

Direct NaBH₄/H₂O₂ fuel cells

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Abstract

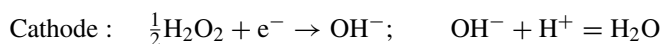
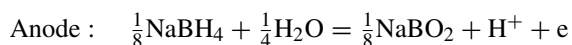
A fuel cell (FC) using liquid fuel and oxidizer is under investigation. H₂O₂ is used in this FC directly at the cathode. Either of two types of reactant, namely a gas-phase hydrogen or an aqueous NaBH₄ solution, are utilized as fuel at the anode. Experiments demonstrate that the direct utilization of H₂O₂ and NaBH₄ at the electrodes results in >30% higher voltage output compared to the ordinary H₂/O₂ FC. Further, the use of this combination of all liquid fuels, provides numerous advantages (ease of storage, reduced pumping requirements, simplified heat removal, etc.) from an operational point of view. This design is inherently compact compared to other cells that use gas phase reactants. Further, regeneration is possible using an electrical input, e.g. from power lines or a solar panel. While the peroxide-based FC is ideally suited for applications such as space power where air is not available and a high energy density fuel is essential, other distributed and mobile power uses are of interest.

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1. Introduction

A novel direct sodium borohydride (NaBH₄) /hydrogen peroxide (H₂O₂) fuel cell (FC) is under development jointly by the University of Illinois, Urbana-Champaign (UIUC), NPL Associates, Inc. (NPL), and CU Aerospace (CUA) [1–6]. This cell utilizes H⁺ transport through a proton exchange membrane (PEM) with the reactions:



An alternate cell which uses H₂ from a hydrogen generator to fuel the anode has also been studied, but for applications requiring compact systems and regeneration, the NaBH₄ version is of prime interest and is stressed here. If the cell is run on fuels from fuel reservoirs, we term the FC to be an open cycle. If both fuels

are periodically regenerated by reverse electrical charging, they are termed closed (regenerative) cycles.

While the use of NaBH₄ and H₂O₂ in an aqueous form, has been considered earlier by various groups, the concept remains undeveloped so the present research involved solving many new issues. This combination of fuels paves the way for a new type unitized design, which is inherently compact compared to other cells that use gas phase reactants. When operated in the regenerative mode, the FC serves the same function as a battery, but with improved operational characteristics. As described here, specialized catalysts and diffusion electrodes have been developed to optimize the cell performance. Initial experimental results indicate a conversion efficiency over 60% at a practical current density of 250 mA cm⁻² and a power density over 0.6 W cm⁻², at room temperature and ambient pressure. Such performance is in general better than that of traditional FCs. These excellent properties make the NaBH₄/H₂O₂ FC a very promising candidate for a variety of small mobile power applications as well as for high power applications, especially for space or underwater use where oxygen is not readily available from air.

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Hydrogen peroxide (H_2O_2) is a well known oxidizer for space propulsion [7]. The British Black Arrow launch vehicle had used the unique propellant combination of H_2O_2 with kerosene, giving a sea level specific impulse of 265 s. Hydrogen peroxide is also widely utilized for underwater power systems, for example, in torpedo propulsion [8].

Recently there has been a revived interest in using H_2O_2 for aerospace power applications, as emphasized by the recent International Hydrogen Peroxide Propulsion Conference [9]. This revival is driven by environmental concerns and accelerated by the dropping price of H_2O_2 .

The use of hydrogen peroxide in FCs is a relatively new development, however. The Naval Underwater Weapon Center (NUWC), Swift Enterprises, and others had fabricated some semi-FC devices using Al for the anode [10–12]. Very recently, full FCs based on $\text{H}_2/\text{H}_2\text{O}_2$ and on $\text{NaBH}_4/\text{H}_2\text{O}_2$ have been investigated at NPL/UIUC and elsewhere [13–15]. Meanwhile studies at Swift Enterprises have shown that bioelectrocatalysts (BEC) can electrocatalyze the reduction of hydrogen peroxide without appreciable peroxide decomposition. All these results have shown the general feasibility of a peroxide-based electrochemical cell. For space or underwater applications where air independence is a must, H_2O_2 -based FC systems are an ideal choice.

Conventional space power systems often involve photovoltaics (PV) and batteries. The current solar cell technology has a practical efficiency less than 20% while the specific energy of modern batteries is limited to 150–180 Wh kg^{-1} . Because the PV/battery systems have fairly low power and energy densities, their mass fraction of the total spacecraft weight, and the launch packaging volume is excessive for spacecraft requiring high power. Examples of such high power application include future concepts for large radar apertures, high performance electric propulsion, and manned surface rovers for Mars mission, which are clearly beyond the capacity of ordinary battery systems. A power system based on FC is promising in principle because of a higher energy density (on the order of 1000 Wh kg^{-1}). However, the space application of traditional H_2/O_2 FC is severely hampered by the lack of efficient storage for H_2 and O_2 . The direct $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC, described here, notably addresses that issue by offering storage of high energy density liquids, but also provides a compact system with ease of heat removal through the liquids and minimal pumping power requirements.

Other studies have investigated direct use of NaBH_4 at the anode, but have generally used air at the cathode [16,17]. Much work has been directed at use of NaBH_4 for hydrogen storage where H_2 generation is the goal as opposed to H^+ as needed in the direct FC application. This distinction is discussed in more detail in the section on catalysis selection.

Major experimental achievements to date in this peroxide FC study include: (1) open circuit voltage (OCV) > 1.2 V for a $\text{H}_2/\text{H}_2\text{O}_2$ FC and OCV > 1.75 V for the $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC, the latter corresponding to maximum efficiency > 75%, under ambient pressure and temperature; (2) a power density > 0.6 W cm^{-2} , for both cells, under ambient pressure and temperature, using Nafion 101; (3) the first $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC stack to date that generates more than 500 W; (4) an innovative manufacturing

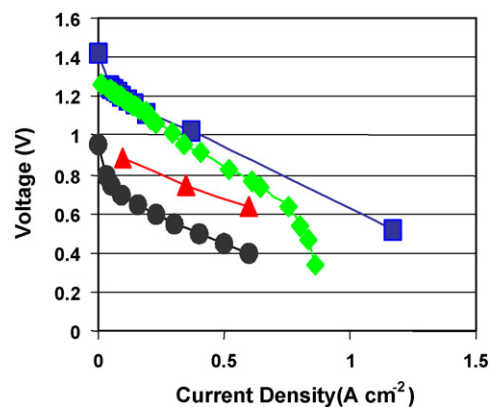


Fig. 1. Peroxide-based FCs (both the $\text{H}_2/\text{H}_2\text{O}_2$ and $\text{NaBH}_4/\text{H}_2\text{O}_2$ types) offer higher $V-I$ densities than traditional FCs under similar conditions. Blue line: $\text{NaBH}_4/\text{H}_2\text{O}_2$; green: $\text{H}_2/\text{H}_2\text{O}_2$; red: alkaline FC; black: PEM FC. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of the article.)

process for making cost effective diffusion layers and membrane electrode assemblies (MEA) for the $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC.

As shown in Fig. 1, the peroxide-based FCs (both $\text{H}_2/\text{H}_2\text{O}_2$ and $\text{NaBH}_4/\text{H}_2\text{O}_2$ types) offer higher voltage and current density than those obtained from traditional FCs at similar conditions. (Higher performance H_2/O_2 $V-I$ curves have been reported in some instances, in any case, with the higher OCV offered by the peroxide cell, its performance is generally superior, though exact values depend on specific cell comparisons.) With all-liquid reactants in the borohydride/peroxide FC, the fuel/oxidizer management becomes a relatively simple task, while fuel storage is kept light and compact.

1.1. H_2O_2 as a FC oxidizer

Safe and high power/energy density oxidizers are needed for compact power systems, and hydrogen peroxide is ideally suited to such applications for the following reasons.

H_2O_2 is one of the most powerful oxidizers. By using proper electrocatalysts, H_2O_2 can be converted into hydroxyl radicals (OH^\bullet) with reactivity second only to fluorine. This reaction is very important to efficient FC operation if peroxide is to be used as an oxidizer. Combined with different fuels, H_2O_2 forms a potent rocket propellant. With hydrogen the specific impulse is over 322 s in vacuum [7].

H_2O_2 is a natural metabolite of many organisms and decomposes into oxygen and water only. H_2O_2 is also formed by the action of sunlight on water, a purification process of Nature. Consequently, H_2O_2 has none of the environmental problems associated with most other chemical oxidizers.

H_2O_2 is now produced at over a billion pounds per year. The high volume production results in very low cost.

In comparison, other typical rocket oxidizers such as liquid oxygen (LOX) and N_2O_4 have severe limitations. The use of N_2O_4 in a FC is not desired because of its extreme toxicity. LOX is environmentally sound, but is not suitable for long-time storage due to its fast vaporization. The Dewar lifetime for one ton of LOX is only on the order of 1 month, while most

satellites today call for a mission-duration of several years. Bottled high-pressure oxygen is not an ideal option either because of rather low storage efficiency (often $\sim 0.3 \text{ kg l}^{-1}$) and large tankage mass fraction.

For FC operation in particular, H_2O_2 has some additional benefits:

Higher current density from higher mass density: Being a liquid phase, peroxide is a thousand times denser than a gas phase reactant, for example oxygen, in a typical FC. This mass difference has potential for much higher current density.

Single-phase transport on the FC electrode increases reaction rate: In a traditional FC, the two-phase transport of the reactant and product species is a limiting process for the FC operation [18]. Moreover, water generated in the FC reaction tends to flood the pores of gas diffusion layers, further slowing down the reactant transport. A direct H_2O_2 FC largely solves this problem.

Overcoming the traditional O_2 reduction over-potential problem: The slow kinetics of oxygen reduction in a traditional FC limits the current/power density and the energy conversion efficiency. The oxygen reduction reaction at the cathode is:



This reaction involves the simultaneous transfer of four electrons, and therefore has a low probability of occurrence [19–22]. It is well known that the exchange current density of O_2 -reduction is six orders of magnitude lower than that of H_2 -oxidation [23]. In comparison, the H_2O_2 reduction process at the cathode,



is a two-electron-transfer process and has a lower activation barrier. As a result, the peroxide FC therefore has a higher efficiency.

1.2. NaBH_4 as a FC fuel

Most FCs need a fuel high in its hydrogen content to function properly. The use of aqueous solution of NaBH_4 as a hydrogen carrying medium is relatively a new development [1–6,16]. Combined with hydrogen peroxide in a FC it brings about some added advantages:

Compact and convenient all-liquid operation: The complicated fuel management components in the traditional FC system, such as fuel reformer, gas compressor and humidifier, are no longer needed in a direct $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC. Quick start-up is also naturally guaranteed.

Built-in super-capacitor: The contact between the carbon particles of the electrode and the all liquid anolyte/catholyte forms a solid–liquid double layer, whose structure mimics that of a super-capacitor. Therefore, the $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC has excellent short-time overload capability similar to a super-capacitor.

Unitized regeneration: Using all-liquid fuel/oxidizer enables unitized regeneration, because the catalytic electrodes and

the membrane electrolyte need to be hydrophilic only, unlike in ordinary H_2/O_2 where hydrophilic and hydrophobic phases are both required to maintain a fragile three phase (gas–liquid–solid) interface. Storage of the regenerated reactants in the $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC is not a problem either.

Fast discharge/recharge: The aqueous solutions of borohydride and peroxide give the FC excellent fast discharge/recharge property, because of the fast dynamics of H^+ and OH^+ ions in a water-based solution. The fast/deep charge/discharge is of paramount importance for applications such as low Earth orbit (LEO) applications, effectively translated into a high LEO cycle energy density.

2. Experimental

The objective of the work described here was the demonstration of the operation of a 500 W stack using liquid fuels. Prior to doing that, however, studies were carried out to select appropriate catalysts and design the bipolar plates. These preliminary studies are described next followed by preliminary results from runs with the 500 W stack.

Several small (nominal 5 W size) single cell PEM FCs using the new reactants were fabricated at Swift Enterprises [24] and the University of Illinois. The use of a PEM instead of a liquid electrolyte significantly reduces reactant cross-over which can be severe otherwise. The catalysts used in the NPL/UIUC/CUA part of work were restricted to noble metals and some transition metal compounds whereas studies at Swift are based on bio-electrocatalysts, such as horseradish peroxidase, microperoxidase-11, and metal-5,10,15,20-tetrakis-(*p*-methoxyphenyl)porphyrin). The latter have the advantage of negligible peroxide decomposition at a price of reduced current/power density. Results from the bio-electrocatalyst studies are incomplete and will be presented later.

2.1. FC construction

Construction of the small test cell is quite similar to that of the 500 W stack with the obvious exception of changes such as incorporating bipolar plates for stacking proposes. Thus the following description is generic to both size units. The membrane electrode assembly fabrication process starts with the catalysts. Most of the carbon-supported noble metal catalysts are purchased while the transition-metal-type is prepared in lab by mixing the compound powder with acetylene blacks. A representative process is described as follows. Carbon supported Pt catalyst (Alfa Aesar 40 wt% Pt on Cabot XC-72) powder is first homogeneously dispersed in isopropanol, which is then mixed with 5 wt% Nafion solution. The ink is then brushed/sprayed onto a piece of carbon paper (Toray) or carbon cloth (E-Tek), which acts as a reactant diffusion layer. The carbon substrate here acts as “reactant diffusion layer” instead of the often termed “gas diffusion layer” because liquid phase reactants are used instead. The catalyst coated diffusion layers, which will later be referred to as diffusion electrodes, are then dried out in an oven at 80°C for 1 h. The effective loading of the catalyst is maintained at 1 mg cm^{-2} throughout the studies at NPL/UIUC/CUA.

A Dupont Nafion 112 membrane is used as the electrolyte. It was boiled in aqueous solution of 3 wt% H_2O_2 + 3 wt% H_2SO_4 for 1 h before rinsing in de-ionized (DI) water for 2 h. The Nafion PEM is then activated by 0.5 M H_2SO_4 for 2 h, followed by a triple rinse in DI water. The activated Nafion PEM is then held together by two reactant diffusion electrodes and hot-bonded together at 125 °C, under a pressure of 1000 psi. This hot-pressing typically last about 30 s and concludes the fabrication of the MEA.

The MEA is then sandwiched between perforated stainless steel plates, or other graphite flow-field plates which also act as electrical contact. The whole assembly is fastened together with the help of bolts, nuts, and two end plates. The liquid-tight seal is formed by elastomers such as silicone, neoprene or polyurethane. Fig. 2a and b shows a finished 5-W test unit.

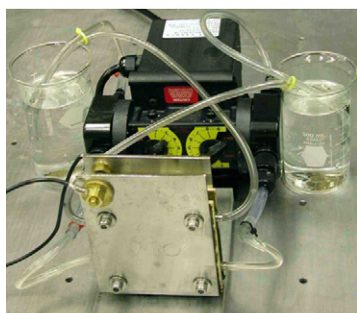
2.2. Selection of catalysts for 500 W stack

One of the important objectives of this research was to find electrocatalysts that efficiently catalyze the reduction of hydrogen peroxide. The noble-metal-type catalysts such as Pt usually give excellent performance in terms of power density but simultaneously tend to decompose peroxide very fast. This is undesirable from a fuel efficiency point of view. Therefore, catalysts compatible with peroxide without causing spontaneous decomposition are needed, and little information of this type is available in the literature.

Catalysts based on transition metals have been studied at NPL/UIUC/CUA because it is well known that transition metal ions such as Fe^{2+} are very effective in directly reducing hydrogen peroxide into hydroxyl ions. Furthermore, they



(a)



(b)

Fig. 2. NPL/UIUC/CUA direct peroxide 5 W test cell. (a) A 5 W $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC. (b) A 5 W $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC during test.

Table 1
Observed catalyst compatibility with reactants

Suspected catalyst	Compatibility	
	H_2O_2	NaBH_4
Ni on alumina silica	Stable	Stable
Ni coated graphite	Stable	Stable
$\text{Ni}[\text{OH}]_2$	Stable	Stable
$\text{Ni}[\text{OH}]_2$ w/ Co	Unstable	Stable
Gold on Vulcan	Stable	Stable
Glassy splinter carbon	Stable	Stable
TiB	Unstable	Unstable
NiAl raney type	Stable	Unstable
Titanium	Stable	Stable
Niobium	Stable	Stable
Iridium oxide	Unstable	Unstable
Iridium black	Unstable	Unstable
Platinum on carbon	Unstable	Unstable
Palladium black	Unstable	Stable

are obviously more affordable than noble metal catalysts in real-world applications.

To initiate the search for compatible catalysts, initial testing of candidates was done where catalysts were simply introduced into the liquid reactants in small quantities to ascertain reactant/catalyst stability. Results are given in Table 1. In this table “stable” indicates no visible gas production while gas evolution occurred in the cases marked “unstable”.

Based on these results, catalyst testing was performed in the 5-W test FC described earlier. A methodology was to first use platinum as the anode catalyst while the cathode catalyst was varied among the various candidates. Then once an “optimal” cathode catalyst was selected the anode catalyst was varied. Results for the various cathode catalyst tests are presented in Fig. 3. Gas evolution at the cathode was observed in the case of several catalysts and this is marked in the “decomp” in the figure legend. Decomposition “wastes” the fuel (reduce fuel efficiency) and lower the cell efficiency. Also it is not desirable in a sealed cell due to safety concerns. Thus, some catalysts were not selected, despite their higher $V-I$ curves. The latter is due to their higher activity (higher exchange current density) which in part leads to the gas evolution. Thus the catalyst selection represents a tradeoff between the cell efficiency and performance. Based on this reasoning gold (Au) was selected for the cathode catalyst. In addition to minimal decomposition of H_2O_2 , Au is easily applied and resistant to corrosion. Cost was not considered as a key factor at this stage of development but could force use of different catalysts in later commercialization efforts. While these results remain preliminary (we continue to search for an even better catalyst), Au was then used for tests to select the anode catalyst for construction of the 500 W stack.

Polarization curves for various anode catalysts are shown in Fig. 4. Vulcan supported gold was used as the catalyst on the cathode in all runs. Again discarding cases marked “decomp” and “unstable” palladium (Pd) was selected as a best candidate for the anode catalyst.

Hence for initial tests of the 500 W cell described next the palladium and gold were employed for the anode and cathode

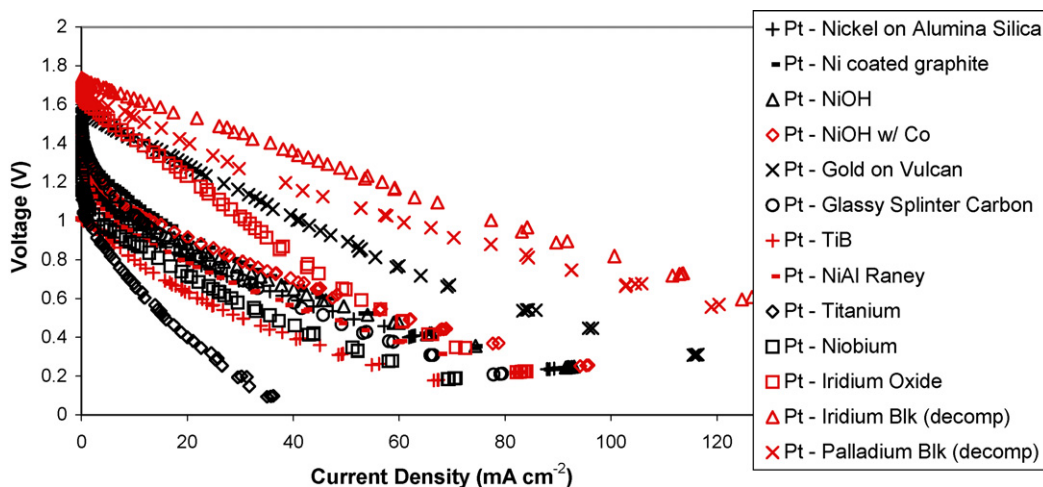


Fig. 3. Cathode catalyst performance testing, Au selected.

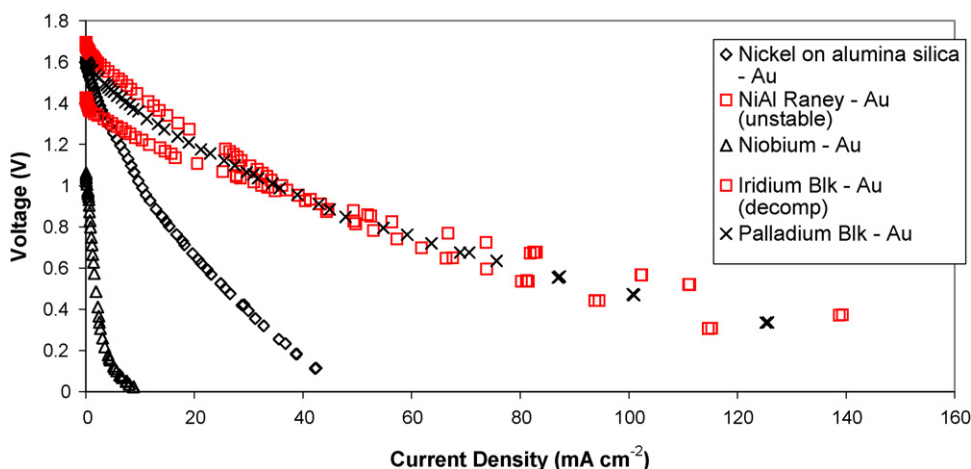


Fig. 4. Anode catalyst performance testing, Pd Blk selected.

catalysts, respectively, for their high performance and relative stability.

2.3. Bipolar plate design for 500 W stack

A serpentine design shown in Fig. 5 was utilized for the bipolar plates and the 500 W stack based on the following considerations:

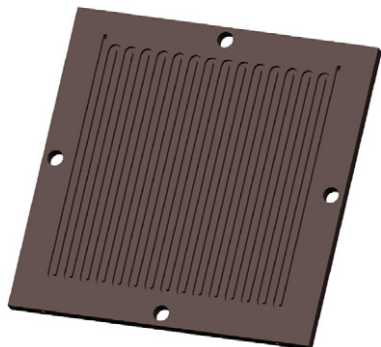


Fig. 5. 500 W bipolar plate design.

- the many loop serpentine provide very even distribution of fuel over the diffusion and catalyst layers;
- the higher pressure loop caused by the serpentine do not cause excessive pumping requirement.

The resulting plate dimensions are:

- 2.3-mm channel width;
- 2.0-mm channel depth;
- 12 cm × 12 cm active area.

Bipolar plates were composed of graphite, purchased from McMaster-Carr. Inlet and outlet fittings provided by Beswick Engineering. The manufacturing process included CNC milling of flow channels. Other features, such as inlets, outlets, and holes were created using standard endmill. The porosity of purchased graphite is rather large and can allow the reactant to seep into the plates. To prevent this, graphite was sealed with heating process applied by POCO Inc.

External inlets and outlets were used to connect the stacks in view of a concern about NaBH_4 conductivity possible causing a short circuit with conventional manifolding. With external

Table 2
Bipolar plates operational parameters

Flow rate of approximately $200 \text{ cm}^3 \text{ min}^{-1}$
Pressure drop expected for series flow is 17 psi for cathode and 8 psi for anode
Expected temperature rise of approximately 15°C
Heat flux will be approximately 500 W

connections the non-conductive tubing between cells for series flow prevents electrical shorting. The bipolar plate parameters are summarized in Table 2.

3. 500 W stack assembly and test results

Photographs of the 500 W stack being assembled are given in Fig. 6. The active area per stack was 144 cm^2 and 15 stacks were employed to provide a total active area of 2160 cm^2 . The stack was loaded using an AMREL PLW6K-60–1000 water-cooled programmable dc electronic load. Voltage and temperature measurements were recorded using a National Instruments data acquisition system. The system consists of a SCXI-1000, SCXI-1600 and SCX-1102B. Current measurements were taken directly from the AMREL load through a RS-232 interface. All data was managed using a NI Labview interface. The reactants were pumped using a MasterFlex/LS peristaltic pump in conjunction with for two-channel Easy-Load II pump heads.

Results for preliminary test runs with this stack are given in Fig. 7. The data shown was taken after 20 min into the run to establish a steady state condition. It seen from this figure operation at 500 W is achieved at $\sim 29 \text{ A}$ and 17 V. These results are consistent with expectations based on the test data obtained with the 5 W single cells. Thus the stack design appears to provide an effective power scale up. Future work will include two important steps: extension to several kilowatt stacks and work on a corresponding regenerative stack design.

3.1. $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC manufacturing

Based on the experience gained with the small test units and the 500 W stack, most of the H_2O_2 FC parts can be readily fabricated in house at NPL/UIUC. Cell designs have been formulated for units with powers ranging from 10 W up to several kilowatt, depending upon the desired application. The 15 W FC shown in Fig. 8 provides a good example of a small cell. It employs

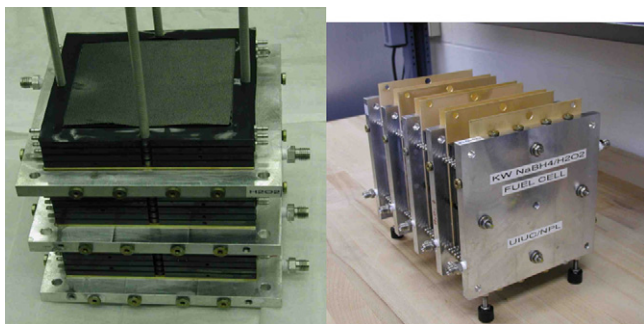


Fig. 6. The 500 W NPL/UIUC $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC during assembly and as assembled.

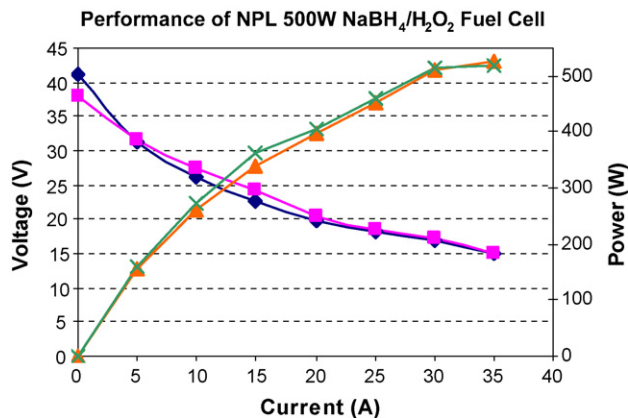


Fig. 7. $V-I$ and $P-I$ performance of the 500 W NPL/UIUC/CUA $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC. Blue and purple line: initial $V-I$ and after 20 min. Green and orange line: initial $P-I$ and after 20 min. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of the article.)

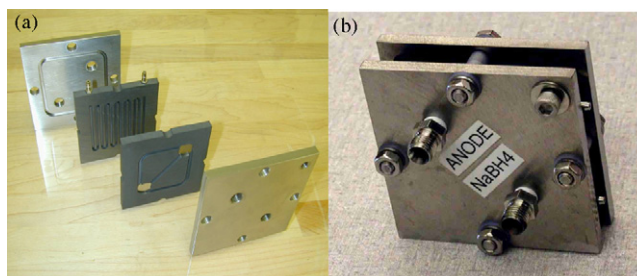


Fig. 8. (a) Flow-field and end plates for a 15 W $\text{NaBH}_4/\text{H}_2\text{O}_2$ test FC fabricated by NPL/CUA. (b) 15 W $\text{NaBH}_4/\text{H}_2\text{O}_2$ test FC as assembled.

an integrated cooling channel to dissipate the waste heat generated in the relative small 25 cm^2 active areas. This small cell has generated 36 W at some 60°C , representing the highest power density of any FC reported to date working at sub- 100°C . Thus it is of interest for power applications while the large stacks can compete in the kilowatt power level range.

4. Potential space applications

The $\text{NaBH}_4/\text{H}_2\text{O}_2$ FC offers a number of potential advantages for space applications such as for energy storage at base sites, backup power units, rovers, crew vehicle power. The benefits for such applications include:

- high specific power source for Earth/Moon/Mars missions;
- fast discharge/recharge comparable to nickel–hydrogen battery.

Based on an extrapolation of the present open cell experimental data (research on the regenerative version, not described here, is still in progress, so that extrapolation is less certain), the performance expected for space exploration is summarized in Table 3. This table shows both open cycle and closed cycle (regenerative) operation. As seen the predicted performance significantly exceeds the state of art (SOA) performance for

Table 3
Comparison of NaBH₄/H₂O₂ FC performance for various space missions

TPM	SOA	Predicted, NaBH ₄ /H ₂ O ₂
Energy density (open-cycle)	250 Wh kg ⁻¹ (Li batteries)	1000 Wh kg ⁻¹
Energy density (closed-cycle)	65 Wh kg ⁻¹ (Ni–H ₂ batteries)	120 Wh kg ⁻¹
Mission duration	20 days (H ₂ /O ₂ FC)	>90 days

TPM, technical performance measure; SOA, state of art.

competitive batteries and FCs that are contenders for such operations.

5. Summary and conclusions

In summary, there are a number of prominent features that distinguish the NaBH₄/H₂O₂ FC from the H₂/O₂ versions and conventional batteries. From a performance point of view, a space power systems [25] based on an open-cycle NaBH₄/H₂O₂ FC have the following distinct advantages:

- (1) very high energy density (over 2580 Wh kg⁻¹ theoretical, over 1000 Wh kg⁻¹ achieved experimentally, nearly 10 times higher than current state-of-the-art batteries used for space applications;
- (2) very high volume power density because of the direct utilization of H₂O₂ at the cathode;
- (3) the ability to overload for a short period of time simply by increasing the concentration of H₂O₂ at the cathode
- (4) the potential for a very high efficiency (over 60%) because the use of H₂O₂ overcomes the oxygen over-potential problem inherent to prior H₂/O₂ FC designs;
- (5) a very long cycle life is expected due to the catalytic electrode design (extended runs are in progress);
- (6) environmentally safe;
- (7) long-time storage of energetic materials; (8) low operational cost.

Initial regenerative operation was carried out in NPL/UIUC/CUA and experimental details will be reported elsewhere. For the regenerative (closed-cycle) operation, the NaBH₄/H₂O₂ FC technology has the following distinct merits:

- (1) high gravimetric (mass) energy density of 65 Wh kg⁻¹ proved, and potentially 125–200 Wh kg⁻¹; both nominal and on orbit;
- (2) much improved low Earth orbit and medium Earth orbit (MEO) cycle performance; LEO/MEO performance is at least three times higher than the current state-of-the-art lithium ion batteries;
- (3) fast discharge/recharge properties, as required by LEO/MEO operation, and preferred by future high power missions;
- (4) very long cycle life due to the catalytic electrode design.

The abovementioned merits make NaBH₄/H₂O₂ FC an ideal candidate for future Lunar and Mars missions. One such application will be powering extraterrestrial surface rovers. The Apollo type rovers had electric motors totaling some 1 kW. Its energy storage consisted of primary silver–zinc battery cells. The typical energy density for such batteries is on the order of 100 Wh kg⁻¹. Utilizing a NaBH₄/H₂O₂ FC could readily extend the rover mission duration and range by a factor of 5–10. Moreover the possible regeneration of NaBH₄/H₂O₂ FC will also add flexibility to future rover exploration and enable novel mission profiles.

Experiments have been performed to investigate the properties and application potential of peroxide-based FCs for space power systems. Studies of watt-level prototype cells have confirmed the feasibility and excellent performance of the direct, all liquid, NaBH₄/H₂O₂ FC. Such a technology offers many advantages for space applications. Parametric system analyses were also carried out to study the feasibility of 500 W and 5-kW FC units for future Lunar and Mars missions. The studies confirm that power systems based on this new FC technology have an energy density at least five times that of the state of the art battery systems.

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