



## Engineering of the bipolar stack of a direct NaBH<sub>4</sub> fuel cell

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### ABSTRACT

When a fuel cell (FC) utilizes liquid fuels directly, a few complications arise due to the conductance or the potential conductance of the fuel. Fuel cell stacks are typically designed in a bipolar fashion so that the voltage of individual cells can be added up in series to give an adequate and convenient output voltage. The conductivity of fuels brings about two risks if the bipolar stack is not properly designed and engineered. On one hand, the conductive liquid fuel may short circuit the neighboring cells of a bipolar FC stack with traditional integrated fuel manifolds. On the other hand, the conductive fuel may pass a high voltage to some parts of the cell through an ordinary manifold, causing excessive corrosion. These issues need to be addressed through a cell-isolation fuel distribution network (FDN). The function of such an FDN is to increase the shunting resistance of neighboring cells, so as to maintain a reasonable open circuit voltage. Also, the presence of a gas phase in the liquid fuel during cell operation affects fuel circulation and therefore needs to be considered in the FDN design. On the plus side, a liquid fuel, in contact with high surface area FC electrodes, functions as a super-capacitor, giving the FC an excellent pulse overload capacity. Also the fuel itself is a fair coolant, enabling high power density at minimal increase in stack weight. These considerations are applied to a kilowatt NaBH<sub>4</sub>/H<sub>2</sub>O<sub>2</sub> fuel cell stack to generate the desired operational characteristics.

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### 1. Introduction

The proposed future hydrogen economy has to come up with an effective means in hydrogen storage and transport. Hydrogen, as we know it, is not particularly ready to handle, especially in its gaseous form. Its adoption in fuel cells, therefore, often requires fuel reformers of one sort or another, which is inconvenient to say the least. These issues have raised considerable interests in fuel cells that feed directly on dense and chemically compound fuels. Often in a liquid form, such fuels are easy to manage and store. The direct methanol fuel cell (DMFC), as one example, has been around for more than a decade. More recently, formic acid [1,2], solution of sodium borohydride [3–7], and even oxidizers such as hydrogen peroxide [7–10], have been

shown to work in direct cells, demonstrating impressive performance.

With all the benefits inherent to a direct liquid fuel cell, its engineering is nevertheless complicated by a few physical/chemical processes when a liquid is used at fuel cell (FC) electrodes. Liquid fuels, or their reaction products, may conduct electricity, and this may short circuit a fuel cell stack. Current shunting, if any, is not really an issue for a single cell. For multi-cell FC stacks with a bipolar plate design, however, it may greatly reduce the stack voltage and efficiency if precautions are not taken properly.

Through careful theoretical deduction, simulation and modelling, the authors predicted such a phenomenon during the research and development on a kilowatt sodium borohydride/hydrogen peroxide (or NaBH<sub>4</sub>/H<sub>2</sub>O<sub>2</sub> in short hereafter) fuel cell stack. Theoretical and experimental measures were taken to minimize possible adverse effects, with very encouraging results. The authors therefore believe that we can contribute to the fuel cell research community by sharing the relevant results here.

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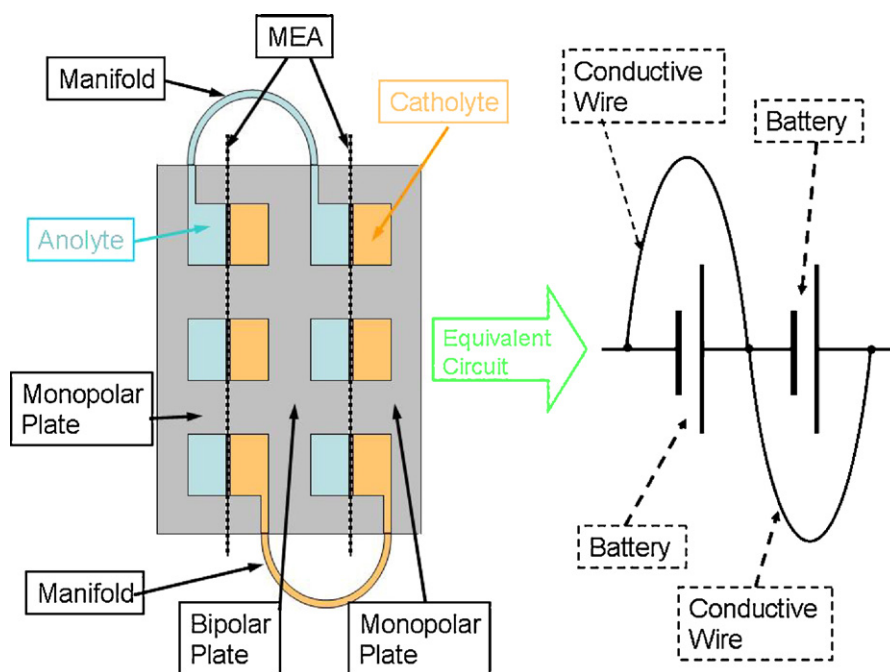


Fig. 1. Conductive fuel may short circuit adjacent cells in a bipolar stack.

Table 1

Conductivity ( $\text{mS cm}^{-1}$ ) of selected solutions important to the  $\text{NaBH}_4/\text{H}_2\text{O}_2$  fuel cell

Solute–solvent	Temperature ( $^{\circ}\text{C}$ )	Weight percentage of solute			
		5%	10%	15%	20%
$\text{NaBH}_4\text{--H}_2\text{O}$	20	110.8	198.7	$\sim 217^{\text{a}}$	$\sim 224^{\text{a}}$
$\text{NaOH--}20\text{ wt\% NaBH}_4\text{ water solution}$	25	$\sim 220^{\text{a}}$	$\sim 330^{\text{a}}$	$\sim 280^{\text{a}}$	$\sim 240^{\text{a}}$
$\text{H}_2\text{O}_2\text{--H}_2\text{O}$	20	4.7	8.3	9.0	10.5
$\text{H}_2\text{SO}_4\text{--}20\text{ wt\% H}_2\text{O}_2\text{ water solution}$	25	141.8	$\sim 281^{\text{b}}$	$\sim 379^{\text{b}}$	$\sim 460^{\text{b}}$

<sup>a</sup> Estimated with standard conductivity curve of NaOH.

<sup>b</sup> Estimated with standard conductivity curve of  $\text{H}_2\text{SO}_4$ .

## 2. Shunting of neighboring cells

To understand why the conductive fuel poses a problem for bipolar stacks, take the stack in Fig. 1 as the example. It consists of two cells in series. The manifolds are represented schematically by tube-like hoses. In reality, an integrated manifold like that in a (gas-fueled) ordinary FC stack is much shorter and wider. It hence is much less resistive, aggravating the problem.

In this particular case, the anolyte manifold shunts the anode and cathode of the cell on the left and the catholyte one short circuits the cell to the right. The open circuit voltage is thus severely reduced. If the stack has more than two cells, the situation is still very similar and it will be discussed later.

### 2.1. Conductivity of liquid fuels

A finite conductivity in the fuel brings about two effects to a bipolar cell stack. First of all, it brings about corrosion to the part of stack at higher electric potential. This already happens to very low conductivity of  $10\ \mu\text{S cm}^{-1}$  or maybe even lower. Higher conductivity causes more severe corrosion. Secondly, if the conductivity climbs beyond  $1\ \text{mS cm}^{-1}$ , the current shunting problem of neighboring cells becomes noticeable. We measured the resistance of the fuel important to our studies here and the results are summarized in Table 1. The tests were carried out with a VWR Scientific Products Model 5005 conductivity meter. The Model 5005's effec-

tive range has an upper limit of  $200\ \text{mS cm}^{-1}$  and hence is unable to measure some highly conductive solutions. In those cases, the number quoted in Table 1 represents an estimate based on known conductivity curves of common chemicals and empirical solution chemistry.

The strongly acidic and basic fuels that adopted in our research have conductivity on the order of  $200\ \text{mS cm}^{-1}$ . Such an order of magnitude of course has severe current shunting issue if not properly addressed. However, even an apparently benign fuel such as organics could have problems developed during its life cycle. Therefore we summarize some of often used type in Table 2.

Organic fuels, when pure, typically are highly resistant to electric current. For example,  $1\ \text{cm}^3$  of methanol, when in a cubic form and pure, would have a resistance higher than  $10^6\ \Omega$  at the room temperature. Such a high resistance should not cause any practical current shunting problem. However, this high resistivity is rarely maintained in a practical fuel, during its whole operational cycle. Take the direct methanol fuel cell for the example. First of all, even

Table 2

Conductivity of selected fuel important to direct liquid fuel cells

Fuel	Concentration (wt%)	Temperature ( $^{\circ}\text{C}$ )	Conductivity ( $\mu\text{S cm}^{-1}$ )
Methanol	Pure	18	0.44
Formic acid	4.94	18	5500
Methanal	44	38	175

if one starts with a 100%  $\text{CH}_3\text{OH}$ , reaction products like water and  $\text{CO}_2$  will make the fuel a chemical solution. This, in turn, greatly increases its conductivity. Secondly, reaction intermediates due to the FC action tend to be readily ionized in water. For DMFC, the typical intermediates are formic acid and methanal (formaldehyde) [11,12]. Formic acid, even at a low concentration of 5 wt%, is already conductive enough to bring down shunting resistance to  $100\ \Omega$ , for adjacent cells in an conventional bipolar stack with integrated manifolds. Last but not least, additives to the fuel could increase its conductivity by orders of magnitude. For example, DMFC with anion exchange membranes often add KOH or NaOH to improve performance, which makes an excellent conductor when solvated by the product water.

The bipolar stack may corrode even if the liquid fuel is highly resistant, if the traditional manifold is utilized. Suppose that we have a stack generating a high voltage, say 40 V. Even though the fuel is highly resistive, it still functions more or less as an electrolyte. Consider the space between the lowest voltage anodes, the highest voltage cathodes, which is filled with electrolyte (fuel) from the conventional manifold. This is nothing other than an electrolytic cell, though a type with a high internal resistance. The cathodes would therefore undergo excessive corrosion caused by the high voltage. A similar effect happens to other electrodes which take high electric potentials. Even in the case of a DMFC with air as the oxidizer, the anodes of higher voltage are not immune to such a corrosive attack.

This current shunting phenomenon might not limit itself to direct liquid fuel cell stacks. The authors have studied some  $\text{H}_2/\text{O}_2$  stacks before. Sometimes the stack performance degrades faster than expected at very heavy load. At the beginning it was very puzzling as to its origin. With the experience in the liquid fuel FC stack, we now understand its origin. We found the stack corrosion is correlated to water accumulation in the air flow-field/manifold of the stack. For the traditional  $\text{H}_2/\text{O}_2$  type, water tends to accumulate under heavy load, and corrosion of the electrodes is accelerated. This is especially severe to those parts at higher potentials of the stack.

## 2.2. Equivalent circuits

Consider a specific example of  $\text{NaBH}_4/\text{H}_2\text{O}_2$  bipolar stack with four cells in series. The open circuit voltage of a single  $\text{NaBH}_4/\text{H}_2\text{O}_2$  cell is around 1.6 V. Now suppose that the stack has an ordinary integrated manifold machined/molded/stamped in graphite/stainless steel bipolar plates. When the stack is filled with reactants, the equivalent circuit is given in Fig. 2(a). The resistance  $r$  is that of the fuel in the manifold between two neighboring cells. Because both borohydride fuel solution and the peroxide oxidant have fairly high conductivity, around  $200\ \text{mS cm}^{-1}$ ,  $r$  is only a few ohms. Such a low resistance severely short circuit the cells in concern. The net result is an unbearably low stack voltage even if the stack does not drive any load.

There are essentially two steps to resolve the inter-cell or inter-stage short-circuiting problem. The key is to first make the manifold nonconductive, i.e., it is made of polymers. Then secondly, one needs to add a long and constricted flow path between the traditional manifold and the electrochemically active regions of cell, or membrane electrode assembly (MEA). Such a path, itself made of polymers, will introduce a relatively large resistance due to the fuel's own resistivity. Such a resistance, shown in Fig. 2(b) as  $R$ , greatly increases the effective shunt resistance between successive cells. One needs to determine the proper geometry of the manifold so that the shunt resistances are large enough. Such a combination of nonconductive manifold with the constricted path forms the cell-isolation fuel distribution network (CIFDN).

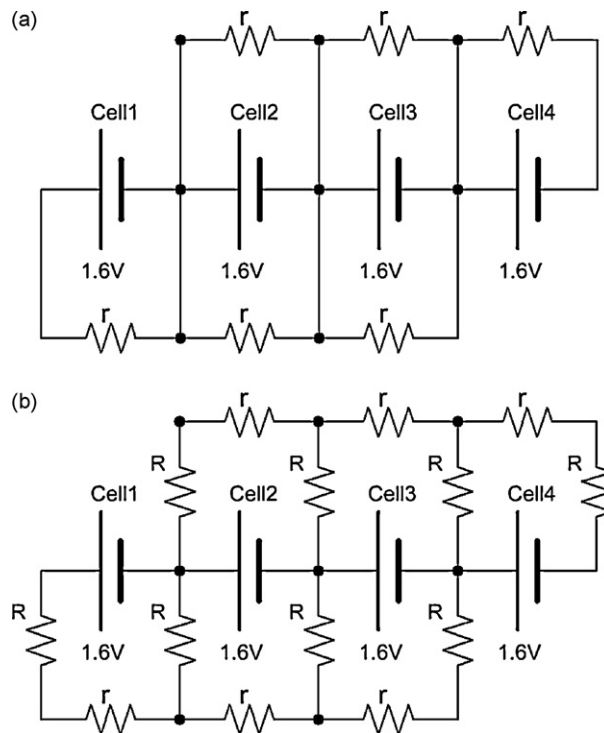


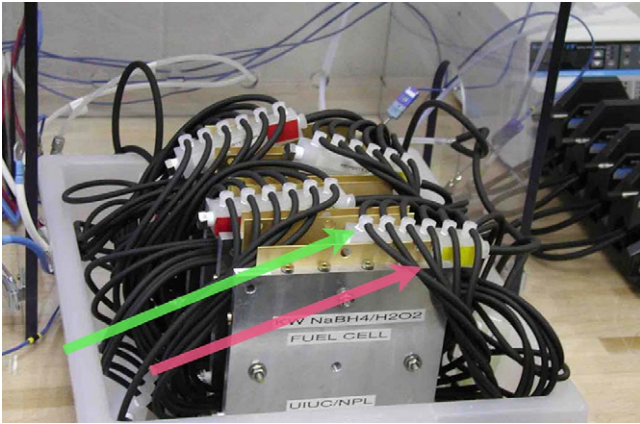
Fig. 2. (a) Equivalent circuit for a bipolar stack of four  $\text{NaBH}_4/\text{H}_2\text{O}_2$  cells, with conventional fuel manifold. (b) Equivalent circuit when a cell-isolation fuel distribution network is added between the conventional manifold and individual cells.

## 2.3. Cell-isolation fuel distribution network

There are also two different practical approaches to achieve the aforementioned objective, the CIFDN. One still can, in principle, build a (non-traditional) integrated manifold bipolar plate with stainless steel (or graphite) combined with polymers. This should be a more elegant solution in the long run but involves higher initial capital investment. Alternatively one can separate the conductive bipolar plates with external polymeric manifold. The latter approach is simpler to implement, but it comes at the cost of a messy stack and leak-prone fittings. To prove the concept, we adopted the second approach and developed a separate manifold system to verify the shunt-reducing design. The fuel-feed plumbing basically consists of a network of Viton tubing and polymer manifold as shown in Fig. 3. The bipolar plate itself does not have any integrated manifold opening. Instead the fuels are fed edgewise through four fittings, two for each side of the graphite bipolar plate. In the particular setting of Fig. 3, the fuel is fed in parallel to the cells. This maximizes the power output but has some drawbacks as we will see later.

The equivalent circuit after the addition of polymer manifold is already shown in Fig. 2(b). The  $R$  is on the order of  $1000\ \Omega$ . The insertion of  $R$  increases the shunting resistance between cells, and therefore boosts the stack open circuit voltage and reduces loss.

As a side note, similar cell-isolation fuel distribution network can be designed for a  $\text{NaBH}_4/\text{air}$  fuel cell stack. The current shunting on the air side is not of a concern unless it is flooded too easily. This almost reduces the manifolding complexity by half. The comparison between a  $\text{NaBH}_4$  FC stack with traditional manifolds and that with cell-isolation ones is shown in Fig. 4. A typical  $\text{NaBH}_4/\text{air}$  has an OCV of 1.2 V on average. For traditional manifold, the  $r$  is on the order of few ohms too. The shunting is severe as well and the adoption of CIFDN is therefore essential for a proper bipolar stack design. A slight difference when compared to the case of  $\text{NaBH}_4/\text{H}_2\text{O}_2$  is

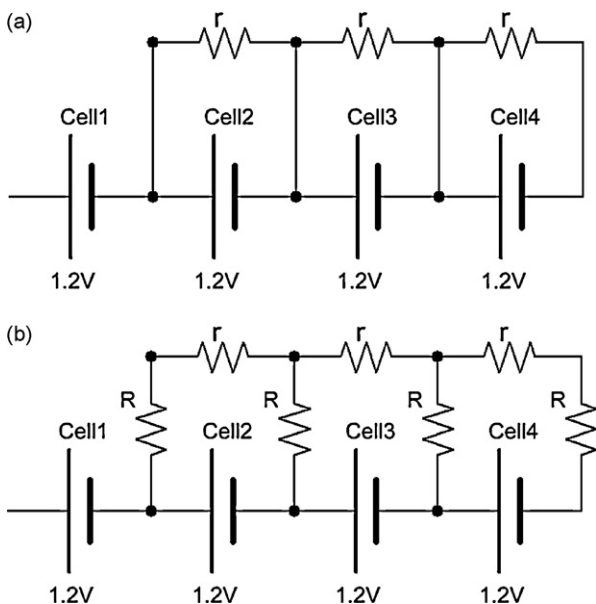


**Fig. 3.** The CIFDN of this 24-cell NaBH<sub>4</sub>/H<sub>2</sub>O<sub>2</sub> FC stack consists of polymer manifold (one such part is pointed by the green (upper) arrow), and a number of Viton tubes, indicated by the red arrow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

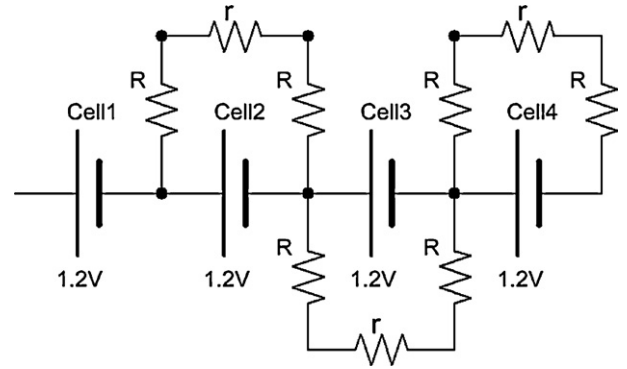
that the leftmost cell is not shorted. The reason is simple: the air manifold should be highly resistant under normal conditions.

Because  $r \ll R$ , the corresponding hydrodynamic flow resistances follow similar relation at parts of CIFDN where  $r$  and  $R$  are defined. The hydrodynamic resistances at  $r$  are then negligible. The cells, depicted in both Figs. 2 and 4(b), are then fed essentially in parallel. Similar case is found in the specific real-world stack feeding scheme of Fig. 3. The parallel feed has the benefit of maximized flow rate. However, the stack corrosion problems are still severe because the high voltage parts of the stack are pitted against the lower potential ones through a resistance of a few  $r$ . Because  $r$  is small, the corrosion is fast.

The serial-feed scheme is thus proposed to address the corrosion issue. To easier understand the point, take the relatively simple case of NaBH<sub>4</sub>/air fuel cell stack as the example. One only needs to consider the CIFDN for NaBH<sub>4</sub>. As shown in Fig. 5, higher potential part of the stack, for example, the cathode of Cell2, is no longer in direct electric commutation with the lower potential part of the stack, say



**Fig. 4.** (a) Equivalent circuit for a bipolar stack of four NaBH<sub>4</sub>/air cells, with conventional fuel manifold. (b) Equivalent circuit when a cell-isolation fuel distribution network is added between the conventional manifold and the individual cells.



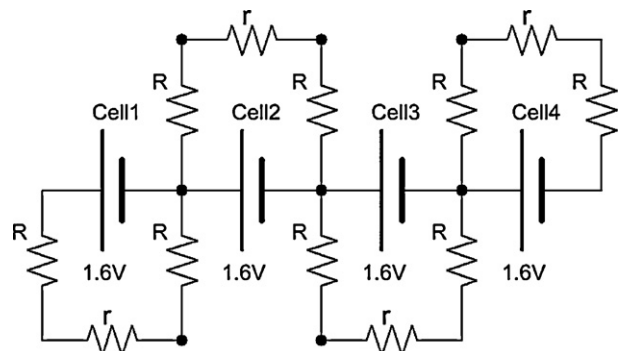
**Fig. 5.** Equivalent circuit for a bipolar stack of four NaBH<sub>4</sub>/air cells, with CIFDN in serial feed.

the anode of Cell4. Instead the cathode has to go through a resistor network of  $6R + 3r$  to reach the latter anode. Because  $R$  is big, the corrosion rate is much reduced. More importantly, the cathode of Cell3 maintains a voltage only 1.2 V lower than that on the preceding cathode (Cell2), effectively reducing corrosion to practically zero.

For NaBH<sub>4</sub>/H<sub>2</sub>O<sub>2</sub> fuel cell, the equivalent circuit is more complicated due to the added CIFDN for the peroxide, as given in Fig. 6. Note that such a schematic is simplified at Cell2 and Cell3: there are actually two  $R-r-R$   $\pi$ -shaped resistor networks for each of the two cells. One is from the borohydride FDN and the other from the peroxide one, to make a total of two ICFDN. One such network for either Cell2 or Cell3 is not shown for the sake of clearance.

In practice, one can combine the two fuel-feed schemes to get desired results. For example, the hydrogen peroxide side has negligible gas evolution during cell operations. Therefore, peroxide can be fed to the individual cells in series. The NaBH<sub>4</sub> side is preferably fed in parallel to reduce gas evolution so as to maximize power. The gas evolution is from the direct decomposition of borohydride at the anode side, therefore constituting a loss. However, such a parallel configuration still has the undesired corrosion characteristics. Therefore, one can, for example, divide the stack of 24 cells into 6 groups of 4 cells each. The cells are fed in parallel within each group, while the plumbing between the successive groups is in series. Power performance is then balanced with stability in such a mixed approach.

The serial-feed scheme has its own drawbacks. It tends to have high pressure build-up if the electrode gases excessively during the FC operation, due to direct decomposition of reactants. The problem may somehow be mitigated with optimization on other aspects of the stack design, such as flow-field geometry, diffusion layer properties and so on. More detailed research is highly desired in this direction.



**Fig. 6.** Equivalent circuit for a bipolar stack of four NaBH<sub>4</sub>/H<sub>2</sub>O<sub>2</sub> cells, with CIFDN in serial feed.



### 3. Experimental

The design and fabrication of the 1 kW stack was earlier described elsewhere [10].

Five cooling plates machined from aluminum are inserted for the purpose of temperature control. Such a water-cooling measure is more of a trial nature, but not of absolute necessity because the liquid fuels can function as a coolant, at least for tests lasting not too long. The outer plates also act as endplates where the bolts and nuts clamp the stack together. The cell can operate without the cooling plates' functioning, but for calibration and testing purpose, the plates are included anyway. The electric contact plates shown in Fig. 3 have a golden luster. These are made from gold-plated copper sheets to help isolate the corrosive reactants from the aluminum cooling plates. Still some corrosion happens as it is very difficult to eradicate the seeping and creeping of reactants from the gaps between bipolar plates and the edge fittings. Therefore more thorough researches on protective coating of aluminum are highly desired. Also a properly engineered integrated manifold should much reduce the leakage in the future.

A typical benchmark test is carried out with 15 wt%  $\text{NaBH}_4$  aqueous solution stabilized by 15 wt%  $\text{NaOH}$ , and 20 wt%  $\text{H}_2\text{O}_2$  solution stabilized with 5%  $\text{H}_3\text{PO}_4$ , sometimes with 5%  $\text{H}_2\text{SO}_4$  as well. The reactants were at room temperature before being fed to the fuel cell. The  $V$ - $I$  curve was read from an AMREL PLW6K water cooled electronic load controlled by an IBM-PC compatible computer.

The fuel, both oxidizer and the reducing agent, are typically circulated by a Masterflex L/S peristaltic pump. The pump has separate pumping heads for the peroxide and borohydride. The maximal pumping rate is limited to  $420 \text{ ml min}^{-1}$  overall, for peroxide and borohydride combined. This was found to severely limit the fuel cell power achievable.

The bipolar plates adopted in the stack use a single channel serpentine flow-field design. The plates are made of graphite, with the flow-field machined in place. The raw graphite turned out to be porous and pervious to both fuels. The surface has to be deposited with a chemical vapor deposition (CVD) carbon to plug the pores. The serpentine flow-field is simple but in retrospect it also caused excessive flow pressure build-up, especially at the anode side. Further, there is a certain degree of gassing at the anode when the current draw is large. The gassing, or gas evolution, results from the hydrolytic decomposition of the fuel or the oxidizer. The gas accumulation increases pressure gradient in the cell and therefore limits the flow rate that can be achieved with the fuel pump. The adoption of long tubing in the CIFDN also aggravated the problem. In order to increase the shunt resistance, the Viton tubes are at least 6 in. and often up to 2 ft in length. Combined with a small internal diameter of  $\sim 3 \text{ mm}$ , this causes a gas pressure build-up as large as that from the serpentine flow-field. Initially all of the manifolds are staged in series as shown in Fig. 5. It was found to give a paltry power output of  $\sim 240 \text{ W}$  for the whole stack because excessive borohydride decomposition simply deprived many cells of the fuel.

#### 3.1. Voltage and power performance

Finally, the authors decided to change the fuel feed to parallel. Some polymer manifolds, as shown in Fig. 3, were purchased off-shelf and combined with the Viton tubing. The CIFDN was replumbed to make it parallel. This measure immediately improved the power performance to over 500 W. The initial however sketchy results were reported before [10] and the more detailed  $V$ - $I$  and  $P$ - $I$  curves are repeated here in Fig. 7. In both cases, the fuels were circulated by the peristaltic pump only. Four Easy-Load II pump heads were utilized, two for each fuel. This gives a combined flow rate of  $210 \text{ ml min}^{-1}$  each for both the peroxide and the borohydride. The

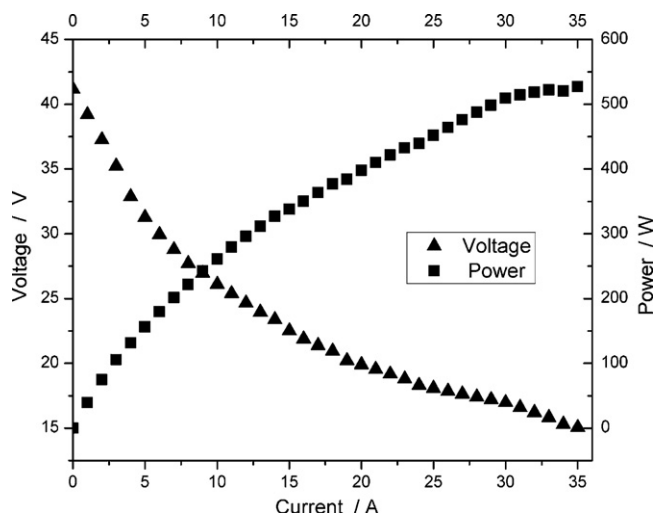


Fig. 7. Voltage-current and power-current (steady state) performance of the 24-cell  $\text{NaBH}_4/\text{H}_2\text{O}_2$  stack, at pumping rate of  $210 \text{ ml min}^{-1}$ , for both borohydride and peroxide.

power increase from serial to parallel feed is therefore significant even without change in the pumping rate.

This result was encouraging because it confirmed our initial diagnostic on the fuel-feeding issue. We hence followed on and investigated if the stack power output can be further enhanced with improved fuel circulation. Because of severe gas evolution, the  $\text{NaBH}_4$  side is the bottleneck to power output. We therefore added a Cole-Parmer 76302-70 diaphragm pump for the circulation of the anolyte. This adds another  $340 \text{ ml min}^{-1}$  circulation to the anodes. The flow through the anodes was much improved and the power was almost doubled to 983 W as extrapolated from Fig. 8. The increase in power is not proportional to that in circulation, however. This should not come as a surprise after all. The improvement in power output may just level off once the flow condition is improved to the point where it is no longer the bottleneck to the desired electrochemical reaction.

The new results largely confirmed our theoretical analysis of the short-circuiting and fuel-feeding problems. The maximal steady-state power density is roughly  $280 \text{ mW cm}^{-2}$ . Although this is far from the highest power density that has been achieved on a single

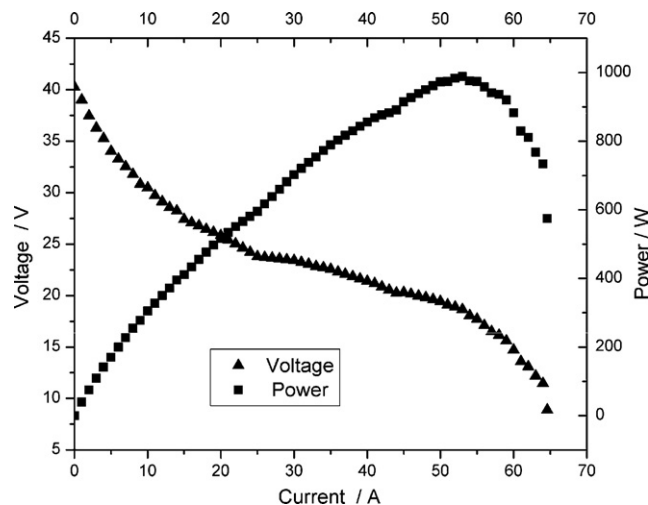


Fig. 8. Voltage-current and power-current (steady state) performance of the 24-cell  $\text{NaBH}_4/\text{H}_2\text{O}_2$  stack, at pumping rate improved to  $550 \text{ ml min}^{-1}$ , for the borohydride side.

**Table 3**  
Maximal power at different configurations of stack, feed, circulation rate

Number of cells in stack	Anode		Cathode		Max power (W)	Power density ( $\text{W cm}^{-2}$ )
	Feed	Rate ( $\text{ml min}^{-1}$ )	Feed	Rate ( $\text{ml min}^{-1}$ )		
2	Serial	105	Serial	105	~90	~0.313
24	Serial	210	Serial	210	~240	~0.069
24	Parallel	210	Parallel	210	520	0.15
24	Parallel	550	Parallel	210	983	0.284

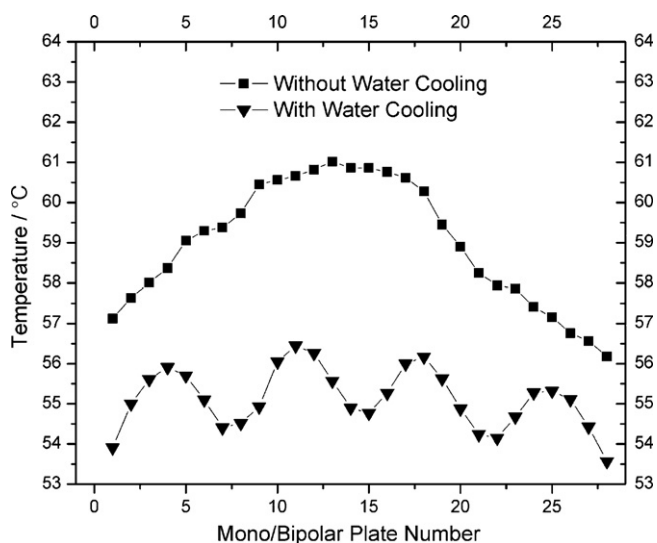
cell scale, it nevertheless constitutes a significant breakthrough for a complex and novel FC system of the kilowatt scale. We routinely break  $600 \text{ mW cm}^{-2}$  at a 10 W class test cell, but corrosion and fuel feeding are no problem at all in that case. For multi-cell stacks, the FDN have significant influence on the power performance. To increase the power, the fuel feeding is preferably parallel. This however likely reduces long term durability by speeding-up corrosion. These two conflicting requirements have to be reconciled, a task not found in a single cell or few-cell stacks. The results on various combinations of stack, fuel feed and circulation is summarized in Table 3. It is clear that when the stack is short, say made of two cells, it is much easier to reach high power density.

For  $\text{NaBH}_4/\text{H}_2\text{O}_2$  FC, the power density typically would increase with reactant concentration. For hydrogen peroxide, concentration up to 50% has been verified to work in this type of FC. Therefore, the power from the 1 kW stack may be further increased by the simple means of concentrated fuel and performance-enhancing additives.

### 3.2. Temperature characteristics

One advantage of direct liquid fuel cell is the fuel is also a coolant, provided a proper radiator or cooler is design to use with the fuel. Thermocouples were tapped into the stack to monitor the temperature during operation. During the test, the mass of reactants were 3.3 kg combined. This acted as a heat-sink for the waste heat generated during the operation, provided that the test does not last too long and the power is not too high. Otherwise the fuel would heat up too much because we do not have an adequate radiator. The power was limited to 500 W or below to satisfy such a condition.

The temperature variation across the stack is given in Fig. 9, for operations with or without water cooling. The temperature without



**Fig. 9.** Temperature variations at the 28 monopolar or bipolar plates across the 24-cell  $\text{NaBH}_4/\text{H}_2\text{O}_2$  stack, with five water-cooling plates interlaced.

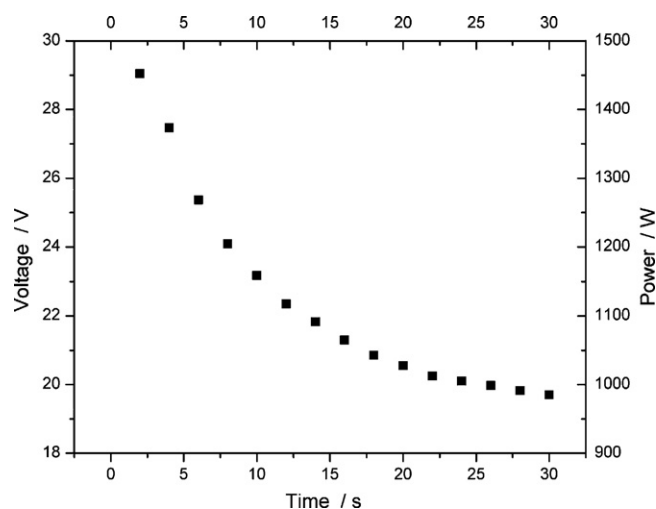
water cooling was recorded after the stack had been in operation for 20 min, pulling a constant current of 25 A. After this measurement of  $T$ , water cooling was turned on. Twelve minutes was given to allow for a thermal equilibrium. Then the temperature was measured again to give the second group of data in Fig. 9. The cooling is from free flow tap water, and flow rate was at  $\sim 800 \text{ ml min}^{-1}$ .

The maximal temperature difference with and without cooling is a mere  $7^\circ\text{C}$ . Therefore the cooling properties of the liquid fuel itself are demonstrated. The uneven temperature distribution of the stack may be attributed to uneven ventilation inside the fume hood. The cooling water itself entered the stack from one side and exited from the other, being heated up in the process. This should also contribute to a temperature imbalance.

### 3.3. Pulsing performance

It is common to notice that a liquid-fueled FC can reach a higher power output than the nominal, for a short time, after it is put to open circuit condition for a few minutes. The catalytic electrodes are often composed of carbon materials of high surface area. An electrolytic double layer is formed at the liquid–solid interface when the electrodes are in contact with the liquid fuel. In essence, a super-capacitor forms in parallel with the fuel cell. At open circuit, the electrochemical reaction generates an electromotive force (potential) and charges up the super-capacitor. Shortly after the close of circuit, the super-capacitor discharges in parallel to the fuel cell and enables it to reach power rating higher than the nominal.

The power overloading of the current  $\text{NaBH}_4/\text{H}_2\text{O}_2$  fuel cell is tested as the following procedure. Open the circuit for 2 min, with the fuel circulation stopped. Then turn on fuel circulation and after 5 s start drawing current from the cell stack at 50 A. The voltage is recorded versus time at 2 s intervals. The result is shown as



**Fig. 10.** Pulse power performance of the 1 kW  $\text{NaBH}_4/\text{H}_2\text{O}_2$  fuel cell stack.

Fig. 10. The 5-s pulse output is roughly 1350 W and the 10-s is nearly 1200 W.

The concentration of  $\text{NaBH}_4$  can be as high as 35 wt% stabilized with alkalis alone. It can be further increased, up to 50% when stabilized with ammonium hydroxide. Although the presence of ammonium may pose a problem for the consumer market, it is not a limiting factor for specific niche applications, such as space and underwater. The real (electrical) energy density, of the  $\text{NaBH}_4/\text{H}_2\text{O}_2$  fuel cell can therefore reach as high as  $600 \text{ Wh kg}^{-1}$  at a current density of  $200 \text{ mA cm}^{-2}$ . The above number should be understood in the context of a large FC system where the major fraction of the overall system mass is the stored reactant. If highly concentrated fuel such as 85% high test peroxide (HTP) is used, will be around  $1000 \text{ Wh kg}^{-1}$ .

### 3.4. FDN for other fuel cells

The procedure outlined here with the specific case of  $\text{NaBH}_4/\text{H}_2\text{O}_2$  FC can be adapted to other FC stacks. It is well known that corrosion is still an issue for lifetime of a  $\text{H}_2/\text{O}_2$  cell stack [13]. Even 316 l stainless steel parts have excess corrosion in a stack. The authors believe that such corrosion is at least partly attributed to the design of the manifold. DMFC has a similar problem where even the noble metal catalysts cannot last long [14,15]. One key to address such issues could be, as the authors believe, to make the manifold electrically insulate, under a variety of operational conditions.

## 4. Conclusion

To the best of the authors' knowledge, the research reported here on  $\text{NaBH}_4/\text{H}_2\text{O}_2$  FC produced the first all liquid-type fuel cell stack in the kilowatt range. The studies also predicted and partly solved the complicated manifold issue caused by the conductivity of the liquid fuel. Because the current shunting and corrosion problems can be caused by other liquid fuels or liquid reaction products, for

example alcohols and water, the analyses and solutions outlined here are not limited to direct borohydride fuel cells. The same principle should also help improve stack performance and lifetime in other types of fuel cell.

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