

Demonstration of a Compact Hydrogen Fuel Cell Power System for UAS Propulsion

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ABSTRACT

We have assembled and demonstrated a prototype power system that uses an innovative hydrogen generator to fuel an ultra-compact PEM fuel cell that is suitable for use in small unmanned aerial system (UAS) propulsion systems. The hydrogen generator uses thermal decomposition of ammonia borane (AB) to produce hydrogen from a very compact and lightweight package. An array of AB fuel pellets inside a low pressure container is activated sequentially to produce hydrogen on demand as it is consumed by the fuel cell. The fuel cell plant utilized in the power system prototype has been flown as part of several small UAS development programs and has logged hundreds of hours of flight time. The plant was designed specifically to be readily integrated with a range of hydrogen fueling subsystems and contains the balance of plant necessary to facilitate stand-alone operation. Based on results of these tests, we produced a conceptual design for a flight system. We project overall gravimetric and volumetric power densities of 350 W hr/L and 600 W hr/kg.

CITATION: Izenson, M., Bieszczad, J., Magari, P., and Sisco, J., "Demonstration of a Compact Hydrogen Fuel Cell Power System for UAS Propulsion," *SAE Int. J. Aerosp.* 7(1):2014, doi:10.4271/2014-01-2223.

INTRODUCTION

Small, air-launched unmanned aerial systems present formidable design challenges for the propulsion system. Tube-launched systems are very small—standard launch tube diameters are only 6 to 8 in. These very small volumes combined with the need for flight times of several hours means that high power density and high energy density are both critical. Furthermore, the very challenging operational environment -- in which the aircraft is subject to extreme temperature, shock, and vibration -- limits the mechanical complexity. For these reasons, batteries have been the power source of choice for small UAS thanks to their high power density and overall simplicity. However, their relatively low energy density limits flight time.

Power requirements for these small aircraft were studied by Bishop et al. [1]. They identified a range of ground support missions for tube-launched small UAS and estimated the power needed to fulfill these missions. They found cruise power requirements in the range 150 to 400 W with peak power demand in the range 230 to 844 W. Total energy storage requirements were in the range 50 to 350 W-hr, but larger values would enable longer-duration missions and significantly enhance aircraft performance.

This paper describes a fuel-cell propulsion system that promises to overcome the energy density limitations of battery systems while meeting the operational requirements for service on small UAS. The system comprises a compact fuel cell with a very high density hydrogen generator ([Figure 1](#)). The hydrogen generator is an all-solid-state system that produces hydrogen gas through rapid heating of ammonia borane (AB). The hydrogen powers a fuel cell, which produces electricity to continuously charge a hybrid battery. In this configuration the fuel cell can run at essentially steady state while the battery can accommodate rapid changes in power demand.

In an earlier paper [2], we presented initial results from a program to develop the AB hydrogen generator and integrate it with a PEM fuel cell. That paper presented results from early development of the AB fuel pellets, preliminary tests of an AB hydrogen generator, and results from an initial trial with a PEM fuel cell. This paper presents new results showing considerable improvements in the intrinsic hydrogen storage density of the AB fuel pellets (over 10 wt% hydrogen), data from a one-hour demonstration of a prototype hydrogen generator, and results from tests under representative power loadings that combined the AB hydrogen generator with a PEM fuel cell design for small UAS. Based on these data, we have projected our

hydrogen generator design for future small UAS applications and predicted the power and energy densities that should be possible.

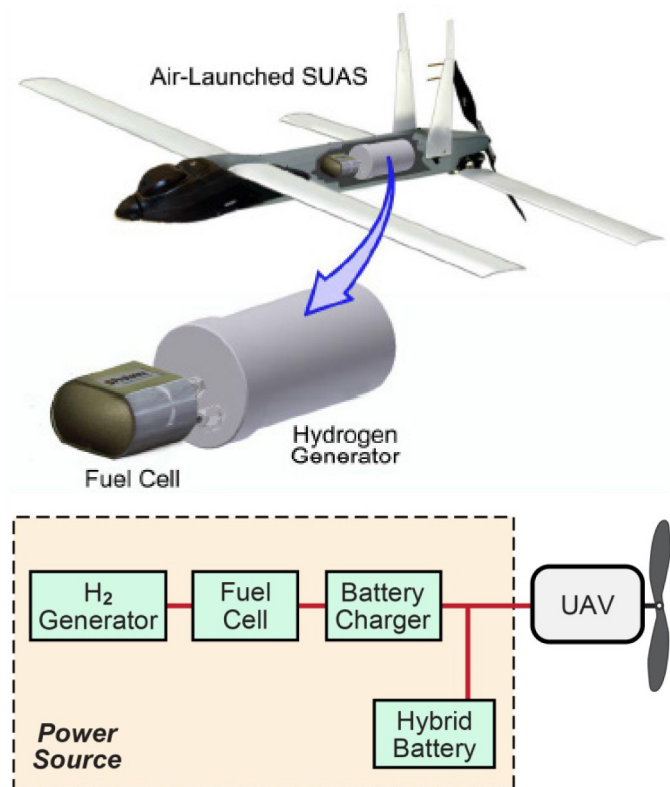


Figure 1. Fuel cell power system concept for small UAS.

SMALL UAS POWER SYSTEM COMPONENTS

The small UAS power system has two major components: the hydrogen generator and the PEM fuel cell. The hydrogen generator uses an innovative ignition and control scheme to enable high hydrogen yield from a very compact package. The fuel cell incorporates advanced stack and balance-of-plant components to achieve very high energy density.

Hydrogen Generation from Ammonia Borane

Ammonia borane (H_3NBH_3) is naturally rich in hydrogen. When heated, AB decomposes to form a solid residue and release up to 2 moles H_2 per mole of AB, resulting in an intrinsic hydrogen storage density of 0.13 g H_2 /g AB. Decomposition begins at relatively low temperature (roughly 90°C), but the rate and extent of reaction increase with higher temperatures. Since the decomposition reaction is exothermic, a hydrogen generator based on thermal decomposition must be designed to control ignition and avoid a chain reaction.

The AB hydrogen generator comprises an array of fuel pellets (Figure 2) stored in a small vessel. Each fuel pellet is made from AB pressed around a small pyrotechnic heat source.

Figure 3 illustrates the basic concept for the hydrogen generator. The hydrogen pressure in the vessel gradually drops as hydrogen flows to the fuel cell (step 1 in the figure).

The generator's control system includes a pressure transducer that monitors this pressure. When the pressure falls to the generator's minimum operating pressure (10 psig in this example), the control system activates the next fuel pellet in the array (step 2 in the figure). A small current pulse ignites the pyrotechnic element (2a), which heats the AB and releases hydrogen (2b). The newly released hydrogen re-pressurizes the vessel (step 3) so it can continue to supply hydrogen to the fuel cell. This process continues until all the fuel pellets are consumed.

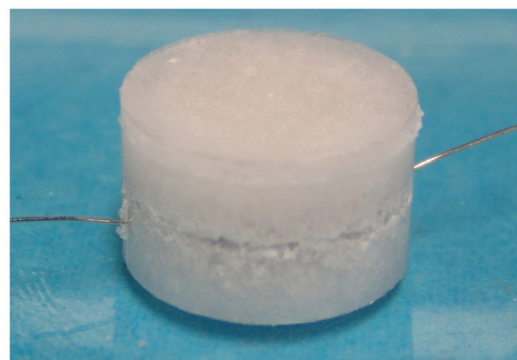


Figure 2. AB fuel pellet. The 1.4 g pellet provides 2 W-hr worth of hydrogen for a typical PEM fuel cell.

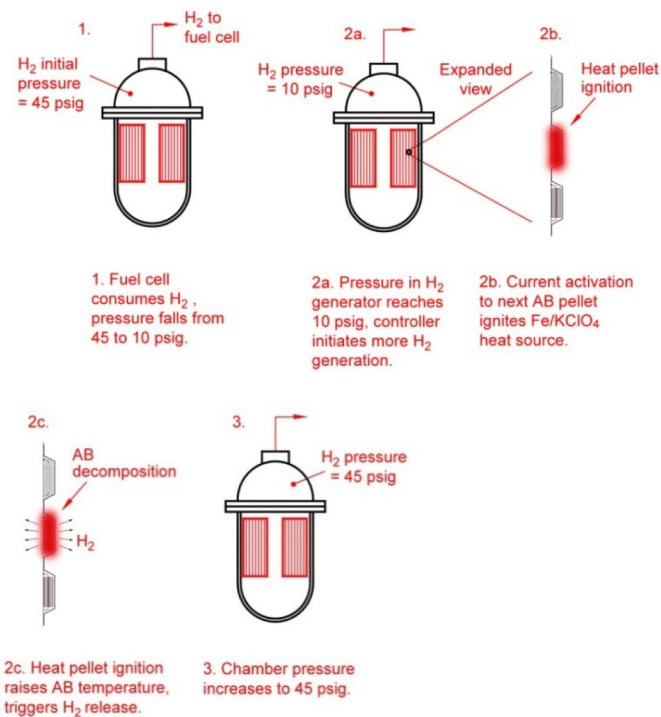


Figure 3. Concept for AB hydrogen generator.

The AB technology is capable of achieving very high overall hydrogen densities -- up to 5% by weight and up to 21 g H_2 /L of volume. The reasons for this high energy density are:

1. The fuel pellets themselves have intrinsically high energy density. We will show later that each fuel pellet can exceed 10 wt% H_2 .

2. Because the hydrogen is released only as needed, the vessel does not need to be designed to withstand high pressures. As a result, the vessel itself can be very lightweight.
3. Because the heat pellets provide very high temperatures for decomposition, the hydrogen produced in this process has low levels of impurity and the additional mass needed to purify the hydrogen is small.

Compact PEM Fuel Cell System

The compact PEM fuel cell plant utilized in the power system prototype was developed by Protonex specifically for small UAS. The plant found initial application in the Naval Research Laboratory's (NRL) Ion Tiger UAS [3], which is still being flown, and later in the NRL's XFC UAS [4]; both of these platforms utilize a compressed hydrogen fuel source. The system has demonstrated consistent performance during numerous flight tests, some as long as 48 hours [3], and many of the plants delivered have seen hundreds of hours of total operational time.

The plant was designed specifically to be readily integrated with a range of hydrogen fueling subsystems and is a natural fit for the present feasibility study. The system, shown in Figure 4, includes the balance of plant necessary to facilitate stand-alone operation and includes air, fuel, and coolant control systems. The system is capable of providing 200 W of continuous power with maximum power capability exceeding 550 W.

Hydrogen is nominally supplied to the plant's fuel cell stack in a dead-headed configuration. Through proprietary hydrogen flow management techniques the system is capable of achieving up to 99% hydrogen utilization efficiency. Any fuel supply subsystem integrated with the plant must be capable of providing a constant hydrogen supply pressure under a defined range of continuous and pulse flow conditions. The plant's range of pressure and flow requirements have provided a foundation upon which to design the hydrogen generator prototype.

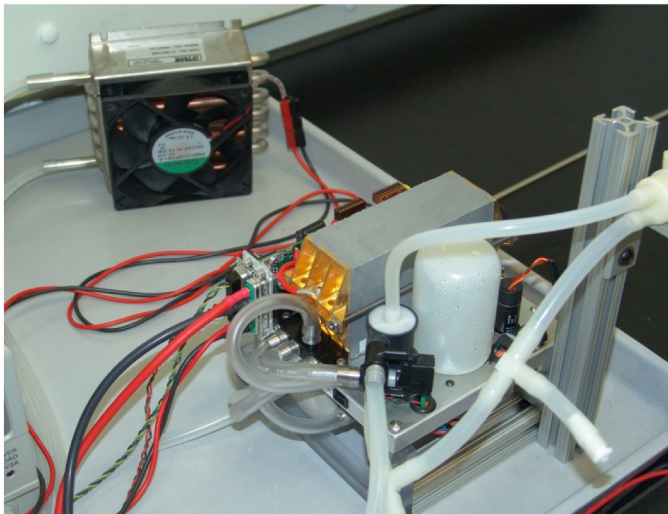


Figure 4. Hardware for demonstration testing.

HYDROGEN GENERATOR PROTOTYPE DEMONSTRATIONS

Prototype demonstration to date has had three primary technical objectives:

1. Increasing the hydrogen yield from individual fuel pellets.
2. Development of a control system that enables continuous H_2 production.
3. Packaging optimization to identify the best possible packing density of fuel pellets in the reactor vessel.

Improvements in Hydrogen Storage Density

We made significant improvements to the hydrogen density of individual fuel pellets. We assembled test fuel pellets with a range of design parameters, activated the test pellets in a small reaction vessel, and measured the amount of hydrogen produced. We were able to improve the specific hydrogen generation density by more than a factor of two compared to the initial design.

Test pellets differed in the heat pellet composition, heat pellet size and shape, and the overall size and shape of the AB pellet that surrounded the heat source. The general approach was to find the heat pellet composition that maximized hydrogen yield for a given pellet geometry. We then tested various heat and fuel pellet geometries while keeping the pellet composition fixed at that level. All the geometries we tested comprised a heat pellet disk embedded in a cylindrical AB pellet. We varied the thickness and diameters of both the heat pellet and the AB pellet. The fuel pellet shown in Figure 2 is the final design that we used for prototype demonstrations.

To run a test, we installed the test pellet in the vessel and filled the vessel with inert gas to the starting pressure. After igniting the pellet, we waited until the vessel reached thermal equilibrium and recorded the new pressure and temperature. The amount of hydrogen generated by each pellet was computed from the vessel's internal pressure and temperature before and after each test firing.

$$m_{H_2} = n_{H_2} M_{H_2} = M_{H_2} \left(\frac{p_f}{T_f} - \frac{p_i}{T_i} \right) \frac{V}{R_U} \quad (1)$$

Where: m_{H_2} is the mass of hydrogen generated by pellet (kg), M_{H_2} is the molecular weight of hydrogen (2.014 kg/kmol), n_{H_2} is the number of moles of hydrogen generated by the test pellet, p_i and p_f are the vessel pressures before and after the test, respectively (Pa), T_i and T_f are the vessel temperatures before and after the test, respectively (K), V is the volume of the test vessel (m^3), and R_U is the universal gas constant (8,314 J/kmol-K).

Figure 5 shows the results of this series of tests. The x-axis represents the heat pellet composition, and the y-axis is the ratio of hydrogen mass to the initial fuel pellet mass expressed