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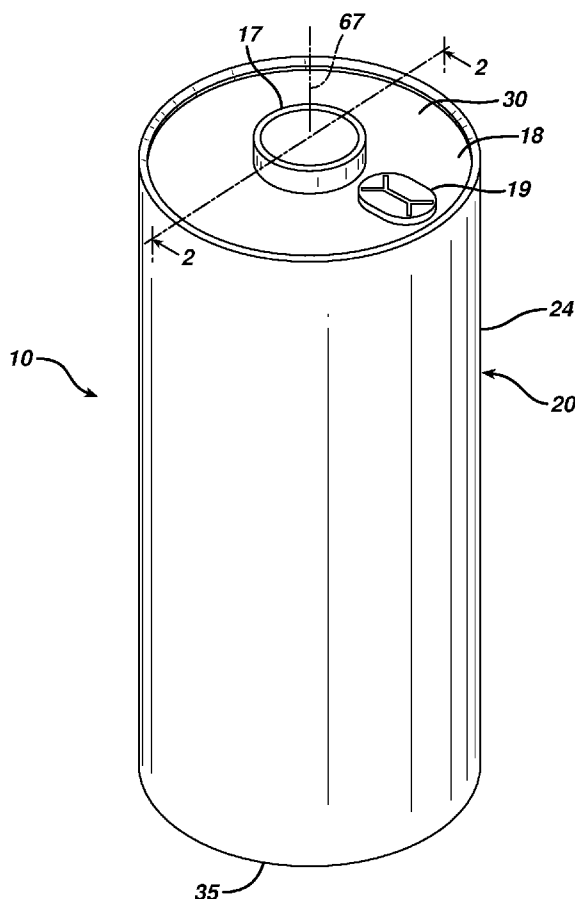
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[Continued on next page]

(54) Title: LITHIUM CELL



(57) Abstract: A primary cell having an anode comprising lithium and a cathode comprising iron disulfide (FeS₂) and carbon particles. The electrolyte comprises a lithium salt dissolved in a nonaqueous solvent mixture which contains an alkyl ester, preferably an alkyl acetate. The electrolyte solvent may also include an organic cyclic carbonate. A cathode slurry is prepared comprising iron disulfide powder, carbon, binder, and a liquid solvent. The mixture is coated onto a conductive substrate and solvent evaporated leaving a dry cathode coating on the substrate. The anode and cathode can be spirally wound with separator therebetween and inserted into the cell casing with electrolyte then added.

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LITHIUM CELL

FIELD OF THE INVENTION

The invention relates to lithium cells having an anode comprising lithium and a cathode comprising iron disulfide and an electrolyte comprising a lithium salt and nonaqueous solvent which includes an alkyl acetate, preferably methyl acetate.

BACKGROUND

Primary (non-rechargeable) electrochemical cells having an anode of lithium are known and are in widespread commercial use. The anode is comprised essentially of lithium metal. Such cells typically have a cathode comprising manganese dioxide, and electrolyte comprising a lithium salt such as lithium trifluoromethane sulfonate (LiCF_3SO_3) dissolved in a nonaqueous solvent. The cells are referenced in the art as primary lithium cells (primary Li/MnO_2 cells) and are generally not intended to be rechargeable. Alternative primary lithium cells with lithium metal anodes but having different cathodes are also known. Such cells, for example, have cathodes comprising iron disulfide (FeS_2) and are designated Li/FeS_2 cells. The iron disulfide (FeS_2) is also known as pyrite. The Li/MnO_2 cells or Li/FeS_2 cells are typically in the form of cylindrical cells, typically an AA size cell or 2/3A Li/MnO_2 cell. The Li/MnO_2 cells have a voltage of about 3.0 volts which is twice that of conventional Zn/MnO_2 alkaline cells and also have higher energy density (watt-hrs per cm^3 of cell volume) than that of alkaline cells. The Li/FeS_2 cells have a voltage (fresh) of between about 1.2 and 1.5 volts which is about the same as a conventional Zn/MnO_2 alkaline cell. However, the

energy density (watt-hrs per cm^3 of cell volume) of the Li/FeS₂ cell is also much higher than a comparable size Zn/MnO₂ alkaline cell. The theoretical specific capacity of lithium metal is high at 3861.7 mAmp-hr/gram and the theoretical specific capacity of FeS₂ is 893.6 mAmp-hr/gram. The FeS₂ theoretical capacity is based on a 4 electron transfer from 4Li per FeS₂ to result in reaction product of elemental iron Fe and 2Li₂S. That is, 2 of the 4 electrons reducing the valence state of Fe⁺² in FeS₂ to Fe and the remaining 2 electrons reducing the valence of sulfur from -1 in FeS₂ to -2 in Li₂S.

Overall the Li/FeS₂ cell is much more powerful than the same size Zn/MnO₂ alkaline cell. That is for a given continuous current drain, particularly for higher current drain over 200 milliAmp, in the voltage vs. time profile the voltage drops off much less quickly for the Li/FeS₂ cell than the Zn/MnO₂ alkaline cell. This results in a higher energy obtainable from a Li/FeS₂ cell compared to that obtainable for a same size alkaline cell. The higher energy output of the Li/FeS₂ cell is also clearly shown more directly in graphical plots of energy (Watt-hrs) versus continuous discharge at constant power (Watts) wherein fresh cells are discharged to completion at fixed continuous power outputs ranging from as little as 0.01 Watt to 5 Watt. In such tests the power drain is maintained at a constant continuous power output selected between 0.01 Watt and 5 Watt. (As the cell's voltage drops during discharge the load resistance is gradually decreased raising the current drain to maintain a fixed constant power output.) The graphical plot Energy (Watt-Hrs) versus Power Output (Watt) for the Li/FeS₂ cell is considerably above that for the same size alkaline cell. This is despite that the starting voltage

of both cells (fresh) is about the same, namely, between about 1.2 and 1.5 volt.

Thus, the Li/FeS₂ cell has the advantage over same size alkaline cells, for example, AAA, AA, C or D size or any other size cell in that the Li/FeS₂ cell may be used interchangeably with the conventional Zn/MnO₂ alkaline cell and will have greater service life, particularly for higher power demands. Similarly the Li/FeS₂ cell which is primary (nonrechargeable) cell can be used as a replacement for the same size rechargeable nickel metal hydride cells, which have about the same voltage (fresh) as the Li/FeS₂ cell.

The Li/MnO₂ cell and Li/FeS₂ cell both require non aqueous electrolytes, since the lithium anode is highly reactive with water. One of the difficulties associated with the manufacture of a Li/FeS₂ cell is the need to add good binding material to the cathode formulation to bind the Li/FeS₂ and carbon particles together in the cathode. The binding material must also be sufficiently adhesive to cause the cathode coating to adhere uniformly and strongly to the metal conductive substrate to which it is applied.

The cathode material may be initially prepared in a form such as a slurry mixture, which can be readily coated onto the metal substrate by conventional coating methods. The electrolyte added to the cell must be a suitable nonaqueous electrolyte for the Li/FeS₂ system allowing the necessary electrochemical reactions to occur efficiently over the range of high power output desired. The electrolyte must exhibit good ionic conductivity and also be sufficiently stable to the undischarged electrode materials (anode and cathode) and to

the resulting discharge products. This is because undesirable oxidation/reduction reactions between the electrolyte and electrode materials (either discharged or undischarged) could thereby gradually contaminate the electrolyte and reduce its effectiveness or result in excessive gassing. This in turn can result in a catastrophic cell failure. Thus, the electrolyte used in Li/FeS₂ cell in addition to promoting the necessary electrochemical reactions, should also be stable to discharged and undischarged electrode materials.

Primary lithium cells are in use as a power source for digital flash cameras, which require operation at higher power demands than is supplied by individual alkaline cells. Primary lithium cells are conventionally formed of an electrode composite comprising an anode formed of a sheet of lithium, a cathode formed of a coating of cathode active material comprising FeS₂ on a conductive metal substrate (cathode substrate) and a sheet of electrolyte permeable separator material therebetween. The electrode composite may be spirally wound and inserted into the cell casing, for examples, as shown in U.S. patent 4,707,421. A cathode coating mixture for the Li/FeS₂ cell is described in U.S. 6,849,360. A portion of the anode sheet is typically electrically connected to the cell casing which forms the cell's negative terminal. The cell is closed with an end cap which is insulated from the casing. The cathode sheet can be electrically connected to the end cap which forms the cell's positive terminal. The casing is typically crimped over the peripheral edge of the end cap to seal the casing's open end.

The anode in a Li/FeS₂ cell can be formed by laminating a layer of lithium on a metallic substrate such as copper. However, the anode may be formed of a sheet of lithium without any substrate.

The electrolyte used in a primary Li/FeS₂ cells are formed of a "lithium salt" dissolved in an "organic solvent". Representative lithium salts which may be used in electrolytes for Li/FeS₂ primary cells are referenced in U.S. patents 5,290,414 and U.S. 6,849,360 B2 and include such salts as: Lithium trifluoromethanesulfonate, LiCF₃SO₃ (LiTFS); lithium bistrifluoromethylsulfonyl imide, Li(CF₃SO₂)₂N (LiTFSI); lithium iodide, LiI; lithium bromide, LiBr; lithium tetrafluoroborate, LiBF₄; lithium hexafluorophosphate, LiPF₆; lithium hexafluoroarsenate, LiAsF₆; Li(CF₃SO₂)₃C, and various mixtures.

Examples of some organic solvents which are referenced in the art for possible use in connection with organic solvents for electrolytes for primary Li/FeS₂ cells are as follows: propylene carbonate (PC), ethylene carbonate (EC), butylene carbonate (BC), dimethoxyethane (DME), ethyl glyme, diglyme and triglyme, dimethoxypropane (DMP), dioxolane (DIOX), 3,5-dimethylisoxazole (DMI), tetrahydrofuran (THF), diethyl carbonate (DEC), ethylene glycol sulfite (EGS), dioxane, dimethylsulfate (DMS), 3-methyl-2-oxazolidone, and sulfolane (SU), and various mixtures. (See, e.g. U.S. patents 5,290,414 and U.S. 6,849,360 B2).

In U.S. 5,290,414 is specifically reported use of a beneficial electrolyte for FeS₂ cells, wherein the electrolyte comprises a lithium salt dissolved in a solvent comprising

dioxolane in admixture with an acyclic (non cyclic) ether based solvent. The acyclic (non cyclic) ether based solvent as referenced may be dimethoxyethane, ethyl glyme, diglyme and triglyme, with the preferred being 1-2 dimethoxyethane (DME). A specific lithium salt ionizable in such solvent mixture(s) is given as LiCF_3SO_3 (LiTFS) or $\text{Li}(\text{CF}_3\text{SO}_2)_2\text{N}$ (LiTFSI), or mixtures thereof. A co-solvent selected from 3,5-dimethylisoxazole (DMI), 3-methyl-2-oxazolidone, propylene carbonate (PC), ethylene carbonate (EC), butylene carbonate (BC), and sulfolane.

In U.S. 6,849,360 B2 is specifically disclosed an electrolyte for an Li/FeS_2 cell, wherein the electrolyte comprises the salt lithium iodide dissolved in the organic solvent mixture comprising 1,3-dioxolane (DIOX), 1,2-dimethoxyethane (DME), and small amount of 3,5-dimethylisoxazole (DMI).

Thus, it should be evident from the above representative references that the choice of a particular organic solvent or mixture of different organic solvents for use in conjunction with any one or more lithium salts to produce a suitable electrolyte for the Li/FeS_2 cell is challenging. This is not to say that many combinations of lithium salts and organic solvents do not produce a Li/FeS_2 cell will not work at all. But rather the problems associated with such cells using an electrolyte formed with just any combination of lithium salt and organic solvent is that the problems encountered will likely be very substantial, thus making the cell impractical for commercial usage. The history of development of lithium cells in general, whether lithium primary cells, e.g. Li/MnO_2 , Li/FeS_2 , or rechargeable lithium or lithium ion cells reveals

that just any combination of lithium salt and organic solvent cannot be expected to result in a good cell, that is, exhibiting good, reliable performance.

As an example of a purported advantageous electrolyte mixture the above references reveal advantageous use of dioxolane in combination with an acyclic (non cyclic) ether based solvent, preferably 1,2-dimethoxyethane (DME) to produce an effective electrolyte in conjunction with use of conventional lithium salts. However, dioxolane has the disadvantage of cost and handling.

Accordingly, it is desired to employ solvents for the Li/FeS₂ cell electrolyte which are more cost effective and easier to handle than dioxolane. Such solvents are, for example, ethylene carbonate (EC) and propylene carbonate (PC), which are less expensive and easier to store and handle than dioxolane. Ethylene carbonate (EC) and propylene carbonate (PC) alone or in admixture and also in admixture with dimethoxyethane (DME) have produced very suitable solvents for electrolytes for use in connection with Li/MnO₂ cells, particularly when the lithium salt for the electrolyte comprises LiCF₃SO₃ (LITFS). (See, e.g. U.S. 6,443,999 B1)

However, experiments with such electrolytes and electrolyte solvent systems, that is, comprising ethylene carbonate (EC) and propylene carbonate (PC) solvents, while effective in Li/MnO₂ cells result in deficiencies when employed, per se, in the context of the Li/FeS₂ cell. One of the difficulties is that such ethylene carbonate/ propylene carbonate electrolyte solvent mixtures tend to cause or exacerbate the problem of lithium passivation, which normally

occurs at least to a degree during the discharge life of the Li/FeS₂ cell. Lithium passivation occurs during the Li/FeS₂ cell during discharge or storage as a result of gradual reaction with the lithium metal surface in the anode with electrolyte, particularly the electrolyte solvent. A insoluble layer is gradually formed on the lithium metal surface, which tends to passivate the lithium metal surface. Such surface layers, some more debilitating than others, can reduce the rate of the electrochemical reaction involving the lithium anode metal during cell discharge, thus interfering with proper cell performance.

Another problem encountered with the use of ethylene carbonate/ propylene carbonate electrolyte solvent mixtures for Li/FeS₂ cells is that such solvents tend to cause or exacerbate the problem of initial voltage delay (voltage drop) which may occur typically during an initial phase or initial period of cell usage. Such voltage drop, which can occur at the onset of a new period of cell usage, can reduce the running voltage of the cell for a brief period and thus interfere with attainment of expected consistent, reliable, cell performance. Voltage delay is usually associated with increase of internal resistance of the cell, and usually linked to resistance of the passive layer on the lithium anode.

Accordingly, it is desired to produce a Li/FeS₂ cell employing an effective electrolyte therein which reduces or suppresses the rate of lithium anode passivation by preventing or retarding the formation of debilitating passive layer on the surface of the lithium anode.

It is desired to produce a Li/FeS₂ cell having an effective electrolyte therein which reduces the amount of voltage delay (voltage drop) occurring at the onset of any new discharge period, or prevents any significant voltage delay from occurring during normal cell usage.

In particular it is desired to produce an electrolyte for the Li/FeS₂ cell wherein the electrolyte comprises a cyclic organic carbonate solvent, in particular a cyclic glycol carbonate desirably such as, but not limited to, ethylene carbonate, propylene carbonate, butylene carbonate, and mixtures thereof. (It should be understood that these aforementioned carbonates are cyclic glycol carbonates but they are conventionally referenced in the art as above named ethylene carbonate, propylene carbonate, and butylene carbonate).

It is desired to produce an electrolyte for a Li/FeS₂ cell wherein the electrolyte comprises a solvent which is free of dioxolane.

SUMMARY OF THE INVENTION

The invention is directed to lithium primary cells wherein the anode comprises lithium metal. The lithium may be alloyed with small amounts of other metal, for example aluminum, which typically comprises less than about 1 wt.% of the lithium alloy. The lithium which forms the anode active material, is preferably in the form of a thin foil. The cell has a cathode comprising the cathode active material iron disulfide (FeS₂), commonly known as "pyrite". The cell may be in the form of a button (coin) cell or flat cell. Desirably the cell may be in the form of a spirally wound cell

comprising an anode sheet and a cathode composite sheet spirally wound with separator therebetween. The cathode sheet is produced using a slurry process to coat a cathode mixture comprising iron disulfide (FeS_2) particles onto a conductive metal substrate. The FeS_2 particles are bound to the conductive metal substrate using desirably an elastomeric, preferably, a styrene-ethylene /butylene-styrene (SEBS) block copolymer such as Kraton G1651 elastomer (Kraton Polymers, Houston, Texas). This polymer is a film-former, and possesses good affinity and cohesive properties for the FeS_2 particles as well as for conductive carbon particle additives in the cathode mixture.

In an aspect of the invention the cathode is formed of a cathode slurry comprising iron disulfide (FeS_2) powder, conductive carbon particles, binder material, and solvent. (The term "slurry" as used herein will have its ordinary dictionary meaning and thus be understood to mean a wet mixture comprising solid particles.) The wet cathode slurry is coated onto a conductive substrate such as a sheet of aluminum or stainless steel. The conductive substrate functions as a cathode current collector. The solvent is then evaporated leaving dry cathode coating mixture comprising the iron disulfide material and carbon particles preferably including carbon black adhesively bound to each other and with the dry coating bound to the conductive substrate. The preferred carbon black is acetylene black. The carbon may optionally include graphite particles blended therein.

After the wet cathode slurry is coated onto the conductive substrate, the coated substrate is placed in an oven and heated at elevated temperatures until the solvent

evaporates. The resulting product is a dry cathode coating comprising iron disulfide and carbon particles bound to the conductive substrate. On a dry basis, the cathode preferably contains no more than 4% by weight binder, and between 85 and 95% by weight of FeS_2 . The solids content, that is, the FeS_2 particles and conductive carbon particles in the wet cathode slurry is between 55 and 70 percent by weight. The viscosity range for the cathode slurry is from about 3500 to 15000 mPas. (mPas = mNewton x sec/m²). After the anode comprising lithium metal and cathode comprising iron disulfide, with separator therebetween, are inserted into the cell housing, a nonaqueous electrolyte is added to the cell.

In a principal aspect of the invention the desired nonaqueous electrolyte for the lithium/iron disulfide cell comprises a lithium salt dissolved in an organic solvent, which preferably comprises an acyclic (non cyclic) organic ester, desirably an alkyl ester. The alkyl ester solvent is desirably an alkyl acetate, which has been determined to have properties that make it an excellent solvent for certain lithium salts resulting in production of suitable electrolytes for use in lithium/iron disulfide cells. The alkyl acetate solvent is preferably blended in admixture with cyclic organic carbonates such as ethylene carbonate and/or propylene carbonate solvents. The preferred electrolyte solvent mixture thus comprises a cyclic organic carbonate, preferably a cyclic glycol carbonate such as ethylene carbonate, propylene carbonate or butylene carbonate, and mixtures thereof, in admixture with an alkyl acetate. (The electrolyte solvent may also include dimethylcarbonate and/or ethyl methyl carbonate). The alkyl acetate may be selected from methyl acetate, ethyl acetate, propyl acetate, and mixtures thereof. However, methyl

acetate is preferred because of its lower viscosity. The next preferred alkyl acetate is ethyl acetate because it has properties similar to methyl acetate. Higher esters, such as alkyl propionates, for use as an electrolyte solvent or electrolyte solvent additive for lithium/iron disulfide cells could also be useful. But because of their much higher viscosity, it is not expected that such alkyl propionates or higher esters would prove to be as suitable electrolyte solvents for the lithium/iron disulfide cell as the methyl acetates. A very desirably electrolyte solvent for the lithium/iron disulfide cell has been determined to be a blend of the alkyl acetate in a mixture containing both ethylene carbonate and propylene carbonate.

A preferred electrolyte solvent comprises methyl acetate (MA) (formula $C_3H_6O_2$) in admixture with propylene carbonate (PC) (formula $C_4H_6O_3$) and ethylene carbonate (EC) (formula $C_3H_4O_3$). Propylene carbonate and ethylene carbonate are cyclic organic carbonates. Propylene carbonate has a Chemical Abstracts Service (CAS) Registry identification, CAS No. 108-32-7; ethylene carbonate has a CAS No. 96-49-1; and methyl acetate has a CAS No. 79-20-9. Basic property data for these solvents is readily available, for example, in the Condensed Chemical Dictionary, 10 Edition, Revised by Gessner G. Hawley, Van Nostrand Reinhold Company. Additional property and formula data is also available, for example, by entering the above solvent names, ethylene carbonate, propylene carbonate (as well as butylene carbonate), and methyl acetate (MA), into the Google search web site: www.Google.com.

A preferred electrolyte solvent comprises a mixture of methyl acetate (MA), in admixture with propylene carbonate

(PC) and ethylene carbonate (EC). Each of these solvents are resistant to oxidation by FeS_2 and are stable to the discharge products of the Li/ FeS_2 system. Such solvent mixture does not interfere adversely with the properties of the binder material. For example, such solvent mixture does not react with the elastomeric binder, e.g. Kraton G1651 styrene-ethylene/butylene-styrene block copolymer, in sufficient degree to noticeably interfere with the binder properties. Preferably the electrolyte solvent mixture comprises methyl acetate (MA) between about 5 and 95 vol.%, propylene carbonate (PC) between 1 and 94 vol%, and ethylene carbonate (EC) between 1 and 50 vol%. The electrolyte solvent mixture may be free of dioxolane, that is, may contain no detectable amount of dioxolane. The electrolyte solvent mixture may be essentially free of dioxolane, that is, contain only trace amounts of dioxolane, e.g. less than 100 ppm of the solvent mixture, e.g. less than 50 ppm dioxolane, e.g. less than 25 ppm dioxolane. At such low concentrations the trace amounts of dioxolane would not be expected to serve any particular function.

A desirable electrolyte mixture for the Li/ FeS_2 cell of the invention has been determined to comprise the lithium salt lithium trifluoromethane sulfonate, LiCF_3SO_3 (LiTFS) and/or lithium bistrifluoromethylsulfonyl imide, $\text{Li}(\text{CF}_3\text{SO}_2)_2\text{N}$ (LiTFSI) dissolved in an organic solvent mixture comprising alkyl acetate propylene carbonate (PC), and ethylene carbonate (EC). (The alkyl acetate as above indicated is preferably methyl acetate (MA).) A preferred electrolyte mixture has been determined to be an electrolyte solution comprising 0.8 molar (0.8 mol/liter) concentration of $\text{Li}(\text{CF}_3\text{SO}_2)_2\text{N}$ (LiTFSI) salt dissolved in an organic solvent mixture comprising about

75 vol.% methyl acetate (MA), 20 vol.% propylene carbonate (PC), and 5 vol.% ethylene carbonate (EC). Elemental iodine (I_2) is desirably added to such electrolyte mixture for Li/FeS₂ cells. Alternatively, elemental bromine or mixtures of elemental iodine and bromine may be added to such electrolyte mixture for Li/FeS₂ cells. The elemental iodine is preferably added to the electrolyte mixture so that it comprises between about 0.01 and 5 wt.% of the electrolyte mixture, preferably about 0.5 wt.% of the electrolyte mixture. (The elemental bromine or mixtures of elemental iodine and bromine may also be added to the electrolyte mixture so that it comprises between about 0.01 and 5 wt.% of the electrolyte mixture, preferably about 0.5 wt.% of the electrolyte mixture.) Most all of the elemental iodine added to the electrolyte mixture remains in elemental form, that is, does not convert to ionic form when added. It is estimated that at least 90 percent of the added elemental iodine (or bromine) stays in elemental form when added to the above electrolyte solvent mixture. (The term "elemental iodine" as used herein includes iodine, I^0 , and the normal diatomic state of iodine, I_2 . Similarly the term "elemental bromine" as used herein includes bromine, Br^0 , and the normal diatomic state of bromine Br_2 .)

It has been determined that such electrolyte mixture comprising elemental iodine resolves the problem of voltage delay (voltage drop) which may otherwise occur at the onset of a fresh discharge period of Li/FeS₂ cells employing electrolyte comprising cyclic organic carbonate solvents such as ethylene carbonate (EC) and/or propylene carbonate (PC). That is, when the elemental iodine (I_2) is added to the above electrolyte solvent mixture comprising methyl acetate (MA), propylene carbonate (PC), and ethylene carbonate (EC), there is

essentially no voltage delay observed or else the voltage delay is greatly reduced.

It has been determined that such electrolyte mixture to which elemental iodine has been added also reduces the rate of lithium passivation in the anode of the Li/FeS₂ cell compared to the same electrolyte mixture comprising methyl acetate (MA), ethylene carbonate and/or ethylene propylene solvents without the elemental iodine added thereto.

If the cathode slurry comprising FeS₂ powder and conductive carbon is coated onto a sheet of aluminum substrate (cathode current collector), the presence of elemental iodine in the electrolyte can also retard the rate of aluminum surface corrosion which can develop during normal usage or storage of the Li/FeS₂ cell. The beneficial effect of adding elemental iodine to the electrolyte is discussed in commonly assigned Application Ser. No. 11/479,328.

Also the presence of methyl acetate (MA) together with elemental iodine additive and cyclic organic carbonates, such as ethylene carbonate and propylene carbonate, appears to alter the chemical nature of the passive layer which gradually develops on the lithium anode surface as the Li/FeS₂ cell discharges. The changed composition of surface layer on the lithium anode appears to retard the rate of lithium anode passivation compared to use of the same carbonate electrolyte solvent without the methyl acetate and iodine additive. It is predicted that similar beneficial effects may be obtained by adding elemental bromine or mixtures of small amounts of elemental bromine and iodine to the methyl acetate (MA), ethylene carbonate/ propylene carbonate electrolyte solvent.

The electrolyte solvent mixture of the invention also does not undergo reaction with the electrode materials or discharge products or result in excessive gassing during normal usage. The electrolyte mixture of the invention may be beneficially employed in a coin (button) cell or wound cell for the Li/FeS₂ cell system.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A is a cross sectional view of an improved Li/FeS₂ cell of the invention as presented in a button cell embodiment.

Fig. 1 is an isometric view of an improved Li/FeS₂ cell of the invention as presented in a cylindrical cell embodiment.

Fig. 2 is a partial cross sectional elevation view of the cell taken through sight lines 2-2 of Fig. 1 to show the top and interior portion of the cell.

Fig. 3 is a partial cross sectional elevation view of the cell taken through sight lines 2-2 of Fig. 1 to show a spirally wound electrode assembly.

Fig. 4 is a schematic showing the placement of the layers comprising the electrode assembly.

Fig. 5 is a plan view of the electrode assembly of Fig. 4 with each of the layers thereof partially peeled away to show the underlying layer.

DETAILED DESCRIPTION

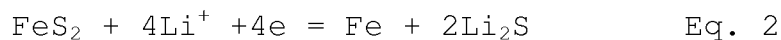
The Li/FeS₂ cell of the invention may be in the form of a flat button cell or a spirally wound cell. A desirable button cell 100 configuration comprising a lithium anode 150 and a cathode 170 comprising iron disulfide (FeS₂) with separator 160 therebetween is shown in the Fig. 1A.

The Li/FeS₂ cell as in cell 100 has the following basic discharge reactions (one step mechanism):

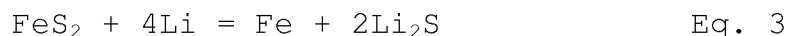
Anode:



Cathode:



Overall:



The example of Li/FeS₂ testing vehicle is button cell 100 shown in Fig. 1A may be in the form of a primary (nonrechargeable) cell. In the button cell 100 (Fig. 1A) a disk-shaped cylindrical cathode housing 130 is formed having an open end 132 and a closed end 138. Cathode housing 130 is preferably formed from nickel-plated steel. An electrical insulating member 140, preferably a plastic cylindrical member having a hollow core, is inserted into housing 130 so that the outside surface of insulating member 140 abuts and lines the inside surface of housing 130. Alternatively, the inside surface of housing 130 may be coated with a polymeric material that solidifies into insulator 140 abutting the inside surface of housing 130. Insulator 140 can be formed from a variety of

thermally stable insulating materials, for example ~~nylon or~~ polypropylene.

A cathode current collector 115 comprising a metallic grid can be inserted into the cell so that it abuts the inside surface of the closed end 138 of the housing 30. The cathode current collector 115 may desirably be composed of a sheet of expanded stainless steel metal foil, having a plurality of openings therein, thus forming a stainless steel grid or screen. The expanded stainless steel metal foil is available as EXMET foil 316L-SS from Dexmet Corp. Preferably, however, the cathode current collector 115 is composed of a sheet of aluminum, which is more conductive. (The cathode current collector 115 may be a sheet of aluminum alloyed with common aluminum alloy metals such as magnesium, copper, and zinc.) Such aluminum current collector sheet 115 may also have a plurality of small openings therein, thus forming an aluminum grid. The cathode current collector 115 can be welded onto the inside surface of the closed end 138 of the housing 130. (Optionally, the same type of current collector grid, preferably of expanded stainless steel metal foil with openings therein, may be welded to the inside surface of the closed end of the anode cover 120.) An optional conductive carbon base layer 172 comprising a mixture of graphite and polytetrafluoroethylene (PTFE) binder can be compressed into the cathode current collector 115. The cathode material 170 comprising the FeS_2 active particles may then be coated onto such conductive base layer 172. This may be termed a "staged" cathode construction.

The cathode material 170 of the invention comprising iron disulfide (FeS_2) or any mixture including iron disulfide (FeS_2) as active cathode material, may thus be inserted over optional conductive base layer 172 so that it overlies current

collector sheet 115. The cathode active material, that is, the material undergoing useful electrochemical reaction, in cathode layer 170 can be composed entirely of iron disulfide (FeS_2). The cathode 170 comprising iron disulfide (FeS_2) powder dispersed therein can be prepared in the form of a slurry which may be coated on both sides of a conductive metal foil, preferably an aluminum or stainless steel foil. Such aluminum or stainless steel foil may have openings therethrough, thus forming a grid or screen. Alternatively, the cathode 170 comprising iron disulfide (FeS_2) powder dispersed therein can be prepared in the form of a slurry which is coated on just the side of an aluminum or stainless steel foil facing separator 160. In either case a conductive base layer 172, as above described, may be employed in which case cathode 170 is inserted in the cell so that it overlies conductive base layer 172 as shown in Fig. 1A.

Alternatively, the cathode 170 comprising iron disulfide (FeS_2) powder dispersed therein can be prepared in the form of a slurry which may be coated directly onto a conductive substrate sheet 115 to form a cathode composite. Preferably conductive substrate sheet 115 is formed of a sheet of aluminum (or aluminum alloy), as above described, and may have a plurality of small apertures therein, thus forming a grid. Alternatively, the conductive substrate sheet 115 may be a sheet of stainless steel, desirably in the form of expanded stainless steel metal foil, having a plurality of small apertures therein.

The cathode slurry comprises 2 to 4 wt% of binder (Kraton G1651 elastomeric binder from Kraton Polymers, Houston Texas.); 50 to 70 wt% of active FeS_2 powder; 4 to 7 wt% of

conductive carbon (carbon black and graphite); and 25 to 40 wt% of solvent(s). (The carbon black may include in whole or in part acetylene black carbon particles. Thus, the term carbon black as used herein shall be understood to extend to and include carbon black and acetylene black carbon particles.) The Kraton G1651 binder is an elastomeric block copolymer (styrene-ethylene/butylene (SEBS) block copolymer) which is a film-former. This binder possesses sufficient affinity for the active FeS_2 and carbon black particles to facilitate preparation of the wet cathode slurry and to keep these particles in contact with each other after the solvents are evaporated. The FeS_2 powder may have an average particle size between about 1 and 100 micron, desirably between about 10 and 50 micron. A desirable FeS_2 powder is available under the trade designation Pyrox Red 325 powder from Chemetall GmbH, wherein the FeS_2 powder has a particle size sufficiently small that of particles will pass through a sieve of Tyler mesh size 325 (sieve openings of 0.045 mm). (The residue amount of FeS_2 particles not passing through the 325 mesh sieve is 10% max.) The graphite is available under the trade designation Timrex KS6 graphite from Timcal Ltd. Timrex graphite is a highly crystalline synthetic graphite. (Other graphites may be employed selected from natural, synthetic, or expanded graphite and mixtures thereof, but the Timrex graphite is preferred because of its high purity.) The carbon black is available under the trade designation Super P conductive carbon black (BET surface of $62 \text{ m}^2/\text{g}$) from Timcal Co.

The solvents preferably include a mixture of C_9 - C_{11} (predominately C_9) aromatic hydrocarbons available as ShellSol A100 hydrocarbon solvent (Shell Chemical Co.) and a mixture of primarily isoparaffins (average M.W. 166, aromatic content

less than 0.25 wt.%) available as Shell Sol OMS hydrocarbon solvent (Shell Chemical Co.). The weight ratio of ShellSol A100 to ShellSol OMS solvent is desirably at a 4:6 weight ratio. The ShellSol A100 solvent is a hydrocarbon mixture containing mostly aromatic hydrocarbons (over 90 wt% aromatic hydrocarbon), primarily C₉ to C₁₁ aromatic hydrocarbons. The ShellSol OMS solvent is a mixture of isoparaffin hydrocarbons (98 wt.% isoparaffins, M.W. about 166) with less than 0.25 wt% aromatic hydrocarbon content. The slurry formulation may be dispersed using a double planetary mixer. Dry powders are first blended to ensure uniformity before being added to the binder solution in the mixing bowl.

A preferred cathode slurry mixture is presented in Table 1:

Table I
Cathode Slurry

	<i>Wet Slurry (wt.%)</i>
Binder (Kraton G1651)	2.0
Hydrocarbon Solvent (ShellSol A100)	13.4
(ShellSol OMS)	20.2
FeS ₂ Powder (Pyrox Red 325)	58.9
Graphite (Timrex KS6)	4.8
Carbon Black (Super P)	0.7
Total	100.0

The total solids content of the wet cathode slurry mixture 170 is shown in above Table 1 is 66.4 wt.%

The wet cathode slurry 170 is applied to the current collector 115 using intermittent roll coating technique. As

above indicated current collector sheet 115 is optionally precoated with a carbon base layer 172 before the wet cathode slurry is applied. The cathode slurry coated on the metal substrate 115 is dried gradually adjusting or ramping up the temperature from an initial temperature of 40° C to a final temperature of about 130° C in an oven until the solvent has all evaporated. (Drying the cathode slurry in this manner avoids cracking.) This forms a dry cathode coating 170 comprising FeS₂, carbon particles, and binder on the metal substrate 115. The coated cathode is then passed between calendering rolls to obtain the desired cathode thicknesses. A representative desirable thickness of dry/ cathode coating 170 is between about 0.172 and 0.188 mm, preferably about 0.176 mm. The dry cathode coating 170 thus has the following desirable formulation: FeS₂ powder (89 wt.%); Binder (Kraton G1651), 3 wt.%; Graphite (Timrex KS6), 7 wt.%, and Carbon Black (Super P), 1 wt%. The carbon black (Super P carbon black) develops a carbon network which improves conductivity.

The cathode composite comprising current collector sheet 115, cathode base layer 172, and dry cathode coating 170 thereon may then be inserted into cathode housing 130. A separator sheet 160 preferably comprising a microporous polypropylene may then be inserted over the cathode coating 170.

A nonaqueous electrolyte for the Li/FeS₂ cell may then be added so that it fully penetrates through separator sheet 160 and cathode layer 170. A nonaqueous electrolyte mixture can be added so that it becomes absorbed into the separator and cathode coating. The desired nonaqueous electrolyte comprises a

lithium salt or mixture of lithium salts dissolved in an organic solvent.

The nonaqueous electrolyte comprises a lithium salt dissolved in an organic solvent, which preferably comprises an acyclic (non cyclic) organic ester, desirably an alkyl acetate. The alkyl acetate solvent has been determined to have properties that make it an excellent solvent for certain lithium salts resulting in production of suitable electrolytes for use in Li/FeS₂ cells. The alkyl acetate solvent is preferably blended in admixture with cyclic organic carbonates such as ethylene carbonate and propylene carbonate solvents. The desired electrolyte solvent mixture thus comprises a cyclic organic carbonate, preferably a cyclic glycol carbonate such as ethylene carbonate, propylene carbonate or butylene carbonate, and mixtures thereof, in admixture with an alkyl acetate. (The electrolyte solvent may also include dimethylcarbonate and/or ethyl methyl carbonate). The alkyl acetate may be selected from lower alkyl acetates such as methyl acetate, ethyl acetate, propyl acetate, and mixtures thereof. However, methyl acetate is preferred because of its lower viscosity. Ethyl acetate is the next preferred alkyl acetate, because it has properties similar to methyl acetate. Higher esters, such as alkyl propionates, for use as an electrolyte solvent or electrolyte solvent additive for lithium/iron disulfide cells could also prove useful. But because of their much higher viscosity, it is not expected that such alkyl propionates or higher esters would prove to be suitable electrolyte solvents for the lithium/iron disulfide cell. A preferred electrolyte solvent comprises the alkyl acetate blended in a mixture containing both ethylene carbonate and propylene carbonate.

A desirable solvent comprises methyl acetate (MA), propylene carbonate (PC), and ethylene carbonate (EC). Preferably the methyl acetate (MA), comprises between about 5 and 95 vol.%, propylene carbonate (PC) comprises between 1 and 94 vol%, and ethylene carbonate (EC) comprises between 1 and 50 vol% of the electrolyte solvent mixture. A desirable electrolyte for the Li/FeS₂ cell has been determined to comprise the lithium salts lithium trifluoromethanesulfonate having the chemical formula LiCF₃SO₃ which can be referenced simply as LiTFS and/or lithium bistrifluoromethylsulfonyl imide having the formula Li(CF₃SO₂)₂N which can be referenced simply as LiTFSI, preferably in admixture, dissolved in an organic solvent mixture as above comprising methyl acetate (MA), propylene carbonate (PC), and ethylene carbonate (EC).

A preferred electrolyte has been determined to be an electrolyte solution comprising 0.8 molar (0.8 mol/liter) Li(CF₃SO₂)₂N (LiTFSI) salt dissolved in an organic solvent mixture comprising about 75 vol.% methyl acetate (MA), 20 vol.% propylene carbonate (PC), and 5 vol.% ethylene carbonate (EC). Preferably lithium salt Li(CF₃SO₂)₂N (LiTFSI) is dissolved in the above preferred electrolyte. Elemental iodine in the amount comprising about 0.5 wt% of the electrolyte is desirably added to the electrolyte. The electrolyte mixture is desirably added on the basis of about 0.4 gram electrolyte solution per gram FeS₂.

A layer of anode material 150, typically a sheet of lithium or lithium alloy may then be placed over separator sheet 160. The anode cover 120, formed preferably from nickel-plated steel, is inserted into open end 132 of housing 130 and

peripheral edge 135 of housing 130 is crimped over the exposed insulator edge 142 of insulating member 140. The peripheral edge 135 bites into insulator edge 142 closing housing 130 and tightly sealing the cell contents therein. The anode cover 120 also functions as the negative terminal of the cell and housing 130 at the closed end 138 functions as the positive terminal of the cell.

In another embodiment the Li/FeS₂ cell may be in the configuration of a cylindrical cell 10 as shown in Fig. 1. The cylindrical cell 10 may have a spirally wound anode sheet 40, cathode 60 with separator sheet 50 therebetween as shown in Figs. 2-5. The Li/FeS₂ cell 10 internal configuration, apart from the difference in cathode composition, may be similar to the spirally wound configuration shown and described in U.S. patent 6,443,999. The anode sheet 40 as shown in the figures comprises lithium metal and the cathode sheet 60 comprises iron disulfide (FeS₂) commonly known as "pyrite". The cell is preferably cylindrical as shown in the figures and may be of any size, for example, AAAA (42 x 8mm), AAA (44 x 9 mm), AA (49 x 12 mm), C (49 x 25 mm) and D (58 x 32 mm) size. Thus, cell 10 depicted in Fig. 1 may also be a 2/3 A cell (35 x 15mm). However, it is not intended to limit the cell configuration to cylindrical shape. Alternatively, the cell of the invention may have an anode comprising lithium metal and a cathode comprising iron disulfide (FeS₂) having the composition and nonaqueous electrolyte as herein described in the form of a spirally wound prismatic cell, for example a rectangular cell having the overall shape of a cuboid.

For a spirally wound cell, a preferred shape of the cell casing (housing) 20 is cylindrical as shown in Fig. 1. Casing

20 is preferably formed of nickel plated steel. The cell casing 20 (Fig. 1) has a continuous cylindrical surface. The spiral wound electrode assembly 70 (Fig. 3) comprising anode 40 and cathode composite 62 with separator 50 therebetween can be prepared by spirally winding a flat electrode composite 13 (Figs. 4 and 5). Cathode composite 62 comprises a layer of cathode 60 comprising iron disulfide (FeS_2) coated onto metallic substrate 65 (Fig. 4).

The electrode composite 13 (Figs. 4 and 5) can be made in the following manner: The cathode 60 comprising iron disulfide (FeS_2) powder dispersed therein can be initially prepared in the form of a wet slurry which is coated onto a conductive substrate sheet 65, preferably a sheet of aluminum or stainless steel expanded metal foil, to form a cathode composite sheet 62 (Fig. 4). If an aluminum sheet 65 is used it may be a sheet of aluminum without openings therethrough or may be a sheet of expanded aluminum foil (EXMET expanded aluminum foil) with openings therethrough thus forming a grid or screen.

The wet cathode slurry mixture having the composition shown above in Table 1 comprising iron disulfide (FeS_2), binder, conductive carbon and solvents is prepared by mixing the components shown in Table 1 until a homogeneous mixture is obtained.

The above quantities (Table 1) of components of course can be scaled proportionally so that small or large batches of cathode slurry can be prepared. The wet cathode slurry thus preferably has the following composition: FeS_2 powder (58.9 wt.%); Binder, Kraton G1651 (2 wt.%); Graphite, Timrex KS6

(4.8 wt%), Actylene Black, Super P (0.7 wt%), Hydrocarbon Solvents, ShellSol A100 (13.4 wt%) and ShellSol OMS (20.2 wt%)

The cathode slurry is coated onto one side (optionally both sides) of a conductive substrate or grid 65, preferably a sheet of aluminum, or stainless steel expanded metal foil. The cathode slurry coated on the metal substrate 65 is dried in an oven preferably gradually adjusting or ramping up the temperature from an initial temperature of 40° C to a final temperature not to exceed 130° C for about 1/2 hour or until the solvent has all evaporated. This forms a dry cathode coating 60 comprising FeS₂, carbon particles, and binder on the metal substrate 65 and thus forms the finished cathode composite sheet 62 shown best in Fig. 4. A calendering roller is then applied to the coating to obtain the desired cathode thicknesses. For an AA size cell, the desired thickness of dry/ cathode coating 60 is between about 0.172 and 0.188 mm, preferably about 0.176 mm. The dry cathode coating thus has the following desirable formulation: FeS₂ powder (89.0 wt.%); binder, Kraton G1651 elastomer (3.0 wt.%); conductive carbon particles, preferably graphite (7 wt.%) available as Timrex KS6 graphite from Timcal Ltd and conductive carbon black (1 wt%) available as Super P conductive carbon black from Timcal. The carbon black develops a carbon network which improves conductivity. Optionally between about 0 and 90 percent by weight of the total carbon particles may be graphite. The graphite if added may be natural, synthetic or expanded graphite and mixtures thereof. The dry cathode coating may typically comprise between about 85 and 95 wt.% iron disulfide (FeS₂); between about 4 and 8 wt.% conductive carbon; and the remainder of said dry coating comprising binder material.

The cathode substrate 65 can be a sheet of conductive metal foil, for example, a sheet of aluminum or stainless steel, with or without apertures therein. The cathode conductive substrate 65 is preferably a sheet of aluminum. The aluminum sheet 65 may ~~desirably~~ have a plurality of small apertures therein, thus forming a grid or screen. Alternatively, cathode conductive substrate 65 may be formed of a sheet of stainless steel expanded metal foil (EXMET stainless steel foil from Dexmet Company, Branford, Conn.) having a basis weight of about 0.024 g/cm² forming a mesh or screen with openings therein. The EXMET expanded stainless steel foil may have openings therethrough forming a grid or screen. The cathode conductive substrate 65 secures the cathode coating 60 and functions as a cathode current collector during cell discharge.

The anode 40 can be prepared from a solid sheet of lithium metal. The anode 40 is desirably formed of a continuous sheet of lithium metal (99.8 % pure). Alternatively, the anode 40 can be an alloy of lithium and an alloy metal, for example, an alloy of lithium and aluminum. In such case the alloy metal, is present in very small quantity, preferably less than 1 percent by weight of the lithium alloy. Upon cell discharge the lithium in the alloy thus functions electrochemically as pure lithium. Thus, the term "lithium or lithium metal" as used herein and in the claims is intended to include in its meaning such lithium alloy. The lithium sheet forming anode 40 does not require a substrate. The lithium anode 40 can be advantageously formed from an extruded sheet of lithium metal having a thickness of desirably between about

0.10 and 0.20 mm desirably between about 0.12 and 0.19 mm, preferably about 0.15 mm for the spirally wound cell.

Individual sheets of electrolyte permeable separator material 50, preferably of microporous polypropylene having a thickness of about 0.025 mm is inserted on each side of the lithium anode sheet 40 (Figs. 4 and 5). The microporous polypropylene desirably has a pore size between about 0.001 and 5 micron. The first (top) separator sheet 50 (Fig. 4) can be designated the outer separator sheet and the second sheet 50 (Fig. 4) can be designated the inner separator sheet. The cathode composite sheet 62 comprising cathode coating 60 on conductive substrate 65 is then placed against the inner separator sheet 50 to form the flat electrode composite 13 shown in Fig. 4. The flat composite 13 (Fig. 4) is spirally wound to form electrode spiral assembly 70 (Fig. 3). The winding can be accomplished using a mandrel to grip an extended separator edge 50b (Fig. 4) of electrode composite 13 and then spirally winding composite 13 clockwise to form wound electrode assembly 70 (Fig.3).

When the winding is completed separator portion 50b appears within the core 98 of the wound electrode assembly 70 as shown in Figs. 2 and 3. By way of non limiting example, the bottom edges 50a of each revolution of the separator may be heat formed into a continuous membrane 55 as shown in Fig. 3 and taught in U.S. patent 6,443,999. As may be seen from Fig. 3 the electrode spiral 70 has separator material 50 between anode sheet 40 and cathode composite 62. The spirally wound electrode assembly 70 has a configuration (Fig. 3) conforming to the shape of the casing body. The spirally wound electrode assembly 70 is inserted into the open end 30 of

casing 20. As wound, the outer layer of the electrode spiral 70 comprises separator material 50 shown in Figs. 2 and 3. An additional insulating layer 72, for example, a plastic film such as polyester tape, can desirably be placed over a of the outer separator layer 50, before the electrode composite 13 is wound. In such case the spirally wound electrode 70 will have insulating layer 72 in contact with the inside surface of casing 20 (Figs. 2 and 3) when the wound electrode composite is inserted into the casing. Alternatively, the inside surface of the casing 20 can be coated with electrically insulating material 72 before the wound electrode spiral 70 is inserted into the casing.

A nonaqueous electrolyte mixture can then be added to the wound electrode spiral 70 after it is inserted into the cell casing 20. The desired nonaqueous electrolyte comprises a lithium salt dissolved in an organic solvent. A desirable solvent comprises methyl acetate (MA), propylene carbonate (PC), and ethylene carbonate (EC). Preferably the methyl acetate (MA) comprises between about 5 and 95 vol.%, propylene carbonate (PC) comprises between 1 and 94 vol%, and ethylene carbonate (EC) comprises between 1 and 50 vol% of the electrolyte solvent mixture. A desirable electrolyte for the Li/FeS₂ wound cell has been determined to comprise lithium salts lithium trifluoromethanesulfonate having the chemical formula LiCF₃SO₃ which can be referenced simply as LiTFS and/or the lithium salt Li(CF₃SO₂)₂N (LiTFSI) dissolved in an organic solvent mixture comprising methyl acetate (MA), propylene carbonate (PC), and ethylene carbonate (EC).

A preferred electrolyte has been determined to be an electrolyte solution comprising 0.8 molar (0.8 mol/liter)

concentration of LiTFSI salt dissolved in an organic solvent mixture comprising about 75 vol.% methyl acetate (MA), 20 vol.% propylene carbonate (PC), and 5 vol.% ethylene carbonate (EC). Elemental iodine in the amount comprising about 0.5 wt% of the electrolyte is desirably added to the electrolyte. The electrolyte mixture is desirably added on the basis of about 0.4 gram electrolyte solution per gram FeS_2 for the spirally wound cell (Fig. 2).

An end cap 18 forming the cell's positive terminal 17 may have a metal tab 25 (cathode tab) which can be welded on one of its sides to inside surface of end cap 18. Metal tab 25 is preferably of aluminum or aluminum alloy. A portion of the cathode substrate 65 may be flared along its top edge forming an extended portion 64 extending from the top of the wound spiral as shown in figure 2. The flared cathode substrate portion 64 can be welded to the exposed side of metal tab 25 before the casing peripheral edge 22 is crimped around the end cap 18 with peripheral edge 85 of insulating disk 80 therebetween to close the cell's open end 30. End cap 18 desirably has a vent 19 which can contain a rupturable membrane designed to rupture and allow gas to escape if the gas pressure within the cell exceeds a predetermined level. Positive terminal 17 is desirably an integral portion of end cap 18. Alternatively, terminal 17 can be formed as the top of an end cap assembly of the type described in U.S. patent 5,879,832, which assembly can be inserted into an opening in the surface of end cap 18 and then welded thereto.

A metal tab 44 (anode tab), preferably of nickel can be pressed into a portion of the lithium metal anode 40. Anode tab 44 can be pressed into the lithium metal at any point

within the spiral, for example, it can be pressed into the lithium metal at the outermost layer of the spiral as shown in Fig. 5. Anode tab 44 can be embossed on one side forming a plurality of raised portions on the side of the tab to be pressed into the lithium. The opposite side of tab 44 can be welded to the inside surface of the casing either to the inside surface of the casing side wall 24 or more preferably to the inside surface of close end 35 of casing 20 as shown in Fig. 3. It is preferable to weld anode tab 44 to the inside surface of the casing closed end 35, since this is readily accomplished by inserting an electrical spot welding probe (an elongated resistance welding electrode) into the cell core 98. Care should be taken to avoid contacting the welding probe to the separator starter tab 50b which is present along a portion of the outer boundary of cell core 98.

The primary lithium cell 10 may optionally also be provided with a PTC (positive thermal coefficient) device 95 located under the end cap 18 and connected in series between the cathode 60 and end cap 18 (Fig. 2). Such device protects the cell from discharge at a current drain higher than a predetermined level. Thus, if the cell is drained at an abnormally high current, e.g., higher than about 6 to 8 Amp, for a prolonged period, the resistance of the PTC device increases dramatically, thus shutting down the abnormally high drain. It will be appreciated that devices other than vent 19 and PTC device 95 may be employed to protect the cell from abusive use or discharge.

Example

Experimental Test Lithium Coin
Cells with Cathode Comprising FeS₂

Experimental test Li/FeS₂ coin cells 100 (Fig. 1A) were prepared as follows:

Experimental Test Cell Assembly:

A coin shaped cathode housing 130 of nickel plated steel and a coin shaped anode housing (cover) 120 of nickel plated steel is formed of a similar configuration shown in Fig. 1A. The finished cell 100 had an overall diameter of about 25 mm and a thickness of about 3 mm. The weight of FeS₂ in the cathode housing 130 was 0.125 g. The lithium was in electrochemical excess.

In forming each cell 100, an Arbor press with a 0.780-inch die was used to punch out two stainless steel grids (316L-SS EXMET expanded metal foil). One stainless steel grid was centered inside of coin cell cathode housing 130 forming cathode current collector sheet 115. The other stainless steel grid (not shown) was resistance welded to the inside surface of closed end of the anode housing (cover) 120. The grids were welded to their respective housings using a Hughes opposing tip tweezers welder. The welder was set at 20 watts-seconds and a medium pulse. The welds that were formed were evenly spaced around the perimeters of the grids over intersecting points of mesh strands. For each cell, six to eight welds were formed per grid.

A plastic insulating disk (grommet) 140 was then attached to the edge of anode cover 120 (Fig. 1A). A lithium disk 150 formed of a sheet of lithium metal having a thickness of 0.032 inch (0.813 mm) was punched out in a dry box using an Arbor press and a 0.75 inch hand punch. The lithium disk 150 forming the cell's anode was then pressed onto the stainless steel

grid against the inside surface of the closed end of anode cover 120 using an Arbor press.

A microporous polypropylene separator 160 (Celgard CG2400 separator from Celgard, Inc.) was cut into eight-inch strips and punched out using a hand punch having a diameter of 0.9375 inch and set aside.

Cathode conductive base layer 172 was prepared as follows:

Add 75g of graphite (Timrex KS6 graphite) and 25g of tetrafluoroethylene (Teflon) powder to a tumbler (with weights) and let run overnight in hood. Add contents to a blender (~10g at a time) and blend on high for 1 minute. Pour blended contents into a container, label, and store until ready for use. When ready for application of cathode base layer 172, the cathode housing 130 was placed in a die. The cathode base layer 172 (0.500g) was impacted onto the stainless steel grid 115 by using a ram connected to a Carver hydraulic press. The cathode base layer 172 had the composition 75 wt.% graphite and 25% Teflon powder.

A cathode slurry was then prepared and coated over one side of an aluminum sheet (not shown). The components of the cathode slurry comprising iron disulfide (FeS_2) were mixed together in the following proportion:

FeS_2 powder (58.9 wt.%); Binder, styrene-ethylene/butylene-styrene elastomer (Kraton G1651) (2 wt.%); Graphite (Timrex KS6) (4.8 wt%), Carbon Black (Super P carbon black) (0.7 wt%), Hydrocarbon Solvents, ShellSol A100 solvent (13.4 wt%) and ShellSol OMS solvent (20.2 wt%).

The wet cathode slurry on the aluminum sheet was then dried in an oven between 40⁰ C and 130⁰ C until the solvent in the cathode slurry all evaporated, thus forming a dry cathode coating comprising FeS₂, conductive carbon and elastomeric binder on a side of the aluminum sheet. The aluminum sheet was an aluminum foil of 20 micron thickness. The same composition of wet cathode slurry was then coated onto the opposite side of the aluminum sheet and similarly dried. The dried cathode coatings on each side of the aluminum sheet was calendered to form a dry cathode 170 having a total final thickness of about 0.176 mm, which includes the 20 micron thick aluminum foil. The dry cathode coating 170 had the following composition:

FeS₂ powder (89.0 wt.%); Binder Kraton G1651 elastomer (3.0 wt.%); conductive carbon particles, graphite Timrex KS6 (7 wt.%) and carbon black, Super P (1 wt%).

The composite of the dry cathode coating 170 coated on both sides of the aluminum sheet was then die punched into the cathode housing 130 onto carbon base layer 172. This was done by placing cathode housing 130 within a die. A cut to size composite of aluminum sheet coated on both sides with dry cathode coating 170 was then aligned directly over cathode base layer 172 within housing 130. A ram was then inserted into the die holding housing 130, and the die was moved to a hydraulic press. Four metric tons of force was applied using the press to punch the composite into the cathode housing 130 so that it was impacted against cathode base layer 172. The die was then inverted and the housing 130 gently removed from the die. The surface of the exposed cathode layer 170 had a

smooth, consistent texture. The finished cathode coin was then placed in a vacuum oven and was heated at 150° C for 16 hours.

A preferred electrolyte formulation of the invention was prepared. The preferred electrolyte comprise 0.8 molar (0.8 mol/liter) concentration of $\text{Li}(\text{CF}_3\text{SO}_2)_2\text{N}$ (LiTFSI) salt dissolved in an organic solvent mixture comprising about 75 vol.% methyl acetate (MA), 20 vol.% propylene carbonate (PC), and 5 vol.% ethylene carbonate (EC). In the preparation of the test cells elemental iodine (I_2) in amount of about 0.5 wt.% was added to this electrolyte solution.

The cathode coin, that is, cathode housing 130 with dried cathode 170 therein, was placed into a glass coin holder for vacuum filling with electrolyte. A rubber stopper with an attached burette fill tube was placed on top of the cathode coin holder. The fill valve on the tube was closed and the vacuum valve was opened for approximately one minute.

The electrolyte of above described formulation of the invention containing 0.5 wt.% elemental iodine, was slowly added using a pipette. The vacuum valve was closed and the burette valve was opened. After about one minute, the vacuum valve was shut off, and the fill valve was opened slowly to fill the cathode housing 130 and allow cathode 170 to absorb most of the electrolyte.

The filled cathode coin was removed using plastic tweezers, and was placed on the base of a crimper so that it sat securely on the base. A pipette was used to flood the coin with the excess of electrolyte that was left over in the glass holder.

The microporous polypropylene separator (Celgard CG2400 separator) was placed on top of the electrolyte wet cathode layer 170 and was centered. The cathode housing 130 was then re-flooded with electrolyte.

An anode coin, that is, the anode cover 120 with lithium anode sheet 150 therein was placed on top of the cathode housing 130 and was centered within a mechanical crimper until the anode cover 120 fit evenly inside of the cathode housing 130. A mechanical crimper arm was then pulled down all of the way to crimp the peripheral edge 135 of the cathode housing 130 over the edge of insulating disk 140. This process was repeated for each cell. After each cell had been formed, the outside surfaces of the housings of the cells were wiped cleaned with methanol.

Control (Comparative) Cells

A control group of identical lithium/iron disulfide coin cells of same size and identical anode and cathode composition and same cell construction as the experimental test cells was prepared, with the exception of the electrolyte. That is, the only difference between the control cells and the above described experimental test cells was that the electrolyte was different. The electrolyte used in the control cells was of the type described in U.S. 5,290,414 and 6,218,054 utilizing dioxolane solvent and contained 70 vol.% of dioxolane (DIOX), 30 vol.% of dimethoxyethane (DME) with 0.8 M LiI (lithium Iodide) salt and 0.2 wt% 3,5-dimethylisoxazole (DMI). By contrast, the electrolyte used in the experimental test cells, as above described in the preceding test cell assembly, is

representative of the electrolyte of the invention, as applied to the lithium/iron disulfide cell.

Electrochemical Performance of Experimental Test Cells

Compared to Control Cells:

After the cells had been formed, the discharge capacity of each cell was tested using a test that was meant to mimic the use of the cell in a digital camera scaled down based on the weight of cathode active material.

Digital Camera test consists of the following pulse test protocol: Step 1: 10 cycles wherein each cycle consists of both a 26 milliWatt pulse for 2 seconds followed immediately by a 12 milliWatt pulse for 28 seconds; step 2 is then 55 minutes rest. Steps 1 and 2 are continued until a cut off voltage of 1.05 Volt is reached. Two groups of coin cells were assembled by the above procedure. The Control group of cells as above indicated were filled with the following electrolyte:

70 vol.% of dioxolane (DIOX), 30 vol.% of dimethoxyethane (DME) with 0.8 M LiI (lithium Iodide) salt and 0.2 wt% 3,5-dimethylisoxazole (DMI) dissolved in the above mixture of solvents.

The experimental test cells were were filled with the following electrolyte of the invention: 0.8 M of $\text{Li}(\text{CF}_3\text{SO}_2)_2\text{N}$ (LiTFSI) salt dissolved in an organic solvent mixture comprising 75 vol.% methyl acetate (MA), 20 vol.% propylene carbonate (PC), and 5 vol.% ethylene carbonate (EC) with 0.5 wt.% I_2 added to this electrolyte solution. Ten cells per group were assembled.

Complex impedance of each coin cell was measured by using Solartron Electrochemical Interface 1287 with Frequency Response Analyzer 1255.

The experimental test cells and the control group of cells were subjected to the following discharge pulse test protocol conducted under ambient room temperature:

Step 1: 10 cycles wherein each cycle consists of both a 26 milliWatt pulse for 2 seconds followed immediately by a 12 milliWatt pulse for 28 seconds; step 2 is then 55 minutes rest. Steps 1 and 2 are continued until a cut off voltage of 1.05 Volt is reached.

Discharge of cells was done on Maccor 4000 cycling equipment. The running voltage observed for the experimental test group of cells was similar to the running voltage of control group. For example the running voltage observed for the experimental test group of cells was 1.3 V, and the running voltage observed for the control cells was 1.35 V. The experimental test group and control group of cells exhibited essentially no noticeable voltage drop during the first 50 pulses. That is, the running voltage of the experimental cells during the first 50 pulses was at steady level and very nearly the same (within 50 millivolts) as the running voltage of the control group of cells.

The cells are discharged to the same cut off voltage of 1.05 volts using the same pulsed discharge test. The running voltage and total delivered number of pulses for the life of the cells, for the experimental group was similar to the control group.

The experimental group of cells exhibited 5 Ohms resistance on average caused by buildup of a passivation layer on the surface of the lithium metal anode, while the control group of cells exhibited 3.5 Ohms resistance caused by such passivation layer. This difference in resistance is caused by differences in the chemical nature and amount of accumulated coating (passivation layer) on the surface of the lithium metal anode resulting from side reaction between the lithium metal anode and the electrolyte solvent mixture. This difference in impedance of the passive layer for the experimental group vs. the control group is negligible, and does not noticeably affect the cells' performance.

In conclusion the test experimental cells using the electrolyte of the invention performed about as well as the control cells which used the dioxolane (DIOX)/ dimethoxyethane (DME) electrolyte solvent under the conditions tested. But the electrolyte of the invention is easier and safer to handle and more cost effective.

The above cell tests were conducted at ambient room temperature, however, it is expected that the same Li/FeS₂ test cells filled with the electrolyte mixture of the invention containing lower alkyl acetates such as methyl acetate, would show similar good performance over a wide temperature range (0°C to 60°C) in view of the low viscosity of such lower alkyl acetates.

Although the invention has been described with reference to specific embodiments, it should be appreciated that other embodiments are possible without departing from the concept of

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the invention and are thus within the claims and equivalents thereof.

CLAIMS

What is claimed is:

1. A primary electrochemical cell characterized in that said cell comprises a housing; a positive and a negative terminal; an anode comprising lithium; a cathode comprising iron disulfide (FeS_2) and conductive carbon, said cell further comprising a nonaqueous electrolyte comprising a lithium salt dissolved in a nonaqueous solvent mixture comprising an alkyl ester.

2. The cell of claim 1 wherein the alkyl ester comprises alkyl acetate selected from the group consisting of methyl acetate, ethyl acetate, and propyl acetate, and mixtures thereof.

3. The cell of claim 1 wherein the lithium salt is selected from the group consisting of LiCF_3SO_3 (LITFS), $\text{Li}(\text{CF}_3\text{SO}_2)_2\text{N}$ (LiTFSI), and mixtures thereof.

4. The cell of claim 1 wherein said nonaqueous solvent mixture further comprises cyclic organic carbonate selected from the group consisting of ethylene carbonate, propylene carbonate, and butylene carbonate, and mixtures thereof.

5. The cell of claim 1 wherein the electrolyte comprises a lithium salt comprising $\text{Li}(\text{CF}_3\text{SO}_2)_2\text{N}$ (LiTFSI) dissolved in a nonaqueous solvent mixture comprising an alkyl acetate, ethylene carbonate (EC), and propylene carbonate (PC).

6. The cell of claim 5 wherein said nonaqueous solvent further comprises elemental iodine.

7. The cell of claim 6 wherein the elemental iodine comprises between about 0.01 and 5.0 percent by weight of said electrolyte.

8. The cell of claim 1 wherein said cathode comprising iron disulfide (FeS_2) and conductive carbon is coated onto a substrate sheet comprising aluminum.

9. The cell of claim 1 wherein the anode comprises a sheet of lithium or lithium alloy.

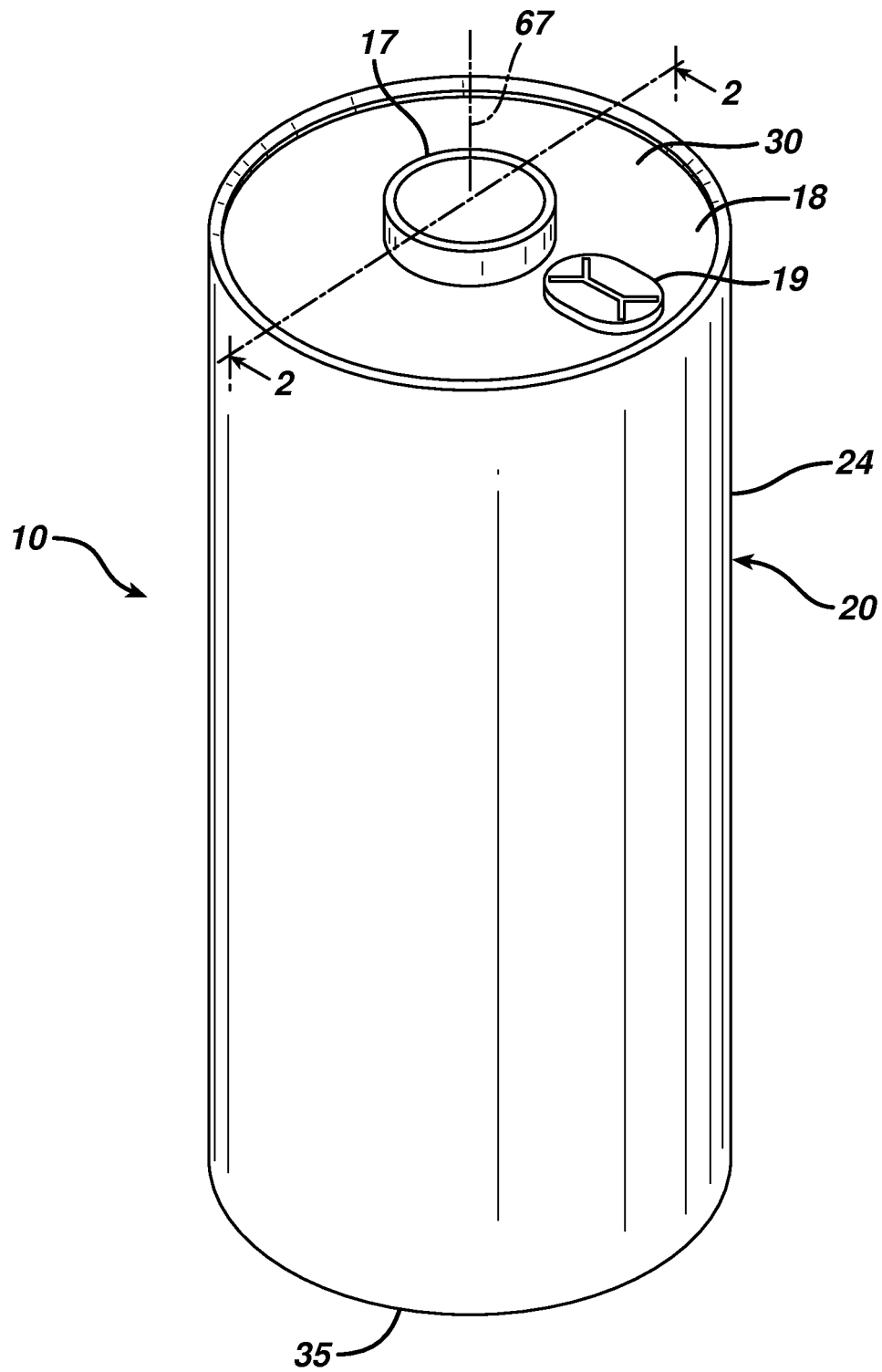
10. The cell of claim 1 wherein said conductive carbon comprises a mixture of carbon black and graphite.

11. The cell of claim 1 wherein said cathode further comprises a binder comprising an elastomeric material.

12. The cell of claim 1 wherein said cathode comprising iron disulfide (FeS_2) is in the form of a coating bound to a metallic substrate and wherein said anode comprising lithium and said cathode are arranged in spirally wound form with a separator material therebetween.

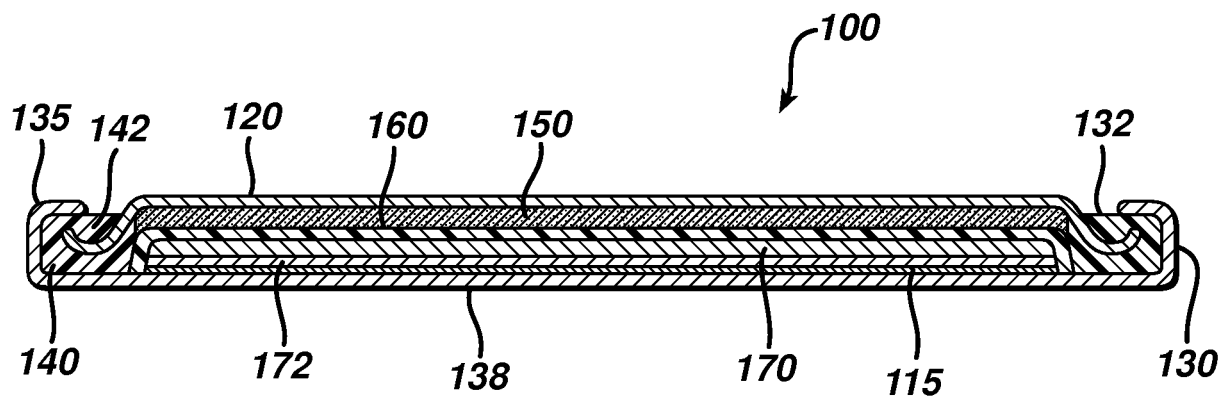
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FIG. 1

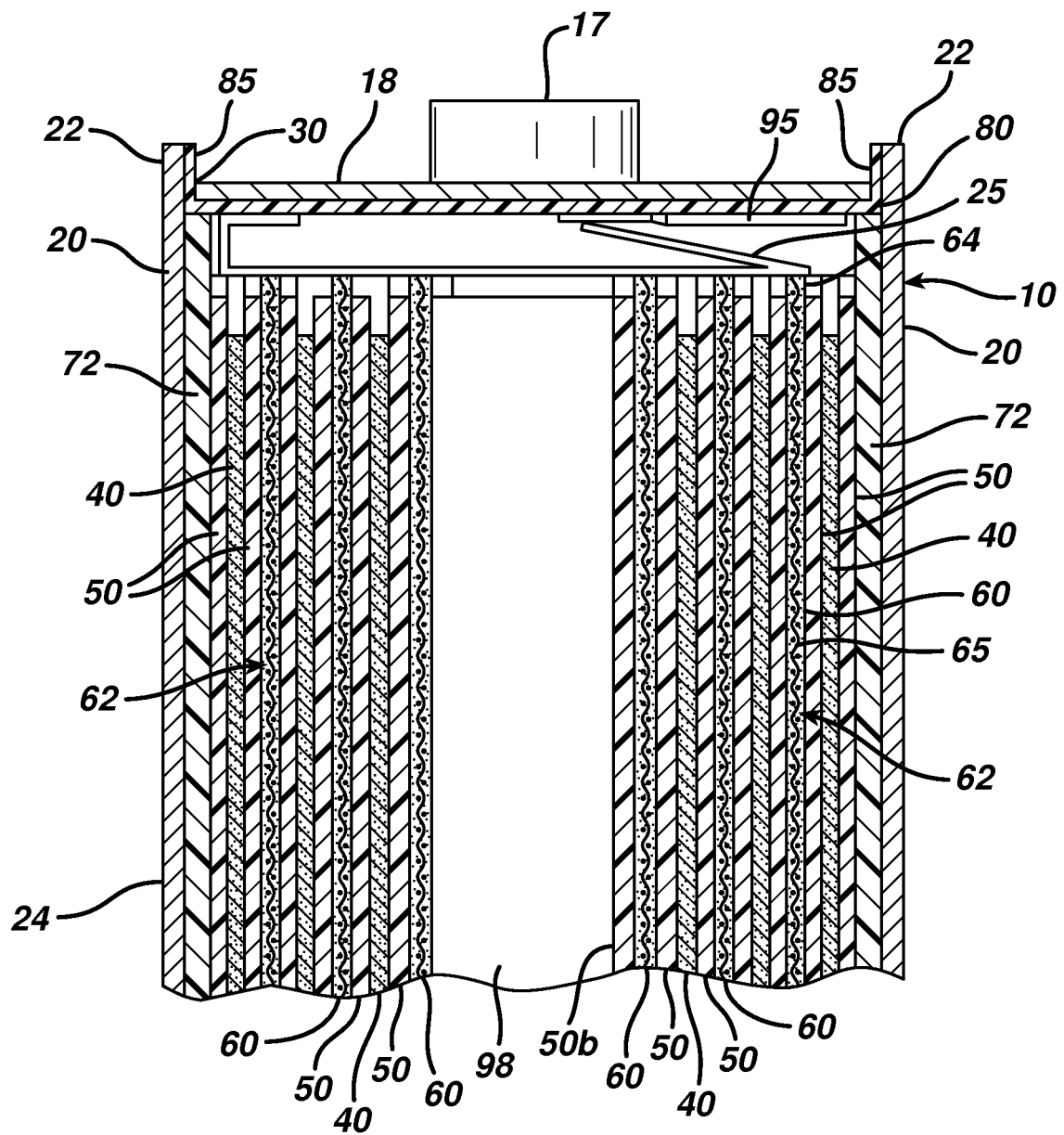


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FIG. 1A

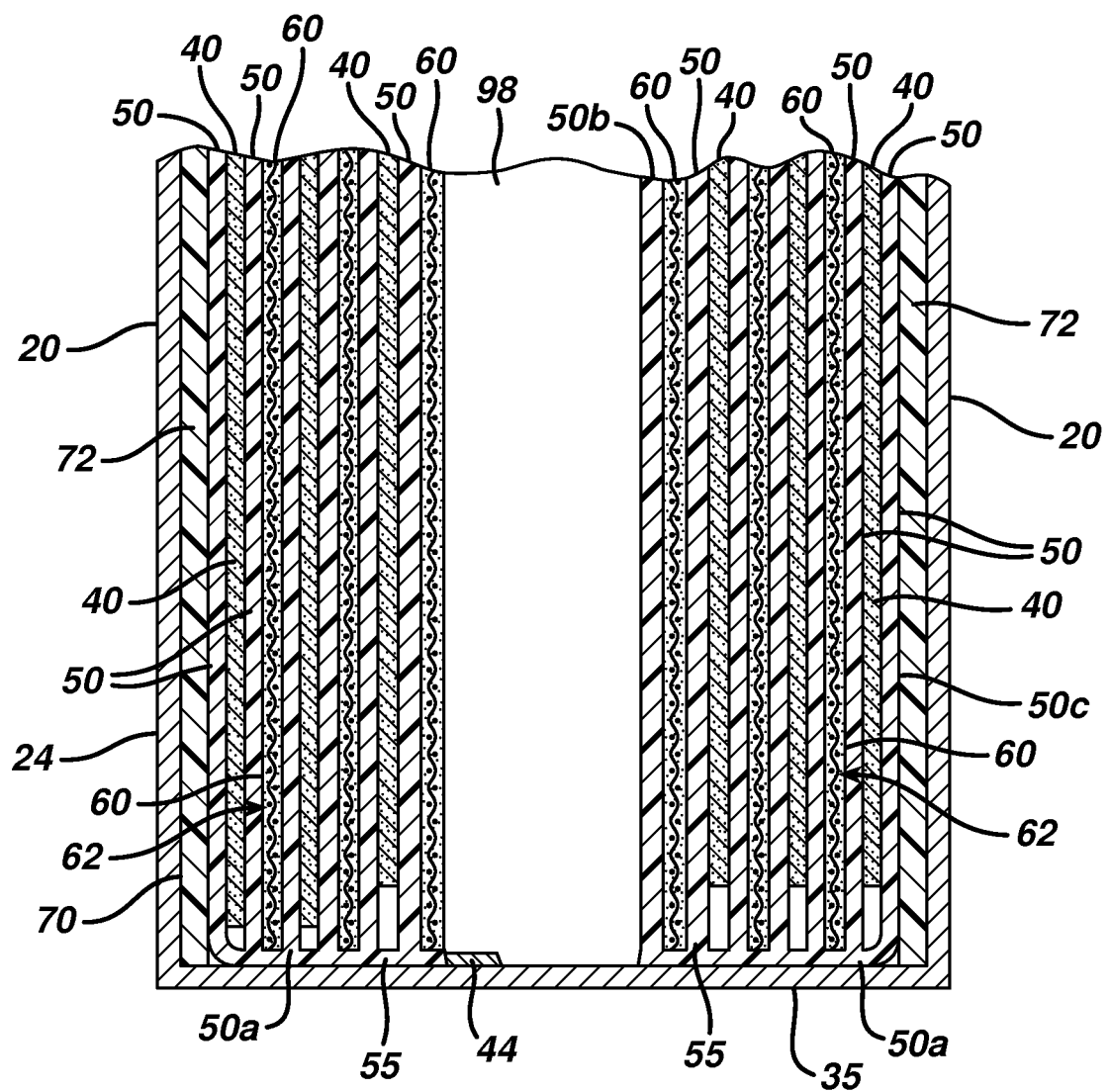


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FIG. 2

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FIG. 3



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FIG. 4

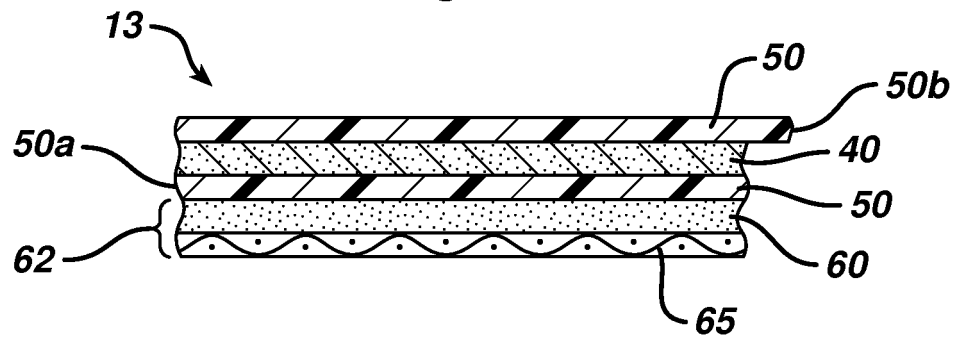


FIG. 5

