

Sodium borohydride based hybrid power system

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Abstract

Sodium borohydride's properties make it a good source of hydrogen for use with a fuel cell for an on-demand system that is easily controllable and has no idle costs. Previous work, as described in the literature, indicated that ruthenium (Ru) is an efficient catalyst for generating hydrogen from sodium borohydride. Tests were conducted to evaluate catalyst loading with the results of these tests indicating that the hydrolysis rate is affected by the loading of the catalyst. It was also apparent that the substrate surface is not completely occupied by Ru at the lower loadings, and that increased loadings are needed to optimize the reaction rate. A differential rate test with a fixed bed reactor was also conducted. It was observed that temperature has a significant effect on the rate of reaction. Feed rate also affected the rate of reaction with lower feed rates (longer residence time in the reactor) having higher reaction rates. A bench-top hybrid system was also developed and tested. This test bed demonstrated how a system based on a chemically generated hydrogen-fed proton exchange membrane fuel cell could be integrated with batteries to provide a hybrid power system that can meet the demands of a highly varying electrical load up to four times the rated output of the fuel cell.

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1. Background

While convenience of disposable or rechargeable batteries is sufficient for many applications, the energy density of batteries can be problematic for portable power applications. Although there is a significant amount of research and development being focused on fuel cells, which holds much promise, significant issues remain with respect to the fuel source. Hydrogen storage using pressurized tanks is not practical for many applications due to the low storage density and the high pressures. Reforming hydrocarbon fuels into hydrogen is likewise not practical for many applications. Chemical storage/extraction also suffers from low storage densities. The properties of sodium borohydride (NaBH_4), however,

which is primarily used as a reductant in the synthesis of organic chemical compounds and as a bleaching agent in the manufacture of paper, make it an interesting alternative for hydrogen storage for portable fuel cell applications.

In the late 1930s and early 1940s researchers at the University of Chicago produced a number of new borohydride compounds, including aluminum borohydride [1,2], beryllium borohydride [3], lithium borohydride [4], and gallium borohydride [5]. Having obtained these new volatile compounds, they were requested to investigate new volatile uranium compounds in support of the war effort. As a result, uranium borohydride [6,7] was successfully synthesized as a potential alternative to uranium hexafluoride. Other new compounds, including sodium borohydride, were discovered in an effort to produce uranium borohydride in quantity. The urgency to produce large quantities of uranium borohydride subsided when issues concerning uranium hexafluoride were overcome. Although much of the team's work on uranium and sodium borohydrides was not published until well after

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the war was over, the Army Signal Corps became interested in sodium borohydride [6,8] as a potential source of field-generated hydrogen [9–11] for signal balloons, and various researchers investigated it as a potential propellant for rocket engines [11].

In their work on sodium borohydride, Schlesinger et al. investigated the solubility [8] and hydrolysis [9] of sodium borohydride. Their studies showed that the aqueous solutions of the compound at nominal temperatures resulted in a rapid release of a small amount of hydrogen, with the rate slowing as the pH increased due to the increased presence of the borate ion [9].

They also showed that complete hydrolysis could be achieved rapidly by the addition of acid to the solution (acid catalysis) [9]. A number of catalysts were tested and found to accelerate the hydrolysis reaction as well, with cobalt chloride the most effective of those tested. Considerable foaming of the by-product was noted as a potential problem.

Properties of sodium borohydride have been addressed by a number of researchers. Davis et al. determined the heat of formation by first determining the specific heat, density, and heat of reaction when reacted with excess dilute hydrochloric acid [12]. Johnston and Hallett measured the heat capacity of sodium borohydride, as well as calculated the entropy and enthalpy from 15 to 300 K [13]. Stockmayer et al. determined the standard free energy of formation for the aqueous borohydride ion as well as an estimate for the standard entropy for the ion [14]. The heat of solution of sodium borohydride was measured and the heat of formation and the entropy derived by Gunn and Green [15].

As mentioned previously, Schlesinger and Brown demonstrated acid catalysis of the hydrolysis reaction of aqueous sodium borohydride. Other researchers have investigated the kinetics of this acid catalysis [16–19], showing that the hydrolysis was first order with respect to the hydronium and borohydride ions. A kinetic scheme consisting of two pseudo-first-order reactions in the series was suggested to interpret the data [18].

Schlesinger's early work on sodium borohydride investigated the effects of several catalysts on the hydrolysis reaction. In that work it was shown that of the catalysts investigated, that iron, cobalt, and nickel salts were most effective [9]. Brown and Brown investigated the use of platinum family metal salts as well as nickel and cobalt. Aqueous solutions of the metal salts with aqueous sodium borohydride produced a precipitate that was an extremely active catalyst for the hydrolysis reaction and proved to be significantly more effective than metals investigated by Schlesinger [20]. Ruthenium (Ru) and rhodium showed the most effectiveness.

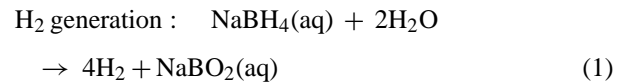
Amendola et al. investigated the hydrolysis reaction using Ru catalysts [21]. They looked at the effects of varying sodium borohydride and sodium hydroxide concentrations, as well as temperature on reaction rates. Amendola observed zero-order kinetics with respect to a given temperature and suggested that diffusion-controlled first-order kinetics dominate where catalyst sites were not totally occupied (i.e., low

NaBH₄ or high catalyst weights) [22]. They also tested prototype generators including both a batch type (similar to a Kipp generator) and a tubular flow type generator [21].

2. Approach

From this body of previous research, it is apparent that sodium borohydride has a number of properties that potentially makes it an excellent source of hydrogen. These properties are:

1. Sodium borohydride reacts spontaneously with water to generate hydrogen according to the reaction:



The overall reaction occurs at a moderate rate initially, quickly slows, and then ceases as the concentration of the basic borate ion in the aqueous product solution increases.

2. The reaction rate is a function of pH. The rate can be increased by the addition of acid to the system to counter the base effect of the borate ion or the rate can be suppressed by raising the pH.
3. The rate of the reaction and the extent to which the reactants are converted to products can be increased significantly in the presence of catalysts. A number of catalysts have been investigated with Ru found to be the most effective for promoting hydrogen generation.
4. As indicated by the stoichiometry in Eq. (1), the hydrolysis reaction derives half of the product's hydrogen from solution water, effectively doubling the storage density of the hydride. In a 20 wt % solution, the storage density of hydrogen is about 4.3 wt %.

Sodium borohydride-generated hydrogen can be readily coupled with a fuel cell or a hydrogen internal combustion engine. The approach addressed here involves hydrogen generated from sodium borohydride for use in a fuel cell. A hybrid approach with the fuel cell providing energy needs and peak power transients handled by an electrical storage element has been investigated. While our studies have focused on a system on the order of 500 W, this approach could be scaled up (to tens of kilowatts) or down (to tens of watts) as appropriate.

Fig. 1 shows a block diagram for a power system based on this approach. The basic power system is indicated by the dashed red line.

3. System description

The majority of previous work on the hydrolysis reaction utilized batch reactions and reactors, with the notable exception of a portion of the work of Amendola. The approach taken here is based on a flow reactor for continuous generation

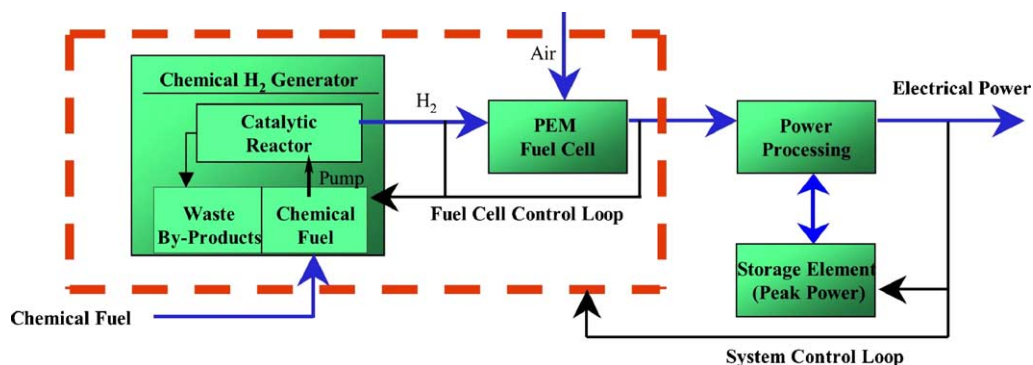


Fig. 1. Power system block diagram. Power system is based on a fuel cell using chemically generated hydrogen to meet steady-state loads and a storage element to meet peak loads.

of hydrogen. A fixed bed reactor with sodium borohydride fed through a catalyst bed provides a simple approach for a continuous, controllable system.

A schematic of a reactor is shown in Fig. 2. The reactor consists of a hollow tube with top and bottom end caps, and screens to contain the catalyst material. The feed solution is pumped through the reactor. Upon contact with the catalyst, the hydrolysis reaction is initiated resulting in the generation of both the hydrogen gas and the reaction by-products. The quantity of catalyst, the feed rate, and the feed solution concentration are all key parameters in the reactor operation, and are discussed in more detail below.

In such a system the power demand provides the feedback to control the feed rate of the sodium borohydride solution (Fig. 1) with a key advantage that there are no significant idle costs. When demand goes to zero, the pump is simply shut down and the production of hydrogen and electric power stopped, thus increasing overall system efficiency. Based on previous work on catalysts, Ru was selected, with different catalyst loading and substrates investigated.

The concentration of the sodium borohydride solution is another key parameter. The solubility of NaBH₄ in water is approximately 35 wt % at 23 °C [23]. While higher concentrations increase the specific energy, this type of reactor can be susceptible to clogging with reaction by-product. Our testing had indicated that concentrations greater than 25 wt % showed a greater propensity for clogging, leading us to focus on concentrations in the 20–25 wt % range. At a concentra-

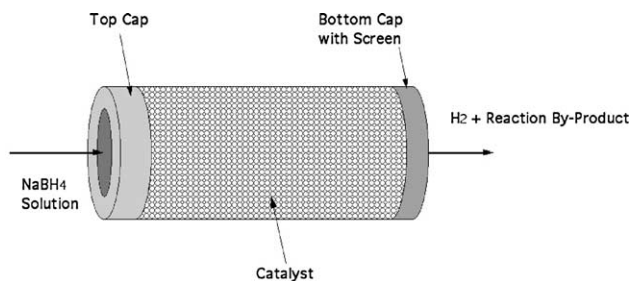


Fig. 2. Schematic representation of the fixed bed reactor. Sodium borohydride solution is fed through the catalyst bed providing a simple approach for a continuous, controllable system.



Fig. 3. Glass fixed bed reactor. The reactor allows the visualization of the catalytic reaction. As the sodium borohydride solution enters the catalyst bed and begins to react, H₂ is generated along with the sodium borate reaction by-product, visible in the left most quarter of the reactor.



Fig. 4. Tubular H₂ generator. Stainless steel tubular generator is shown with the pump. Hydrogen and the reaction by-products exit through the bottom.



Fig. 5. Horizontal H₂ generator. The reactor, which is coiled in the lid is shown with pump, pressure sensor, and the by-product catch vessel.

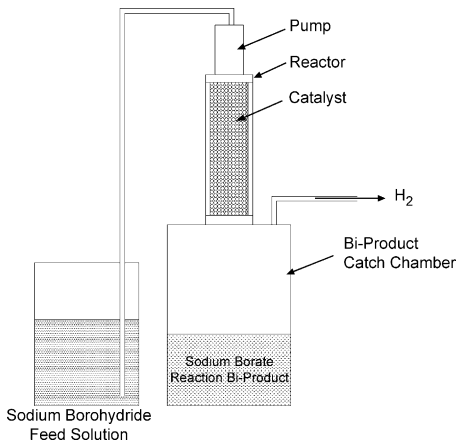


Fig. 6. Schematic representation of the reactor test. The schematic shows the test setup employed for each reactor. Pressure sensors and pressure relief valves are not shown in the schematic.

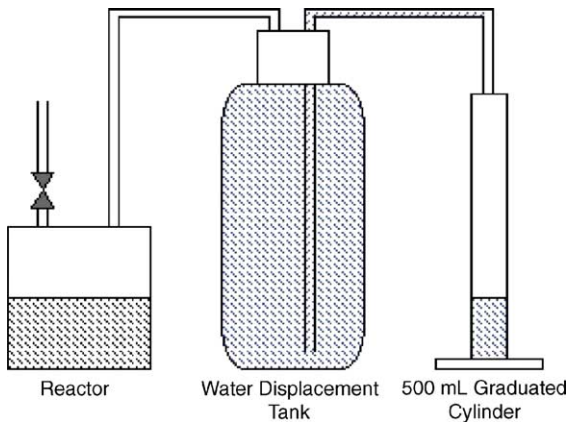


Fig. 7. Experiment configuration. The configuration was used to measure the quantity of hydrogen generated from a batch reactor containing sodium borohydride and catalyst using water displacement.

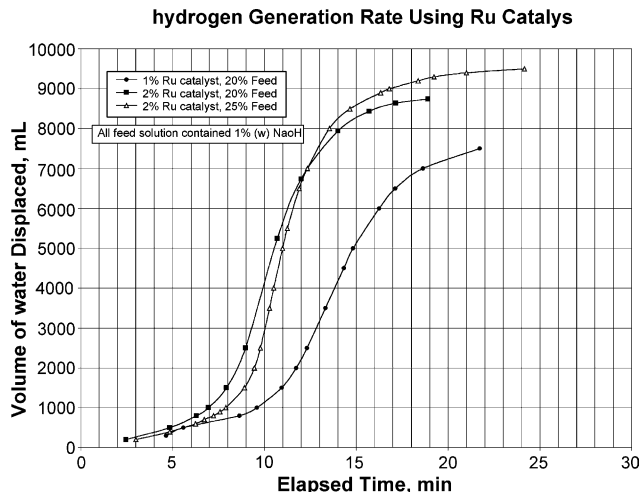


Fig. 8. Hydrogen generation reaction rates. Measured from experimental setup shown in Fig. 7.

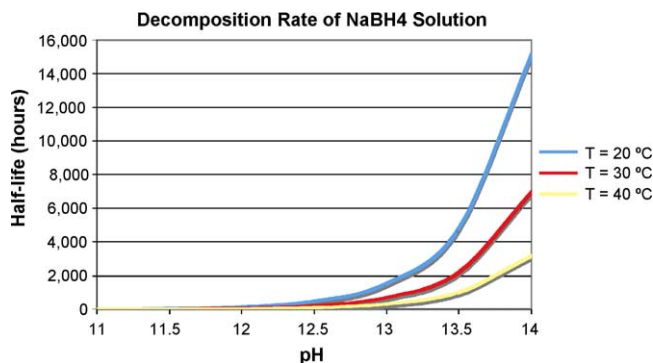


Fig. 9. Sodium borohydride decomposition rate. The half-life in h for a sodium borohydride solution is shown as a function of pH. As can be seen, increasing the pH by adding sodium hydroxide can have a dramatic effect on the shelf-life of sodium borohydride solution.

tion of 25 wt %, the effective weight percentage of hydrogen from NaBH₄ in the feed solution is 2.6 wt %, as opposed to 10.5 wt % in pure, undissolved NaBH₄. As indicated by the stoichiometry in Eq. (1), the hydrolysis reaction derives half

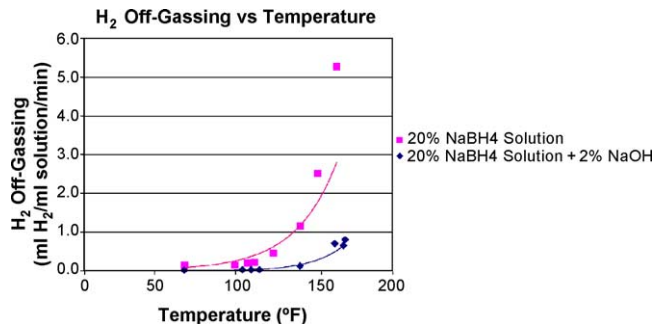


Fig. 10. Hydrogen off-gassing test data. H₂ off-gassing from sodium borohydride solution was measured at temperatures between 50 and 170 °F. The quantity of hydrogen generated was measured using the water displacement method. The addition of 2 wt % sodium hydroxide significantly reduced the quantity of hydrogen generated.

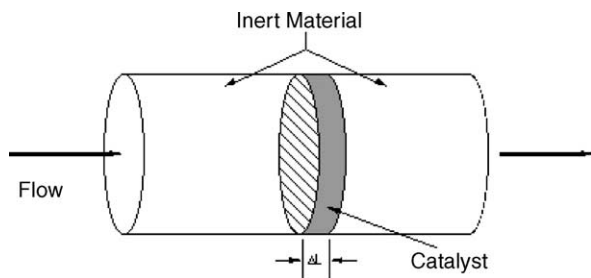


Fig. 11. Differential reactor schematic. The reactor consists of inert material with a thin layer of catalyst and can be used to determine the reaction rate per unit catalyst.



Fig. 12. Differential reactor. Shown with by-product catch vessel, pump and pressure sensor.

of the product's hydrogen from solution water, effectively doubling the storage density of the hydride. Taking into account hydrogen generation contributions from both NaBH_4 and the feed solution water, the effective maximum hydrogen storage density of the feed solution is about 5.2 wt %,

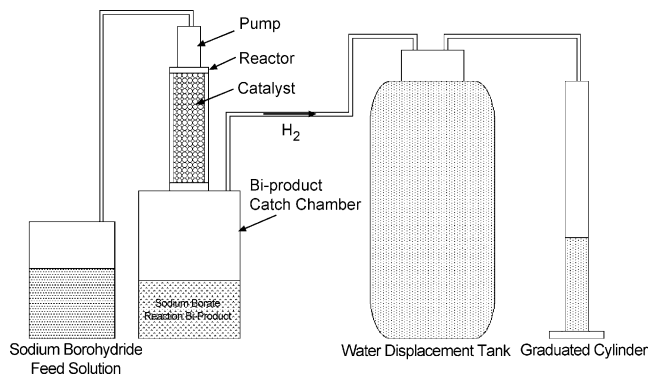


Fig. 13. Differential reactor test setup for measuring hydrogen generated using water displacement.

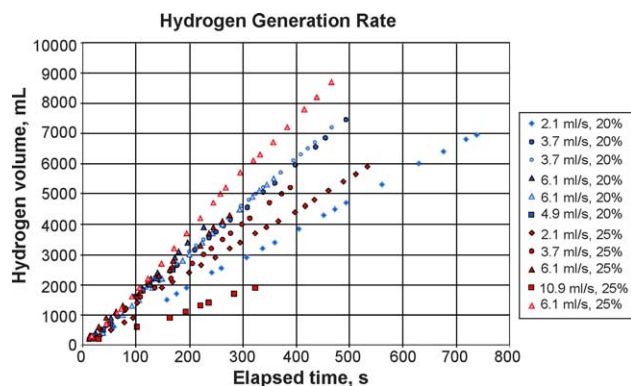


Fig. 14. Raw rate data with no thermal control. Data measured using differential reactor for feed solution concentrations of 20 and 25% at feed rates between 2.1 and 10.9 ml min^{-1} .

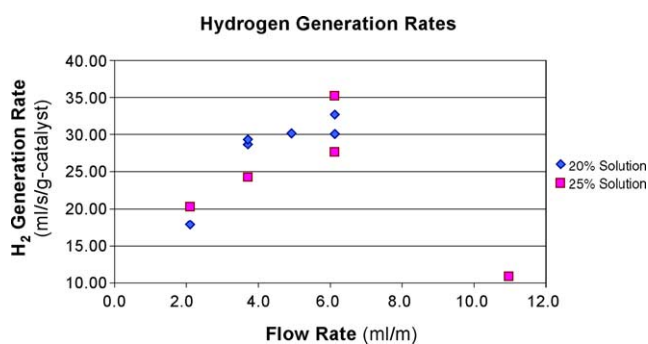


Fig. 15. Hydrogen generation rates for data obtained from differential reactor for feed solutions concentrations of 20 and 25% at feed rates between 2.1 and 10.9 ml min^{-1} with no thermal controls (raw data shown in Fig. 13).

which corresponds to a specific energy of 1.7 kWh kg^{-1} . For comparison purposes, the U.S. Department of Energy has set target goals for hydrogen storage for fuel cell applications of 6 wt % and 2 kWh kg^{-1} .

A series of reactors have been used to study this approach. All of these reactors, while somewhat different, are similar to that shown in Fig. 2. A glass reactor was used to allow visualization of the reaction process and the transport of the

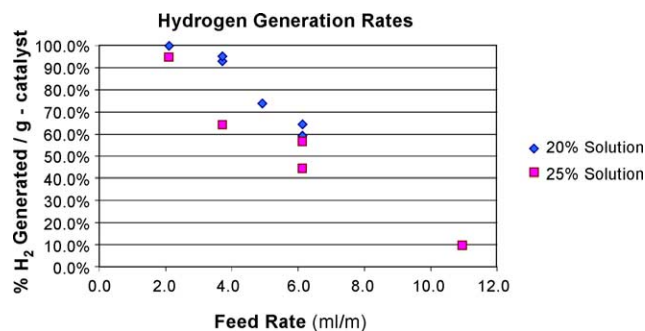


Fig. 16. Rate data showing the percent of H_2 actually converted, compared to the theoretical maximum, and normalized/g of catalyst. Data obtained from differential reactor for feed solutions concentrations of 20 and 25% at feed rates between 2.1 and 10.9 ml min^{-1} with no thermal controls (raw data shown in Figs. 13 and 14).



Fig. 17. Bench-top hybrid power system. The system includes the fuel cell, hydrogen generation system, transient handler, controller, and light bank for load.

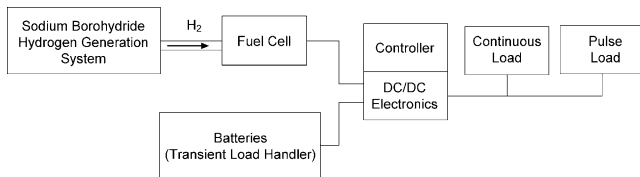


Fig. 18. Schematic representation of the bench-top hybrid power system, showing the fuel cell, hydrogen generation system, transient handler, controller, and simulated load.

reaction by-products out of the reactor. The glass reactor is shown in Fig. 3 after the introduction of the sodium borohydride solution. The reaction by-products are visible in the left third of the reactor.

Other reactors that have been fabricated and tested are shown in Figs. 4 and 5. Fig. 4 is a tubular stainless steel reactor similar to the glass reactor in Fig. 3. Fig. 5 shows a horizontal reactor built into the lid of the catch vessel.

For the different configurations tested, the systems included a pump, reactor, and a vessel to catch the reac-

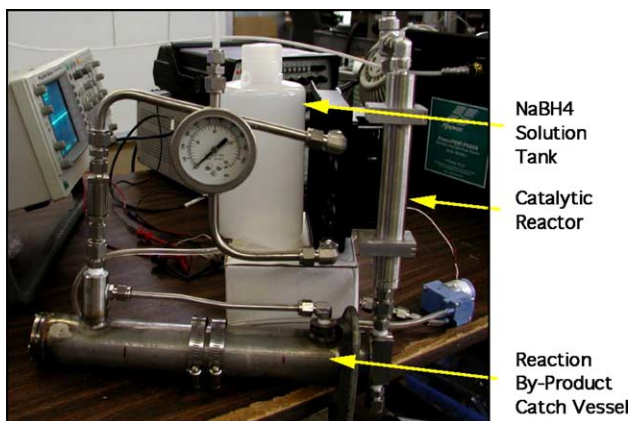


Fig. 19. Hydrogen generator for bench-top power system. Shown is the reactor, pump, and by-product catch vessel.

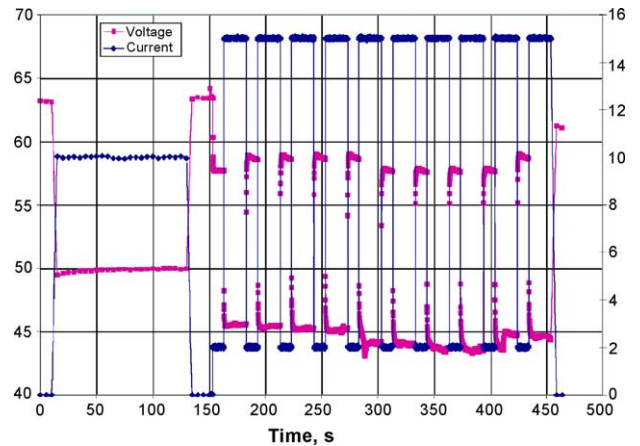


Fig. 20. Fuel cell test data. Simulated load was varied between 100 and 650 W. Nearly instantaneous transition between loads demonstrates excellent load following of the fuel cell.

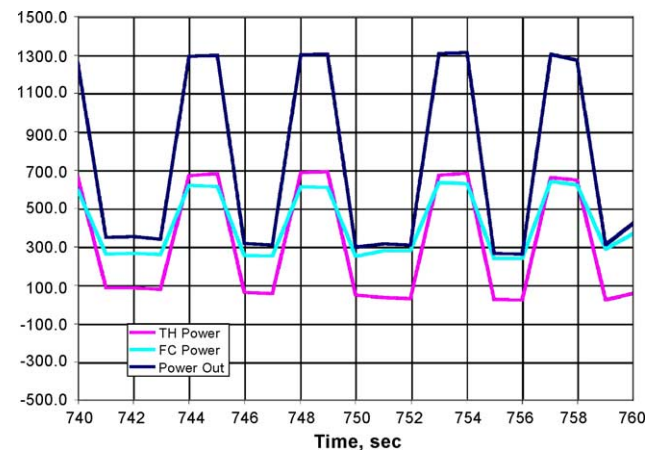


Fig. 21. Hybrid power system test data. The fuel cell provides steady-state power and the batteries provide power to meet pulses that exceed fuel cell capability. Power pulses of 1300 W are shown being met by both systems working together.

tion by-products (Fig. 6). Although, the target power output for the configurations tested was in the 200–500 W range, the approach is scalable for either larger or smaller capacities.

4. Experimental approach

Scoping tests were performed to evaluate the effects of Ru catalyst concentration and NaBH₄ feed concentration on the rate of hydrogen generation by NaBH₄ hydrolysis. The objective of the test was to determine if the rate of hydrogen generation is limited by the availability of hydrolysis sites on the catalyst or by the rate of diffusion of reactant to these reaction sites. The intent was to determine if operating hydrolysis systems using higher catalyst loadings was an effective means of increasing the hydrogen generation rate. The presumption is that, if the rate of hydrogen release in-

creases with higher Ru catalyst loadings but is not affected by reactant concentration, the rate of hydrogen generation is limited by the reaction at the catalyst surface. Conversely, if H₂ generation increases with higher reactant concentrations in the feed solution, but is unaffected by Ru loading, the rate is controlled by the rate of diffusion of the reactant to the catalyst surface.

Tests were performed under three sets of conditions. In the first test, the Ru loading on the carbon substrate was 1 wt % and the NaBH₄ concentration in the feed solution was 20 wt %. In the second test, the Ru loading was 2 wt % and the feed solution NaBH₄ concentration was 20 wt %. In the third test, the Ru catalyst loading was 2 wt % and the NaBH₄ concentration in the feed solution was 25 wt %. NaOH was added to the feed solution used in all tests to a concentration of 1 wt % to suppress uncatalyzed hydrolysis. The system was not preheated, and no attempt was made to control the temperature of the experimental system during testing, as we were looking for relative differences in reaction rates.

The test configuration used is shown in Fig. 7. In each test, the feed solution was added to a stirred vessel containing catalyst chips and the mass of catalyst present in the reactor was 0.5 g. At the start of each test, 20 ml of feed solution were introduced to the reaction chamber through a valved feed tube. The feed tube was valved closed immediately after the solution was delivered. The solution and catalyst were agitated continuously using a magnetically-driven stirring bar. The volume of gas evolved was measured in terms of the volume of water displaced from a tank that was connected to the reactor outlet.

The results of the test are presented in Fig. 8. Under each test condition the rate of gas generation increased after an initially slow rate of evolution. The low initial rate reflects two aspects of the test system. First, the initial gas generated had to pressurize the system sufficiently for water to be displaced and collected. Second, the rate of the reaction increased after initiation as the temperature of the system increased due to the exothermic nature of the reaction.

Significant differences are apparent in the rate of hydrogen generation as a function of catalyst loading. At the 1 wt % Ru, 20 wt % NaBH₄ condition the maximum rate of generation was approximately 11 min⁻¹, occurring between 13 and 14 min after introduction of the feed. At the 2 wt % Ru, 20 wt % NaBH₄ condition the maximum rate is approximately 21 min⁻¹, occurring between 10 and 11 min after introduction of the feed. Other than a slight offset, little difference is apparent in results obtained at different feed concentrations when the catalyst loading was unchanged.

The results of the test indicate that the hydrolysis rate is affected by the loading of the catalyst. Since the same mass of catalyst was used in all three tests, and since the substrate surface areas should be approximately equal, it is also apparent that the substrate surface is not completely occupied by Ru at the lower (1 wt %) loading, and that increased loadings are needed to optimize the reaction rate.

4.1. Off-gassing

Spontaneous hydrolysis of sodium borohydride solution occurs over time, with the rate dependent on concentration, pH, and temperature. The hydrolysis in water causes a rise in the pH, decreasing the rate of decomposition. Typically sodium hydroxide is added to increase the pH and slow the hydrolysis. The rate of decomposition can be estimated by

$$\log_{10} t_{1/2} (\text{min}) = \text{pH} - (0.034T - 1.92) \quad (2)$$

where $t_{1/2}$ is the half-life in minutes and T the temperature (K) [23]. Fig. 9 shows the half-life in hours versus pH for solution at various temperatures. As can be seen, increasing the pH makes a significant difference in the “shelf-life” of sodium borohydride solution.

A test to observe the effects of temperature and the suppression of the reaction with increased pH was conducted and the results are illustrated in Fig. 10. In this test, sodium borohydride solution was heated and the quantity of hydrogen generated measured. The test was conducted for solutions with and without sodium hydroxide. As can be seen, even 2 wt % sodium hydroxide has a significant effect on the amount of hydrogen spontaneously generated.

4.2. Differential reactor

A differential reactor (Fig. 11) can be used to determine the rate of reaction as a function of either concentration or partial pressure and consists of a tube containing a small amount of catalyst within a bed of inert material. Due to the small amount of catalyst and the comparatively large volumetric flow rates, the concentration is essentially constant and the reaction rate uniform within the bed. The rate of reaction is typically determined per unit mass of catalyst as a function of reactant concentration [24]. Given a target rate of reaction, the amount of catalyst required to obtain that rate can be determined. The rate can also be determined as a function of the reactant feed rate.

To provide input for the design of a fixed bed reactor, a series of differential reactor experiments were conducted. Initial tests were conducted at ambient temperature without thermal regulation. A small amount of catalyst, ~0.5 g, occupying a relatively small percentage of the 4 in. long × 1 in. diameter tube, was used. The goal was to minimize the amount of reaction taking place in order to conduct the experiment in as near isothermal conditions as possible. The remainder of the reactor was filled with inert glass beads. Reactant was fed into the differential reactor at a constant rate and the quantity of hydrogen generated determined by measuring displaced water. The reactor is shown in Fig. 12 and the experimental setup in Fig. 13. Data was collected for two concentrations of feed solution, 20 and 25 wt %, at multiple flow rates.

Fig. 14 shows the raw data collected for both feed solutions. The near constant reaction rate for each test condition

and the variation with respect to feed rate are clearly visible. Fig. 15 shows the gas production rates for each of the conditions tested, with test results normalized per gram of catalyst. The most striking result is the significant decrease in the H₂ generation rate for the highest feed rate, $\sim 11 \text{ ml min}^{-1}$.

In Fig. 16 the same data is presented in a slightly different manner. The percentage of H₂ generated with respect to the theoretical maximum (Eq. (2)) is normalized with respect to the amount of catalyst and plotted versus the feed rate. As noted previously, normalizing with respect to the quantity of catalyst is typical for differential reactors. From this plot, it is apparent that as the feed rate increased, the percentage of H₂ conversion decreased. Two mechanisms could lead to this effect. First, heating effects at the slower feed rates could result in increased temperature and a higher conversion rate. Thus, at the higher feed rates the increased flow removed the heat generated by the reaction, negating any increased reaction rate due to increased temperature. (Levy showed that increased temperature has a significant effect on the reaction rate, up to a 50% increase per 5 °C [25].) Second, the increased flow could limit the amount of feed exposed to the catalyst, thereby limiting the reaction.

The results shown in Fig. 16 can provide insight into the design of future reactors. The data, as shown, gives an indication of the amount of catalyst required at a given feed rate to convert the available hydrogen from the feed solution, as described in Eq. (2). For example, at a feed rate of 2 ml min^{-1} , the data implies that full conversion (100% of theoretical maximum) could be expected with a gram of catalyst. Likewise, at a flow rate of 6 ml min^{-1} of 20 wt % solution, a conversion rate of >60% of the theoretical maximum could be anticipated per gram of catalyst. Increasing the quantity of catalyst would be required for full conversion. These results should allow for designing future reactors that convert all of the hydrogen while minimizing the amount of catalyst required. Using the minimum amount of catalyst for a given feed rate will have the benefit of reducing the risk of reactor clogging.

5. Sample application

A sample application is the bench-top hybrid power system developed and tested in conjunction with AeroVironment, Inc. The purpose of this system was to demonstrate the ability of a hybrid power supply system based upon a fuel cell for steady-state loads, chemical generated hydrogen for the fuel cell, and rechargeable batteries for transient demands, to meet the needs of a portable system with highly varying loads. To achieve this objective, the target was to be able to handle peak transient loads equal to about four times the nominal steady-state capability of the fuel cell.

The system configuration consisted of four primary elements, a fuel cell, rechargeable batteries to handle peak loads, chemically generated hydrogen, and a system controller (Figs. 17 and 18). The fuel cell was a commercially

available PEM H-Power fuel cell that was nominally rated at 500 W of continuous power from 42 to 60 V. The transient handling system consisted of commercially available nickel-metal-hydride batteries that provided pulse power up to 1.5 kW at 42 V.

The controller, which monitors currents, voltages, the transient handler state of charge, as well as other parameters, maintains the state of charge of the transient handler between 20 and 80%. When a pulse load in excess of the capability of the fuel cell system is sensed, power from the transient handlers is made available to make up the shortfall, thus drawing power from the transient handler system and fuel cell system in parallel. When the pulse load subsides, the fuel cell system handles the entire load and the batteries' state of charge is assessed to determine if power from the fuel cell is needed to recharge the batteries. Through the repeating of this cycle, the fuel cell always operates at rated power as the system controller regulates the transient handler voltage to avoid battery damage and to maintain a high state of charge.

Hydrogen for the fuel cell was chemically generated using sodium borohydride in a catalytic reactor as previously described. The hydrogen generation system, shown in Fig. 19, consisted of a catalytic reactor, pump, feed solution vessel, by-product catch vessel, and a heat exchanger for cooling the hydrogen gas prior to entry into the fuel cell. The system was self-regulating in that the feed pump stalled, regardless of flow rate, as the pressure increased to a pressure between 15 and 25 psig. As the fuel cell consumed the hydrogen and the pressure dropped, the pump would resume pumping until it stalled again. To evaluate the load following capability of the fuel cell system, a simulated load was varied between 100 and 650 W in a series of steps (Fig. 20). The transition between the loads is nearly instantaneous, demonstrating excellent load following capabilities.

The system was also tested with a 150 W continuous load and transient loads of up to 1850 W with a bank of lights used to provide the load. Fig. 21 shows the fuel cell and transient handler working together to provide 1300 W of pulsed power.

This application successfully demonstrated that a fuel cell hybrid power supply is a viable option for supplying the power and energy needs for remote, portable, and mobile systems, including those with highly varying loads. Supplying a fuel cell with chemically generated hydrogen as a part of a hybrid power system was successfully demonstrated. Additionally, the ability to augment the fuel cell with an integrated power storage element that handles transient peak loads equal to several times the steady-state capability was also demonstrated. This effectively provided the capability to handle loads up to four times the rated output of the fuel cell while tracking highly varying power demands, with no idle cost. While demonstrated with a steady-state load of 500 W and a peak capability of 2 kW, this type of system is scalable over a wide range and could be applicable for systems requiring a few watts to systems requiring 100 kW.

6. Summary

The properties of sodium borohydride make it a potentially good source for providing hydrogen for use with a fuel cell for certain applications. It lends itself to use in an on-demand system that is easily controllable and has no idle costs, thereby increasing efficiency. Previous work, as described in the literature indicated that Ru is an efficient catalyst for the hydrolysis of sodium borohydride. Tests that were conducted with Ru catalysts on a carbon substrate indicated that the hydrolysis rate is affected by the loading of the catalyst and that the substrate surface is not completely occupied by Ru at the lower loadings, and that increased loadings are needed to optimize the reaction rate. A differential rate test with a fixed bed reactor was also conducted. It was observed that temperature has a significant effect on the rate of reaction. Feed rate also affected the rate of reaction with lower feed rates (longer residence time in the reactor) having higher reaction rates. The data obtained from this test can be used to provide a design basis for future reactors. A bench-top hybrid power system was also developed and tested. This system demonstrated chemically generated hydrogen fed to a fuel cell, integrated with rechargeable batteries providing a hybrid power system that can meet highly varying demands with loads up to four times the rated output. While this system was demonstrated with a specific capacity, it can be readily scaled to meet a wide range of system requirements.

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References

- [1] H.I. Schlesinger, R.T. Sanderson, A.B. Burg, *J. Am. Chem. Soc.* 61 (1939) 536.
- [2] H.I. Schlesinger, R.T. Sanderson, A.B. Burg, *J. Am. Chem. Soc.* 62 (1940) 3421–3424.
- [3] A.B. Burg, H.I. Schlesinger, *J. Am. Chem. Soc.* 62 (1940) 3425–3429.
- [4] H.I. Schlesinger, H.C. Brown, *J. Am. Chem. Soc.* 62 (1940) 3425–3429.
- [5] H.I. Schlesinger, H.C. Brown, G.W. Schaeffer, *J. Am. Chem. Soc.* 65 (1943) 1786–1787.
- [6] H.I. Schlesinger, et al., *J. Am. Chem. Soc.* 75 (1953) 186–190.
- [7] H.I. Schlesinger, H.C. Brown, *J. Am. Chem. Soc.* 75 (1953) 219–221.
- [8] H.I. Schlesinger, H.C. Brown, H.R. Hoekstra, L.R. Rapp, *J. Am. Chem. Soc.* 75 (1953) 199–204.
- [9] H.I. Schlesinger, et al., *J. Am. Chem. Soc.* 75 (1953) 215–219.
- [10] H.A. Beatty, U.S. Department of Commerce, PB-6330, 1944.
- [11] H.I. Schlesinger, Final Report to Signal Corps Ground Signal Agency on Contract No. W3434-SC-174, PB-6331, 1944.
- [12] W.D. Davis, L.S. Mason, G. Stegeman, *J. Am. Chem. Soc.* 71 (1949) 2775–2781.
- [13] H.L. Johnston, N.C. Hallett, *J. Am. Chem. Soc.* 75 (1953) 1407–1408.
- [14] W.H. Stockmayer, D.W. Rice, C.C. Stephenson, *J. Am. Chem. Soc.* 77 (1955) 1980–1983.
- [15] S.R. Gunn, L.G. Green, *J. Am. Chem. Soc.* 77 (1955) 6197–6198.
- [16] R.E. Davis, G.C. Swain, *J. Am. Chem. Soc.* 82 (1960) 5949–5950.
- [17] R.E. Davis, E. Bromels, C.L. Kibby, *J. Am. Chem. Soc.* 84 (1962) 885–892.
- [18] J.A. Gardiner, J.W. Collat, *J. Am. Chem. Soc.* 87 (1965) 1692–1700.
- [19] W.H. Stockmayer, R.R. Miller, R.J. Zeto, *J. Phys. Chem.* 65 (1961) 1076–1077.
- [20] H.C. Brown, C.A. Brown, *J. Am. Chem. Soc.* 84 (1962) 1493–1494.
- [21] S.C. Amendola, et al., *Int. J. Hydrogen Energy* 25 (2000) 969–975.
- [22] S.C. Amendola, et al., *J. Power Sources* 85 (2000) 186–189.
- [23] Sodium Borohydride Digest, Morton International Inc., 1995.
- [24] H.S. Fogler, *Elements of Chemical Reaction Engineering*, Prentice-Hall, New Jersey, 1999.
- [25] A. Levy, J.B. Brown, C.J. Lyons, *Ind. Eng. Chem.* 52 (1960) 211–214.