

METAL-AIR FUEL CELL

FIELD

[0001] The present invention relates to a metal-air fuel cell and uses thereof including use as a long-life, mechanically rechargeable, direct-current power source for devices and products.

BACKGROUND

[0002] The reference in this specification to any prior publication, or information derived from it, or to any matter which is known, is not, and should not be taken as an acknowledgement or admission or any form of suggestion that the prior publication, or information derived from it, or known matter forms part of the common general knowledge in the field of endeavour to which this specification relates.

[0003] Many products, in particular household and portable devices are designed to be powered by batteries, such as AA-cell, C-cell and D-cell batteries. Disadvantages when using such traditional batteries include: relatively short operational lifetime and limited shelf-life i.e. expiry due to degradation of the internal (closed system) components over time even when not in use. These devices are therefore also alternatively powered by other sources, including solar power or kerosene.

[0004] Disadvantages of using kerosene as an alternative power source include: high monthly costs; environmental pollutant (millions of tonnes of CO₂ and black carbon released into the atmosphere contributing to global warming); adverse impact on health (e.g. lungs, eyes, skin and general wellbeing); potential fire hazard (due to flammability); safe storage and regular purchase issues; not suitable as a power source for some products and devices (such as emergency beacons, radios, communications equipment and recharging docks for USB devices); and even the potential for poisoning caused by accidental drinking due to confusion as a beverage.

[0005] Disadvantages of using solar energy as an alternative power source include: variability in amount and duration of sunshine (particularly during winter); impact of rain (which can reduce solar potential to near zero during tropical rainy / monsoonal season); cloudy conditions and fog can reduce power generation (by approximately 10-80%); shadows and haze can also reduce the effectiveness of solar power; impact of the sun's latitude (angle of the sun) and need to adjust position of solar capture device for effective capture; must be located outdoors to capture sunshine leaving them at risk of damage from

external elements as well as theft; and limitations of solar devices themselves in that they are not rechargeable so must be disposed of at the end of their life.

[0006] Metal-air fuel cells, such as magnesium-air fuel cells can also be used as an alternative to traditional batteries. Metal-air fuel cells are considered to offer certain advantages including: high energy density; low price; and long storage potential.

[0007] Generally speaking, metal-air fuel cells operate by suspension in an ionic aqueous solution, such as sea water or other saline solutions, which acts as the electrolyte between the air cathode and anode. The air cathode is exposed to oxygen to allow the electrochemical reaction to occur. By-products of this electrochemical reaction include:

- a) release of hydrogen gas (and minute amounts of chlorine gas); and
- b) waste materials from anode degradation (e.g. metal hydroxides).

[0008] Metal-air fuel cell technology is not without its disadvantages, including: leakage of the electrolyte from the cell; exposure of the electrodes to excess electrolyte causing performance interference; sealing problems; gas (e.g. hydrogen and chlorine) build-up and venting issues; dangerous temperature and pressure build up caused by runaway exothermic redox reactions, waste management issues associated with anode degradation (e.g. impaired cathode life caused waste material accumulation within the fuel cell in the absence of regular cleaning and electrolyte replacement).

[0009] Magnesium-air fuel cells have a typical lifespan of 50 to 100 hours before requiring replacement of the anode. Performance of the air cathode also often diminishes very rapidly after only 100 to 200 hours of use, or even during storage after initial use. Some metal-air fuel cells require stringent regular maintenance and cleaning activities by the user in order to maximize air cathode life.

[0010] Typical metal-air fuel cell configurations are exemplified by: US Patent Number 3,519,486 (7 July 1970), Huebscher, R.G. et. al.; and US Patent Number 3,963,519 (15 June 1976), Louie, H.P.

[0011] US3,519,486 describes a trapped electrolyte fuel cell that includes internal reservoir(s)/chamber(s) in the bottom of the cell to capture excess electrolyte. The captured excess electrolyte forms electrolyte pool(s) in which the electrodes and a matrix are positioned. The matrix is made of a material resistant to potassium hydroxide, such as a fibrous asbestos matting (column 2, lines 4-5). The cell must be sealed to prevent leakage of the electrolyte. Further, as the reservoir(s) are positioned in the bottom of the cell, the cell

must be positioned in an upright orientation to ensure electrolyte pooling and operation of the cell.

[0012] US3,963,519 describes another trapped electrolyte fuel cell with a protective shield spacer. The spacer provides structural strength to the cell and protects the cathode while permitting air to pass over the entire surface of the cathode. This design was considered an advance over earlier heavy-framed metal/air battery constructions that were considered unsuitable for use as primary and secondary lightweight metal-air cells of AA, C and D cell configurations. A liquid-tight configuration to internally seal the electrolyte is described.

[0013] Neither US3,519,486 nor US3,963,519 describes a process for removing or isolating accumulated anode-degradation waste and/or venting by-products to alleviate pressure build-up.

[0014] Development of metal-air fuel cell technologies is ongoing. For example Aqua Power System, Japan is presently seeking to advance metal-air fuel cell technology as described in at least the following three PCT patent applications and marketed as their “Realistic Magnesium Air Fuel” (RMAF) system technology (<http://aquapowersystems.com/technology/how-aqua-powers-technology-works/>, website accessed 19 December 2016).

[0015] WO2014/097909 (Aqua Power System, Japan; also published as US2015/0340704 A1), discloses a metal-air fuel cell with a layered cathode body including water repellent and electrically conductive carbon material(s). The resulting fuel cell is described as highly water repellent, air permeable, and leakage resistant.

[0016] WO2014/115880 (Aqua Power System, Japan; also published as US2015/0364800 A1), provides a magnesium-air fuel cell with a comparatively shorter distance between the anode and the cathode to improve the electrochemical reaction. The height and width of the fuel cell, relative positioning of the anode and cathode, and use of a water supply pipe further including a reaction gas discharge pipe is said to generate a stable supply of power for a relatively long period of time. However, as the inlet to the reaction gas discharge pipe may be located within the cell, the reaction gas discharge pipe may undesirably leak electrolyte and/or gas.

[0017] WO2014/115879 (Aqua Power System, Japan; also published as US2015/0380693 A1), discloses a magnesium-air fuel cell that can be turned on and off by virtue of a lid, that when fastened brings the terminals into contact to switch the power ‘on’ and when loosened, turns the power ‘off.’

[0018] RMAF technology is understood to be incorporated into a number of commercial products including a water-activated 1.5V AA battery (<http://aquapowersystems.com/products/batteries/>, website accessed 19 December 2016). However, as disclosed in the website, the Aqua Power battery is configured as a fixed-sized, closed system which requires manual introduction of the electrolyte via a small, hand-operated pipette.

[0019] Fluidic, Inc., (US) is another company presently seeking to advance metal-air fuel cell technology. The Fluidic, Inc., platform technology is understood to be incorporated into the first commercialised rechargeable zinc-air battery (<http://fluidicenergy.com/technology/>, website accessed 19 December 2016).

[0020] Fluidic, Inc., describe various advances in metal-air fuel cell technology including, for example: use of a dopant to increase the conductivity of the metal fuel oxidation product, i.e. the anode is doped degenerately (WO2014/062385, Fluidic, Inc.); use of additives in the ionically conductive medium to enhance electrodeposition and/or extending the cell's capacity (WO2014/160144, Fluidic, Inc.); hetero-ionic aromatic additives (WO2014/160087, Fluidic, Inc.); additives comprising poly(ethylene glycol) tetrahydrofurfuryl; and control of the concentration of additives in the ionic conductive medium (WO2016/123113 and WO2012/030723, Fluidic, Inc.). Other claimed advances resulting from design modifications include: to accommodate a gaseous oxidant receiving space (WO2013/066828, Fluidic, Inc.); a catch tray containing a catalyst material to catalyse the oxidation of waste particulates (WO2012/012364, Fluidic, Inc.); an anode having a scaffolding structure (WO2011/163553, Fluidic, Inc.); a fuel cell having a plurality of electrodes (WO2011/130178 and WO2012/037026, Fluidic, Inc. respectively) and multiple fuel cell systems (WO2011/035176, WO2012/106369 and WO2010/065890, Fluidic, Inc. respectively).

[0021] In general, the Fluidic, Inc. metal-air fuel cell technology is akin to conventional rechargeable batteries in that the process is reversible because the anode is not consumed and further that the anode is "doped" or coated to stop it from degrading.

[0022] Despite numerous advances in metal-air fuel cell technology, there remains an ongoing need to overcome certain disadvantages associated with the technology and to provide new sources of direct current power particularly in the form of batteries, for use in devices and products which are affordable, accessible, environmentally friendly (re-usable, recyclable), have a long-life (shelf and/or operation), are reliable and safe.

SUMMARY

[0023] Throughout this specification and the claims which follow, unless the context requires otherwise, the word “comprise” and variations thereof such as “comprises” and “comprising”, will be understood to include the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any other integer or step or groups of integers or steps.

[0024] The present invention provides a metal-air fuel cell comprising:

- (a) an anode;
- (b) a positionable air cathode;
- (c) an absorbent material layer adapted to retain electrolyte, the absorbent material layer positioned intermediate the anode and the air cathode such that it contacts the anode;
and
- (d) an elastic air cathode positioning means adapted to position the air cathode to ensure that the air cathode remains in contact with the absorbent material layer while accommodating any change in volume of the absorbent material layer;

wherein the absorbent material layer functions as an ionic transfer bridge between the anode and the cathode by retaining electrolyte.

[0025] Preferably the anode, the absorbent material layer and the air cathode are coaxially arranged such that the air cathode substantially surrounds the absorbent material layer and the absorbent material layer substantially surrounds the anode.

[0026] Preferably the anode, the absorbent material layer and the air cathode are provided in a laminate or ‘sandwich-layered’ arrangement such that, for example, the air cathode overlies the absorbent material layer which in turn overlies the anode.

[0027] Preferably the elastic air cathode positioning means is positioned around a cross-sectional perimeter of the metal-air fuel cell.

[0028] Preferably the elastic air cathode positioning means is either incorporated within or provided separate to the air cathode, and is selected from: an O-ring, a deformable polymeric material, an elastic (or rubber) band or an expandable mesh.

[0029] Preferably the metal-air fuel cell is contained within an open housing unit.

[0030] Preferably the metal-air fuel cell is activated or re-activated for use by allowing the absorbent material layer to retain electrolyte (e.g. by dipping the metal-air fuel cell in a liquid).

[0031] Preferably the absorbent material layer is pre-impregnated with ions to form electrolyte when the absorbent material layer retains water.

[0032] Preferably the absorbent material layer comprises a sub-layer of absorbent material that is pre-impregnated with ions, and a sub-layer of absorbent material that is not pre-impregnated with ions.

[0033] Preferably the absorbent material layer changes volume upon absorption or depletion of retained electrolyte, and/or capture of anode waste material.

[0034] Preferably the absorbent material layer comprises a woven or non-woven fibrous material or a combination thereof. It is further preferred that the absorbent material layer comprises fibrous cellulose, bamboo fibre or a combination thereof.

[0035] Preferably the anode comprises a magnesium alloy.

[0036] Preferably the air cathode comprises a sheet layer. It is further preferred that the air cathode is hydrophobic, air-permeable and comprises a layered Teflon material.

[0037] Preferably the metal-air fuel cell further comprises a paper separator layer located between the absorbent material layer and the air cathode to support and contain the absorbent material layer and/or further isolate and protect the cathode from anode waste precipitates.

[0038] In an embodiment the metal-air fuel cell is adapted and/or used to provide a direct current power source for use to power the operation of a product or device. Preferably the product or device is selected from the group consisting of: torches (including flashlights, mag-lights, pen lights); lights and lighting products or devices (including globe lights, LED lights, strobe lights and Christmas lights); safety or temporary lighting applications (including for road works); lanterns (including camping lanterns and Chinese lanterns); combination products (including flashlight-lantern combinations convertible between operation as a flashlight and as a lantern); household products (including electrical toothbrushes and shavers) emergency beacons (including EPIRB and directional finders); radios (analogue and digital); communications equipment (including radios, CB radios and small audio devices); toys (i.e. battery powered), power banks for rechargeable products and recharging docks for USB devices (small electronic products including mobile phones, i-pods, i-pads).

Definitions

[0039] Unless otherwise herein defined, the following terms will be understood to have the general meanings which follow.

[0040] "Air permeability" means, with respect to a material, one that is capable or has the ability to allow air to flow, diffuse or otherwise pass through it.

[0041] "Absorbent" means, with respect to a material, one that is capable or has the ability or tendency to soak up or absorb a fluid (liquid or gas), in particular, a liquid.

[0042] "Activate" means, with respect to the metal-air fuel cell of the invention, to make ready (active or operative) for use i.e. to generate electricity through a redox reaction of the metal-air fuel cell.

[0043] "Contractible" means, with respect to a material or object, capable of or adapted to decrease in size and/or volume by shrinking or contracting.

[0044] "Dipping" means the process of placing or immersing something briefly into a liquid.

[0045] "Dry storage" means to process of storing in dry conditions, that is, in a low humidity environment and devoid of atmospheric moisture.

[0046] "Elastic" means, with respect to a material or object, one that is capable of or has the ability to resume its original size and shape spontaneously after being stretched or compressed or otherwise deformed.

[0047] "Electrolyte" means a solution (liquid or gel, preferably liquid) that comprises ions and is capable of or has the ability to conduct electricity.

[0048] "Expandable" means, with respect to a material or object, one that is capable of or adapted to increase in size and/or volume by expansion.

[0049] "Hydrophobicity" means, with respect to a material, one that is capable of or has the ability to repel (as opposed to attract or absorb) water.

[0050] "Mechanically rechargeable" means, with respect to a fuel-cell or battery, the replacement of the consumed anode, for example, in the case of a magnesium anode, the magnesium material is a storage medium for the electrons that are released during the chemical reaction and the magnesium material is consumed in the process.

[0051] "Pressure build-up" means, with respect to gas(es), the build-up of pressure due to gas(es) in a sealed or closed system.

[0052] "Shelf-life" means, with respect to a product, the period, length or duration of time for which the product remains usable including fitness for its original purpose.

[0053] "Venting" means, with respect to gas(es), the process of releasing gas(es) from a sealed or closed system including for example, via an outlet.

[0054] "Waste" means unwanted material or by-product(s) resulting from a process, such as for example in the case of a magnesium metal-air fuel cell, the magnesium hydroxide and/or gases such as hydrogen and chlorine that are produced from the electrochemical reaction in the cell when in use.

[0055] "Wicking" means the process of absorbing or drawing a liquid into or through a material by capillary action.

BRIEF DESCRIPTION OF THE FIGURES

[0056] The invention is further described with respect to the accompanying figures which illustrate preferred embodiments of a metal-air fuel cell according to the present invention. Other embodiments of the invention are possible, and consequently, the particularity of the accompanying drawings is not to be understood as superseding the generality of the preceding description of the invention.

[0057] FIGURE 1A: Shows a cross-sectional cutaway side view of a traditional magnesium-air (MgO_2) fuel cell as known in the art.

[0058] FIGURE 1B: Shows a cross-sectional partial cutaway side view of a magnesium-air fuel cell according to an embodiment of the invention.

[0059] FIGURE 2: Shows a cross-sectional cutaway side view of the magnesium-air fuel cell of FIGURE 1B to illustrate the uptake (absorption) of the liquid electrolyte (saline) by the absorbent material layer when dipped in liquid electrolyte.

[0060] FIGURE 3A: Shows a cross-sectional cutaway side view of the traditional MgO_2 cell of FIGURE 1A to illustrate the cell's gas build-up (fuel-cell reaction by-product) and venting process when in use.

[0061] FIGURE 3B: Shows a cross-sectional cutaway side view of the metal-air fuel cell of FIGURE 1B to illustrate the cell's gas build-up (fuel-cell reaction by-product) and venting process when in use.

[0062] FIGURE 4A: Shows a cross-sectional cutaway side view of the MgO_2 cell of FIGURE 1A, to illustrate build-up of corrosive magnesium anode waste precipitates (fuel-cell reaction by-product) on the cathode from use.

[0063] FIGURE 4B: Shows a cross-sectional cutaway side view of the metal-air fuel cell of FIGURE 1B, to illustrate prevention or reduction of corrosive magnesium anode waste precipitates (fuel-cell reaction by-product) build-up on the cathode from use.

[0064] FIGURE 5A: Shows a cross-sectional cutaway side view of the MgO_2 cell of FIGURE 1A, to illustrate the process of deposition and build-up of magnesium anode waste precipitates (fuel-cell reaction by-product) in the cell during use.

[0065] FIGURE 5B: Shows a cross-sectional cutaway side view of the metal-air fuel cell of FIGURE 1B to illustrate the capture or containment of magnesium anode waste by the absorption material in the cell during use.

[0066] FIGURE 6A: Shows a perspective view of a metal-air fuel cell according to the invention to illustrate the concentric layered (co-axial arrangement) construction of the internal anode rod, intermediate absorbent material layer, paper separator layer and external air cathode layer held or positioned in place with an elastic air cathode positioning means (such as an elastic O-ring or mesh) to accommodate expansion (and contraction) of the absorbent material layer upon uptake/absorption (or depletion) of the adsorbed liquid electrolyte and/or collection of anode waste precipitates over time through use.

[0067] FIGURE 6B: Shows a cross-sectional cutaway front view of the fuel cell of Figure 6A to illustrate the concentric layered (co-axial) construction before expansion of the absorbent material layer.

[0068] FIGURE 6C: Shows a cross-sectional cutaway front view of the fuel cell of Figure 6A to illustrate the concentric layered (co-axial) construction after expansion of the absorbent material layer.

[0069] FIGURE 7: Shows an exploded view of a magnesium-air fuel cell according to an embodiment of the invention to illustrate its various components.

[0070] FIGURE 8 shows a cross-sectional cutaway front view of a magnesium-air fuel cell to illustrate the absorbent material layer according to an embodiment of the invention.

[0071] FIGURE 9: Presents the endurance (milliAmps) test results for prototype Cells 1, 2 and 3 according to an embodiment of the invention over approximately 750 hours (Example 1, Experiment 1).

[0072] FIGURE 10: Presents the comparative power output (milliAmps) test results for a traditional MgO_2 cell and a prototype cell according to an embodiment of the invention over approximately 500 operating hours (Example 1, Experiment 2).

[0073] FIGURE 11: Presents the performance testing results (milliAmps) of prototype Cells 1, 2 and 3 according to an embodiment of the invention over approximately 500 hours (Example 1, Experiment 3).

DETAILED DESCRIPTION

[0074] FIGURE 1A shows a traditional MgO_2 cell as known in the art. The MgO_2 cell comprises a centrally positioned Mg anode (1) within a closed container (2) containing aqueous electrolyte (3) into which the anode is suspended. Air cathode (4) is incorporated into the outer wall of the container such that a redox reaction with the outside atmosphere can take place resulting in ionic exchanges occurring between the anode and cathode via the electrolyte.

[0075] As shown in FIGURE 3A, gas by-products generated by the MgO_2 cell of FIGURE 1A will build up in a void (12) within the closed system. These gas by-products must be vented (13) to the atmosphere through a vent hole (14) which allows the gas to vent but prevents electrolyte (3) leakage.

[0076] FIGURE 4A illustrates degradation of anode (16) of the MgO_2 cell of FIGURE 1A and corresponding anode waste precipitates (e.g. magnesium hydroxide) build-up (17) on the cathode (4).

[0077] In contrast to FIGURE 1A, FIGURE 1B shows a metal-air fuel cell according to an embodiment of the invention in which a magnesium anode (5) is positioned within an open container (6) comprising one or more vents (7) and surrounded by an absorbent material layer (8) which in turn is surrounded by the air cathode (9).

[0078] FIGURE 2 illustrates uptake of liquid electrolyte (10) by the metal-air fuel cell of FIGURE 1B. Electrolyte (10) is absorbed by the absorbent material layer (8) via a wicking action in the direction of arrows (11) when dipped into the electrolyte.

[0079] As shown in FIGURE 3B, the metal-air fuel cell of FIGURE 1B provides an open housing unit (6) with vents (7) that allow for gas exchange (including oxygen intake) and venting of the gas by-products in the direction of arrows (15).

[0080] While anode (5) is described as a magnesium anode, alternative metals, alloys or combinations of alloys to provide suitable anodes will generally be known to those skilled in the art. Suitable alternative metals include Li, Ca, Al, Zn and Fe. Preferably, the anode comprises a magnesium alloy such as "AZ31B" having the following composition:

Aluminium:	2.5 - 3.5
Copper:	0.05 max
Iron:	0.005 max
Magnesium:	Balance
Manganese:	0.2 min
Nickel:	0.005 max
Silicon:	0.1 max
Zinc:	0.6 - 1.4

[0081] As the anode (5) may be adapted to be internally, preferably centrally, located within the metal-air fuel cell, the anode may generally be formed in the shape of a rod or a cylinder and can be formed through extrusion. Where the metal-air fuel cell is alternatively configured in a sandwich-layered (i.e. laminate) arrangement, the anode, the absorbent material layer and the air cathode may each be provided as a substantially flat layer. This configuration may be particularly desirable in replacing certain rectangular battery shapes such as existing 9V batteries.

[0082] Air cathodes (9) that may be suitable for use in the metal-air fuel cell of the invention will generally be known to those skilled in the art. Suitable properties of the air cathode (9) include hydrophobicity and air-permeability. Preferably the air cathode (9) is in the form of a sheet layer adapted to accommodate the change in volume of the absorbent material layer (8) upon expansion and contraction. Preferably the air cathode (9) is hydrophobic and air-permeable and comprises a layered Teflon material. Still more preferably the air cathode (9) may comprise a layered Teflon material, carbon and nickel plated wire.

[0083] The absorbent material layer (8) may be a material with properties making it suitable for absorbing and retaining an absorbed amount of electrolyte. The absorbent material layer (8) essentially functions to transport the ions in the absorbed amount of electrolyte between the air cathode and the anode. It is therefore considered to act as an ionic bridging system (or ionic transfer bridge) which is required for operation of the cell.

[0084] The absorbent material layer (8) may be made from an absorbent material that is able to absorb and hold or retain electrolyte by a process of wicking, drawing, capillary action, or similar. The absorbent material may be selected based on its possessing one or more of, preferably all of the following properties:

- wicking and electrolyte retaining ability;
- ability to expand to accommodate an increase in volume due to the absorption of the liquid electrolyte and/or retention of the anode waste materials;
- ability to encapsulate solid particles so as to capture and/or retain the solid waste;
- ability to function as an “ionic bridge”; and/or
- ability to allow for exchange or diffusion of gases (i.e. for oxygen gas diffusion process and release of gas by-products during operation of the cell).

[0085] The absorbent material layer (8) may be made from a combination of air-permeable water absorbing, hydrophilic and/or hydrophobic materials and be conductive or non-conductive. Suitable materials may include woven or non-woven materials or combinations thereof produced from microfiber, rayon, cotton, cotton wool, hemp, wool, hessian, natural fiberwood pulp, aerogel composites, bamboo fibre pulp and/or any suitable combination thereof. Preferably the absorbent material layer comprises fibrous cellulose, bamboo fibre pulp or a combination thereof.

[0086] The performance of the absorbent material layer (8) may be enhanced with additives such as, for example, the addition of sphagnum and polyacrylate as well as other super absorbent gels derived from petroleum which will be familiar to those in the art.

[0087] The cell may be activated or re-activated for use when the absorbent material layer comprises an absorbed amount of electrolyte. The absorbent material layer (8) may comprise an absorbed amount of electrolyte following absorption of an electrolyte or water (when the absorbent material layer is pre-impregnated with ions). A preferred alternative arrangement of the absorbent material layer is set out and described in relation to FIGURE 8, which will be subsequently described in further detail.

[0088] The types of electrolyte that may be suitable for use in the metal-air fuel cell of the invention will be generally known to those in the art. Suitable examples may include but are not limited to an aqueous solution comprising ions such as NaCl (e.g. salt water, sea water and saline solutions), electrolytes (e.g. sports drinks), urine and alkaline solutions (e.g. KOH) and water (e.g. when the absorbent material is pre-impregnated with ions).

[0089] As shown in FIGURE 4B, anode waste precipitates (18) are captured within the absorbent material layer (8) of the metal-air fuel cell of FIGURE 1B and are prevented from making direct contact with the air cathode (9). This process is similarly illustrated in FIGURES 5A and 5B respectively, in which 5A illustrates anode waste precipitates build-up (17) on the cathode (4) of the MgO_2 cell of FIGURE 1A, while FIGURE 5B illustrates capture of anode waste precipitates (18) within the absorbent material layer (8) of the metal-air fuel cell of FIGURE 1B.

[0090] FIGURE 6A presents an metal-air fuel cell according to the invention which provides a co-axial arrangement of internal anode rod (19), substantially surrounded by absorbent material layer (20), which is in turn substantially surrounded by a paper separator layer (20A). The paper separator layer (20A) is in turn substantially surrounded by air cathode layer (21). Air cathode layer (21) is positioned by an elastic air cathode positioning means (22), such as an elastic O-ring or mesh, to retain contact with the absorbent material layer (20). The metal-air fuel cell is therefore able to accommodate expansion (and contraction) of the absorbent material layer upon uptake (or depletion) of the liquid electrolyte and/or collection of anode waste precipitates over time. In an alternative arrangement, the elastic air cathode positioning means could be incorporated into the air cathode layer such as by weaving elastic material into the air cathode.

[0091] A cross-sectional view of the fuel cell of FIGURE 6A is also presented to illustrate the absorbent material layer (20) before expansion (FIGURE 6B) and after expansion (FIGURE 6C). As shown in FIGURES 6B and 6C, the air cathode layer (21) remains positioned in contact with the absorbent material layer (20), and paper separator layer (20A), by virtue of the elastic air cathode positioning means.

[0092] FIGURE 7 shows an exploded view of a metal air fuel cell according to the invention to illustrate some of its various components. Magnesium anode (28), absorbent material layer (29), paper separator layer (29A) and air cathode (30) are co-axially arranged such that the air cathode (30) surrounds the paper separator layer (29A), which surrounds the absorbent material layer (29), which in turn surrounds the magnesium anode (28). Elastic air cathode positioning means (27) – formed of O-rings in the present embodiment – ensure

contact between the air cathode (30) and the absorbent material layer (29). The co-axial arrangement of electrodes is positioned within a vented housing (32). The vented housing (32) is closed at respective ends by a top lid (25) and a bottom lid (33), each held in place by a screw (24) secured to the anode (28). A contact ring (23) situated outside the top lid (25) provides a terminal from air cathode (30) and is connected to air cathode (30) by contact tab (31). Rubber or plastic O-rings (27A) and plastic washers (26) seal each end of the electrode arrangement and any electrolyte retained therein from other components to protect against corrosion.

[0093] As demonstrated by FIGURE 7, components of the metal-air fuel cell may be easily replaced by unscrewing one of the screws (24) holding either the top lid (25) or the bottom lid (33) in place to access the arrangement of electrodes. The magnesium anode (28) (and air cathode (30)) may therefore easily be replaced, providing an energy source that can be mechanically-recharged in a simple manner.

[0094] FIGURE 8 shows a cutaway view of a metal-air fuel cell of the invention to illustrate a preferred embodiment of the absorbent material layer. The metal-air fuel cell comprises in sequence moving inward from the outer circumference: air cathode positioning means 35, air cathode 34, paper separator layer 36 to support and contain the absorbent material layer, and further isolate and protect the cathode from anode waste precipitates, pre-impregnated sub-layer 37 of the absorbent material layer (being pre-impregnated with ions), non-impregnated sub-layer 38 of the absorbent material layer (being not pre-impregnated with ions), and anode 39.

[0095] According to the preferred embodiment illustrated the configuration of the absorbent material allows for control of the dissolution of ions into the retained electrolyte. This may in turn allow for control of matters such as dissipation or concentration of heat of solution arising when ions are dissolved into solution. This configuration may also allow control over the composition of electrolyte within sub-layers of the absorbent material layer particularly where, for example, pre-impregnated ions have a slow dissolution rate. This may in turn allow control of reaction-rates and temperature within the absorbent material layer and the metal-air fuel cell, noting that the redox reaction between the cathode and anode will typically be exothermic. In this way, higher temperatures caused by runaway redox reactions may be contained within particular zones or sub-layers of the absorbent material layer (e.g. sub-layer 37 as provided in the embodiment shown in FIGURE 8) that allow for greater evaporative cooling and resultant reduction in electrolyte content to restrict the runaway redox reaction.

[0096] As suggested by the drawings and preceding description, the metal-air fuel cell of the invention advantageously allows for expansion and contraction of the absorbent material layer upon absorption/release of electrolyte and/or capture of anode waste material. Further, potential advantages of the invention may include:

- the metal-air fuel cell may be simply and conveniently activated and re-activated on demand by dipping the absorbent material into electrolyte, and deactivated by being allowed to dry out between uses. This provides a metal-air fuel cell with a “dormant” mode in which components are not consumed, and the associated potential for a long shelf-life without any appreciable or significant loss in performance power of the cell;
- by providing a novel wicking and retention system for the electrolyte, the invention that may allow for configurations avoiding bulky water vessels and requiring less electrolyte, thereby reducing the weight of the cell while eliminating the potential for electrolyte leakage caused by, for example, tipping the fuel-cell from an upright position;
- by providing the metal-air fuel cell in an open housing unit, the invention may overcome disadvantages present in closed metal-air fuel cell systems, such as gas pressure build up and effective sealing of electrolyte, while also improving oxygen intake and venting of by-products;
- convenient replacement and recycling of components. The anode, the absorbent material layer, and the air cathode may be simply and conveniently replaced and recycled to provide an environmentally-friendly mechanically rechargeable device; and/or
- the novel wicking and retention system for the electrolyte may allow for increased thermal control to prevent a runaway exothermic reaction. Metal-air fuel cells work by creating an exothermic redox reaction between the anode and the cathode. In traditional metal-air fuel cells this creates the potential for runaway exothermic reactions, in which pressure and heat within the cell may rise to dangerous levels. The absorbent material layer of the invention allows for improved evaporation and venting of electrolyte as temperatures increase within the cell. This may in turn control runaway reactions by reducing available electrolyte through evaporation, thereby slowing the reaction. Any redox reaction within the cell would completely stop upon full evaporation of the electrolyte.

[0097] The metal-air fuel cells of the present application are, depending on their size, considered to potentially provide a power source equivalent to the use of 90-100 traditional

AA batteries. This is based on the known electrical storage of the materials in comparison to standard carbon AA dry cell batteries. An AA standard carbon battery has a storage capacity of less than one watt-hour (Wh) of energy (see for example, <http://www.allaboutbatteries.com/Energy-tables.html>, website accessed 19 December 2016).

Table: *Energy storage in AA batteries* (table reproduced from <http://www.allaboutbatteries.com/Energy-tables.html>, website accessed 19 December 2016)

Battery Type	Avg. voltage during discharge	Milli-Amp hours (mAh)	Watt-hours Wh	Joules J
Alkaline Long-life	1.225	2122	2.60	9360
Carbon-zinc	1.1	591	0.65	2340
Nickel-Cadmium	1.2	1000	1.20	4320
NiMH	1.2	2100	2.52	9072
Lithium Ion	3.6	853	3.1	11050

[0098] The magnesium alloy used has a storage capacity of one watt-hour (Wh) for every gram of material by weight. Accordingly, a 50 g magnesium alloy rod provides a potential 50 watt hours or storage whereas a heavier or larger magnesium rod, for example 150 grams provides 150 watt-hours of storage. The reference for Magnesium Galvanic Energy Density is as follows.

Metal-Air Types	Magnesium	Aluminium	Zinc
Specific Gravity	1.74	2.70	7.13
SHE	-2.363	-1.662	-0.763
Energy # electrons	2	3	2
Open circuit voltage	1.7	1.2	1.3
Anode composition	>90%	99.999%	99.99%
Current capacity Ah/kg	2200	2500 (alloy)	740
Electrolyte	Salt water	KOH	KOH
pH electrolyte	6 – 8	13 – 14	13 - 14

EXAMPLES

[0099] To test performance of the metal-air fuel cells according to the invention, a series of experiments were conducted using prototype cells constructed in accordance with the invention. In Experiment 1 prototype cells were tested alone. In Experiments 2 and 3, prototype cells were tested against a traditional MgO_2 fuel cell constructed substantially in accordance with FIGURES 1A, 3A and 4A.

Experiment Parameters

[0100] Identical anode and cathode materials were used in all tests.

Magnesium Anode

[0101] An extruded magnesium AZ31B rod (anode) having the following composition resulting in a magnesium anode composition of approximately (typically) 96% pure magnesium:

Aluminium:	2.5 - 3.5
Copper:	0.05 max
Iron:	0.005 max
Magnesium:	Balance
Manganese:	0.2 min
Nickel:	0.005 max
Silicon:	0.1 max
Zinc:	0.6 - 1.4

Air Cathode

[0102] An air cathode with sufficient hydrophobicity, consisting of layered Teflon material, carbon and nickel plated wire.

Configuration of traditional MgO_2 fuel cell

[0103] The traditional MgO_2 cell was of commonly understood configuration such that the magnesium anode was contained within a vessel of 5% saline water solution electrolyte, and the air cathode formed part of the vessel wall structure.

Configuration of Prototype cells

[0104] The prototype cells consisted of a 45 gram magnesium anode and an air cathode consisting of layered Teflon material, carbon and nickel plated wire. The anode was encapsulated in an absorbent material (woven cotton material rolled and woven into a mat-like substance). The air cathode was wrapped around the absorbent material and secured with elastic O-rings to allow for expansion.

Test Methodology

[0105] Electronic measurements were conducted using hand-held multimeters, of well-known voltage and amperage measurement accuracy (typically well within 1%) and stored in a climate-controlled environment. The instruments were allowed to warm up before measurements commenced.

[0106] The tests were conducted on a 24-hour basis in a climate controlled laboratory with typically 65% humidity and a constant air temperature of 25 degrees Celsius. The traditional MgO₂ cells were maintained by carefully emptying and replacing the saline electrolyte every 24 hours, while the prototype cells were dipped, for approximately 10 seconds, in the same saline solution every 24 hours.

[0107] An electronic load in the form of a high-efficiency DC to DC converter circuit powering 3 LEDs was used. This circuit was specifically designed to maximize load on the cells at all times, whilst maximizing brightness of the LEDs.

Experiment 1: Improvement in lifetime and performance of metal-air fuel cell (or endurance testing)

[0108] The experiment was conducted using three identically constructed prototype cells labelled as Cell 1, Cell 2 and Cell 3. The target was to generate at least 250 milliamps at over 1.2 volts (under constant electrical load) for 250 hours (the claimed run time in products).

[0109] Cell 1 and Cell 2 had a continuous electrical load (i.e. 24 hours per day) while control Cell 3 ran for four (4) hours per day under electrical load.

[0110] The voltage of each cell was not recorded daily but on a regular random basis. All cells maintained over 1.2V for the duration of the test and typically between 1.3V and 1.65V.

Results

[0111] The results are presented in Table 1 below and Figure 9.

Table 1: Endurance testing results (milliAmps) of Cells 1, 2 and 3 according to an embodiment of the invention over approximately 750 hours

Hours	Cell 1 (24/day) MilliAmps	Cell 2 (24/day) MilliAmps	Cell 3 (4/day) MilliAmps
24	520	470	420
48	270	380	380
72	250	290	360
96	210	510	510
120	190	250	310
144	180	540	530

Hours	Cell 1 (24/day) MilliAmps	Cell 2 (24/day) MilliAmps	Cell 3 (4/day) MilliAmps
168	680	610	590
192	420	520	590
216	450	610	490
240	410	590	520
264	440	360	350
288	380	450	390
312	490	380	510
336	440	260	660
360	450	230	510
384	300	330	330
408	240	300	280
432	280	290	480
456	430	410	480
480	380	330	380
504	280	490	580
528	330	450	420
552	380	430	360
576	430	580	500
600	320	500	480
624	460	350	410
648	250	370	380
672	240	310	280
696	260	380	410
720	250	350	170
744	180	340	280
768	150	240	280

[0112] The results show that the prototype cells exceeded the 250 milliamp target threshold after 264 hours, as follows:

Cell 1: 440 mA

Cell 2: 360 mA

Cell 3: 350 mA

[0113] The test duration was extended and after 504 hours, again the 250 mA threshold was still exceeded as follows:

Cell 1: 280 mA

Cell 2: 490 mA

Cell 3: 580 mA

[0114] Cells 2 and 3 continued to show improved performance.

[0115] At the 740-hour mark, two of the three cells still exceeded the 250 mA target power output threshold, as follows:

Cell 1: 180 mA

Cell 2: 340 mA

Cell 3: 280 mA

[0116] After several repeated experiments with similar observations and results it was concluded that the cells exceeded lifecycle endurance expectations (i.e. the 250 mA target) by a factor of three.

[0117] Based on these results, it is anticipated that the cells would, in most applications perform for at least 250 hours and in many cases in excess of 500 hours with a satisfactorily or target power output of above 250 mA and 1.2 volts.

Experiment 2: Improvement in lifetime and performance of cathode

[0118] In order to test the lifetime and performance of the cathode, a comparative experiment was conducted using identically constructed prototype cells (labelled as Prototype Cell 1 and Prototype Cell 2) and identically constructed traditional MgO₂ cells (labelled as Traditional Cell 1 and Traditional Cell 2).

Results

[0119] The results are presented in Table 2 below and Figure 10.

Table 2: Comparative power output (milliAmps) of a traditional MgO₂ cell and a prototype cell according to an embodiment of the invention over approximately 500 operating hours

Hours	Traditional Cell 1 Power Output (mA)	Traditional Cell 2 Power Output (mA)	Prototype Cell 1 Power Output (mA)	Prototype Cell 2 Power Output (mA)
24	1330	1110	420	680

Hours	Traditional Cell 1 Power Output (mA)	Traditional Cell 2 Power Output (mA)	Prototype Cell 1 Power Output (mA)	Prototype Cell 2 Power Output (mA)
48	1510	1210	360	420
72	1060	910	510	450
96	950	720	440	410
120	720	740	310	440
144	540	300	530	380
168	370	280	590	490
192	400	270	590	440
216	250	230	490	450
240	280	310	520	310
264	220	230	350	240
288	170	230	390	280
312	300	200	510	430
336	123	204	660	380
360	160	170	510	280
384	140	160	330	330
408	120	140	280	380
432	140	100	480	430
456	120	100	480	320
480	130	110	380	460
504	110	60	580	420

[0120] The results show that the MgO₂ traditional cell, after a commonly observed initial first-activation power peak, rapidly declined in electrical performance, and then subsequently continued to degrade at a steady pace. After 500 hours of continuous operation the traditional MgO₂ cells failed to generate more than 10% of the original initial electrical power output.

[0121] In comparison, after 500 hours of continuous operation, the prototype cell was able to maintain over 70% of the original electrical power output in one instance and over 100% of the output in another – clearly showing power output improvement well over the initial first-activation output.

[0122] It is well-known that the pores of air cathodes in Mg-Air cells become increasingly blocked by precipitates that form during discharge and consumption of magnesium (e.g. magnesium hydroxide precipitates). This in turn negatively affects oxygen gas diffusion such that the reaction diminishes, degrading the air-cathode performance over time. The

microstructure and air-permeability of carbon-based air-cathode materials is thus a critical factor that affects the electrochemical performance of MgO_2 cells.

[0123] Upon review, the air-cathodes of the traditional MgO_2 cells were completely degraded, covered in a solid white material (solidified magnesium hydroxide) and were also observed to be badly corroded and therefore no longer useable.

[0124] In comparison, the air cathodes in the prototype cells appeared normal and were re-used for future experiments with little or no loss of performance.

[0125] After several repeated experiments with identical observations and identical results it was concluded that, in contrast to traditional MgO_2 cell configuration, the prototype cells demonstrated improved lifetime and performance of the cathode.

Experiment 3: Improvement in performance of metal-air fuel cell associated with waste accumulation in the absorbent material layer

[0126] A series of experiments and tests were performed to characterise the benefits and effectiveness of the waste management system incorporated into the cells of the present application.

[0127] The absorbent material layer for each cell tested according to an embodiment of the invention comprised of a fibrous cellulose / bamboo material having a similar consistency to female sanitary products. The expandable, anode-encapsulating absorbent material layer functioned to provide an “ionic bridge” between the anode and cathode after dipping into an electrolyte solution (salt water) in order to initiate and sustain the ionic reaction which may last up to several days. As demonstrated by the following results, the ionic exchange process was observed to improve in the cell over time with the accumulation of anode waste material (magnesium hydroxide) generated as a by-product of the reaction.

Results

[0128] The results are presented in Table 3 below and Figure 11.

Table 3: Performance testing results (milliAmps) of Cells 1, 2 and 3 according to an embodiment of the invention over approximately 500 hours

Hours	Cell 1 (mA)	Cell 2 (mA)	Cell 3 (mA)
24	440	880	450

Hours	Cell 1 (mA)	Cell 2 (mA)	Cell 3 (mA)
48	580	780	380
72	530	650	310
96	460	470	240
120	460	290	170
144	500	160	140
168	340	170	100
192	330	210	120
216	360	170	140
240	290	220	150
264	280	230	150
288	350	320	350
312	410	250	220
336	400	300	280
360	400	300	300
384	410	280	300
408	390	290	320
432	340	240	350
456	360	300	360
480	320	220	420
504	300	250	430

[0129] The results show that as the magnesium hydroxide “waste” accumulates, the electrical performance (electrical output) of the cells actually improved until the magnesium anode material was fully consumed. This is evident from the 100-hour mark onwards in all performed tests. That is, once the initial drop in power has stabilized, the results show that the cell output subsequently progressively improves and as a result, the electrical performance (power output) increases.

[0130] Without wishing to be bound by theory, the inventors believe that this unexpected phenomenon may take place as a result of any or all of the following:

- anode waste captured over time within the absorbent material layer provides better conductive or ionic paths to enhance the reaction;
- as the cell expands during accumulation of waste , more electrolyte is adsorbed by the absorbent material and made available for reaction;

- the surface area of the cell where the reaction is taking place is increased allowing for increased reaction; and/or
- the pores of the air cathode are protected from magnesium hydroxide precipitates so that oxygen gas diffusion is not significantly impaired.

[0131] Based on the results of the experiments and observations, it was considered that, the unique design, engineering and operation of metal-air fuel cells according to the invention allows for filtering and/or capturing anode waste precipitates within the absorbent material, which in turn:

- protects pores found within the air-cathode from blockage by waste particulates, in turn allowing for critical oxygen gas diffusion across the air cathode;
- effectively prevent the waste precipitates otherwise degrading the air-cathode; through salt ingress or corrosion (e.g. salt migration due to “salt creep” i.e. salt crystal migration resulting in salt ingress and/or corrosion), potentially also improving the life of the cathode and other cell components such as contacts, wiring and/or electronics;
- render regular internal cleaning of the cell to remove accumulated waste unnecessary; and/or
- may actually enhance the performance of the cell as the waste precipitates collect or are captured within the absorbent material.

[0132] Metal-air fuel cells according to the invention may offer an affordable, low-cost power source for use in the developing world. It is anticipated that such metal-air fuel could provide approximately five (5) hours of light usage per day for less than the cost of 0.05 USD/day in the first year (including the initial cost of device). This would reduce in subsequent years to 0.01 USD/day. It is further noted that all constituent parts are exchangeable and replaceable (being ideal for third-world applications) and the entire cell is inherently safe as even short circuits have no detrimental effects other than the consumption of the anode metal.

[0133] Metal-air fuel cells according to the invention may therefore provide to provide a portable, light-weight (i.e. light and sturdy unit construction that avoids bulky water vessels and/or containers), eco-friendly, exchangeable, powerful (i.e. may be powerful enough to drive a myriad of electrical and electrical applications not previously possible with certain known metal-air fuel cells), scalable and miniaturised direct current generator (i.e. may be miniaturised to be used in “classic” previously battery dominated areas such as D-cells and other battery only form factors); and/or to offer the potential of an environmentally friendly, or “green”, power source for products and devices (when compared to, for example, traditional batteries, solar and kerosene as the constituent parts are eco-friendly and commonly

available allowing for excellent recyclability of the entire device, the cathode itself is also removable and suitable for recycling.

[0134] Modifications and variations as would be deemed obvious to the person skilled in the art are included within the ambit of the present invention as claimed in the appended claims.

[0135] Unless the context otherwise requires, "position" means, when used as a verb, to put or arrange something in a new location or shape, and "positioning" and "positionable" are to be construed accordingly.

CLAIMS

1. A metal-air fuel cell comprising:
 - (a) an anode;
 - (b) a positionable air cathode;
 - (c) an absorbent material layer configured to retain electrolyte, the absorbent material layer positioned intermediate the anode and the air cathode such that it contacts the anode; and
 - (d) an elastic air cathode positioning means configured to position the air cathode to ensure that the air cathode remains in contact with the absorbent material layer while accommodating any change in volume of the absorbent material layer;wherein the absorbent material layer functions as an ionic transfer bridge between the anode and the cathode by retaining electrolyte.
2. The metal-air fuel cell according to claim 1, wherein the anode, the absorbent material layer and the air cathode are coaxially arranged such that the air cathode substantially surrounds the absorbent material layer and the absorbent material layer substantially surrounds the anode.
3. The metal-air fuel cell according to claim 1, wherein the anode, the absorbent material layer and the air cathode are provided in a laminate arrangement
4. The metal-air fuel cell according to any one of claims 1 to 3, wherein the elastic air cathode positioning means is positioned around a cross-sectional perimeter of the cell.
5. The metal-air fuel cell according to any one of claims 1 to 4, wherein the elastic air cathode positioning means is either incorporated within or provided separate to the air cathode, and is selected from: an O-ring, a deformable polymeric material, an elastic (or rubber) band or an expandable mesh.
6. The metal-air fuel cell according to any one of claims 1 to 5, wherein the metal-air fuel cell is contained within an open housing unit.
7. The metal-air fuel cell according to any one of claims 1 to 6, wherein the metal-air fuel cell is activated or re-activated for use by allowing the absorbent material layer to retain electrolyte.

8. The metal-air fuel cell according to any one of claims 1 to 7, wherein the absorbent material layer is pre-impregnated with ions to form electrolyte when the absorbent material layer retains water.
9. The metal-air fuel cell according to any one of claims 1 to 8, wherein the absorbent material layer comprises a first absorbent material sub-layer pre-impregnated with ions and a second absorbent material sub-layer not pre-impregnated with ions.
10. The metal-air fuel cell according to any one of claims 1 to 9, wherein the metal-air fuel cell is activated or re-activated for use by dipping the metal-air fuel cell in a liquid so as to retain electrolyte.
11. The metal-air fuel cell according to any one of claims 1 to 10, wherein the absorbent material layer changes volume upon adsorption or depletion of retained electrolyte or water, and/or capture of anode waste material.
12. The metal-air fuel cell according to any one of claims 1 to 11, wherein the adsorbent material layer comprises a woven or non-woven fibrous material or a combination thereof.
13. The metal-air fuel cell according to any one of claims 1 to 12, wherein the adsorbent material layer comprises fibrous cellulose, bamboo fiber or a combination thereof.
14. The metal-air fuel cell according to any one of claims 1 to 13, wherein the anode comprises a magnesium alloy.
15. The metal-air fuel cell according to any one of claims 1 to 14, wherein the air cathode comprises a sheet layer.
16. The metal-air fuel cell according to any one of claims 1 to 15, wherein the air cathode is hydrophobic, air-permeable and comprises a layered Teflon material.
17. The metal-air fuel cell according to any one of claims 1 to 16, wherein the metal-air fuel cell further comprises a paper separator layer located between the absorbent material layer and the air cathode to support and contain the absorbent material layer and/or further isolate and protect the cathode from anode waste precipitates captured in the absorbent material layer.

18. The metal-air fuel cell according to any one of claims 1 to 17, when used to provide a direct current power source for use to power the operation of a product or device.
19. The metal-air fuel cell according to claim 18, wherein the product or device is selected from the group consisting of: torches (including flashlights, mag-lights, pen lights); lights and lighting products or devices (including globe lights, LED lights, strobe lights and Christmas lights); safety or temporary lighting applications (including for road works); lanterns (including camping lanterns and Chinese lanterns); combination products (including flashlight-lantern combinations convertible between operation as a flashlight and as a lantern); household products (including electrical toothbrushes and shavers) emergency beacons (including EPIRB and directional finders); radios (analogue and digital); communications equipment (including radios, CB radios and small audio devices); toys (i.e. battery powered), power banks for rechargeable products and recharging docks for USB devices (small electronic products including mobile phones, i-pods, i-pads).