A battery rated at 1 C means that a 1,000 amp-hour battery would provide 1000 amps for one hour if discharged at 1 C rate. The same battery discharged at 0.5 C would provide 500 amps for two hours. At 2 C, the 1,000 amp-hour battery would deliver 2,000 amps for 30 minutes.

[0083] A battery rack is a mechanical structure in which cells are mounted.

[0084] A battery module is a collection of cells mounted in a battery rack frame assembly of convenient size.

[0085] A battery pack is an assembly of many individual cells connected electrically. The assembly may include subassemblies or modules comprised of individual cells. The battery pack usually, but not always, has one overall positive and negative terminals for charging and discharging the cells in the pack.

[0086] Float service as applied to a battery means operating the battery under rigid voltage conditions to overcome self-discharge reactions while minimizing overcharge and corrosion of the cell's positive grid.

[0087] Charge and Discharge Rates are commonly measured as a fraction or multiple of the nominal ampere-hour capacity of the cell, C. For example, a C/2 charge rate is a charge rate of half the nominal ampere-hour rating and a 10 C discharge rate is a discharge rate of 10 times the nominal ampere-hour rating.

[0088] As used herein, "at least one", "one or more", and "and/or" are open-ended expressions that are both conjunctive and disjunctive in operation. For example, each of the expressions "at least one of A, B and C", "at least one of A, B, or C", "one or more of A, B, and C", "one or more of A, B, or C" and "A, B, and/or C" means A alone, B alone, C alone, A and B together, A and C together, B and C together, or A, B and C together.

BRIEF DESCRIPTION OF THE DRAWINGS

[0089] FIG. 1 is a schematic of a typical prior art large capacity cell showing typical current flow path. This is prior art.

[0090] FIG. 2 is a schematic of a large capacity cell of the present invention showing typical current flow path.

[0091] FIG. 3 is a schematic of a typical prior art large capacity cell showing typical heat flow path. This is prior art.

[0092] FIG. 4 is a schematic of a large capacity cell of the present invention showing heat flow path.

[0093] FIG. 5 shows a schematic representation of an electrode plate deformation mechanism. This is prior art.

[0094] FIG. 6 is an isometric view of a grid structure of the present invention showing its integral bus bar-side plate segment.

[0095] FIG. 7 is an isometric view of nine stacked grid structures.

[0096] FIG. 8 is an isometric view of two grid assemblies with separators.

[0097] FIG. 9 is an isometric view of a positive plate-separator-negative plate stack assembly.

[0098] FIG. 10 is an isometric view of a plate stack assembly with end plates.

[0099] FIG. 11 is an isometric view of a plate stack assembly strapped in compression.

[0100] FIG. 12 is an isometric view of a plate stack assembly prior to installation in a case.

[0101] FIG. 13 is an isometric exploded view of some interior components.

[0102] FIG. 14 is an isometric view of a case for the internal components.

[0103] FIG. 15 is an isometric exploded view of a cell of the present invention.

[0104] FIG. 16 is an isometric view before final assembly.

[0105] FIG. 17 is an isometric view of several components.

[0106] FIG. 18 is an isometric view of the cell after final assembly.

[0107] FIG. 19 is an isometric view of two cells in longitudinal arrangement.

[0108] FIG. 20 is an isometric view of several cells in lateral arrangement.

[0109] FIG. 21 is an isometric view illustrating current flow through a plate pair.

DETAILED DESCRIPTION

[0110] The cell of the present invention has been designed specifically for partial state of charge use. It is designed for a large ampere-hour capacity cell with improved power, heat transfer, resistance to shock and vibration and lifetime characteristics compared to prior art cells. The cell cross-section is preferably approximately square or rectangular for efficient space unitization in a large battery pack. The length can be changed to provide a scalable capacity (from approximately 200 to approximately 4,500 ampere-hours) using the same parts. The following describes some of the principal features of the cell:

[0111] The cell is preferably designed for:

[0112] uniform use of cell electrochemistry (long HEV life);

[0113] improved heat transfer from plates to case wall;

[0114] high power output due to lower ohmic resistance;

[0115] terminal designed and positioned to minimize longitudinal or lateral cell interconnect pattern;

[0116] high vibration/shock capability (direct grid to case wall support, electrode compression independent of case);

[0117] same number of unique parts, independent of size scale of the cell;

[0118] approximately 200 to approximately 4,500 ampere-hours capacity, scalable by a change in length;

[0119] unique geometry using extruded case and internal electrode compression plates;

[0120] terminals at opposite ends for reduced interconnect length;

[0121] compression of electrodes by internal compression plates and tension band;

[0122] unique grid, bus bar and terminal arrangement; Specific features of the cell of the present invention:

[0123] approximately equal electric resistance for all current paths from the positive bus bar to the negative bus bar—this is accomplished by opposing grid current collection and is designed for benefits in partial state-of-charge operation, power and usable energy;

[0124] large grid perimeter current collection and heat transfer plates—the grid is formed with an integral enlarged perimeter current collector to replace the conventional grid tab. The integral enlarged perimeter current collector provides grid structural support directly to the case walls;

[0125] extruded plastic case (e.g. ABS or polypropylene). Design to facilitate structural integrity and provide capacity scalability by changes in cell length;

[0126] minimum part count—a change in capacity is accomplished by a change in length of the extruded case, all other parts the same;

[0127] terminal placement to minimize cell interconnect length. Dual terminal configuration placed on the ends of the cell;

[0128] pressure relief valve placement to facilitate cell longitudinal axis rotation—end to end connections; and

[0129] internal end plates with tension strap to maintain plates compression independent of plastic case.

[0130] The design of the present invention achieves these goals in part by:

[0131] uniform current density between electrodes by “cross flow” design (typically large capacity cells utilize a “U-flow” design);

[0132] uniform use of electrode active material leads to a longer electrode pair life in HEV application;

[0133] the bus bar current travels an identical length regardless of plate location in cell stack; and

[0134] uniform use of all electrode pairs means a longer cell life.

[0135] The benefits of this approach include:

[0136] cell design is expected to significantly improve hybrid cycle-life (amp hour throughput);

[0137] significant reduction in ohmic resistance;

[0138] significant improvement in heat transfer; and/or

[0139] significant improvement in grid structural support for high vibration/shock applications.

[0140] As can be appreciated, the cross-section of the cell can be cylindrical or elliptical. In these cases, the length of the cell can still be changed to provide a scalable cell capacity. In these cases, the current density remains substantially uniform between opposing electrodes and a substantially equal electric resistance should exist for all current paths from the positive bus bar to the negative bus bar. In addition, the heat dissipation advantages and the structural advantages of the cell will remain.

[0141] In the following descriptions, lead-acid chemistry will be used to illustrate the invention. However, the principles illustrated are applicable to other electrochemical cell chemistries such as for example, nickel-metal hydride; nickel-zinc; and lithium ion.

Current Flow Distribution

[0142] FIG. 1 is a schematic of a typical prior art large capacity internal cell construction showing the approximate path of current flow on the plate surfaces. This figure illustrates a stack 102 of three negative plates and three positive plates where the positive plates are encased in separators. In this example, arrows 107 indicate the flow of current along a positive plate 101. The current flows at ever-increasing current density towards a tab 106 which is connected to a positive bus bar 103, the bus bar 103 having, in this example, two terminals 105. All the current along the plate 101 flows through the tab 106 and along the bus bar 103 to the terminals 105. In this example, the positive/negative plate pairs are electrically in parallel. The current flow in the negative terminals, negative bus bar, negative tabs and negative plates is similar but in the opposite direction to their positive counterparts. Current flows from the negative plates across the electrolyte impregnating the separator material to its neighboring positive plates. As can be seen, the current density is highest nearest the tab 106 and current flow direction varies significantly over the surface of

the plate. This typically causes the electrode surface near the tabs of the plate to deteriorate at different rates (usually at a higher rates) than the electrode surface at larger distances from the tabs.

[0143] FIG. 2 is a schematic of a large capacity cell internal construction of the present invention showing the approximate path of current flow on the plate surfaces. This figure illustrates a stack of eight positive plates and nine negative plates where the positive plates are encased in separators. Both positive and negative plates are formed by grids with integral enlarged perimeter current collector segments **202** where a further enlarged portion **203** forms a bus bar segment. In this example, arrows **204** indicate the flow of current along a positive plate. The current flows across the electrode plates along paths, that are approximately perpendicular to the bus bars **201** and **202**, and then along the perimeter current collector to a terminal (shown in a later figure) inserted into the end of the enlarged section. In this example, the positive/negative plate pairs are electrically in parallel. The current flow in the negative grid structure and perimeter current collector is similar but in the opposite direction to its positive counterparts. Current flows at approximately uniform current density from the negative plate across the electrolyte impregnating the separator material to its neighboring positive plate. As can be seen, the direction of current flow is approximately uniform over the entire plate. This allows the electrodes, which include the grid and paste material, to change over time at a reasonably constant rate over each electrode's entire surface area, tending to extend the life of the plates and hence the cell.

Internal Heat Flow Distribution

[0144] FIG. 3 is a schematic of a typical prior art large capacity cell internal construction showing the approximate paths of heat flow on the plate surfaces. This heat is the heat generated by the ohmic resistive losses in the electrolyte and plates of the cell. This figure illustrates a stack **301** of three negative plates and three positive plates where the positive plates are encased in separators. In this example, arrows **302** indicate the flow of heat along either a positive or negative plate. If the sides of the plates are close to the insides of the case walls (not shown), then heat can traverse the gap between the edge of the plates and the case wall. If the case walls are sufficiently thin, then heat can flow through the case walls to the outside where it can be removed, for example, by a forced convection cooling system. Typically, only a small fraction of heat flows out the bottom of the cell because the cell normally rests on a non-conductive surface to isolate the cell from electrical ground faults. Also, a small fraction of heat flow may follow the path of the tabs and bus bar. Little heat will be removed through the top of the case because of an air gap above the plate stack that absorbs gas vented from the cell reactions, especially during overcharging. Some heat may flow across the plates (orthogonal to arrow **302**) but the lowest net resistance to heat flow is commonly across the plates as shown by arrow **302**.

[0145] FIG. 4 is a schematic of a large capacity cell of the present invention showing the approximate paths of heat flow on the plate surfaces. This figure illustrates a stack **401** of nine negative plates and eight positive plates where the positive plates are encased in separators. As in FIG. 2, both positive and negative plates are formed by grids with integral enlarged perimeter current collector segments where

a further enlarged portion forms a bus bar segment. In this example, arrows **402** indicate the flow of heat along either a positive or negative plates. The flow of heat is primarily along the plate towards the integral enlarged perimeter current collector. A small amount of heat can flow away from the integral enlarged perimeter current collector but it has to flow across a resistive gap formed by separator material and electrolyte to reach the integral enlarged perimeter current collector of the adjacent plate of opposite electrical polarity. In this configuration, the sides of the perimeter current collectors are intimately in reasonably intimate contact with the insides of the case walls (described in subsequent figures). In this configuration, the heat flow can readily traverse the contact area between the side of the perimeter current collector and the inside of the case wall. The case walls are made sufficiently thin so that heat can flow efficiently through the case walls to the outside where it can be removed, for example, by a forced convection cooling system. Typically, only a small fraction of heat flows out the bottom of the cell because the cell normally rests on a non-conductive surface to isolate the cell from electrical ground faults. Also, a small fraction of heat flow may follow the path of the enlarged bus bar segment. Little heat will be removed through the top of the case because of an air gap above the plate stack that absorbs gas vented from the cell reactions, especially during overcharging. Some heat may flow across the plates (orthogonal to arrow **402**) but the lowest net resistance to heat flow is commonly along the plates as shown by arrow **402**.

Structural Integrity

[0146] FIG. 5 shows a schematic representation of a plate deformation mechanism for the construction of prior art cells such as shown in FIGS. 1 and 3. This mechanism may be enabled by application of a strong force such as intense vibration or shock loading caused by dropping for example or by prolonged vibration such as experienced by a locomotive moving along the tracks. In many prior art large capacity batteries, the cells are fabricated by stacking a series of positive and negative plates separated by a separator material. Next, positive and negative bus bars are then typically welded to positive and negative tabs that extend from the tops of the positive and negative plates respectively, as shown for example in FIGS. 1 and 3. The tabs for the negative plates are typically located off to one side of the plate while the tabs for the positive plates are located off to the opposite side. This positioning, which is shown for example in FIGS. 1 and 3, allows the bus bars to be attached so that positive and negative terminals are sufficiently far apart to avoid incidental electrical shorting. The bus bars therefore hold the positive and negative plates in the desired position with the remainder of the stacked structure held in position by friction between the plates and separator material. An extra negative plate may be added on the end of the stack so that the negative bus bar, when attached to all the negative plates, allows the negative plates on the ends of the stack to hold the assembly together to a necessary extent to allow installation into a battery case. Next, the stacked assembly is typically positioned tightly inside a battery container case. The battery case therefore holds the stacked assembly in the desired position where now the inside walls of the battery case, again aided by friction between the plates and the separator material and by the clamping action of the bus bars, secure the plates and separator layers in the stacked assembly from moving relative to one another. Finally, the

separator material is impregnated with an appropriate electrolyte and the top of the battery case is installed. FIG. 5 shows a typical plate 501, which may be positive or negative, and its electrode tab 502 offset to one side of the top of the plate 501. When the plate 501 is welded to its bus bar, the plate becomes mechanically attached to the bus bar. However, except for frictional forces between the plates and the separator material, all plates can rotate about an axis 503 that is approximately coincident with its tab 502. In the case of severe and prolonged vibration or shock loading, the net effect of the changing gravity and frictional forces may be to cause a plate such as 501 to rotate about an axis such as 503. The rotation may occur as a result of the tab being deformed which is a likely mechanism for a material such as lead. The corner 505 of the plate 501 can rotate downward by a small amount causing the plate 501 to come to a new position shown by the a new plate position 504. This amount of plate movement can result in a significant change in the resistance between adjacent positive and negative plates since the separator material is generally compressible and even more deformable than the plate material and will change its shape and volume to adjust to the new plate position. It is noted that, when electrolyte is added to complete the fabrication process of the battery, that the friction between the plates and separator material is generally reduced.

[0147] FIG. 6 is an isometric view of a grid structure of the present invention showing its integral enlarged perimeter current collector segment. FIG. 6 illustrates a typical positive or negative plate which consists of a grid section 601 on which the appropriate positive or negative paste is applied. Also shown are an integral enlarged perimeter current collector segment 602 which has a further enlarged portion 603 which functions as a bus bar and a top and bottom sub-segment 604 which provides structural rigidity. The segments 601, 602, 603 and 604 are preferably all part of a single cast lead structure.

Cell Design

[0148] FIG. 7 is an isometric view of a stack 701 of nine grid structures, each grid structure 702 identical to the structure shown in FIG. 8. This figure illustrates how the enlarged portions 703 stack together to form a bus bar. This enlarged portion is preferably rounded in cross-section but may be elliptical, slightly rectangular or square in cross-section. This figure also illustrates how the side sections 704 of the perimeter current collector, stack together to form a side plate. As can be seen, the top and bottom sub-segments 705 stack together to give the structure rigidity and help maintain proper separation between plates.

[0149] FIG. 8 is an isometric view of two grid assemblies with separators. FIG. 8 shows separator pockets 802 which are slipped over plates 801. The separators 802 fit closely along the inside of the raised portions of the perimeter current collector which comprises a side plate sub-segment 803 and top and bottom sub-segments 805. Typically and preferably, the separator pockets encase the positive plates but alternately the separators be used to encase negative plates. In some cases it may be desirable to use thin separator pockets to encase both positive and negative plates.

[0150] FIG. 9 is an isometric view of a positive plate-separator-negative plate stack assembly illustrating how a negative stack 901 comprised of nine plates is interlaced with a positive stack comprised of eight plates 902 to form

a cell, where all plate assemblies are connected electrically in parallel. The top and bottom sub-segments 904 and 905 of the perimeter current collectors form a rigid structure and provide space 906 along the top and bottom for compression assembly (described later) and gas venting. In this figure, a negative grid 903 is shown facing outwards.

[0151] FIG. 10 is an isometric view of a plate stack assembly with end plates. The end plates 1001 and 1002 complete a stack of positive and negative plates. The end plates contain a groove 1003 which allows a compression strap to tie the assembly together in positive compression. The groove 1003 also has sufficient clearance to allow gas venting as will be described in a subsequent figure. The end plates 1001 and 1002 also include a passage 1004 in the enlarged section that lines up with the enlarged bus bar segments of the grid plates. This provides for insertion of an electrical terminal as described in subsequent figures.

[0152] FIG. 11 is an isometric view of a plate stack assembly with end plates which are strapped in compression. The end plates 1101 and 1102 hold the stack in compression with strap 1103. This strap may be elastic or have some other means of tightening (not shown) so as to maintain the plate stack within a desired range of compression (typically the cells would be maintained under positive compression force equivalent to a pressure of about 10 to about 100 kPa, depending on the strength of the separator material. The compression is meant to be high enough to prevent active paste particles from dislodging and moving around while not being so high that the separator matrix is distorted or electrolyte is squeezed from the separator matrix). The strap 1103 may be designed to maintain the plate stack within a desired range of compression as the plates and/or separators expand and contract slightly with temperature, level of charge, discharge or charging episodes. This positive compression is known to extend cell lifetime as it prevents movement and sloughing of paste material on the positive and negative plates. In many prior art large energy storage cells, compression of the plate stack is often obtained by forcing the stack into a case and relying on the case to maintain compression. This method has no provision for maintaining compression on the stack when the stack shrinks relative to the interior case walls.

[0153] FIG. 12 is an isometric view of a plate stack assembly with end caps prior to installation in a case. End caps 1201 and 1202 are added to the stack and are positioned on the end plates described in FIG. 11. The end caps 1201 and 1202 contain openings 1203 for gas vents on both the top and bottom of the end caps 1201 and 1202. The end caps 1201 and 1202 do not provide compression for the stack but do form the outside ends of the cell. As can be seen, the end caps include a passage 1204 in the enlarged section that lines up with the enlarged bus bar segments of one set of grid plates on one side but no passage on the opposite side 1205. In this example, the passages 1204 on the right front side will contain the negative cell terminals while the passages (not shown) on the left back side will contain the positive cell terminals.

[0154] FIG. 13 is an isometric exploded view of interior components for further reference. This view shows a negative plate 1302, a positive plate 1303 and its separator pocket 1304, and an end plate 1305. A stack 1301 with some of these components assembled is also shown.

[0155] FIG. 14 is an isometric view of a case 1402 for containing the internal components. The case 1402 is an integral plastic container molded to provide for the perimeter current collectors of the stacked plate assembly. The case in this example is shown with molded sections 1401 for the bus bar assemblies and other molded sections 1403 to allow for gas vents. As can be seen, the case can be made longer to accommodate a larger stack of plates. The ability to readily scale the storage capacity of the cell by making the cell longer is an important feature of the present invention as it allows the cell to be scaled up or down in electrical storage capacity by changing only the case length. As can be appreciated, the shape of the molding can be changed for different geometries of perimeter current collectors and different aspect ratios of the plate widths and heights.

[0156] FIG. 15 is an isometric exploded view showing most of the components of the cell of the present invention. FIG. 15 shows internal components such as a negative grid 1502, a positive grid 1503 and a separator 1504. These are stacked together as shown by an assembly 1507 and the stack held together in compression by end plates 1505 and strap 1506, as described previously. The strapped stack along with its end caps 1506 are fit into the case 1501 as will be described subsequently. Then, components such as vents 1511, vent plugs 1512 and electrode terminals 1513 are installed as also will be described subsequently.

[0157] FIG. 16 is an isometric view showing a case 1601 and a completed stack assembly 1602 aligned for final assembly. As will be described subsequently, the case 1601 may be expanded while the stack assembly 1602 is inserted so that, after insertion, the case 1601 contracts and forms a tight interference fit around the stack assembly 1602.

Vent Configurations

[0158] FIG. 17 is a more detailed isometric view of several components such as a vent port 1702 with its vent hole 1703. Vent ports are typically installed in the top vent opening on one side of the cell and in the bottom vent opening on the opposite side of the cell as shown for example in FIG. 16. The vent ports are designed with a pressure relief means to seal the cell below a first predetermined pressure (typically in the range of 1 psi or less) and to open the vent port above a second predetermined pressure (typically in the range 1 to 3 psi or greater). The pressure relief means may be a Bunsen valve or another low-cost valve arrangement that is compatible with the fumes associated with the gas under pressure. There are a number of prior art means of pressure relief mechanisms known for sealed cells. A vent plug 1701 is used to close off the unused vent openings as also shown in FIG. 16. An electrode terminal 1704 with its recessed connection port 1705 is also shown. In a lead-acid cell, the vent port 1702 and vent plug 1701 are typically made of a material such plastic (for example ABS or polypropylene) that is resistant to corrosion or attack by the electrolyte. The electrode terminal 1704 is typically made of a conductive metal such as lead, copper, aluminum or steel or a composite of these materials.

[0159] The principal purpose of a vent valve is to release pressure during over-charge. A vent valve is typically designed to start relieving pressure at approximately 0.5 to 3 psi and to pass an amount of gas that is greater than would be expected from electrolysis at the end of charging cycle. The issue for fast charging or hybrid operation is that an

individual cell or module could electrochemically fail and then go into electrolysis and a subsequent boiling condition upon the application of maximum current. The problem is that under the above condition typical cell gas vent valves can not pass enough gas and the pressure goes up. As the temperature goes up, the case distorts and finally if the condition persists the case fails along some edge or seam. Often the cell in a HEV application can go some time before it is recognized as having a problem.

[0160] A solution would be to have the normal relief valve and an over-pressure relief plug or burst disk. Under normal conditions the relief plug does nothing. When an over-pressure occurs the over-pressure relief plug blows out. This relieves the over pressure condition and would be designed to give a clear visual indication that the cell has experienced an over pressure condition and must be removed from the pack.

[0161] With the cell of the present invention, another solution may be to have two low pressure relief valves, one on top of a first end cap and one on the bottom of a second end cap. Additionally, there would be two high pressure relief valves, one on the bottom of the first end cap and one on the top of the second end cap. The low pressure relief valves may be set to vent gas when the pressure exceeds a first predetermined level (typically in the range of about 0.5 psi to about 5 psi). When the pressure is reduced below this pressure range, the low pressure relief valve closes. The high pressure relief valves may be set to vent gas when the pressure exceeds a second predetermined level (typically in the range of about 5 psi or higher). In addition, the high pressure relief valves may have a substantially larger orifice than the low pressure relief valves. When either of the high pressure valves are activated, they may be constructed to remain open, and/or sound an alarm on a cell monitoring system, if available.

Cell Construction Method

[0162] FIG. 18 is an isometric view of the cell after final assembly showing the case 1801 and one of the two end caps 1810. A gas vent port 1802 is shown installed in the upper gas vent molded opening of the end cap 1810. A vent plug 1803 is shown installed in the lower gas vent molded opening of the end cap 1810. In the opposite end cap (not visible in this figure), a gas vent port could be installed in the lower gas vent molded opening and a vent plug could be installed in the upper gas vent molded opening. This would allow gas to be vented from either the upper or lower volumes (see volume 906 in FIG. 9) independent of the up or down orientation of the cell. Alternately, four vent ports could be installed in all four gas vent molded openings. Electrode terminals 1804 are shown installed in the molded terminal openings. Electrode terminals of opposite polarity 1805 are shown installed in the molded terminal openings on the opposite end of the cell.

[0163] The present invention is an HEV specific cell design and is a scalable cell that has been designed to improve power, heat transfer and life characteristics compared to other large capacity cells. An important feature of the present invention is the ability to easily fabricate larger capacity cells by increasing the stack size (as determined by the number of positive/negative plate pairs) and lengthening the cell case. This capacity scaling is possible while maintaining a desired end cross-section. This means that a battery

pack can use the same rack system but with different cell counts (and hence overall series string voltage). This allows a trade off between pack voltage and capacity.

[0164] In a preferred embodiment, a cell is fabricated by stacking a number of positive and negative plate elements where the positive and/or negative plate elements have a separator material between them. The positive plate elements include a grid which is intimately connected to a side structure which forms a portion of the positive electrode (integral enlarged perimeter current collector) and a portion of the cell sidewall. The negative plate elements include a grid which is intimately connected to a mirror image side structure which forms a portion of the negative electrode and a portion of the opposite cell sidewall. The cell of the present invention can be used with a separator material impregnated with a liquid electrolyte or it can utilize a gel electrolyte.

[0165] The following is a step by step description of the general order of cell fabrication.

[0166] 1. The cast electrode grids (positive and negative) are made in a conventional manner but with a thicker edge on three sides to form an enlarged perimeter current collector border. The edge or perimeter current collector preferably forms a three-sided enlarged cross-section in plan view of plate.

[0167] 2. The cast electrode grids also employ large over sized rounded corners (preferably round, less preferably square).

[0168] 3. The grids are pasted in a normal fashion to become electrodes. A paste-like mixture of lead oxide, sulfuric acid and water is applied to the positive grids. A paste-like mixture of lead oxide, sulfuric acid, water and expander is applied to the negative grids.

[0169] 4. The positive and negative electrodes are then assembled with separators into a stack. The enlarged perimeter current collectors of the respective positive and negative grids are arranged on respective sides. The additional edge thickness of the enlarged perimeter current collectors on the grids essentially provides the spacing for the opposite polarity electrode and separator and provides structural rigidity to the final stacked assembly.

[0170] 5. The stack is compressed and held by nonconductive end plates and strapping.

[0171] 6. Using a hot plate technique the enlarged perimeter current collectors are all welded together on the respective positive and negative sides, forming a stack that is now electrically connected has substantial structure integrity.

[0172] 7. End terminals are prepared at the respective ends of the stack for the enlarged bus bar sub-segments of the perimeter current collectors, two positive and two negative terminals at opposite ends of the stack.

[0173] 8. The stack is then slide longitudinally into an extruded ABS case that is pre-heated to expand (mechanical expansion of the case is another option).

[0174] 9. The extrusion case has over sized corners, allowing the oversized corner of the now welded grids to key into place

[0175] 10. As the preheated extruded case cools it forms a slight interference fit along the now-welded side sections of the perimeter current collectors of the stack to provide for efficient heat transfer to the appropriate case walls.

[0176] 11. The extrusion is arranged to provide a gas venting space on at least two longitudinal sides of the cell stack.

[0177] 12. Plastic end caps are mounted and sealed by glue (prior art technique).

[0178] 13. Terminals are also sealed by color coded glue (prior art technique).

[0179] 14. Integral to the end caps are relief valves that align with the gas venting spaces.

[0180] 15. Electrolyte is inserted via the relief valve holes and distributes over all electrodes (prior art technique).

[0181] 16. Relief valves are assembled on the end caps completing the cell.

[0182] A high capacity cell of the present invention has a width in the range of about 100 mm to about 300 mm; a height in the range of about 200 mm to about 500 mm; and a length in the range of about 300 mm to about 800 mm. The cell has a mass in the range of about 20 kg to about 400 kg. The cell has an open-circuit voltage in the range of about 1 volt to about 5 volts (depending on the cell chemistry) at the beginning of its life cycle and an ampere-hour capacity in the range of about 200 ampere-hours to about 4,500 ampere-hours at the beginning of its life cycle.

[0183] The grid structures are typically made from lead or lead alloys. The grid structure also comprises an integral perimeter current collector comprised of a side plate segment, a top and bottom segment and an enlarged portion which functions as a bus bar. These may be made of the same material as the grid structure. The integral side plate segment, top and bottom segments and an enlarged portion may also be made of other conductive metals or alloys such as, for example, aluminum or copper or combinations of these metals to improve electrical and thermal conductivity. The enlarged portion which functions as a bus bar may also be hollowed out so that a more conductive metal core can be inserted to further reduce internal ohmic resistance. The end plates, end caps and case may be fabricated from ABS, polypropylene, nylon or any other electrolyte-resistant plastic commonly used for battery cases. The separator material may be any commonly used separator material used in lead-acid batteries such as for example, absorptive glass mat, polypropylene loose weave cloth, hyalite glass, daramic microporous fabric, electrolytic paper and the like.

[0184] The thickness of the grids is typically in the range of about 1 to 10 mm and the thickness of the separators is typically in the range of about 2 to 12 mm. A cell of the present invention may contain from about 10 to about 100 plate pairs.

Connections to Other Cells

[0185] FIG. 19 is an isometric view of two cells in longitudinal arrangement. Positive terminals 1901 are connected to negative terminals 1902 so that the cells are electrically connected in series. In this example, gas vent ports 1903 are shown on the top side of the cells and vent plugs 1904 are shown on the bottom side of the cells for the

end plates in view. As can be seen, the cells can be lined up in a compact series string with couplers **1905** as shown. Alternately, positive terminals can be constructed as male fittings to fit inside negative terminals which may be female. Alternately, the positive terminals may be coupled to the negative terminals using compact coupling unions (not shown). As can also be seen, the sides of the cells are recessed because of the enlarged bus bar channels top and bottom, so that when strings of cells are arranged side by side (not shown), the recessed sides form passage ways that can be used as convective air ducts for efficient cooling. As noted previously, heat preferentially flows from inside the cells along the positive and negative plates to their respective side plates which are in intimate contact with the side walls of the cells.

[**0186**] When a series of cells are connected, they can be physically placed in a longitudinal or lateral pattern. When a series of cells are connected in a longitudinal pattern, they are in an axial position and alternately rotated 180 degrees to make the negative to positive terminals align as shown for example in FIG. 19.

[**0187**] FIG. 20 is an isometric view of several cells in lateral arrangement. Positive terminals **2001** are connected to negative terminals **2002** so that the cells are electrically connected in series. In this example, gas vent ports **2003** are shown on the top sides of alternate cells while vent plugs **2004** are shown on the bottom sides of alternate cells. As can be seen, the cells can be lined up in a compact string with positive terminals being attached to negative terminals by short straps **2005** or specially made U-shaped couplers (not shown). As can also be seen, the sides of the cells are recessed because of the enlarged bus bar channels top and bottom, so that when cells are arranged side by side as shown, the recessed sides form passage ways that can be used as forced air ducts for efficient convective air-cooling.

[**0188**] The straps, couplers or unions that are used to connect adjacent cells may be made from any suitable material such as, for example, copper, aluminum, lead or any combination of these.

Cell Resistance

[**0189**] The total resistance of a cell can be considered in 3 principal parts: (1) resistances in the bus bar structures; (2) resistances across the plate grids; and (3) resistances across the electrolyte between electrode plates. Typically as the plates of a cell are made larger, the relative contributions of the resistances across the electrolyte between electrodes decreases relative to the resistances along the plate grids towards or away from the bus bars. In cells of the size required for large HEV applications, the resistances across the plate grids are of the same order as the resistances across the electrolyte between electrodes so any reductions of the resistances across the plate grids and resistance in the bus bar structures are of significance to overall cell resistance.

[**0190**] In the cell of the present invention, current flows at approximately uniform current density from the negative plates across the electrolyte impregnating the separator material to its neighboring positive plates. Current flows along paths that are approximately perpendicular to the bus bars across the electrode. This minimizes internal plate resistance and maintains an approximately uniform current flow across the electrolyte for all plates in the stack plates.

This geometry also allows heat energy to be generated uniformly by each plate no matter where it is in the stack and directs a major portion of the internally generated heat to a side plate which can be in substantial or even intimate contact with the inside of the plastic case. Additionally, the integral perimeter current collector structure along with active compression of the plate stack gives the cell of this invention a structural rigidity that resists damage caused by shock and vibration. The cell of the present invention incorporates "flow through" design to balance the electrode usage throughout the cell and across each grid. This method directs the current such that no matter which active pair the current crosses on, it travels the same total distance in the bus bar. FIG. 21 is an isometric view illustrating this flow through principle. FIG. 21 shows the current path for the component of current generated by a single plate pair. The current component flows into the positive terminal **2101** along a positive bus bar **2103**, across and through a plate pair and along a negative bus bar **2104** and out the negative terminal **2102**. As can be seen, the component current path for any plate pair will always involve the same length of bus bar. Because current flows in an approximately identical and uniform pattern across each plate, the current density of the current flow through the electrolyte between the plates is also substantially uniform. This allows the electrical potential at any point across the plates to remain substantially constant (the electrical potential being the open-circuit voltage minus the resistive or IR drop). Thus, the electrochemical reactions during either charging or discharging remain substantially uniform over the surface of the plates. This, in turn, allows the surface chemistry to tend to change uniformly over the surface of the plates over the lifetime of cell operation. This uniformity of electrochemical minimizes the tendency to form areas on the plates of lower conductivity, higher sulfation and the like. It can also be seen from FIG. 21, that the voltage measured between the positive and negative bus bars is substantially the same between opposite, or opposing, points anywhere along the length of the bus bars.

[**0191**] The following is a brief analysis of the internal cell resistance of a large cell of the present invention. These are typical values for a typical configuration of the cell. The electrical resistivity (ρ) of lead (Pb) is approximately 0.207 milliohms-mm. To determine the resistive drop (R) in ohms, of a lead component requires the electrical resistivity to be multiplied by the length (L) and divided by the cross section (A) of the component. Only 1 of the 2 terminals will be analyzed. This results in the resistive value of the single path being divided by 2 to account for the other parallel path. Again, due to symmetry, only half the path (positive terminal, positive bus bar, and positive grid) will be analyzed. Multiplication of this value by two will be required to determine the total resistance of the path.

[**0192**] The terminal may include, for example, a copper threading integrally located in the end of the bus bar. Due to copper's low electrical resistivity, the terminal distance can be neglected.

[**0193**] The bus bar consists is formed by the stack of the enlarged sub-sections of the perimeter current collector of each grid, the perimeter current collectors of each stack being welded together to form a lead rod. Additional length will be included to account for the lateral travel throughout

the cross-section of the perimeter current collectors (referred to subsequently as the "C" section).

[0194] The grid is encompassed on one complete and two partial sides by the "C" section. Thus the length of travel in the grid will be estimated as $\frac{1}{2}$ length of a grid side.

[0195] To find the total resistance of the cell, the above value must be multiplied by 2 (to account for other symmetric side) and divided by 2 (to account for parallel terminals). This becomes a total ohmic resistance value of the terminals, bus bars, and grid equal to 0.0386 milliohms.

[0196] In a large prior art cell of comparable size and capacity as the cell of the present invention, the terminal, bus bar, and grid resistance limit the rate of power from the active material. Under high power conditions unequal uneven resistance across the active material can result in electrode state-of-charge imbalance as a function of location. Typically, area and length are used to determine the ohmic resistance of the terminal, bus bar, and grid of a cell.

[0197] A conventional prior art cell may have 4 parallel paths for current to travel through (4 terminal entrance and exits). Only 1 path will be analyzed and its result divided by 4 to account for the parallel paths. The current travels the following path: positive terminal, positive bus bar, positive tab, positive grid, electrolyte (not accounted for), negative grid, negative tab, negative bus bar, negative terminal. The resistive drop is therefore symmetric about the electrolyte. The following analysis will only account for $\frac{1}{2}$ of the path and then be multiplied by two to obtain the total resistive drop for the path.

[0198] The terminal goes through 3 distinct cross-sections as it makes its way to the bus bar. Analysis will begin just below the threaded copper insert (the same as used for the example analysis of the cell of the present invention), since copper's resistivity is $\frac{1}{10}$ th that of lead and therefore a minimal resistance.

[0199] The terminal center-taps the bus bar, meaning that the current flowing through the terminal can travel in two directions (outward) when it reaches the bus bar. These two paths are effectively in parallel. Analysis has shown that current reduces nearly linearly as it proceeds from the center of the bus bar to the end of the bus bar. It is therefore assumed that the average current travels a path length equal to $\frac{1}{2}$ of the half-bus bar part (equivalent to $\frac{1}{4}$ of the specific terminals bus bar length).

[0200] Current flows into the grid from the bus bar through a tab. The current then spreads out through the grid. Average length of travel within the grid is approximated from grid design and size. There are 9 grids and therefore 9 parallel paths for the current to flow.

[0201] To find the total resistance of the cell, the above value must be multiplied by 2 (to account for other symmetric side) and divided by 4 (to account for parallel terminals). This becomes a total Ohmic resistance value of the terminals, bus bars, and grid equal to $R=0.0681$ milliohm

[0202] Thus, the cell of the present invention can reduce internal cell ohmic resistance of the electrode plates and current distribution system by approximately a factor of two over that of a comparable prior art cell, due to the more efficient geometry of the plates with their integral perimeter current collectors. This represents a significant reduction in

total cell resistance for large cells based on the design principles of the present invention.

[0203] A number of variations and modifications of the invention can be used. As will be appreciated, it would be possible to provide for some features of the invention without providing others. For example, in one alternative embodiment, a number of cells can be packaged into a single molded case to form a battery unit with a different output voltage. In the case of lead-acid cells, a number "n" of 2.1 volt cells can be connected electrically in series and packaged in a single or in a composite outer case molded to accept the individual cells to form an "n" times 2.1 volt battery. Additional cells can be added in this way as long as provisions are made for gas venting of cells in the interior of the assembly. This configuration can be deduced from FIG. 19 where the couplers 1905 are collapsed and replaced by a nonconductive separator plate with provisions for internally connecting the bus bars of the two cells and with provisions for internal vent passages.

[0204] As can be appreciated by one skilled in the art, the stackable and scaleable geometry of the present invention can be adapted to flow cells and flow batteries by adding suitable electrolyte tanks, pumps, control valves and electrolyte flow passages in the cells.

[0205] The present invention, in various embodiments, includes components, methods, processes, systems and/or apparatus substantially as depicted and described herein, including various embodiments, sub-combinations, and subsets thereof. Those of skill in the art will understand how to make and use the present invention after understanding the present disclosure. The present invention, in various embodiments, includes providing devices and processes in the absence of items not depicted and/or described herein or in various embodiments hereof, including in the absence of such items as may have been used in previous devices or processes, for example for improving performance, achieving ease and/or reducing cost of implementation.

[0206] The foregoing discussion of the invention has been presented for purposes of illustration and description. The foregoing is not intended to limit the invention to the form or forms disclosed herein. In the foregoing Detailed Description for example, various features of the invention are grouped together in one or more embodiments for the purpose of streamlining the disclosure. This method of disclosure is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the following claims are hereby incorporated into this Detailed Description, with each claim standing on its own as a separate preferred embodiment of the invention.

[0207] Moreover though the description of the invention has included description of one or more embodiments and certain variations and modifications, other variations and modifications are within the scope of the invention, e.g., as may be within the skill and knowledge of those in the art, after understanding the present disclosure. It is intended to obtain rights which include alternative embodiments to the extent permitted, including alternate, interchangeable and/or equivalent structures, functions, ranges or steps to those claimed, whether or not such alternate, interchangeable

and/or equivalent structures, functions, ranges or steps are disclosed herein, and without intending to publicly dedicate any patentable subject matter.

What is claimed is:

1. An electrochemical energy storage device, comprising:
 - (a) a plurality of stacked electrodes arranged in a plurality of electrode plate pairs, each electrode pair comprising an adjacent positive and negative electrode separated by a layer or separator matrix of electrolyte and the plurality of electrode plate pairs being arranged such that adjacent electrodes have opposing polarities;
 - (b) a positive bus bar interconnecting the positive electrodes; and
 - (c) a negative bus bar interconnecting the negative electrodes, wherein at least one of the following is true at charging or discharging rates between about 0.5 C and 2 C;
 - (c1) at least one of the positive and negative bus bars contacts the corresponding positive and negative electrodes, respectively, to provide a substantially uniform current density between each of the corresponding contacted electrodes;
 - (c2) at least one of the positive and negative bus bars contacts physically at least half a length of a peripheral edge of each of the corresponding positive and negative electrode plates, respectively, to maintain a relative orientation of the bus bar and corresponding electrodes substantially constant over time;
 - (c3) for each electrode plate pair, an electron travels an electrical current path of a substantially constant electrical resistance, the current path extending from the positive bus bar, through the positive electrode, traversing the electrolyte and through negative electrode, and to the negative bus bar;
 - (c4) a substantial length of a peripheral edge of at least one of the positive and negative bus bars contacts physically a case enclosing the electrode pairs to remove thermal energy generated by the flow of electricity;
 - (c5) for each electrode plate pair, a substantially constant electrical potential gradient normal to the bus bars exists across any grid structure on the surface of the electrodes;
 - (c6) at any point along the lengths of the positive and negative bus bars, a substantially constant electrical potential exists between opposing points on the bus bars;
 - (c7) for each electrode plate pair, a substantially constant electrochemical potential exists between any opposing points on the electrode pair; and
 - (c8) at any point in an enclosed volume of the device, a substantially constant electrochemical reaction exists.
2. The device of claim 1, wherein (c1) is true.
3. The device of claim 2, wherein the positive electrodes are electrically connected in parallel with the negative electrodes and wherein the at least one of the positive and

negative bus bars contacts physically the entire length of a peripheral edge of the corresponding positive and negative electrode plates, respectively.

4. The device of claim 2, wherein the electrochemical energy storage device is a cell and wherein the current density between the corresponding positive and negative electrodes varies no more than about 15%.

5. The device of claim 1, wherein (c2) is true.

6. The device of claim 5, wherein the electrochemical energy storage device comprises a plurality of cells, wherein the electrode pairs are electrically connected in parallel, and wherein the case contacts the at least one of the positive and negative bus bars substantially along the entire peripheral edge of the bus bar.

7. The device of claim 6, wherein the plurality of stacked electrodes is compressed and maintained in compression by a compression member.

8. The device of claim 1, wherein (c3) is true.

9. The device of claim 8, wherein (c4) is true.

10. The device of claim 1, wherein the at least one of the positive and negative bus bars comprising a plurality of segments, wherein each segment is associated with a corresponding electrode, wherein the bus bar segments are stacked one on top of the other, wherein each of the bus bar segments has a first width, wherein the corresponding electrode contacting each segment has a second width, and wherein the first width is greater than the second width, with the difference in the first and second widths being related to a thickness of an oppositely polarized electrode to be received between the adjacent commonly polarized electrodes contacting the stacked segments.

11. The device of claim 10, wherein the at least one of the positive and negative bus bars is both the positive and negative bus bars, wherein at least one gas venting space is positioned between the positive and negative bus bars, and wherein the case substantially contacts the peripheral edges of the bus bars.

12. The device of claim 7, wherein the positive and negative electrodes are in the form of a grid comprising a paste, wherein the plates are in contact with an electrolyte, wherein a compressible separator material is positioned between adjacent oppositely polarized electrodes, wherein the compressive force exerted on the electrodes ranges from about 10 to about 100 kPa, wherein the compression member is separate from the case, and wherein nonconductive end plates are positioned at either end of the plurality of stacked electrodes.

13. The device of claim 11, wherein high and low pressure relief valves are in fluid communication with the venting space.

14. The device of claim 1, wherein (c5) is true.

15. The device of claim 1, wherein (c6) is true.

16. The device of claim 1, wherein (c7) is true.

17. The device of claim 1, wherein (c8) is true.

18. An electrochemical energy storage device, comprising:

(a) a plurality of stacked electrodes arranged in a plurality of electrode pairs, each electrode pair comprising an adjacent positive and negative electrode and the plurality of electrode pairs being arranged such that adjacent electrodes have opposing polarities;

(b) a positive bus bar interconnecting the positive electrodes;

- (c) a case enclosing the stacked electrodes; and
- (d) a negative bus bar interconnecting the negative electrodes, wherein at least one of the following is true;
 - (d1) the positive and negative bus bars are segmented, each segment physically contacting a corresponding electrode, wherein the positive bus bar segments are stacked one on top of the other to define a plurality of spaced apart positive electrodes and the negative bus bar segments are stacked one on top of the other to define a plurality of spaced apart negative electrodes, each of the negative electrodes being received in a corresponding inter-electrode space between adjacent positive electrodes and each of the positive electrodes being received in a corresponding inter-electrode space between adjacent negative electrodes;
 - (d2) the positive and negative bus bars are segmented, each segment physically contacting at least most of a selected peripheral edge of a corresponding electrode, the adjacent segments being stacked one on top of the other to form the respectively polarized bus bar;
 - (d3) the positive and negative bus bars define at least one gas venting space positioned between the positive and negative bus bars, wherein the case substantially contacts at least most of the peripheral edges of the bus bars;
 - (d4) the plurality of stacked electrodes is compressed and maintained in compression by a compression member separate from the case; and
 - (d5) the case comprises at least one offset member to define a channel between adjacent cases when the cases are positioned side-by-side.

19. The device of claim 18, wherein (d1) is true.

20. The device of claim 18, wherein (d2) is true.

21. The device of claim 18, wherein (d3) is true.

22. The device of claim 18, wherein (d4) is true.

23. The device of claim 18, wherein (d5) is true.

24. A method for manufacturing an electrochemical energy storage device, comprising:

- (a) stacking a plurality of segments of a positive bus bar, each segment being in electrical contact with a positive electrode;
- (b) stacking a plurality of segments of a negative bus bar, each segment being in electrical contact with a negative electrode;
- (c) positioning electrolyte separators between adjacent electrodes;
- (d) intermeshing the stacked positive electrodes and negative electrodes such that positive and negative electrodes are positioned in an alternating sequence; and
- (e) positioning the intermeshed electrodes in a case.

25. The method of claim 24, further comprising:

- (f) heating the case to expand its enclosed volume, wherein step (e) occurs while the enclosed volume is thermally expanded.

26. The method of claim 24, further comprising:

- (f) compressing the intermeshed positive and negative electrodes before the positioning step (e).

27. The method of claim 24, further comprising:

- (f) welding the adjacent bus bar segments of the positive and negative bus bars to form substantially solid positive and negative bus bars after the intermeshing step (d).

28. The method of claim 26, wherein a nonconductive end plate is positioned on either side of the compressed, intermeshed positive and negative electrodes and wherein the case is attached to the end plates to form a sealed enclosure for the electrodes.

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