P&B GLOBAL ENERGY

Aluminum Energy for Fuel Cells

Using an energy source that is both plentiful and fully recyclable will dramatically enhance its utilization and provide benefits globally.

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TABLE OF CONTENTS

Aluminum Energy for Fuel Cells

Breakthroughs in chemistry and technology have provided the opportunity for aluminum, an abundant and fully recyclable metal, to be used as a fuel to generate electricity in fuel cells, both efficiently and economically.

In addition, using an energy source that is both plentiful and fully recyclable will dramatically enhance its utilization and provide benefits globally.

To fully understand the significance of these breakthroughs, it would be important to illuminate the nature of these discoveries.

For decades scientists have been attempting to unleash the extensive stored energy locked in aluminum (enthalpy - theoretical energy density 10.167kWh/kg), because it has one of the highest levels available in any metal or fuel. We can see the power of aluminum when its powder is ignited in fireworks.

Fortunately, the proposed technology has enabled this to become more viable and to be competitive in the energy marketplace, a phenomenon that has not been previously possible.

Having solved the major technical problems for production, the breadth of applications that can be undertaken advantageously is quite extensive. Furthermore, the technology and chemical analysis continues to be refined, adding to future efficiency.

I. History

Aluminum has been a most sought after source of energy for more than 50 years, because of its inherent high energy density, its being lightweight and its being recyclable (a more detailed presentation of aluminum is available in **Appendix III**).
Aluminum has already proven itself to be a viable material in battery applications.
The Zaromb cell, produced in 1960, stored 15 times the energy of a comparable lead acid battery. [1,2]

Fuel cells using different metals really began more than 25 years ago. The driving force in these endeavors was the need to find a reliable, lightweight power source for sophisticated, military and space applications. The weight and limited shelf life of traditional batteries was just not acceptable. Initial attempts, unfortunately, had substantial drawbacks due to corrosion. [3,4] Other attempts led to the use of tine, indium, thallium, iridium or gallium to lower the corrosion. Since the year 2000 some companies, particularly Aluminum Power, Inc., as well as Voltek, Inc., and eVionyx, Inc., have attempted to produce small aluminum-air cells for portable applications. [5] The challenge has been to manufacture cost competitive, efficient products. Most companies have used aluminum alloys in production, at a significant cost increase. [6,7] In addition, expensive additives were added to the mix. Both these issues hampered the recycling of the by-products and created unwanted wastes. These factors, combined with the inability to create an affordable final product, substantially reduced the general commercial viability for all but specialized uses.

II. Present Trends and Capabilities

Undertaking a completely new approach to the use of aluminum as the source of energy for fuel cells included the use of industrial aluminum and a more optimized electrolyte mixture to dramatically release the inherent energy. Because there were no alloys to separate it from, the resulting mix could easily be recycled (see an aluminum recyclable life cycle in **Appendix I**). Furthermore, the use of proprietary, but readily available, chemical formulations will simplify the process to a viable commercialized product.

At the present time there are two substantial technologies that utilize the use of aluminum as the key ingredient. One is known as the Alkaline Aluminum-Air Fuel Cell Technology and the other is the Hydrogen Production for Fuel Cell Technology.

While most other hydrogen-based fuel cell technologies rely on hydrogen stored in a pressurized gas or liquid form, these new technologies derive their power from water and a solid–state fuel. More energy can be liberated over a much longer period of time at a significantly reduced cost, because of the higher relative density of its power source. It is anticipated that aluminum-air fuel cells will be substantially simpler and lower in cost than others, such as PEMFC, Lithium Ion or Nickel-Metalhydride batteries.

Integrated into both these technologies are the crucial uses of both the on-board and the on-demand production of all the required energy. All the energy is held within the aluminum and water until it is requested. There are no outside storage units, nor any problem with stability or combustion.

A. Alkaline Aluminum-Air Fuel Cell

The aluminum-air fuel cell is composed of an aluminum anode set in an aqueous alkaline solution and utilizes a gas diffusion electrode/cathode. The emission-free oxidation of aluminum by oxygen from ambient air provides an efficient power supply. The safe and efficient proprietary components can be housed in a fully self-contained unit. One key to this technology is the use of two quickly replaceable cartridges, one containing the aluminum anode and the other containing an electrolyte mix with water. Once the anode cartridge is replaced, it can be recycled back to aluminum dozens of times for many years (a more detailed presentation of an alkaline fuel cell is available in **Appendix II**)

B. Hydrogen for Fuel Cell

The hydrogen production system is a fully self-contained unit that is capable of producing a virtually unlimited environmentally safe source of hydrogen and it requires no high-pressure storage tanks. This creates unique advantages for utilizing this system, including military applications or for any hydrogen production and storage requirements (perhaps for extensive transportation “refueling” stations). On a technical note, it uses fully recyclable, relatively low cost and easily available chemical components and displays a highly efficient hydrogen output. The high performance, moderate cost, and the level of enhancements in the availability of an ongoing source of pure hydrogen without any pressurized containment, makes this system unlike any other on the market today.

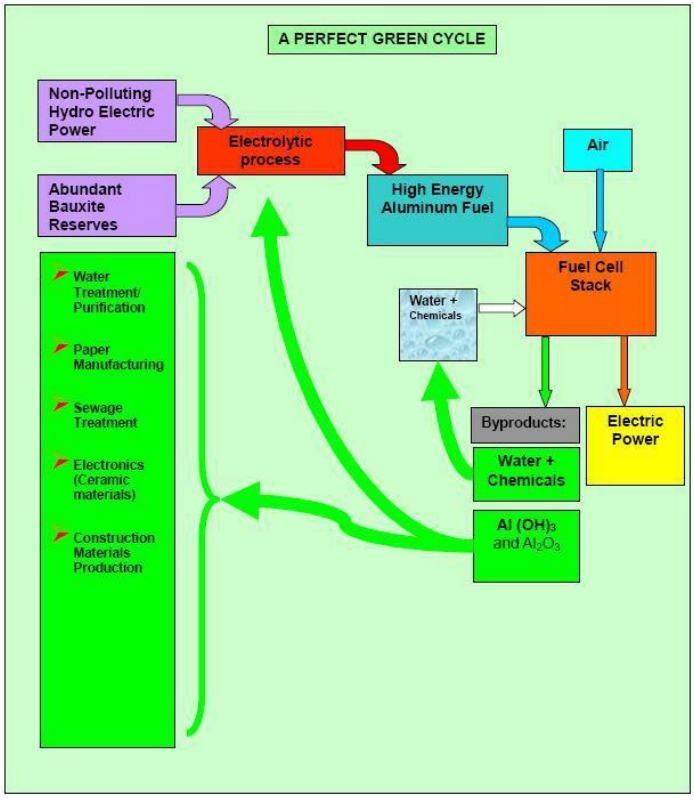
III. **The Green System**

There are no polluting emissions with energy generated by the alkaline aluminum-air fuel cell and hydrogen production and storage technologies. All similarly designed future products should run continuously, quietly, and efficiently, while delivering a high specific energy at a relatively low cost. The new technologies should be more economically competitive than many other green technologies.

Both the electrical energy production cycle and the hydrogen production cycle, create byproducts that include: water and chemicals, which are recycled back into the fuel cell operation; aluminum oxide (Al_2O_3) and aluminum hydroxide $Al(OH)_3$, which are used in a number of industries from water purification and sewage treatment to paper manufacturing and electronics. They can also be fully recycled back into aluminum. No residual waste products destined for a landfill are generated nor are any pollutants emitted into the air (see detailed Aluminum Recycling Diagram in **Appendix I**).

Logistically, the storing, shipping, and distributing of anode cartridges (aluminum plates) and chemicals (dry powder) are much safer than the pressurized hydrogen or methanol used by existing Fuel Cell Power Systems. Furthermore, there should be no safety issues either for travel on airplanes or for any military applications.

Unlike certain other methodologies, which use methanol, natural gas or other fossil fuel products, these technologies will have no environmental or health side effects while generating their electricity or hydrogen. In summary, they deliver electrical energy with zero pollution, complete safety and full recycling.



IV. Applications – Viability and Vision

The diverse applications that new technologies can be integrated into include almost all activities requiring the eventual production of energy, hydrogen and electricity. Given its inherent environmental advantages, relatively good economics and availability, aluminum should eventually become an important part of the renewable energy industry. Obviously, the viable commercialization of the technologies is still in its initial stages, but the potential remains and the most difficult technical barriers have been overcome. Certainly the opportunities mentioned below reflect only a part of the potential.

A. Military

The military has been interested in aluminum as a source of energy for fifty years. They understand the critical advantages of its inherent energy and being lightweight, portable and vastly abundant. The mobile soldier, with his/her multitude of electronic equipment, would be an immediate benefactor. The sophisticated devices used in the field or in remote activities require the benefits integral to these technologies.

B. Hydrogen Storage and Delivery

Hydrogen has a low energy density relative to volume, making it more difficult to store a sufficient amount within a reasonably sized space and it is innately unstable. Delivering or transporting hydrogen in high-pressure storage tanks is cumbersome, expensive and would restrict its use in many places. Using water as the hydrogen source until the hydrogen is released by its chemical reaction with aluminum greatly relieves these problems and eliminates storage, delivery and/or transportation difficulties.

C. Batteries

Traditional rechargeable batteries have a limited shelf life, as well as a limited output capacity and, hence, quickly require an auxiliary power source. Aluminum-air fuel cells may be as much as ten times as dense compared with lead-acid batteries and occupy a fraction of the space or weight. They can be mechanically recharged to its original capacity by simply replacing its cartridges. Numerous uses for uninterrupted reliable remote power include computer data storage banks, critical manufacturing facilities, bank ATMs, telecommunication systems and safety lighting.

D. Portable

The possibilities for use in this arena are greatly enhanced by the longevity of the power output. Laptop computers could have remote operations for more than 24 hours and the same is true for most of the innumerable portable electric devices available today. Any isolated location could have the services it requires without establishing uneconomical electrical connections to the grid or building a huge infrastructure.

E. Stationary

The possibilities for the individual homeowner, supermarket or manufacturing plant (the residential, commercial and industrial applications) to establish an independent source of power off the main electrical grid as either a primary or secondary source of energy is quite viable. The unattractive presence of some fuel generators, with their inherent noise or pollution, is eliminated and replaced with a quiet, unobtrusive unit with no pollution during its operation, providing for the opportunity to place this power source indoors.

F. Transportation

The unique advantage of combining both the inherent energy in aluminum and water with the on-board/on-demand methodology creates an opening for initializing the utilization of the aluminum-air technology and hydrogen generation for use in the bicycle and scooter; golf-car and forklift; boat and yacht; and even the automotive industry. By utilizing the hydrogen generated, in a safe stable environment, the enormous storage and delivery problems are eliminated. The concerns for having to reinvent the infrastructure for hydrogen cars also subside. Obviously, the technical complexities will take time and effort, but the critical points or problems are feasible.

G. Power Plants

The enormous amount of power generated globally creates an infrastructure that cannot be duplicated or replaced in any foreseeable future. However, the need to establish operations in remote locations or for special purposes allows for the possibility of erecting a power operation with a limited amount of infrastructure. Furthermore, delivering the power source becomes significantly easier than building major pipelines or electrical lines. In addition, with a potential global carbon tax being considered, the economics of using aluminum energy as an alternative or as a complimentary part of the solution becomes more crucial. This renewable aluminum energy can become an important part of the energy mosaic.

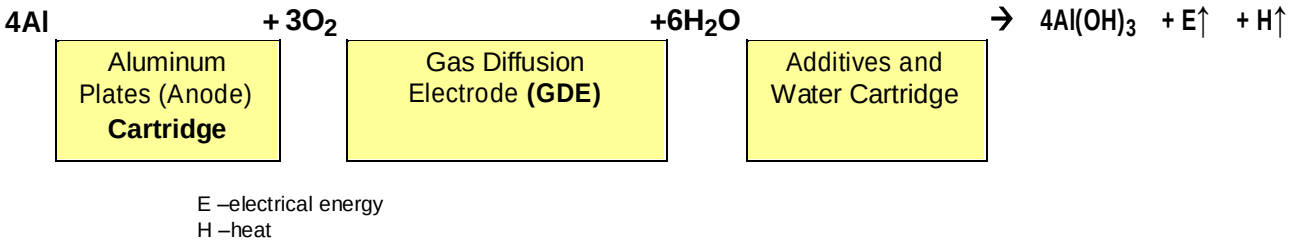
V. Science and Technology

The chemistry components for the two methodologies have some similarities, including some of the basic ingredients and residuals. However, the concepts have some differences and are shown below (a more detailed scientific analysis is available in **Appendix IV**).

A. Alkaline – Aluminum-Air Fuel Cell Technology

This technology generates electricity by converting the internal (heat and chemical) energy of aluminum, water and the oxygen supplied from the surrounding (ambient) air directly to electrical power (with no combustion or moving parts) through a controlled chemical reaction. The generated power is therefore inherently ultra clean, highly efficient and reliable.

Basic electrochemical reaction to generate the electricity:



(a more detailed presentation of an alkaline fuel cell is available in **Appendix II**)

These reactions are further enhanced through proprietary chemical formulations, creating a unique method of energy conversion while using these readily available components. The resulting specific energy **(300-500Wh/kg)** is significantly higher than those obtained from other existing sources of energy (i.e. natural gas, compressed and liquid hydrogen, coal, etc.)

The main advantages of the aluminum-air fuel cell technology are:

- ✓ **Theoretical** limit of energy (enthalpy) is exceptionally high - 10.167 kWh/kg.
- ✓ **Practical** energy conversion process presently is ~ 8.100 kWh electrical energy and heat from 1kg of Aluminum. This is 80% efficiency of the theoretical limit.
- ✓ The resulting **real specific energy** (300-500Wh/kg) can be as much as 10 times the amount of a lead-acid battery.
- ✓ The capability for a **scalable** design allows one to create a complete power system in a wide range of power - from ten watts to hundreds of kilowatts.
- ✓ Simple ability to swiftly mechanically recharge in any conditions, which is extremely important for portable, remote and especially military applications.
- ✓ Fully **recyclable** byproducts with no wastes.
- ✓ The **emission-free** oxidation of aluminum by oxygen in ambient air conditions provides an efficient power supply.
- ✓ Aluminum as a solid fuel source can be **safety stored,** until needed, for an unlimited amount of time. The safe and efficient proprietary components can be housed in a fully self-contained unit.
- ✓ **No flammable or combustible** components inside the power supply system.
- ✓ **Easy to ship**: the battery pack can be shipped separately from the active components.

B. Hydrogen Production for Fuel Cells and Other Applications

The contemporary technologies for hydrogen production for fuel cells use two different methods, depending on the particular application required. Both methods are based on hydrogen production from a water source and assisted by aluminum as an active catalyst.

1. Method of Hydrogen Storage and Production Based on Aluminum Assisted Water Split Technology.

(Suitable for portable applications)

The essence of this method involves periodically (when needed) bringing the aluminum and the water based alkaline electrolyte into contact, to create a reaction for the production of hydrogen and then supplying it directly into a fuel cell power system. The purpose of using the alkaline solution is to dissolve a thin protective layer of oxidation (that forms as soon as the metal is exposed to the air) and to provide the water access to a clean aluminum surface.

The basic exothermic chemical reaction:

$$2Al + 6H_2O \xrightarrow{\text{Alkaline solution with proprietary additives}} 2Al(OH)_3 + 3H_2 \uparrow$$

To produce **1** kg of hydrogen in this reaction requires:

1. **18** kg of water (as the primary source of hydrogen)
2. **9** kg of aluminum (as the consumable catalyst of the chemical reaction of the water split)
3. **2** kg of a non-consumable chemical mix (sodium/potassium hydroxide plus a proprietary mix of additives, just to maintain the effective alkaline solution).

This chemical reaction yields **3.7** percent of the components weight.

In the reaction with oxygen inside the fuel cell power plant **1** kg of hydrogen, generates **9** kg of water (as a fuel cell by-product). By recycling this water back into the hydrogen generator, it will require only **9** kg of water for the next cycles of hydrogen production.

This technique will increase the yield to over **7** percent of the components weight.

Aluminum hydroxide, $Al(OH)_3$, produced as a byproduct, can be fully recycled into aluminum and can be reused for hydrogen production an unlimited number of times.

Unique additives allow the electrolyte solution to react with the aluminum (no alloys) plates to form aluminum hydroxide in crystalline powdered form, which falls to the bottom of the chemical reactor container, leaving the reaction surface clear and active.

2. Method of Hydrogen Storage and Production by Aluminum Hydrolysis

(Suitable for transportation and stationary applications)

The essence of this method, a proprietary technique, involves periodically (when needed) bringing the water steam (at a temperature of 200-300°C), into contact with aluminum. The purpose of using the water steam is to remove a thin protective layer of oxidation (that forms as soon as the metal is exposed to air) and to provide the steam access to a clean aluminum surface, allowing generation of hydrogen and then supplying it directly into a fuel cell power system.

This unique high temperature technique allows the water steam to react with the industrial aluminum (no alloys) plates to form aluminum oxide $\mathbf{Al_2O_3}$ in crystalline powdered form, which falls to the bottom of the chemical reactor container, leaving the reaction surface clear and active.

The basic exothermic chemical reaction of this method:

$$\mathbf{2Al + 3H_2O} \xrightarrow[\text{Water steam 200-300°C}]{} \mathbf{Al_2O_3 + 3H_2} \uparrow$$

The flow rate of hydrogen production in this process is controlled and regulated by the amount of water steam supplied.

To produce **1** kg of hydrogen in this reaction requires:

1. **9** kg of water (as the primary source of hydrogen)
2. **9** kg of aluminum (as the consumable catalyst of the aluminum hydrolysis chemical reaction)

This chemical reaction yields **5.55** percent of the components weight.

As mentioned above, in the reaction with oxygen inside the fuel cell power plant **1** kg of hydrogen generates **9** kg of water (as a fuel cell by-product). By recycling this water back into the hydrogen generator, no additional water will be required for the following cycles of hydrogen production. In this case, once one initially fills the container with water, no additional water is required.

This technique will increase the yield up to **11.1** percent of the components weight.

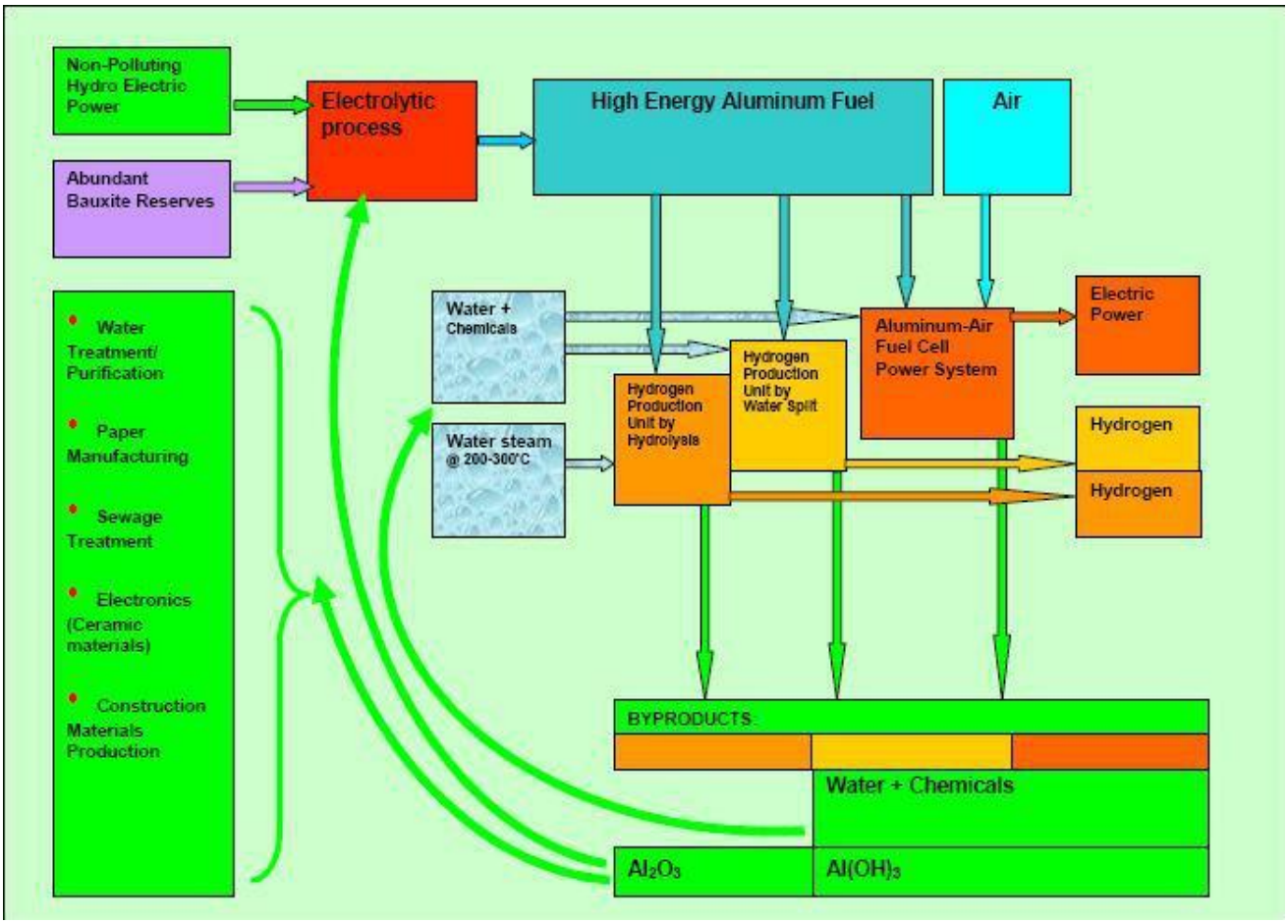
Aluminum oxide, Al_2O_3, produced as a byproduct, can be fully recycled into aluminum and can be reused for hydrogen production an unlimited number of times.

The crucial advantages provided by these methods of hydrogen production include: the high efficiency of hydrogen production; a fully recyclable green technology; a safe, environmentally clean technology; energy that is easy to store and distribute; and available on demand as needed.

VI. Conclusion

Having reviewed the history of aluminum energy for fuel cells and its present capabilities, one must conclude that the utilization of aluminum for fuel cells should become an integral part of the solution for an economically, clean, non-polluting source of energy. Its ability to be used in a wide range of applications lends itself to the possibility that one or more of its inherent characteristics will be a most efficient choice for any number of critical uses. Given its abundance, lightweight and its being fully recyclable, the opportunities for the commercialization of the multiple technologies are quite evident. Certainly numerous design and manufacturing issues still exist, but because the critical technological challenges have been resolved, the potential is certainly quite high.

APPENDIX I. ALUMINUM RECYCLING DIAGRAM



APPENDIX – II

Alkaline Aluminum-Air Fuel Cell – Sample Product Information

Discussed below is a unique alkaline aluminum-air fuel cell technology and its initial fully self-contained portable Power Supply System, the APS 100. The development team has a breakthrough technology in green energy generation, with significant advantages for storage and distribution, conservation and recycling of all materials. Its innovations will lead to a revolution in the use of clean technology and it offers an ideal design for integration into numerous portable, stationary, military and larger energy requiring applications and systems.

Unique Concept and Designs

This technology is using aluminum as its primary fuel source. Because aluminum has theoretical energy density (enthalpy) 10.167kWh/kg, it can be more efficient than other sources of fuel that have significantly lower inherent energy levels.
This alkaline fuel cell technology uses safe and efficient proprietary components in conjunction with a unique design. These enhancements include:

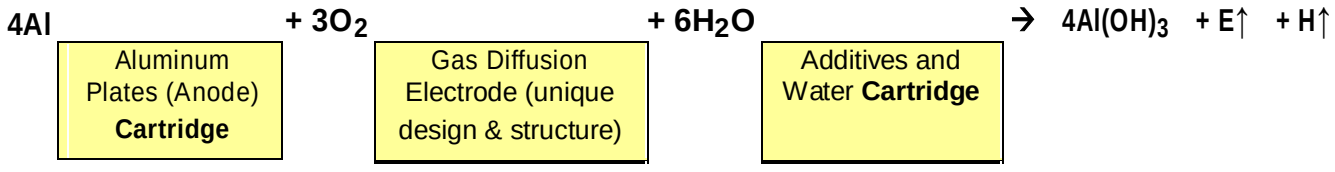
- Catalyzed gas diffusion electrodes, used as cathodes, and their unique mass production process capability (verified by an independent third party; the University of Toronto)
- Composite electrolyte, with readily available, safe and inexpensive components, which allows for the use of industrial aluminum plates as anodes in contrast with the expensive alloys commonly used in the industry today.
- A simple method of replacing cartridges when the unit is completely discharged.
  (Using the APS 100 as an example)

    1. In the fuel cell stack (for 24 hrs of operation) it is required to replace the fuel, the 0.74kg of aluminum plates (they are also used as the anodes).
    2. It is required to replace the 1kg of dry powder electrolyte components and the adding of 4 liters of regular water for generating 24 hours of electrical energy. The whole process takes less than 5 minutes.

Chemistry

The proposed aluminum-air fuel cell generates electrical power in the process of the chemical reaction of aluminum with oxygen supplied from the surrounding (ambient) air.

Basic electrochemical reaction:



E –electrical energy
H –heat

Anode reaction: $4Al^{3+} - 12\,e^{-} + 12OH^{-} \rightarrow 4Al(OH)_3$

Cathode reaction: $3O_2 + 6H_2O + 12e^{-} \rightarrow 12OH^{-}$

These reactions are enhanced with the use of proprietary chemical formulations, creating a unique method of energy conversion while using these readily available components. This result creates a specific energy (350-500Wh/kg) and efficiency (60-80%) that are significantly higher than from other sources of energy (natural gas, compressed and liquid hydrogen, coal, etc.)

The APS 100

The APS 100 offers an ideal design for being integrated into numerous portable and stationary applications.

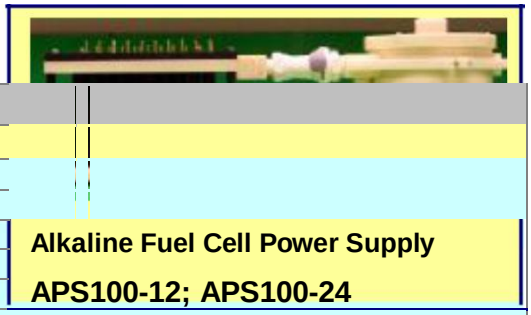
With its present specific energy of over 350 Wh/kg (500 Wh/kg soon to be available), the APS 100 is more than capable of powering multiple wireless laptop computers and numerous other energy requiring devices simultaneously. This is available with a continuous power output of over 100 watts on a single Proprietary Fuel Cartridge.

One dynamic feature of the APS 100 is its ability to mechanically recharge the electrical capacity without any power interruption by simply using another cartridge. This allows the APS 100 to be independent from the electrical grid and, therefore, ideally suited for remote locations and as reliable back-up power supply.

Presently, the scalability of the APS 100 will allow for power requirements of from ten watts to more than ten kilowatts. This provides the power capacity for products as diverse as portable battery recharges, remote silent generators, UPS and back-up power supply systems, electrical bikes, boats and numerous military applications.

Another extraordinary feature of the APS 100 is its ability for a complete discharge (100% Depth of Discharge) with no harm to the battery (unavailable from other batteries) and will not self-discharge when put in storage. It is a completely autonomous power source, fully safe and reliable with no environmental or health side effects.

The technology team has produced a working prototype of the APS 100 that has undergone significant testing in its laboratory. A picture of the APS 100 and its specifications are available on the data sheet below. (The initial core patent is pending.)



Product Data Sheet of APS100		
Performance:		
Rated net Power	100W Nominal	
	200W Maximum	
	250W Peak@30sec	
DC voltage	12±2V	
Oxidizer	Air, breathing	
Fuel (Cartridge Replaceable)	Standard (Industrial) Aluminum Alloy	
Electrolyte Cartridge Replaceable	Alkaline NaOH, KOH, NaCl or mix of that with proprietary additives	
Operating temperature	(-25°C +45°C) (-13°F +113°F)	
	APS100-12	APS100-24
Electrical Capacity, Ah	120	240
Energy, Wh	1500	3000
Specific Energy, Wh/kg	>300	>350
Weight, kg		
Fuel Cell Pack	2.0	2.0
Fuel Cartridge	Aluminum Anode - 0.37; Electrolyte – 2.5 (0.5 dry powder inside)	Anode - 0.74 kg; Electrolyte – 5.0 (1.0 dry powder inside)
APS100 (Fuel Cell Power Supply System)	4.95	7.9
Length x width x height, cm		
Fuel Cell Pack	18.0x12.5x12	18.0x12.5x12
Fuel Cell System	35.0x12.5x12	35.0x12.5x12
Discharge time	12 hours	24 hours
Lifetime, Hrs	>3000	>3000

The Green System – Zero Pollution, Fully Recyclable and Safe

There are no polluting emissions when energy is generated with this alkaline aluminum–air fuel cell technology. All present and future resulting products will run continuously, quietly, efficiently, at high specific energy and relatively low cost. The alkaline fuel cell technology is economically more competitive than other green technologies.

The outputs of this technology include clean electric power: water and chemicals which are recycled into the fuel cell operation; and aluminum hydroxide [$Al(OH)_3$], which is used in a number of industries from water purification and sewerage treatment, to paper manufacturing and electronics. It can also be fully recycled back into aluminum by green and renewable energy. There are no residual waste products destined for a landfill nor any emitted pollutants. (A diagram of this concept is available in Appendix I.)

In addition, storing, shipping and distributing the anode cartridges (aluminum plates) are much safer than the hydrogen or methanol used by existing Fuel Cell Power Systems and would have no safety issues for travel on airplanes or concerns for any military applications.

The APS 100 and future products will have no environmental or health side effects while generating electricity.

It therefore:

- Does not contribute to heavy metals that potentially may leach from solid waste landfills.
- Does not expose the environment and water to lead and acid.
- Does not contain strong corrosive acids.
- Does not cause burns or danger to eyes and skin
-

The introduction of this innovative technology will add a significant boost to green electrical capacity and will have a positive impact on the environment; reducing carbon dioxide, other gas emissions and pollution.

APPENDIX III.

Aluminum as Energy Storage Bank

Aluminum is one of the most plentiful materials on earth. It has a relatively low basic cost and it also has one the highest inherent electrical storage charge per unit weight. There is no cause for concern over possible depletion or exhaustion of the raw material, as 7.3% of the earth's crust is made up of aluminum compounds. Aluminum is so easy to recycle again and again, that it maintains a high value throughout a product's life.

The beginning of the 21st century has so far been characterized by a growing instability in global, political and economic situations. These factors prompted a sharp increase in the demand for reliable non-fossil energy. The severe urgency of having an alternative power source became particularly obvious during multiple massive blackouts both in North America and Europe.

"Inefficient use of energy depletes natural resources and may threaten climate change. While aluminum's attributes in saving energy are highly publicized, perhaps less well known is the material's potential role in generating energy." [8,9,10]

"Aluminum is an **"energy bank"** - the original energy input can be recovered again and again every time the product is recycled. Aluminum can be recycled profitably and repeatedly without loss in quality. Energy is stored in aluminum products and can be re-used. The recuperation of used aluminum products is thus both energy-efficient and cost-efficient for the industry." [1]

"More than 55 percent of the world's aluminum production is powered by renewable hydro-electric power. It is a material that can be profitably recycled without loss of quality, for use by future generations. It is its recyclability, as well as its applications, which justify the significant energy required initially to produce primary aluminum." [9]

The advantages of aluminum can be summarized as follows:

- Abundance
- Low Cost
- High Energy Storage
- Lightness

Aluminum compounds (aluminum oxide and aluminum hydroxide), are commonly used in a number of industries: from water purification and sewage treatment to paper manufacturing and electronics. They can also be fully recycled back into aluminum. No residual waste products destined for a landfill are generated nor are any pollutants emitted into the air. For instance, WHO (World Health Organization) recognized the beneficial effects of the use of aluminum as a coagulant in water treatment to remove unwanted material, including several organisms known to cause disease.

“Aluminum in its everyday form appears to be inert and the thin layer of aluminum oxide that coats the pure metal is a very stable and rugged shell that is responsible for aluminum’s stability at standard atmosphere conditions. Breaking through this barrier and activating the aluminum is/was a key challenge facing the scientists. Rather than rely on ultra pure (99.999 percent) aluminum as the fuel, they chose to alloy the metal and produce alloyed metal plates for use in the cells.” [10]

To become economically viable, the old technology, consisting of expensive anodes and intrinsic additives, had to be completely overhauled. The new Aluminum-air fuel cell technology had to overcome the following challenges:

- Dramatically reduce the cost of anodes, completely eliminating the use of alloys. (Each extra alloy additive increases the cost of the anode two to three fold).

- Completely eliminate the use of non-recyclable intrinsic additives, such as indium, gallium, tin and thallium, etc., thereby dramatically reducing the cost of both production and recycling.

The new Aluminum-Air Fuel Cell and Hydrogen Production and Storage technologies use completely new approaches for design and production:

1. **Using industrial aluminum plates with no alloys;**

2. **Using balanced, completely recyclable electrolyte with proprietary additives.**

Benefits for Aluminum Production Industry.

"More than 55 per cent of the world's primary aluminum (from alumina) is produced using hydro-electric power which is clean, CO_2 free and renewable: e.g. over 80% for Russia and 100% for Norway. Also when energy shortages develop, power can be diverted from aluminum electrolysis to supply the power grid, thus helping to reduce peak period prices for other power users and reduce the need for the construction of marginal peak period electrical generating capacity." [9]

"Currently aluminum production process uses two kinds of energy:

1. Energy from fossil fuel or "dirty energy", used for alumina production from bauxite, and requires ~ 13mJ or 3.6kWh for production of 1kg of alumina;

2. Hydro Energy or "Green and renewable energy", used for production of aluminum from alumina (electrolysis), whereas production of 1kg of aluminum requires 3 kg of alumina."[9]

There are number of benefits of using aluminum as the source of energy – "energy bank".

1) Using Aluminum Oxide and Aluminum Hydroxide, the byproducts of the innovative technologies, in the aluminum production process, will lead to conservation of energy and the cost reduction of aluminum production; completely eliminating "dirty energy" currently being utilized, e.g., from coal, petroleum, etc.; using only renewable and recyclable energy provided by hydro-electric power plants.

2) Using aluminum and water as an energy storage and distributor through alkaline aluminum-air fuel cell and hydrogen production for PEMFC will achieve the following:

    i) Reduce criteria pollution

    ii) Reduce carbon emissions

    iii) The aluminum produced can be stored, distributed and transported anywhere safely.

3) New technologies do not produce any pollutants. The Aluminum byproducts (Aluminum Oxide and Aluminum Hydroxide) are fully recyclable. The electrolyte solution is non-toxic.

4) The use of aluminum as a source of energy will provide a tremendous value added opportunity for a wealth of applications and will dramatically enhance their efficiency and capabilities.

APPENDIX IV.

Science and Technology (Calculations and Formulations)

There are number of advanced scientific calculations and formulations shown below.

Energy of Aluminum as a Fuel

The enthalpy of chemical reaction of aluminum with oxygen to A $_2O_3$ reaches 10.167kWh/kg.

Pourbaix diagrams and reactions of aluminum-water system below clarify aluminum behavior in a water solution, particularly aqueous alkaline solutions.

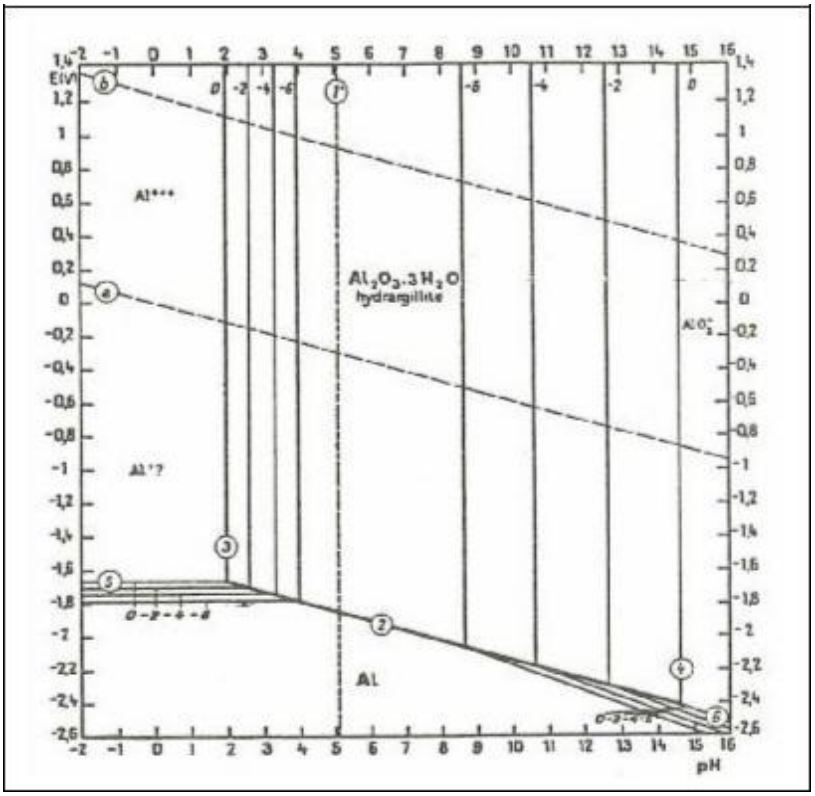


FIG. 1 **Pourbaix Diagrams and Reactions of Aluminum-Water system**

The upper diagrams are the Pourbaix diagrams for the aluminum-water system at standard conditions: temperature 298K (25^{O}C) and pressure 1atm. This diagram shows that aluminum will be attacked at pH values below 4 and at pH values above 10. From experiments high pH values attack aluminum at a faster rate than at lower pH values. [10]

As shown in the Pourbaix diagrams of aluminum water system, below line " **a**", the hydrogen reduction from water will occur (hydrogen generation from water). Since area 6 is placed below line " **a**" and the potential of aluminum in right-and-down area is between 2.4 and 2.72 Volts, then consequently, on the surface of the aluminum plate hydrogen reduction will occur (generation).

Table 1. **Reactions and Equilibrium Potentials of aluminum dissolution process.**

Line	Reaction	Equilibrium Potential (V)
5	$Al = Al^{3+} + 3e^-$	$E = -1.663 + 0.0197 \log(aAl^{3+}) =$ $= -1662 - 0.0197(5.7-3pH)$
2	$2Al + 3H_2O = Al_2O_3 + 6H^+ + 6e^-$	$E = -1.550 - 0.0594\ pH$
6	$Al + 2H_2O = AlO_2^- + 4H^+ + 3e^-$	$E = -1.262 - 0.0788\ pH + 0.0197 \log(aAlO_2^-) =$ $= -1.262 - 0.0788pH + 0.0197(pH-16)$
3	$2Al^{3+} + 3H_2O = Al_2O_3 + 6H^+$	$\log(aAl^{3+}) = 5.70 - 3pH$
4	$Al_2O_3 + H_2O = 2AlO_2^- + 2H^+$	$\log aAlO_2^- = -14.60 + pH$
a	$2H^+ + 2e = H_2$ or $2H_2O + 2e = H_2 + 2OH^-$	$E = 0.000 - 0.059\ pH - 0.03 \log P_{H2}$
b	$O_2 + 4H^+ + 4e = 2H_2O$ or $O_2 + 2H_2O + 4e = 4OH^-$	$E = 1.228 - 0.059\ pH + 0.015 \log P_{O2}$

The complete process of aluminum oxidation is based on the analysis of an aluminum surface dissolution mechanism and is distributed between two areas:

- Anodic sub areas (intrinsic aluminum metal surface) is responsible for aluminum ionization and oxidation and the release of ion Al^{3+} from surface to solution;
- Cathodic sub areas (formed by natural impurities of aluminum, such as Fe, Si, Cu etc.,) on aluminum surface is responsible for hydrogen reduction from water in corrosion reaction on a “solid piece” of aluminum surface.

Depositing the proprietary additives into an electrolyte, significantly increasing the activity of aluminum as described below:

- Selectively activate aluminum surface and evacuation of AlO_2^- ions from aluminum anodic sub areas on aluminum surface;
- Selectively inhibits process of hydrogen reduction from aluminum cathodic sub areas on an aluminum surface;

Aforementioned accomplishment opens the doors for commercialization of affordable final product in alkaline aluminum-air fuel cell and Hydrogen Production and Storage technologies by using the industrial aluminum (with purity 99.95 and above) and water, as an **“energy bank”** fuel, which can be safely transported to any remote areas with incredible energy savings and with much lower cost.

Calculations and Formulation for efficiency of Aluminum-Air technology

The energy conversion in alkaline aluminum-air technology allows for releasing of 8.100kWh (see below) of energy from 1kg of aluminum, or 80% efficiency of its theoretical energy limit of 10.167kWh/kg (enthalpy).

1st method of calculation:

Energy density 8.100kWh/kg coming from Faraday's Law: 1kg of Al can produce 2977.932 Ah

and multiplying by voltage level of 2.72Volts 2977.932*2.72 will result **8099.975 kWh**

2nd method of calculation:

The enthalpy of reaction at the standard state ($\Delta H°$) is a fundamental function related to the internal energy:

$H = U + PV$

Where:

U - Internal energy;

P – Pressure;

V – Volume

For the reaction of aluminum oxidation:

$$\mathbf{2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2}$$

The enthalpy of this reaction is (31.3-36.6) mJ/kg or (8.694-10.167) kWh/kg

Free energy (Gibbs function ΔG**)** is the energy released from the fuel cell by electrochemical reaction at the cell's operating temperature, must be considered [11]:

If there is a potential difference between the electrodes, the electrical motor can do work

$$\mathbf{w = q\Delta E = nFE_{cell}}$$

Where:

q - is charge

w (Work) = the electrochemical energy released by the fuel cell

$$\mathbf{-\Delta G = w = nFE_{cell}}$$

Where:

n - is moles of electrons F

- is a Faraday's constant

E_{cell} - is a potential difference ($E_{cathode} - E_{anode}$)

According to Pourbaix' Diagram and assume pH ≥14 for reaction:

$$\mathbf{Al + 2H_2O = AlO_2^- + 4H^+ + 3e^-}$$

$E_{Anode} = -1.262 - 0.0788\ pH + 0.0197 \log(aAlO_2^-) = -1.262 - 0.0788pH + 0.0197(pH-16) =$ **-2.3Volts**

$E_{Cathode}$=**0.4Volts**

$\Delta G = -nF(E_{Cathode} - E_{Anode}) = -3*(96,485)*(0.4-(-2.32)) = 787,318$ J/(mol Al)

Then, **Free Gibbs energy**:

ΔG=787,318 J/ (mol Al) = 29,160J/g=29,160kJ/kg=**8.099975kWh/kg**

Assume: 1J=1Volt*1Amps*1Sec=1Watt*sec;

1Hour=3600sec;

1 kWh=3600 Watt*sec=3600J

1 Mole of Al is 27g

See graphic illustration on fig. 1 and fig. 2 below:

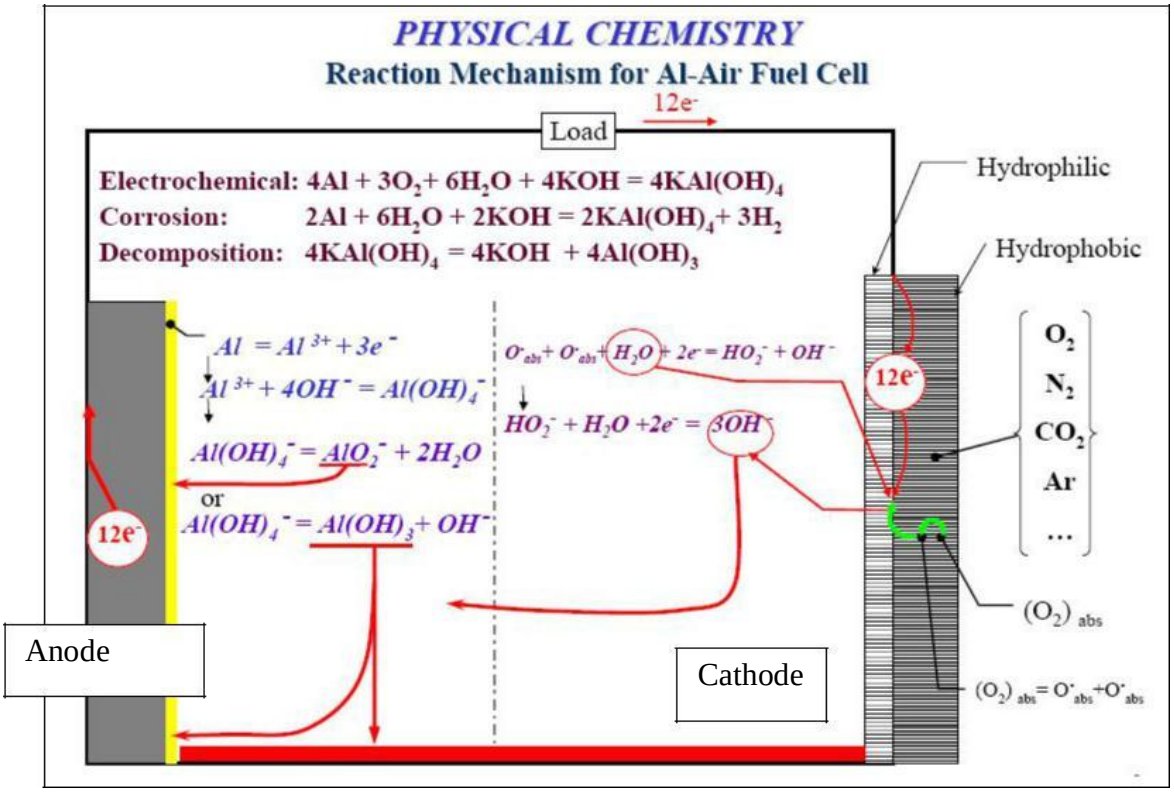


Fig. 1. **Reaction mechanisms for aluminum-air fuel cell**

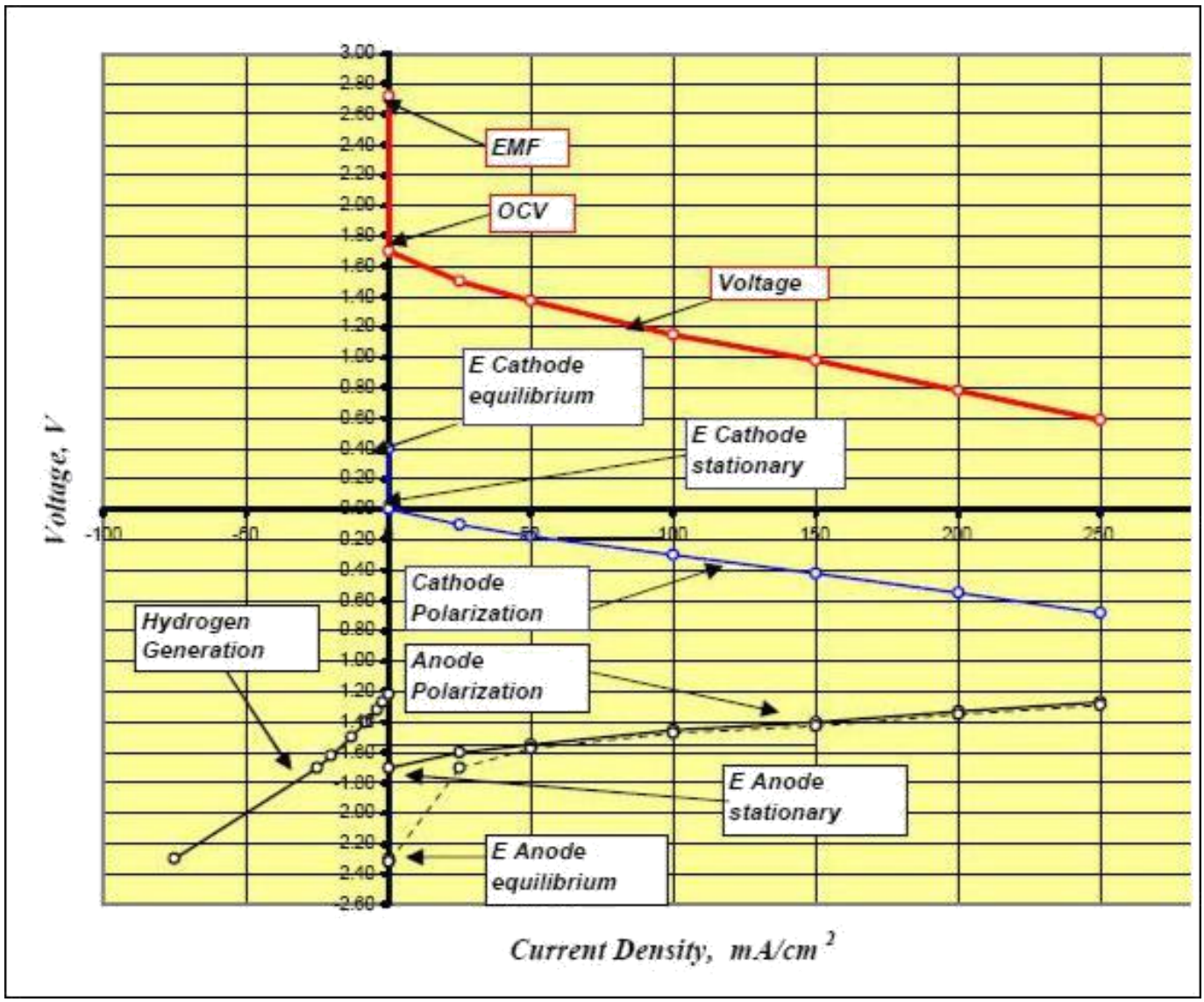


Fig. 2. **Voltage vs. Current density diagram of aluminum-air fuel cell**

Where:

EMF-Electro Motive Force;

OCV-Open Circuit Voltage;

E Anode Stationary – Stationary Potential of aluminum anode;

E Anode Equilibrium – Equilibrium Potential of aluminum anode;

E Cathode Stationary - Stationary potential of cathode;

E Cathode Equilibrium – Equilibrium potential of cathode;

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