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Ultra-Compact Power System for Long-Endurance Small Unmanned Aerial Systems

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ABSTRACT

Air-Launched Small Unmanned Aerial Systems (SUASs) provide critical information to warfighters, but are currently limited by the power and energy available from small electric propulsion systems. This paper describes proof-of-concept testing of a novel power system for SUASs. The power system comprises a compact hydrogen generator and a hydrogen PEM fuel cell. The hydrogen generator uses ammonia borane (AB) as a solid chemical hydrogen storage material and heats the AB to produce hydrogen through thermal decomposition. The innovative ignition and control process generates highly pure hydrogen on-demand from a system that is very compact, lightweight, and rugged. We built a proof-of-concept hydrogen generator and used it to supply hydrogen to a small PEM fuel cell. The proof-of-concept generator used prototypical AB, heat source, control scheme, and purification media to absorb trace amounts of ammonia, borazine, and carbon monoxide (CO). The hydrogen generator operated as expected, producing hydrogen as needed to maintain the supply pressure within specified bounds. The fuel cell produced 4 A/8.6 V for 15 minutes, amounting to 8.6 W-hr of electricity. We measured the fuel cell's current/voltage characteristics before and after the test, and found no measurable change due to operation with AB-generated hydrogen. Based on these data, we scaled up the design of the proof-of-concept unit and produced a design for a 720 W-hr hydrogen generator with a very high hydrogen density (5.6 wt % and 36 g H_2/L). The hydrogen generator is extremely simple and well-suited for operation in an air-launched SUAS. Combined with a compact fuel cell, our system should enable a small power system for SUAS with an overall energy density in the range of 350 to 600 W-hr/kg.

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INTRODUCTION

This paper describes the results of an experimental program to develop a hydrogen generator that can enhance the capabilities of air-launched Small Unmanned Aerial Systems (SUASs) by increasing their power and mission time. Our technical approach (see Figure 1) is based on:

• Chemical storage of hydrogen in ammonia borane (AB), which is a nontoxic, solid powder with a very high intrinsic hydrogen content (19.6 wt% theoretical). Upon rapid thermal decomposition at elevated temperature, AB generates hydrogen with a yield of approximately 1.8 mol_{H2}/mol_{AB} (12 wt%).

• An extremely lightweight and simple method for heating AB using chemical heat pellets.

• An innovative packaging and control scheme for a hydrogen generator that enables on-demand production of high purity hydrogen to power a PEM fuel cell power system. The hydrogen generator has no moving parts and meets the challenging operational requirements for an air-launched system.

• A compact PEM fuel cell power system developed by Protonex Technology Corporation.

Our hydrogen generator uses the chemical energy stored in heat pellets to trigger hydrogen generation through rapid

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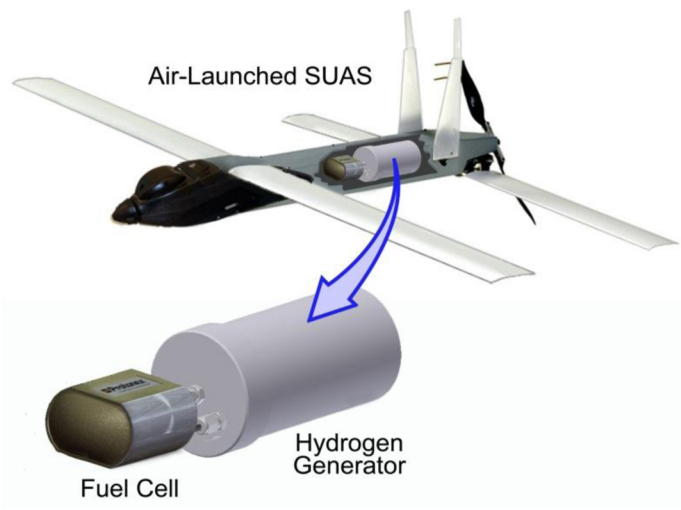
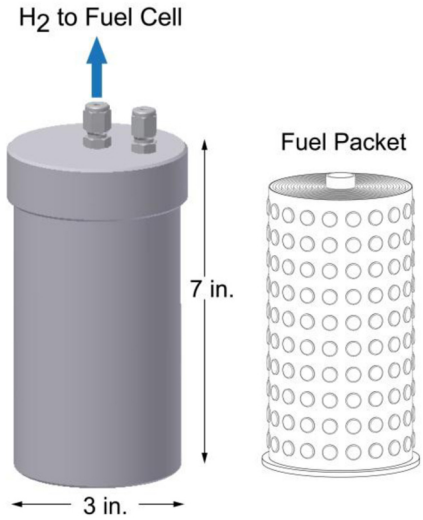


(a) The Hydrogen Generator and Fuel Cell can Meet Requirements for Operation in Air-Launched SUAS



(b) Creare's AB Hydrogen Generator Comprises a Fuel Packet Inside a Small Pressure Vessel

Figure 1. Compact Power System for Air-Launched SUAS Based on Creare's Innovative AB Hydrogen Generator and Protonex's Compact PEM Fuel Cell

thermal decomposition of AB. The hydrogen generator utilizes "blister packaging," in which each small "blister" contains a small amount of AB surrounding an embedded heat pellet. The blister pack doubles as a flexible circuit board that enables the control system to trigger hydrogen generation on-demand from individual blisters by sending small electrical pulses to ignite the heat pellets. The heat pellet rapidly heats the surrounding AB to high temperature and causes formation of hydrogen gas suitable for use in a PEM fuel cell. This approach is insensitive to the environment and flight conditions, and is compatible with the demanding requirements for air-launched SUAS applications. Creare has applied for patents that describe the innovative hydrogen generator concept.[1,2]

This report describes testing and design analysis that proves the feasibility of this approach. We optimized the formulation of our integrated AB and heat pellet blisters to maximize hydrogen yield while maintaining good product purity. We fabricated a first-generation prototype of our blister packaging concept and electronic control system, and demonstrated on-demand hydrogen generation with no blister cross-activation. We integrated our proof-of-concept hydrogen generator with a Protonex fuel cell, and demonstrated we can deliver hydrogen at the required purity and rate required for a PEM fuel cell. We then used data from these proof-of-concept experiments and requirements specified by UAV platform manufacturers to size a prototype hydrogen generator designed for air-launched SUASs. We believe that our compact power system, comprising Creare's AB hydrogen generator and a Protonex PEM fuel cell, will meet or exceed requirements for operation in SUASs and enable significant improvements in mission time compared to conventional hydrogen storage technologies.

Background

Air-launched SUASs offer the potential for significantly enhanced sensing and ground support. However, current technology for SUAS is severely constrained by the power available from conventional batteries, which limits the payload power and overall mission duration. Currently, Li-ion batteries limit the mission duration for air-launched SUAS to 10 to 60 minutes, far less than the minimum 4-hour duration requirements needed for future missions. Batteries will not be able to meet the demands for more power and longer duration needed by future SUASs.

Hydrogen fuel cells are attractive because of their high power density and demonstrated reliability and efficiency. Small fuel cells (built by Protonex) have been investigated as power sources,[3] but most conventional methods for storing hydrogen fuel (such as metal hydrides) are too heavy and bulky, and often are not safe for flight systems. Advanced sodium borohydride cartridges are much smaller; however, the use of water as a reactant in these systems leads to problems due to freezing at the extreme cold temperatures experienced by air-launched systems. A lightweight technique for storing hydrogen that is suitable for use in extreme environments is required before the system can meet the challenging goals for air-launched SUASs.

Thermal decomposition of AB offers a theoretical hydrogen storage density of nearly 20%. In ambient air, AB is a stable, nontoxic, white crystalline substance. At elevated temperatures (90°C to 180°C), AB decomposes exothermically to produce hydrogen and other byproducts via several intermediates. Theoretically, 3 mol of hydrogen could be generated per mol of AB ($H_3NBH_3 \rightarrow 3H_2 + BN$ (s)). In experimental studies, however, the reported achievable yield

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is only 2.2 mol_{H2}/mol_{AB} (Wolf et al. 2000). Although the reported hydrogen yield is less than the theoretical maximum, it is still equivalent to a mass storage density of 14.4 wt%, much greater than any other known practical hydrogen storage solution.

However, in order to enable practical use of AB for hydrogen generation for fuel cells, several challenges must first be overcome, including the need for (1) effective means for providing energy to drive the thermal decomposition of AB in a controlled, on-demand manner, (2) minimization and mitigation of undesirable volatile side products, and (3) design of a lightweight packaging approach that meets SUAS-required gravimetric and volumetric storage densities for hydrogen.

Requirements

Air-launched SUASs must perform in extreme operational and storage environments and be extremely safe. During a mission, the system must perform in a range of operational conditions ranging from launch altitude (cold and low pressure) to near ground level. However, long-term storage of the system prior to use will subject the system to even wider temperature ranges-standard military storage requirements specify temperatures ranging from −40 to +40°C. Since the SUAS will be transported by plane prior to launch, all parts of the power system must meet stringent requirements for safe storage. Most importantly, the power system must not produce any potential explosive or environmental hazards while onboard an aircraft or in storage.

The paper by Bishop (2010)[4] describes the current state of the art in power systems for unmanned aerial systems. Air-launched SUASs fall into Group 1 (0 to 20 lb_m), and deployed systems are powered by Li-ion batteries. Because of the high power requirements (230 to 844 W) and very small size of the battery packs, these systems currently have mission durations only in the range 10 to 60 minutes. However, most operational concepts for air-launched SUAS call for releasing them from larger aircraft at a long standoff distance (typically 30 miles) flying at altitudes of 8000 feet above ground level or higher. Future missions will require a minimum operation duration of 4 hours for air-launched SUASs. For example, Table 1 lists additional requirements specified by SOCOM.

Table 1. Power System Requirements for Future SUAS

Launch altitude	8000 ft AGL or more
Operating altitude	200–1000 ft AGL
Operational temperature	0–35°C
Operational pressure	24–30 in. Hg
Launch tube diameter	6–8 in.
Mission duration	4 hr
Peak power duration	24 min (10% of duration)
Storage longevity	6 months
Peak storage temperature	150°F

TECHNICAL APPROACH

Our hydrogen storage design uses "blister pack" packaging of individual AB pellets, where each pellet embeds an electrically activated chemical heat source to initiate AB decomposition on demand. The key components are: (1) a "blister pack" structure containing many button-sized pellets of AB with integral chemical heat sources, (2) a flexible circuit board that couples each AB/heat source with ignition electronics, and (3) a controller that regulates ignition. The blister pack doubles as a printed circuit board that connects electrical leads for the heat pellets to the system controller. A small electrical pulse ignites the embedded heat source, which releases the energy required for thermal decomposition of the surrounding AB in order to generate hydrogen gas on-demand.

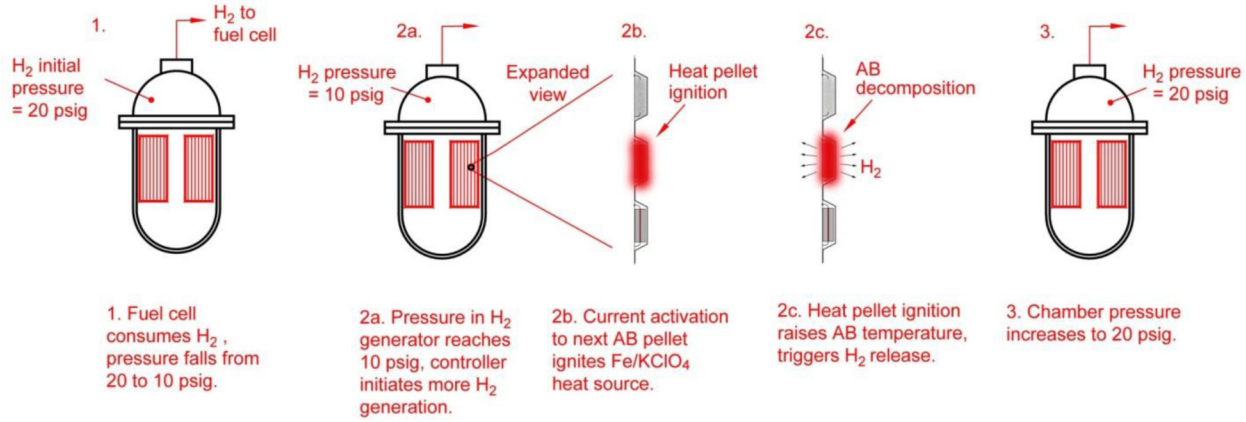

Figure 2. Lightweight Hydrogen Generation Scheme

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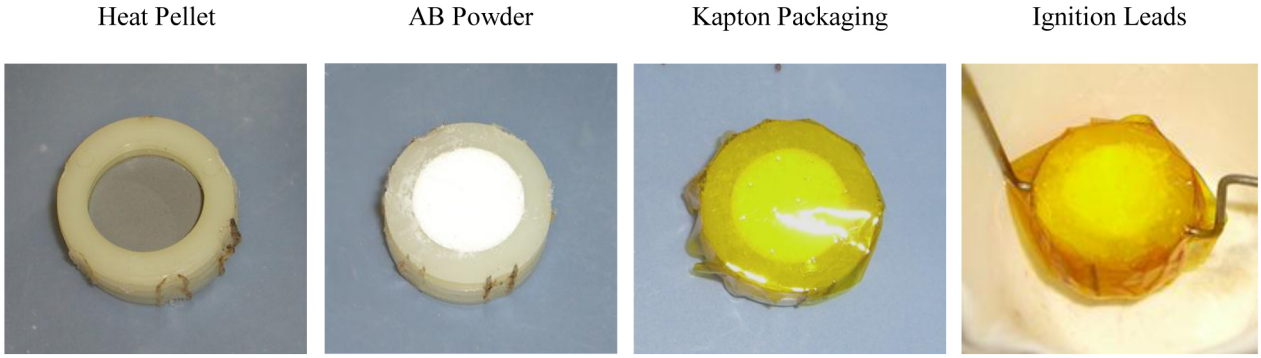

Figure 3. Assembly of Proof-of-Concept AB Packaging

A single fuel packet is comprised of a long strip of AB fuel pellets. The fuel pack may be rolled and inserted in a storage and generation vessel, which also embeds the necessary electronics for system control. Figure 2 details the operational sequence of our hydrogen generation system. Hydrogen is generated in a series of reactions of small quantities of AB contained in a blister pack package design. A reaction is initiated when the pressure in the generator falls below the setpoint pressure (10 psig in the figure, which is a typical operating pressure of the fuel cell). To produce a charge of hydrogen, a small electrical pulse (~100 mJ) ignites a heat pellet embedded in an AB pellet. Upon ignition, the heat pellet undergoes a strong exothermic reaction (while generating zero gas) that releases sufficient energy for thermal decomposition of the surrounding AB pellet, resulting in generation of hydrogen gas.

PROOF-OF-CONCEPT DEMONSTRATIONS

We fabricated a first-generation prototype of our heat pellet-activated, blister-packaged hydrogen generator and electronic control system. The prototype demonstrated on-demand hydrogen generation with an experimental yield of 1.8 mol_{H2}/mol_{AB} with no blister cross-activation. Less than 1 second is required to complete reaction of each packaged blister, generating hydrogen with a purity of greater than 99% by volume. We also demonstrated an approach to remove the small amount of ammonia, borazine, and carbon monoxide from the generated product gas to produce fuel cell-grade hydrogen. We integrated our proof-of-concept hydrogen generator with a Protonex fuel cell, and measured the performance of the fuel cell using high-purity laboratory hydrogen and hydrogen produced by our prototype. The fuel cell performance was identical in both cases.

Measuring Hydrogen Generation

Figure 3 shows the basic assembly approach for our proof-of-concept demonstrations. First we fabricate a heat pellet with embedded ignition leads, then install the heat pellet in an ULTEM pellet holder that was produced by stereolithography. We then distribute 0.45-1.0 g of 99% pure AB powder packed on both sides of the heat pellet and wrap the AB/heat pellet assembly in high-temperature Kapton adhesive film. We cut slits in the film to allow release of hydrogen gas. One of these packages will produce enough hydrogen to generate approximately 1-2 W-hr of electrical energy from a typical PEM fuel cell.

We used these prototypical single-pellet packages to demonstrate and evaluate on-demand hydrogen production. To generate and measure the amount of hydrogen, we installed the single-pellet package in a nitrogen-purged reactor vessel (Figure 4a). The vessel was instrumented with three thermocouples, a pressure transducer, and an analog pressure gauge. All experimental data (Figure 4b) were monitored and recorded in real time using a data acquisition system, allowing us to calculate the hydrogen yield for each experiment. At the conclusion of the experiment, we analyzed the volatile decomposition products (primarily hydrogen) in the reactor using a residual gas analyzer (RGA) and Fourier transform infrared spectroscopy (FTIR).

Optimization of Hydrogen Generation

We found three design parameters had a strong effect on the volume of hydrogen generated for a given mass of AB and heat pellet: (1) purity of the AB, (2) composition of the heat pellet, and (3) the physical design of the AB/heat pellet package. Figure 5 illustrates the progressive increase in the gravimetric storage density (mass of H_2 produced, divided by the combined mass of the AB and heat pellet) with improvements to the AB purity, packaging design, and heat pellet composition.

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