In the disclosed electrochemical cell (10) for the production of an alkaline solution of peroxide, especially on site production, the electrolyte is divided into an aqueous alkaline catholyte (19) and an aqueous alkaline anolyte (17), and the cathode (37) is a gas-diffusion electrode. The active material of the electrolyte side (33) of the gas-diffusion cathode comprises a particulate catalyst support material having a surface area of about 50 to about 2,000 m²/g, and deposited on the particles of this support material, 0.1 to 50 weight-%, based on the weight of the active layer, of gold or gold alloy particles having an average size >50 but less than about 200 Å. These gold or gold alloy particles are substantially selectively catalytic for the reduction of oxygen to peroxide (e.g. HOO⁻). The electrolyte flow patterns are designed to avoid loss of peroxide resulting from oxidation at the anode (39). In the operation of the cell, a product with a hydroxyl/perhydroxyl ratio less than 2:1 can be obtained.
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ELECTROCHEMICAL PEROXIDE GENERATOR AND PROCESS FOR MAKING PEROXIDE

Field of the Invention

This invention relates to electrochemical cells designed to synthesize peroxide (HOO', O_2', or H_2O_2 dissolved in an alkaline medium) by cathodic reduction of an oxygen-containing gas and to processes for operating such cells. An aspect of this invention relates to electrochemical cells for the synthesis of peroxide wherein the electrolyte is divided into an aqueous alkaline catholyte and an aqueous alkaline anolyte. Another aspect of this invention relates to a process for synthesizing peroxide which can be operated at relatively low cell voltages and relatively high current densities and efficiencies.

Description of the Prior Art

It has long been known that hydrogen peroxide can be synthesized electrochemically, taking advantage of modern advances in electrochemical cell technology. The patent literature published on this subject in the late 1960's and early 1970's took into consideration the possibility of using a gas-diffusion cathode. A "gas-diffusion electrode" is normally considered to comprise a structure which is gas permeable on one major surface (sometimes called the "gas side") and electrocatalytic on the opposite major surface, which opposite surface is in contact with the electrolyte and is sometimes called the "electrolyte side". The electrolyte is permitted to permeate into the electrolyte side to a degree sufficient to provide a multi-phase interface between a gaseous reactant, a solid electrocatalytic material, and the electrolyte (which is generally a liquid). However, significant permeation of electrolyte through pores or interstices within the catalytic material of the gas-diffusion electrode at a significant flow rate is neither necessary nor
desirable.

For a representative sampling of disclosures from this late-1960's/early 1970's period, see the several U.S. patents issued to Grangaard, e.g. 3,459,652 (August 5, 1969), 3,462,351 (August 19, 1969), 3,507,769 (April 21, 1970), 3,592,749 (July 13, 1971), and 3,607,687 (September 21, 1971). These disclosures typically contemplate a generally free-flowing catholyte which takes up peroxide (generally in the form of \( \text{HO}_2^- \)) dissolved in the alkaline catholyte and is withdrawn from the cell for the purpose of recovering a product which is intended to be directly useful in industry, e.g. as an alkaline bleach solution.

Experts in the electrochemical synthesis art found the performance of the Grangaard cells to be very disappointing, however, and by the mid-1970's, even the fundamental principles upon which the Grangaard concepts were based were being called into question. For example, according to Oloman and his coworkers, see U.S. Patents 3,969,201 and 4,118,305, issued July 13, 1976 and October 3, 1978, respectively, the Grangaard cells produced an aqueous alkaline product having a peroxide concentration of only about 0.5% with an \( \text{NaOH}/\text{H}_2\text{O}_2 \) ratio (by weight percent) of 4:1 (cf. U.S. 3,459,652). As is known in the art, some uses of bleaching solution, e.g. in the pulp and paper industry, generally call for much higher concentrations of peroxide and/or for \( \text{NaOH}/\text{H}_2\text{O}_2 \) ratios in the range of about 1:1 to about 2:1. Oloman et al, among others, questioned the basic idea of utilizing a gas-diffusion cathode of the classical structure wherein catholyte merely permeates into the electrode structure from the electrolyte side. Thus, by the mid- to late 1970's, prior art workers were directing their attention to cathode structures constructed from a fluid-permeable, electrically conductive mass (e.g. a bed of
conductive catalytic particles or a fixed, porous conductive catalytic matrix) with sufficient porosity to permit a constant trickle or flow of electrolyte through the entire volume (or most of the volume) of the cathode mass. In an electrochemical cell provided with such a fluid-permeable, electrically conductive cathode mass, the cathode can, if desired, fill up the entire cathode compartment, so that all or most of the catholyte is confined to the interior of the cathode mass.

In subsequent developments based upon the packed-bed or porous matrix concept of a cathode, the cathode was in some cases placed in contact with a non-conducting porous matrix (such as a felt) or was employed in a cell having in essence a single electrolyte rather than an electrolyte divided into catholyte and anolyte.

In many patent disclosures illustrating the packed-bed or porous matrix concept of a cathode, the product (generally an alkaline solution of peroxide, most typically catholyte which has been passed through the cathode mass) is collected from an end or edge or other portion of the cathode mass, rather than from a generally free-flowing catholyte which has merely contacted and/or permeated to some degree a surface of the cathode. Alternatively, the product is essentially catholyte which has wicked through a non-conductive, porous mass such as a felt which is in contact with the cathode.

Peroxide-generating cells containing packed-bed or porous-matrix cathodes have in recent years become commercially available for use as on-site peroxide generators, and considerable effort has gone into the optimization of their performance. However, these commercially available cells operate at overall cell potentials ($E_{cell}$) of about 2.0 V and current densities not significantly exceeding 60 amperes.
per square foot (about 64.5 mA/cm² = 645 A/m²). Even assuming a current efficiency of 85 to 90%, a large amount of electrode surface area is required in a typical commercial installation, resulting in higher capital costs to the industrial user.

Moreover, the packed-bed or porous matrix concept of cathode construction has not provided any improvement in quality control as compared to cells utilizing gas-diffusion cathodes. The packed bed or porous matrix can develop "hot spots" in which current densities, etc. are higher than average for the bed or matrix as a whole, thereby creating the risk that some part of the cathode might become "starved" for three-phase interface sites and can place the entire bed or matrix at risk of catastrophic failure. This risk can be reduced through the use of a significant stoichiometric excess of oxygen, but non-uniform consumption of oxygen throughout the cathode bed or matrix still contributes to poor quality control. In addition, bipolar cell construction, with stacking of cells for more efficient overall operation, is problematic, due to the variability in the performance of individual cells.

Accordingly, despite significant advances in the field of on-site electrosynthesis of peroxide over the last twenty years, cell performance is still in need of substantial improvement.
SUMMARY OF THE INVENTION

It has now been discovered that the performance of electrochemical peroxide synthesis cells and processes in terms of operating potentials, range of current densities, cathode lifetime, and the resulting system capital costs can be markedly improved through the use of an electrochemical catalytic material containing gold particles and through the use of a generally free-flowing catholyte which inhibits loss of peroxide due to oxidation of perhydroxyl ion at the anode of the cell. Owing to a unique cathode preparation process incorporating the gold catalyst, the relatively poor performance of the Grangaard cells is not observed during the practice of this invention.

Thus, an electrochemical cell of this invention comprises:

a partitioning means (such as a fluid-permeable separator) for partitioning the cell into an anode compartment and a cathode compartment, the anode compartment containing an anode and an aqueous alkaline anolyte,

a cathode compartment defining a space containing a generally free-flowing aqueous alkaline catholyte, a gas-diffusion cathode having two major surfaces (the cathode occupies, at most, only a minor proportion of the volume of this space), the space defined by the cathode being constructed and arranged to permit generally unrestricted flow of the aqueous alkaline catholyte across one of the major surfaces of the gas-diffusion cathode, i.e. the "electrolyte side" (the other major surface of the cathode, i.e. the "gas side", is in contact with oxygen-containing gas). A catholyte withdrawal means permits withdrawal of the spent catholyte, which is the desired product of peroxide dissolved in an aqueous alkaline medium.
The electrolyte side of the cathode comprises an electrochemically active material which is composed of:
a particulate catalyst support material having a surface area, by the B.E.T. method, of about 50 to about 2000 m²/g,
deposited on the particles of catalyst support material of the active layer, 0.1 to 50 weight-%, based on the weight of the active layer, of a particulate elemental metal comprising gold particles having an average size, measured by transmission electron microscopy, which is greater than about 4 but less than about 20 nanometers, this particulate elemental metal being substantially selectively catalytic for the reduction of oxygen to peroxide ion or hydrogen peroxide, and preferably, a gas-permeable, electrically conductive support material on which the active material is deposited. The active material is preferably rendered hydrophobic by including in it at least 30% by weight, based on the weight of the active layer, of hydrophobic polymer.

Electrical leads in electrical contact with the anode and the cathode of the cell are provided for the external electrical circuit. If desired, the cell can be bipolar and can be electrically connected to one or more additional cells.

In the process of operating this electrochemical cell, the overall cell potential (Ecell) need not exceed 2 volts and can be less than 1.5 V; current densities can range from 700 to 2,000 A/m² (70 to 200 mA/cm²) or more, yet current efficiencies do not suffer and are typically in the range of about 85 to about 95%. In addition, current densities in excess of 300 mA/cm² are attainable. Since the size, and
therefore the cost, of a commercial system is a direct linear function of the electrode area, a substantial improvement in sustainable current density will significantly reduce the system capital costs. This outstanding performance can be obtained under near ambient operating conditions, including temperatures in the range 35-40°C. The hydroxide/peroxide ratio of the resulting product is well-controlled but variable in accordance with the desired use and hence can vary from about 1.6:1 to all higher values. The peroxide yields associated with these product ratios are typically 3-5 wt%.

BRIEF DESCRIPTION OF THE DRAWING

In the accompanying Drawing, wherein like reference numerals denote like parts in the various embodiments of the invention,

FIGURE 1 is a schematic view of a relatively simple embodiment of an electrosynthesis cell of this invention which employs an anolyte-to-catholyte flow and therefore requires only one electrolyte inlet and one electrolyte outlet,

FIGURE 2 is a schematic view, similar to Figure 1, of an especially high-performance embodiment of an electrosynthesis cell of this invention which employs anolyte and catholyte flows which are generally separate but are in fluid communication with each other, and

FIGURE 3 is a greatly enlarged fragmental cross-sectional view of the cathode 30 shown in Figure 1.

DETAILED DESCRIPTION

Turning first to the Drawing, FIGURE 1 illustrates an embodiment of an electrochemical synthesis cell 10 of this invention which is desirable from the standpoint of simplicity. Cell 10 comprises an anode 11, a gas-diffusion cathode 30, a fluid-permeable cell divider or separator 15, an anode lead 39, a cathode lead 37, an inlet 21 for the flowing
electrolyte, an outlet 23 located near anode 11 for the
release of oxygen generated during cell operation, an outlet
25 for the flowing electrolyte, an inlet 27 located near the
"gas side" of cathode 30 for the introduction of an oxygen-
containing gas, and an outlet 29 for excess oxygen-containing
gas. The electrolyte introduced into inlet 21 is supplied
from a source 12 external to cell 10.

Separator 15 divides cell 10 into an anode compartment
17, which is constantly filled with continuously flowing
anolyte, and cathode compartment 19, which is constantly
filled with continuously flowing catholyte, but separator 15
is porous and has sufficient porosity to permit flow-through
of electrolyte and hence migration of ions between
compartments 17 and 19. Cathode 30 (see also FIGURE 3) has a
typical gas-diffusion electrode structure comprising an
electrically conductive sheet-like gas-permeable support
material 31 upon which is superposed an electrocatalytically
active material 33 comprising high surface area particles upon
which tiny particles of gold or a gold alloy have been
deposited. Active material 33 preferably also contains a
hydrophobic binder material, e.g. a highly fluorinated
olefinic polymer or other polyhalohydrocarbon such as
polytetrafluoroethylene, in an amount greater than 25% by
weight, based on the weight of the active material 33, most
preferably about 50 to 70 weight-%. Amounts greater than
about 75 or 80 weight-% can have an unacceptable adverse
impact upon performance without increasing cathode life
significantly as compared to the 70 weight-% level of binder.
Support material 31 can be a carbon cloth, carbon paper, or
teflonated metal screen which serves as a current collector
and which is sufficiently hydrophobic (or has been treated
with a hydrophobic polymer such as a polyhalohydrocarbon e.g.
polytetrafluoroethylene) to prevent flow-through of catholyte. Cathode lead 37 is electrically connected to the support material 31.

An external circuit means (not shown) provides an electrical pathway between anode 11 and cathode 30.

In operation, a fresh aqueous alkaline medium is introduced through inlet 21 into anode chamber 17 to refresh the anolyte, which is constantly being depleted of hydroxyl ion in accordance with half-cell reaction (1):

\[ 2\text{OH}^- \rightarrow \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- \]  

(1)

and which does not receive an adequate flow of hydroxyl ion from the cathode compartment 19, even under the most ideal circumstances, since the half-cell reaction occurring at the cathode, for every two electrons accepted, produces only one mole of hydroxyl ion in accordance with half-cell reaction (2):

\[ \text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{HO}_2^- + \text{OH}^- . \]  

(2)

The electrolyte introduced into anode compartment 17 becomes part of the anolyte, but it also passes through the pores of separator 15 into cathode compartment 19 and out of the cell 10 through outlet 25 at a rate selected to limit the limit migration of perhydroxyl ion into the anode component 17. That is, the direction of flow of electrolyte is maintained (with the aid of a pump) in an anolyte-to-catholyte direction, which is counter to the natural diffusion of hydroxyl ions from cathode compartment 19 to anode compartment 17 and, more importantly, is counter to the tendency of perhydroxyl ions (\(\text{HO}_2^-\)) to migrate into the anode chamber 17, where they are exposed to possible oxidation to oxygen. This undesirable side reaction, represented below by half-cell reaction (3)

\[ \text{HO}_2^- + \text{OH}^- \rightarrow \text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- \]  

(3)
results in the loss of valuable peroxide product and is highly
detrimental to the objectives of this invention.

The spent catholyte, so to speak, which exits the cell
through outlet 25, is the desired product of the
electrosynthesis. Thus, outlet 25 serves as the means for
recovering the alkaline solution of peroxide which can be used
as a bleaching agent or oxidizing agent or solubilizing agent
for treating pulp, paper, and other industrial products. The
alkalinity and the peroxide content in outlet 25 can be
controlled, according to this invention, over a surprisingly
broad range by controlling the parameters of cell operation,
including electrolyte flow and the like. Generally speaking,
the solution in outlet 25 has an alkalinity and a peroxide
content which has been carefully matched to the industrial
needs prevailing at the site of cell 10, so that cell 10 can
serve as an on-site peroxide generator, making just enough
peroxide to satisfy current demand, no more and no less. On-
site generation of peroxide avoids storage of peroxide and
purchase of highly concentrated peroxide from outside sources,
both of which are undesirable and can even be hazardous.

The catholyte in cathode chamber 19 flows along the
surface of active material 33 of cathode 30 and permeates into
active material 33 to a considerable degree, but does not flow
through cathode 30 in the manner catholytes fed to packed-bed
or porous matrix cathodes, for several reasons. First,
support material 31, though permeable to gas, is hydrophobic
and will not permit aqueous media to pass through it. Second,
the volume of active material 31 is very small compared to the
volume of a packed-bed cathode, and it will not accommodate a
voluminous flow of liquid. Moreover, the porosity of cathode
30 is generally in the form of very fine pores which are
better suited to capillary action than high flow rates. In
any event, cathode chamber 19 and cathode 30 are designed to provide a fairly rapid flow of catholyte parallel to the surface of cathode 30.

The oxygen-containing gas introduced through inlet 27 contacts the gas-permeable support material 31 of cathode 30 and permeates into the active material 33. Because of the permeation of catholyte into active material 33, this portion of cathode 30 provides a multitude of sites for a three-phase interface of catholyte, oxygen-containing gas, and solid catalytic material. The oxygen is reduced to peroxide at this three-phase interface, and the perhydroxyl ions diffuse into the catholyte. Turning now to FIGURE 2, the cell 50 shown in this Figure is preferred for more controllable contact times between catholyte and cathode 30, hence more controllable production of peroxide. In addition, the cell design shown in FIGURE 2 may allow for the decoupling of current efficiency and product ratio due to the independent catholyte and anolyte flows. The flow of catholyte through cathode compartment 19 is rapid enough to prevent any significant migration of perhydroxyl ion into anode chamber 17, thereby eliminating the need for a countercurrent flow of electrolyte. In this embodiment, fresh anolyte (from source 14) of independently selected alkalinity continuously enters through inlet 22, thereby keeping the hydroxide ion concentration in anode compartment 17 from being excessively depleted, and the spent anolyte flows out through outlet 24. On the cathode side of cell 50, fresh catholyte (from source 16), also of independently selected alkalinity, enters through inlet 26, and the product of the electrolysinsynthesis flows out through outlet 28. The fresh influx of catholyte through inlet 26 and the constant efflux of catholyte prevent excessive buildup of hydroxide ion in cathode compartment 19, which is very
important with respect to maintaining proper control over the hydroxyl/perhydroxyl ratio of the product effluent. As indicated previously, this ratio can be varied from as low as 1.6:1 to all higher values. Hydroxyl/perhydroxyl ratios as high as 2:1 or even 1.8:1 are unsuitable for many important industrial uses of alkaline peroxide solution, whereas hydroxyl/perhydroxyl ratios as low as 1:1 can create problems in the operation of cells 10 or 50. Accordingly, the particularly preferred hydroxyl/perhydroxyl ratio is in the range of 1.2:1 to 1.7:1.

In this invention, it is preferred to utilize the essentially pure oxygen produced at anode 11. This objective is most easily accomplished by circulating the oxygen through a conduit system 41, external to cell 50, to enrich the oxygen-containing gas introduced through inlet 27 on the cathode side of cell 50. System 41 can be used in cell 10 also, but for simplicity of illustration, system 41 is shown only in association with cell 50.

Except for the flowing electrolyte arrangement (compare inlet 21 and outlet 25 of cell 10 with inlets 22 and 26 and outlets 26 and 28 of cell 50) it will be noted that cells 10 and 50 can otherwise be substantially identical in structure and operation.

The loading of gold or gold alloy in the active material 33 of cathode 30 (of Figures 1 or 2) can range from 0.1 to 50% by weight, based on the weight of active material 33. Loadings in the range of 2 to 20% are preferred. Details of the structure of cathode 30 can best be seen in FIGURE 3, which shows hydrophobic support material 31 (optionally treated with a hydrophobic polymer such as polytetrafluoroethylene or a similar fluorinated hydrocarbon), active material 33, and current collector 35. The details
shown in FIGURE 3 relate to cathode 30 of both Figures 1 and 2, because the structure of cathode 30 is identical in both of those Figures.

Preferred materials for the separator 15 of FIGURE 1 include alkali-resistant porous inorganic oxides and silicates and the like and porous organic polymeric materials which resist strong alkalis, e.g. microporous polyolefins. The separator 23 of FIGURE 2 is a like material, but cation exchange membranes can also be used in the embodiment of FIGURE 2. The preferred anode 11 is an alkali-resistant bulk metal such as nickel or a noble metal, which is preferably porous (e.g. a metal screen or mesh or "expanded metal"). The preferred electrolyte is an aqueous alkaline medium such as an aqueous solution of an alkali metal hydroxide, a highly water-soluble alkaline earth metal hydroxide, or a highly water-soluble quaternary ammonium hydroxide. Alkali metal hydroxide solutions are preferred, and sodium particularly preferred from the cost standpoint.

The preferred oxygen-containing gas introduced through inlet 27 is substantially pure oxygen or a mixture of oxygen with an essentially inert gas such as nitrogen or argon. A particularly convenient way to obtain a suitable O₂/N₂ mixture is to remove the carbon dioxide content of air, e.g. through a compression/condensation or alkaline-scrub technique. Since carbon dioxide can form carbonates in an alkaline electrolyte, and since some carbonates (even alkali metal carbonates) can be less soluble than the corresponding alkali metal hydroxides at cell operating temperatures, resulting in precipitation of carbonate salt in the pores of the cathode, the presence of carbon dioxide in the electrolyte is preferably avoided.

The Active Material

It is well known in the art that a gold-containing
electrocatalyst of a gas-diffusion electrode in an alkaline electrolyte can facilitate the selective reduction of oxygen to peroxide (O$_2^-$, H$_2$O$_2^-$, and/or H$_2$O$_2$), are all referred to in this application as "peroxide"), e.g. in accordance with half-cell reaction (2), above.

This reaction involves a "two electron change" as opposed to the "four electron change" of the complete reduction of oxygen to hydroxide or water. It is also known that gold crystals can catalyze the four-electron change at the (100) face of these crystals, whereas the other crystalline faces (and polycrystalline gold) are specific for the two-electron change. See U.S. Patent 5,041,195 (Taylor et al.), issued August 20, 1991, the disclosure of which is incorporated herein by reference. Although gold-containing electrocatalysts could theoretically be very effective in improving the performance of a peroxide electrosynthesis cell, and although gold is very stable (resistant to corrosion) in alkaline electrolytes, there appears to be very little discussion in the patent literature regarding the use of such electrocatalysts for this purpose, particulate carbon being the material most typically mentioned as suitable for catalysis of the electrosynthesis. Despite its promise of improved peroxide production, formulation of gold-containing electrocatalytically active materials of suitable efficiency can be problematic, and prior art appears to provide very little detailed guidance in this regard.

Surprisingly, the basic principles involved in supporting tiny gold particles on high surface-area carbon, disclosed in the 5,041,195 patent cited above, have been found to be highly useful in the context of this invention, even though these principles relate to gold catalysts specific for the four-electron reaction (complete reduction to hydroxide or water)
rather than the two-electron reaction (partial reduction to peroxide). It has been found that relatively minor modifications of the techniques described in the 5,041,195 patent can provide gold or gold alloy particles which selectively catalyze the two-electron, peroxide-forming reaction.

The techniques of the 5,041,195 patent are directed toward maximizing the formation of tiny monocryystals (averaging less than 50 Å, more typically < 40 Å, in size) which are selective for the four-electron reaction. To obtain supported gold or gold alloy particles which are specific for the two-electron change but are otherwise prepared in accordance with the 5,041,195 patent, one can utilize graphitized carbon as the support material and/or select conditions favoring the formation of somewhat larger metallic particles (i.e. particles having an average size of at least 40 Å, but generally less than 200 Å and preferably about 50 to about 150 Å). It has been found that the tiny monocrylline particles produced according to the 5,041,195 patent can serve as nucleation sites for the "growth" of somewhat larger particles of almost any desired size within the aforementioned preferred range of 50 to 150 Å. For example, the technique described in the 5,041,195 patent can be followed exactly, and the resulting gold-containing nucleation sites can be subjected to a heating step which sinters together some of tiny metallic particles, thereby increasing their average particle size to > 50 Å (> 5 nm).

Suitable catalyst support materials include high surface area carbon and other finely divided inorganic materials (e.g. metallic oxides or the like). Finely divided carbon is presently preferred due to its commercial availability in a range of particle sizes and due to its desirable inherent
catalytic properties. When measured by the B.E.T. method, carbon powders such as furnace blacks, lamp blacks, acetylene blacks, channel blacks, and thermal blacks can provide surface areas ranging from 50 m²/g up to almost 2000 m²/g, surface areas >200 m²/g, e.g. >600 m²/g being preferred. The particle sizes of the carbon in these powders can range from about 5 to about 1000 nanometers (50 to 10,000 Å) but are preferably smaller than 300 nanometers in size. Since the surface area of the gold or gold alloy particles is normally less than that of the high surface area carbon, at least some carbon is exposed to the alkaline electrolyte and is subject to chemical attack, but adequate stability in alkaline media can be obtained with cathodes prepared according to this invention.

Commercially available carbon materials include BLACK PEARLS (trade designation), KETJENBLACK (trade designation), VULCAN (trade designation), "CSX", and Lurgi blacks, BLACK PEARLS and KETJENBLACK being preferred. These materials are described in detail in U.S. Patent 5,041,195, and this description is specifically included in the subject matter incorporated by reference from the 5,041,195 patent.

As indicated above, the preferred method for depositing (forming in situ) gold or gold alloy particles on high surface area carbon is a modification of the methods disclosed in U.S. Patent 5,041,195. Generally speaking, a reducible gold compound in solution is impregnated into the support material with the aid of a polar solvent (e.g. an alcohol or alcohol/water mixture) having adequate wetting characteristics with respect to the support material; the solvent is gently evaporated at moderate temperatures (higher temperatures can be used to obtain somewhat larger gold particles); and the resulting dry or substantially dry material is subjected to chemical reduction with a reducing gas such as substantially
dry hydrogen. The reducible gold compound can be chlorauric acid (HAuCl₄), a salt of this acid, a gold halide, or the like. The resulting gold particles can be smaller than 40 Å in size, but, as indicated above, they can also serve as nucleation sites for further particle growth (e.g. by sintering, as indicated previously). The most preferred active material thus comprises a rather high-surface area gold deposited on an even higher surface area carbon.

As indicated previously, the active material preferably contains at least 30%, generally about 50 to 70 weight-% of polymeric hydrophobic binder. The binder can be introduced into the active material, during its preparation, as a suspension of fine particles of hydrophobic polymer in a carrier such as water or an organic solvent.

The peroxide yield is variable and can readily provide the range of 3-5 wt% typically desired by the pulp and paper industry.

The following Example illustrates the principle and practice of this invention without in any way limiting its scope.

**Part A - Cathode Preparation Step**

Cathodes were prepared as gas-diffusion electrodes (GDE's) from carbon-fiber paper as the gas-permeable support layer and a single deposit of an electrocatalyst layer (electrochemically active material). The preparation process was begun by first sieving the particulate carbon, which is itself an but was used as catalyst support material in this Example, through a -170 mesh (U.S. or Tyler) screen. The particulate carbon support material was then dispersed in an acidified aqueous solution (65 millimolar sulfuric acid). Ultrapure water was used to make this acidified aqueous solution. The carbon was added to the acidified aqueous
solution with stirring and ultrasonification such that when the entire solution was applied to the carbon-fiber paper the
electrocatalyst loading was 5 mg/cm². For each 10 cm x 10 cm
of electrode area the carbon mass was typically 0.517 grams.
A polytetrafluoroethylene (PTFE) binder was then added (30, 50, or 70 wt%), using a dilute aqueous suspension of "TFE-30"
(trade designation of the DuPont Company), and the suspension
was mixed with stirring and ultrasonification. The resulting blend was filtered and the filtrate (deposit on the filter paper) was transferred onto wet-proofed, porous carbon-fiber paper substrate (Toray Industries) to form a uniform layer. The electrode was subsequently cold pressed at 1200 pounds pressure for each 16 in² of electrode area (75 psi, 517 kPa) until dry, hot pressed up to 1200 pounds pressure (75 psi, 517 kPa) for five minutes at 100 C, and sintered stepwise at 100 C for one hour, 200 C for an hour, then finally at 300 C for fifteen minutes.

To produce an electrocatalyst layer with small gold particles required the previously-described modification to the process described in patent 5,041,195. This patent details the techniques directed toward maximizing the formation of tiny monocrystals (averaging less than 50 Å, more typically < 40 Å, in size) which are selective for the four-electron reaction. To obtain supported gold or gold alloy particles which are specific for the two-electron change but are otherwise prepared in accordance with the 5,041,195 patent, one can utilize graphitized carbon as the support material and/or select conditions favoring the formation of somewhat larger metallic particles (i.e. particles having an average size of at least 40 Å, but generally less than 200 Å and preferably about 50 to about 150 Å). It has been found that the tiny monocrystalline particles produced according to
the 5,041,195 patent can serve as nucleation sites for the
"growth" of somewhat larger particles of almost any desired
size within the aforementioned preferred range of 50 to 150 Å.
In this Example, the technique described in the 5,041,195
patent can be followed exactly and is incorporated herein by
reference, except that the resulting gold-containing
nucleation sites were subjected to a heating step in an inert
atmosphere at temperatures ranging from 300 to 1200 °C which
sintered together some of tiny metallic particles, thereby
increasing their average particle size to > 50 Å (> 5
nm).

Part B - Peroxide Generator Apparatus

Two size systems were used to test and evaluate the
cathodes and their performance. Both types employed three-
compartment, flowing electrolyte designs as shown in Figure 2
of the Drawing. The smaller size was original with the
present applicants and was used for small cathodes of area not
exceeding 3.0 cm². These cells were constructed from
polymethacrylate (LUCITE®) with a total cell volume of
approximately 10 ml. A constant electrolyte flow was
maintained by a peristaltic pump and the electrolyte was
recirculated from a continuously mixed 600 ml reservoir. As
shown in Figure 2, the electrolyte compartment was partitioned
into two separate compartments by a cation exchange membrane,
Nafion® 117 (trademark of the DuPont Company). The anode
electrode was a solid nickel sheet. The electrolyte
temperature was maintained above 40 °C by feedback-controlled,
in-line heaters through which the electrolyte passes.
Electrolyte temperature was monitored by insertion of
thermocouples into the fluid entrances and exits. A
mercury/mercury oxide electrode was used as reference. The
internal resistance of the cells was monitored through the use
of an auxiliary platinum wire electrode in combination with an
800 IR Measurement System (Electrosynthesis Corp.). The cells
were operated in constant current mode with a 3-Amp power
supply. Four such cells were constructed and typically
operated simultaneously with a computer-based data acquisition
system.

A larger cell system with cathode area up to 100 cm$^2$ was
prepared by adaptation of a commercial electrolyzer. This
system was referred to as a process development unit (PDU).
and comprised an EA ElectroCell MP (EA Corp., Sweden, obtained
through the Electrosynthesis Corp.), suitably modified as
described below. This cell was chosen over other possible
commercial alternatives as it is more readily adapted for gas
diffusion electrodes. The principal difference between this
and the small apparatus was the variable cathode-anode
spacing. The power supply was proportionately larger and was
purchased from Power Ten Inc. In addition to a cation
exchange membrane, Nafion® 117 (DuPont), an alternative,
relatively inexpensive separator was also successfully used in
the PDU. This was 7-mil (179-µm) thick Teslin® (PPG
Industries Inc.) which is a silica-based, porous, polymeric
material. The Teslin® separator was determined to perform as
well as the Nafion® 117 membrane. Several changes to the EA
ElectroCell MP (commercial system) were necessary to fully
adapt it to serve as the PDU (unit for caustic peroxide
generation via GDE's). These changes were:

(1) The picture frame cathode assembly was replaced with a
machined graphite block. The addition of the graphite
block provides physical support of the carbon backing
layer necessary to compensate for hydrostatic pressure.
The block also ensures a leak-free seal between the
catholyte and gas compartments. We chose graphite to
provide electrical contact and for corrosion resistance. The block was drilled with a matrix of holes to allow gas to uniformly contact the rear surface of the GDE. This matrix of holes accounted for approximately 10% of the active cathode area. Therefore, the cathode-side of the block was machined to form channels leaving only small pegs in which to contact the GDE. Total surface area of these pegs was approximately 10%. The channeling provided uniform gas-flow across the back side of the GDE and 90% cathode area utilization.

(2) The separator frames were replaced with components more compatible with elevated temperature operation. These frames define the cathode-anode gap and have mesh inserts which promote turbulence. The replacement frames were equipped with reinforced flow canals to resist deformation under pressure and elevated temperature.

(3) The solid nickel sheet anode was drilled with a matrix of holes to resemble a mesh. This modification was necessary to allow evolved gas to escape behind the anode, away from the membrane.

(4) Accurate temperature monitoring was also required. This was accomplished by insertion of Teflon®-tipped thermocouple probes directly into the caustic entrance and exit ports of the PDU.

(5) Shut-down of the PDU was necessary for changing gas cylinders and electrolyte and for short-term unattended operation, such as cathode break-in. At the open circuit potential, the cathode begins to oxidize immediately. Removing the electrolyte was insufficient to prevent this, since the cathode and membrane retain moisture for long periods. The PDU stand was modified to allow draining and flushing of the cell with deionized water.
A four-way valve was also added to the gas feed system to allow the cell to be nitrogen-purged to displace oxygen.

**Part C - Performance Data**

Cathodes composed of up to 10 wt% gold on KetjenBlack (trade designation for particulate carbon) were prepared as described in Part A and were mounted in the PDU apparatus as described in Part B. The system was operated at cell temperatures of 45-50 C, with a total anode to cathode gap of 0.8 cm, and for an input electrolyte concentration of 10 wt% NaOH. Cell polarizations (i.e. total cell potential versus current density) of the gold on carbon electrodes were equal to or improved in comparison to the carbon black alone. In addition, the gold-catalyzed electrodes were capable of sustained operation at current densities equal to or exceeding 300 mA/cm². The performance of a 10 wt% gold-on-carbon electrode was 1.34 V at 100 mA/cm², 1.73 V at 200 mA/cm², and 2.08 V at 300 mA/cm².

The reporting operating conditions of the trickle bed cathode system are 2 V at 60 mA/cm². The operating potential for the gold-on-carbon electrode tested here is approximately 1.06 V at 60 mA/cm². Thus, for the same current density a factor of two in power savings per part by weight of peroxide product can be realized. Alternatively, higher current operation may be performed to reduce overall system size thereby reducing the generator capital costs. The 300 mA/cm² current density data indicates that in comparison to the trickle bed system, a GDE-based generator system may be reduced in total electrode area by up to a factor of five. This will translate to a significant reduction in generator system capital costs since these costs are a linear function of electrode area. Further performance improvements, principally due to decreases in the IR losses, are expected as
the gap is decreased to a reasonable commercial limit of 0.5 cm.

Cathode lifetime and cathode cost are critical parameters in determining commercial system operating costs. The more frequently the cells have to be replaced and the more expensive the cells cost, the higher the cost of the electrogenerated peroxide will be and the poorer the comparison will be with simple purchase and storage. Extensive testing of the electrodes in both size systems described in Part B have identified total electrode hydrophobicity to be a critical factor in determining cathode lifetime. The most successful cathodes have incorporated hydrophobic polyhalohydrocarbon polymer, preferably PTFE, into the carbon paper and contain >30 wt.-% PTFE (e.g. 50 and 70 wt.-%) in the electrocatalyst layer, i.e. in the electrochemically active material. With active material containing 50 to 70 wt.-% PTFE, the cathodes will survive for several thousand hours with only minor decreases in performance characteristics.

In view of the relatively low cost of the catalyst components described above, the use of gold in the active material does not increase the manufacturing cost of the gas-diffusion cathode beyond present goals for on-site peroxide generator markets in the U.S. and elsewhere.
What is claimed is:

1. An electrochemical cell for the production of an alkaline solution of peroxide, comprising:
   a partitioning means for partitioning said electrochemical cell into an anode compartment and a cathode compartment,
   an anode compartment containing an anode and an aqueous alkaline anolyte,
   a cathode compartment defining a space containing a generally free-flowing aqueous alkaline catholyte, a gas-diffusion cathode having two major surfaces, said cathode occupying not more than a minor proportion of the volume of said space, said cathode compartment being constructed and arranged to permit generally unrestricted flow of the aqueous alkaline catholyte across a first major surface of said gas-diffusion cathode, said cathode compartment being provided with means for withdrawing peroxide dissolved in said catholyte from said space defined by said cathode compartment, the second major surface of said cathode being gas-permeable and being in contact with an oxygen-containing gas, said first major surface of said cathode comprising an electrochemically active material, said active material comprising:
   a particulate catalyst support material having a surface area, by the B.E.T. method, of about 50 to about 2000 m²/g,
   deposited on the particles of catalyst support material of said active layer, 0.1 to 50 weight-%, based on the weight of the active layer, of a particulate elemental metal comprising gold particles having an average size, measured by transmission electron microscopy, which is greater than about 4 but less than
about 20 nanometers, said particulate elemental metal being substantially selectively catalytic for the reduction of oxygen to peroxide ion or hydrogen peroxide, and

electrical leads in electrical contact with said anode and said gas-diffusion cathode.

2. The electrochemical cell according to claim 1, wherein said partitioning means comprises a liquid-permeable separator for permitting diffusion of anions from said catholyte compartment into said anolyte compartment.

3. The electrochemical cell according to claim 1, wherein said anode compartment includes inlet means for introducing aqueous alkaline anolyte thereunto and outlet means for permitting aqueous alkaline anolyte to flow out of said anode compartment, and wherein said cathode compartment includes inlet means for introducing aqueous alkaline catholyte thereunto.

4. The electrochemical cell according to claim 1, wherein said peroxide is in the form of perhydroxyl ion, HO₂⁻.

5. The electrochemical cell according to claim 1, wherein the ratio of hydroxyl ion to perhydroxyl ion in the catholyte withdrawn from said cathode compartment is less than 2:1.

6. The electrochemical cell according to claim 1, wherein said electrochemical cell is a bipolar cell which is electrically connected to at least one other electrochemical cell of substantially the same construction and having substantially the same mode of operation.

7. The electrochemical cell according to claim 1, wherein said gas-diffusion cathode comprises: a gas-permeable support layer providing said second major surface, said
active material being supported on said gas-permeable
support layer; wherein the particulate catalyst support
material of said active material has a surface area, by
the B.E.T. method, of at least about 200 m²/g; and
wherein said gold particles have an average size,
measured by transmission electron microscopy, which is
greater than 5 nanometers.

8. The electrochemical cell according to claim 1, wherein
said anode comprises an alkali-resistant bulk metal.

9. The electrochemical cell according to claim 1, wherein
said first major surface of said cathode comprises an
electrochemically active material comprising:
  said particulate catalyst support material,
  deposited on the particles of catalyst support
  material, said particulate elemental comprising
gold particles, and blended with said particulate
catalyst support material, about 50 to 70% by
weight, based on the weight of the
electrochemically active material, of a hydrophobic
polymer.

10. A process for producing an alkaline solution containing
peroxide ion in an electrochemical cell, said process
comprising:
  applying an overall cell potential of less than 2
volts at current densities of 200 mA/cm² or more to said
electrochemical cell, said electrochemical cell
comprising a partitioning means for partitioning said
electrochemical cell into an anode compartment and a
cathode compartment; an anode compartment containing an
anode and an aqueous alkaline anolyte; a cathode
compartment defining a space containing a generally free-
flowing aqueous alkaline catholyte, a gas-diffusion
cathode having two major surfaces, said cathode occupying
not more than a minor proportion of the volume of said
space, the second major surface of said cathode being
gas-permeable and being in contact with an oxygen-
containing gas, said first major surface of said cathode
comprising an electrochemically active material, said
active material comprising:

- a particulate catalyst support material having a
  surface area, by the B.E.T. method, of about 50 to about
  2000 m²/g,

- deposited on the particles of catalyst support
  material of said active layer, 0.1 to 50 weight-%, based
  on the weight of the active layer, of a particulate
  elemental metal comprising gold particles having an
  average size, measured by transmission electron
  microscopy, which is greater than about 4 but less than
  about 20 nanometers, said particulate elemental metal
  being substantially selectively catalytic for the
  reduction of oxygen to peroxide ion or hydrogen
  peroxide;

and electrical leads in electrical contact with said
anode and said gas-diffusion cathode;

causing said generally free-flowing catholyte to
flow across said first major surface of said cathode;
contacting said second major surface of said cathode
with an oxygen-containing gas,

forming a multi-phase interface within said cathode,
said interface comprising said active material, said
oxygen-containing gas, and said catholyte,

reducing oxygen to peroxide at said multi-phase
interface and permitting the resulting peroxide to
diffuse into said catholyte, and
withdrawing from said cathode compartment an alkaline solution of peroxide in which the hydroxyl:perhydroxyl ratio is less than 2:1.

11. The process as claimed in claim 10, wherein an aqueous alkaline medium for providing an analyte is introduced into said anode compartment from a source of alkaline medium external to said electrochemical cell.

12. The process as claimed in claim 11, wherein an aqueous alkaline medium for providing a catholyte is introduced into said cathode compartment from a source of alkaline medium external to said electrochemical cell.

13. The process as claimed in claim 10, wherein said electrochemical cell is operated at an overall cell voltage of less than about 1.5 volts, a current efficiency of at least about 85%, and a current density of at least about 700 A/m².

14. The process as claimed in claim 10, wherein oxygen produced by oxidation of hydroxide ion at the anode is collected and introduced into the oxygen-containing gas contacting the second major surface of said cathode.
AMENDED CLAIMS
[received by the International Bureau on 10 January 1996 (10.01.96); original claims 10-14 amended; new claims 15-19 added; remaining claims unchanged (4 pages)]

REPLACEMENT PAGE

1. active material being supported on said gas-permeable support layer, wherein the particulate catalyst support material of said active material has a surface area, by the B.E.T. method, of at least about 200 m²/g; and wherein said gold particles have an average size, measured by transmission electron microscopy, which is greater than 5 nanometers.

8. The electrochemical cell according to claim 1, wherein said anode comprises an alkali-resistant bulk metal.

9. The electrochemical cell according to claim 1, wherein said first major surface of said cathode comprises an electrochemically active material comprising:

   said particulate catalyst support material, deposited on the particles of catalyst support material, said particulate elemental comprising gold particles, and blended with said particulate catalyst support material, about 50 to 70% by weight, based on the weight of the electrochemically active material, of a hydrophobic polymer.

10. A process for producing an alkaline solution containing peroxide ion in an electrochemical cell, characterized in that:

   a) one operates the electrochemical cell at a voltage which can vary with the current density but does not exceed about 2 volts for a current density of at least 200 mA/cm², and said electrochemical cell comprises a partitioning means for partitioning said electrochemical cell into an anode compartment and a cathode compartment; an anode compartment containing an anode and an aqueous alkaline anolyte; a cathode compartment defining a space
containing a generally free-flowing aqueous alkaline catholyte, a gas-diffusion cathode having two major surfaces, said cathode occupying not more than a minor proportion of the volume of said space; the second major surface of said cathode is gas-permeable and is in contact with an oxygen-containing gas, so that the oxygen-containing gas can be contacted with said cathode essentially independently and separately from said generally free-flowing aqueous alkaline electrolyte, said first major surface of said cathode comprises an electrochemically active material, which active material comprises:

a particulate catalyst support material having a surface area, by the B.E.T. method, of about 50 to about 2000 m²/g,

on the particles of catalyst support material of said active layer, 0.1 to 50 weight-%, based on the weight of the active layer, of a particulate elemental metal comprising gold particles having an average size, measured by transmission electron microscopy, which is greater than about 4 but less than about 20 nanometers; said particulate elemental metal is substantially selectively catalytic for the reduction of oxygen to peroxide ion or hydrogen peroxide;

and electrical leads in electrical contact with said anode and said gas-diffusion cathode;

b) one causes said generally free-flowing catholyte to flow across said first major surface of said cathode;

c) one contacts said second major surface of said cathode with an oxygen-containing gas,
thereby forming a multi-phase interface within said
cathode, said interface comprising said active material,
said oxygen-containing gas, and said catholyte,
d) one reduces oxygen to peroxide at said multi-phase
interface and permits the resulting peroxide to diffuse
into said catholyte, and

e) one withdraws from said cathode compartment an
alkaline solution of peroxide in which the
hydroxyl:perhydroxyl ratio does not exceed about 2:1.

11. The process according to claim 10, wherein an aqueous
alkaline medium for providing an anolyte is introduced
into said anode compartment from a source of alkaline
medium external to said electrochemical cell.

12. The process according to claims 10 or 11, wherein an
aqueous alkaline medium for providing a catholyte is
introduced into said cathode compartment from a source of
alkaline medium external to said electrochemical cell.

13. The process according to claim 10, 11, or 12, wherein
said electrochemical cell is operated at an overall cell
voltage of less than 2 volts, a current density of at
least about 200 mA/cm², and a current efficiency of at
least about 85%.

14. The process according to claim 10, 11, 12, or 13, wherein
oxygen produced by oxidation of hydroxide ion at the
anode is collected and introduced into the oxygen-
containing gas contacting the second major surface of
said cathode.

15. The process according to claim 10, 11, 12, 13, or 14,
wherein the alkaline solution of peroxide withdrawn from
the cathode compartment is spent catholyte formed as a
result of said reducing step and is the desired product of the process.

16. The process according to claim 10, 11, 12, 13, 14, or 15, wherein said electrochemical cell is operated at a temperature of at least about 35°C.

17. The process according to claim 10, 11, 12, 13, 14, 15, or 16, wherein the amount of said particulate elemental metal deposited on the particles of catalyst support material ranges from 0.1 to 10 weight-%.

18. The process according to any of claims 10 through 17, wherein said process is carried out for a period of time exceeding a thousand hours, and wherein said gas-diffusion cathode resists chemical attack by the aqueous alkaline catholyte for said period of time.

19. The process according to any of claims 10 to 18, wherein said particulate elemental metal is in the form of particles smaller in size than 5 nm which have been combined together to form particles larger than 5 nm.
# INTERNATIONAL SEARCH REPORT

## A. CLASSIFICATION OF SUBJECT MATTER

<table>
<thead>
<tr>
<th>IPC(6)</th>
<th>US CL</th>
<th>According to International Patent Classification (IPC) or to both national classification and IPC</th>
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<td>C25B 11/03, 11/04, 1/30</td>
<td>204/83. 84, 252, 263, 255, 290R</td>
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## B. FIELDS SEARCHED

**Minimum documentation searched (classification system followed by classification symbols)**

| U.S. | 204/83. 84, 252, 263, 255, 290R |

**Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched**

**NONE**

**Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)**

- APS: ELECTROLYTIC OR ELECTROCHEMICAL; (AU OR GOLD) AND PEROXIDE; ALKALINE OR (SODIUM OR POTASSIUM) (AA) HYDROXIDE; GDE OR GAS ELECTRODE OR CATHODE OR ANODE; OXYGEN OR AIR

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<tr>
<td>X</td>
<td>US, A, 4,969,981 (Rogers et al.) 13 November 1990. See abstract; col. 4, lines 13-65; col. 5, lines 17-18; and col. 9, lines 24-30.</td>
<td>10-14</td>
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<td>Y</td>
<td>US, A, 4,118,305 (Olman et al.) 03 October 1978. See abstract; Fig. 7; col. 1, lines 58-60; col. 2, lines 41-63; col. 3, lines 1-5, lines 31-32, and lines 58-62; col. 4, lines 15-19 and lines 56-62; col. 5, lines 3-5; and EXAMPLES 1 and 2.</td>
<td>10-14</td>
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<tr>
<td>X</td>
<td>US, A, 5,041,195 (Taylor et al.) 20 August 1991 (See col. 1, line 56 to col. 2, line 1 and col. 2, lines 23-26).</td>
<td>1, 3-5, 7-9</td>
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### Further documents are listed in the continuation of Box C. See patent family annex.

- \* Special categories of cited documents:
  - A: document defining the general state of the art which is not considered to be of particular relevance
  - B: earlier document published on or after the international filing date but later than the priority date claimed
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  - E: document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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### Date of the actual completion of the international search

26 SEPTEMBER 1995

### Date of mailing of the international search report

06 NOV 1995

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*Form PCT/ISA/210 (second sheet)(July 1992)*