Lightweight Hydrogen Fuel Cells for Unmanned Aircraft and Small Unit Power

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Abstract:

The Naval Research Laboratory (NRL) has used decades of fuel cell research to create a Navy-owned hydrogen fuel cell prototype for Unmanned Air vehicles (UAVs). During development, a parallel opportunity to apply the hydrogen fuel cell system for small unit power (H-SUP) was identified. The resultant H-SUP prototype offers a low signature solution for electric power production, up to 1.2 kW continuous power, in a ruggedized package. Beyond the advantages of increased specific energy and decreased detectability, H-SUP establishes that fuel cells can be used interchangeably for both organic UAVs and for small unit power in the USMC context of expeditionary advanced base operations (EABO).

Keywords: Hydrogen; fuel cell; unmanned; UAV; expeditionary energy; small unit power; generator

Introduction

The DoD has a critical need for Unmanned Air Vehicles (UAVs) with increased power and endurance. For Group 2 and light Group 3 aircraft in particular, batteries have insufficient specific energy and heavy fuel engines are both inefficient and expensive from a total cost of ownership perspective [1, 2] Hydrogen fuel cells can fill this gap to enable important new capabilities, but there are presently no U.S. vendors of a 1-3 kW hydrogen fuel cell suitable for military use. The Naval Research Laboratory (NRL) has applied decades of fuel cell research to making a Navy-owned hydrogen fuel cell prototype for UAVs. Through an Office of the Secretary of Defense Manufacturing Science and Technology Program (OSD MSTP), this lightweight fuel cell has gone from a laboratory prototype to a Technology Readiness Level (TRL) 7 and Manufacturing Readiness Level (MRL) 7 product. Transition of this fuel cell is now underway via an integration effort led by the Naval Air Warfare Center Aircraft Division (NAWCAD) and sponsored by Naval Aviation Operational Energy (NAOE), with the first adopter being a Group 2 UAV called "Stalker". The Stalker UAV is the Intelligence, Surveillance, and Reconnaissance (ISR) workhorse of the Marine Corps. During development, a parallel opportunity to apply the hydrogen fuel cell system for small unit power (H-SUP) was identified and sponsored by the Office of Naval Research (ONR). The resulting H-SUP prototype provides a low signature solution for electric power generation, at up to 1.2 kW continuous power, in a ruggedized package. Aside from the benefits of improved specific energy and lower detectability, H-SUP proves that fuel cells may be utilized interchangeably for both organic UAVs and small unit power in the USMC context of expeditionary advanced base operations (EABO). This paper describes NRL's development and demonstration of this lightweight hydrogen fuel cell.

Fuel Cell System Development

There are numerous advantages to electric propulsion relative to internal combustion engines (ICE) for group 2 (under 55 lbs.) tactical UAVs, including near silent operation, reduced vibrations, reduced thermal signature, reduced maintenance, and instant starting [1]. High energy density batteries have historically been the primary power source for electric UAVs, but the DoD desires longer endurance flight times than batteries can offer [2]. Hydrogen fuel cells are a good alternative to batteries because of the high specific energy of hydrogen and high efficiency of electrochemical energy conversion. Because of this capability gap that fuel cells fill, and because of the lack of domestic commercial offerings suitable for military use, NRL developed its own lightweight Proton Exchange Membrane Fuel Cell (PEMFC) system (US Provisional Application No. 62/423,975) [3].

It is well understood that PEMFC systems convert hydrogen and oxygen electrochemically into electricity, heat and water. In the case of NRL's design, the PEMFC operates at relatively low temperatures, from 50ºC – 80ºC, and uses a supporting system of pumps, motors, sensors, actuators and controls, known as the Balance of Plant (BoP), to maintain optimal operation. Some distinguishing features of this BoP include a liquid cooling system for heat rejection, a closed cathode design with a passive exchange humidifier for membrane humidification, and an air compressor to deliver oxygen from the ambient air to the cathode (Fig 1. Top).

Furthermore, NRL's lightweight PEMFC borrowed techniques from the automotive fuel cell industry and scaled them down to realize best in class performance. These techniques include:

- Hydro-formed stainless steel bipolar plates for minimizing weight

- Liquid cooling with an ethylene glycol-based coolant for a wide window of ambient operating conditions
- Individual cell voltage monitoring for fuel cell state of health analysis and advanced control
- Material selection rated for 5000 hours of operation

NRL demonstrated a functional laboratory prototype of this fuel cell system in 2020, and subsequently executed a maturation effort to improve its manufacturability. As part of the maturation effort, NRL partnered with Northwest UAV (NWUAV), a small American UAV engine manufacturer (Fig 1. Bottom). Through this partnership, the following improvements were made to the original NRL design:

- More robust and maintainable system controls, including the use of industry standards such as CANBus communication
- Improved state of health monitoring with prototype subsystems replaced by manufacturable ones.
- Fewer fabrication and assembly steps with greater process control
- System layout and packaging improvements to decrease weight and volume, and increase serviceability with simple hand tools
- Component selection to reduce cost and supply chain risk

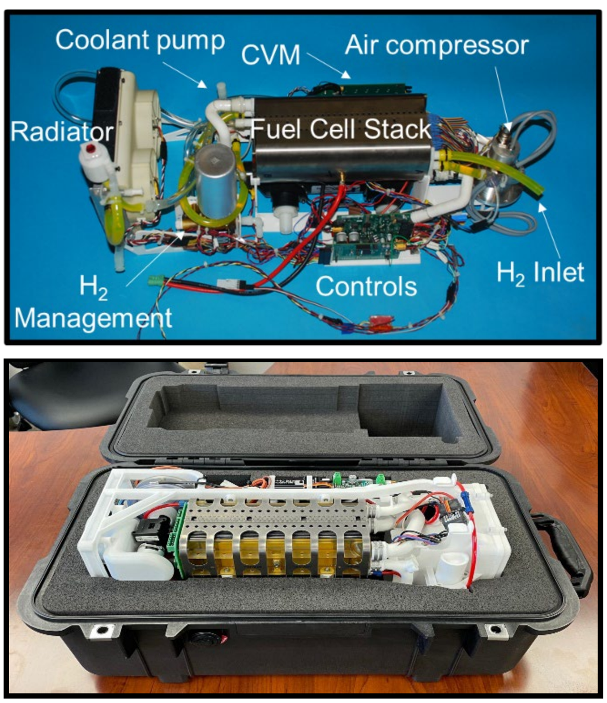

Figure 1. Top: NRL prototype PEMFC. Bottom: NWUAV Manufactured NRL PEMFC.

In addition, a fuel cell production facility at NWUAV was built, with better processes, tooling, and assembly methods [4].

The matured NRL lightweight PEMFC has high nominal specific power at 400 W/kg, and a nominal net power output of 1500 W. At no load, the nominal fuel cell system voltage is approximately 45 V, and at full load the nominal fuel cell system voltage is 26 V.

UAV Application

Upon reaching sufficient TRL and MRL, the NRL PEMFC was sought for integration into a UAV. To integrate into existing UAV electrical architectures, a 1280 W DC/DC converter was implemented to regulate the variable fuel cell voltage to a constant 28 V output.

Most other PEMFC systems of this power class are air cooled, open cathode architectures which are highly sensitive to ambient operating conditions and may not be well suited to operating in austere environments [5-6]. The NRL fuel cell system is designed to support UAV operations in a wide range of ambient conditions.

Because of its high specific power and robust operating envelope, NAWCAD and NRL integrated the lightweight PEMFC system into the Stalker UAV as part of a NAOE program to improve the Stalker's operational capabilities [7].

Figure 2. Front: NRL PEMFC, Rear: Hydrogen Stalker UAV

To date, fuel cell systems built by NWUAV have flown the Stalker UAV several times in flights that demonstrated the operational advantages the NRL PEMFC brings, including greatly improving upon the endurance of the battery version of the Stalker (Fig. 2). This integration effort was particularly significant because the Stalker is a fielded platform that is currently used as an ISR asset by the Marine Corps and Special Forces [8]. The success with the Hydrogen Stalker program has proven that the NRL lightweight PEMFC system is sufficiently capable and mature for military use and transition.

Small Unit Power Application

During the Stalker integration effort, an additional application for the NRL lightweight PEMFC was identified. Many of the advantages of using fuel cells over ICEs to power UAVs also apply to expeditionary power generators. The PEMFC was adapted to provide ground power to expeditionary small units, resulting in a prototype system called "Hydrogen – Small Unit Power" (H-SUP).

USMC Expeditionary units currently rely on power sources such as generators and ground vehicles that have significant audible and thermal signatures and therefore make them vulnerable [9]. Units executing EABO will require improved signature management to avoid detection. Solutions such as batteries and solar panels have the advantage of silent operation, but they suffer from limitations such as low energy density and visible signature. The H-SUP solves this capability gap by repackaging the NRL PEMFC system in a ruggedized case such that it can be used for small unit power with greater energy density than batteries (Fig. 3).

Figure 3. Hydrogen Small Unit Power Prototype

The advantages of H-SUP over the incumbent engine technology are numerous: decreased signature (thermal and acoustic), reduced maintenance burden, lighter weight, and greater modularity. The decreased signature is important for silent watch capabilities in contested environments. Additionally, fuel cells are self-heating with zero emissions and zero self-discharge, so they can supply waste heat to help batteries operate in arctic climates, and hydrogen fuel can be cached for long durations. Furthermore, H-SUP demonstrates that the NRL PEMFC system can be an interoperable power source that supports both UAV and ground power applications.

This interoperability supports the USMC vision of EABO by providing greater operational reach, increasing flexibility to meet changing needs, and simplifying the equipment set that must be transported to and, then supported, at remote locations.

Demonstration

The high energy density of H-SUP can be used to reduce the weight burden and re-supply needs of units, or to supply them with more energy to support energy-intensive loads. This concept was explored at the Technology Operational Experimentation Exercise (TOEE) 22.

At TOEE (Marine Corps Base Camp Lejeune, August 2022), active-duty Marines were trained to operate the H-SUP, and then used it independently to power real USMC payloads for days during Mission Essential Training evolutions [10]. The primary use case for the H-SUP at TOEE was to provide power to the Combat Operations Center for the headquarters element of a rifle company, powering loads like battery chargers and laptops. Previously, the Marines would charge their radio batteries with a charger mounted in a Joint Light Tactical Vehicle (JLTV). To prevent the vehicle battery from dying when they did this, they would turn on the engine and let the vehicle idle, which is inefficient, loud, and has a large thermal signature. That process was repeated hourly throughout the mission to keep the batteries fully charged. With the H-SUP they were able to charge batteries continuously without turning on the JLTV, which not only reduced the Marines' detectability, but also improved their readiness, as they were able to sleep through the night.

The H-SUP was also demonstrated at Marine Corps Base Quantico, Virginia in March 2023 [11]. The concept of operation (CONOP) demonstrated at Quantico involved powering a Network On The Move (NOTM) system with the H-SUP. The NOTM is a fielded communications payload used by the USMC to establish secure networking capabilities in theatre [12]. In this case, the NOTM was mounted to a JLTV which is representative of the typical implementation.

Figure 4. H-SUP powering NOTM

The NOTM would typically be powered by the JLTV battery and the vehicle would idle to keep the battery charged. Not only is the running vehicle highly detectable due to the audible and thermal signatures of the engine, but idling for extended periods accelerates engine degradation, leading to premature maintenance events.

The H-SUP powered the NOTM in two different configurations (Fig. 4), through an auxiliary power input, and by tying into the vehicle's electrical system via the NATO slave port on the front bumper. In both cases the vehicle remained off, decreasing detectability and preventing unnecessary wear and tear on the engine. In the latter case, the H-SUP also provided power to the vehicle electronics, such as cabin lights, headlights, and center console display.

Conclusions

NRL developed a lightweight hydrogen fuel cell system and matured it with a commercial partner to achieve a TRL 7, MRL 7 product. This fuel cell system has utility both in UAV applications and in small unit power due to its high specific energy and low signature. Furthermore, the same fuel cell can be used interchangeably for UAV and ground power applications, enabling a wide range of CONOPs for expeditionary units aligned with EABO.

Next Steps

The Naval Research Laboratory will continue to improve the performance of the fuel cell system across the entire vertical of research and development: from materials selection and fundamental research to implementation of advanced control algorithms and component selection at the system level. As NRL continues to support the transition of the Hydrogen Stalker, other targets for transition will be identified and pursued, such as multi-day UAVs, Group 3 UAVs, and other unmanned vehicle platforms: surface, undersea and ground.

Other existing efforts include building out the H-SUP ecosystem with both larger and smaller systems all based on the same NRL fuel cell technology, and will continue to incorporate warfighter experimentation and feedback early and often to ensure valuable systems are developed.

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