2010 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
POWER & ENERGY MINI-SYMPOSIUM
AUGUST 17-19 DEARBORN, MICHIGAN

FUEL CELLS AND THEIR APPLICATIONS IN TODAY'S BATTLEFIELD: LEVERAGING THEIR ADVANTAGES AND MINIMIZING THEIR SHORTCOMINGS

Dr. Mike Mekhiche
Director, Vehicle Systems
BAE Systems
Johnson City, NY

James Sherman
Business Development Manager
BAE Systems
Johnson City, NY

Bart Mancini, P.E.
Sr. Principal Systems Engineer
BAE Systems
Johnson City, NY

ABSTRACT

This paper will address the details of realizing a silent watch solution using fuel cells while addressing the various complexities associated with their integration into a military vehicle.

INTRODUCTION

Today's battlefield of urban confrontations and asymmetric warfare has led to an ever-increasing need for effective and stealthy means of intelligence gathering to anticipate and prevent enemy plans. There is an inevitable and concurrent increasing need for electric power as more advanced sensing, listening, and observation equipment is continuously being perfected. In the past several years, the Department of Defense, in association with industry leading companies, has focused on improving military vehicle mobility, lethality, and survivability through advanced power management solutions and onboard power generation systems. Such advanced capabilities are providing our armed forces with much-needed tools that improve their effectiveness and maximize their safety. However, additional technological improvements are needed to further enhance "silent watch" operation. Such enhancements come by means of reduced vehicle thermal and acoustic signatures and increased mission duration. Diesel-fueled internal combustion engines meet the need for increased duration, but they require complex means to manage their heat and acoustic emissions. Recent advances in energy storage and fuel cell technologies are providing viable options that can lead to an optimized propulsion and power system solution. Such advances and improvements include reliability, efficiency, power density, fuel reforming, communication, and power management, as well as overall efficiency, safety, and produce-ability. Hence, they do have the ability to overcome the shortcomings of the current silent watch approach. In particular, 10-50kW rated proton exchange membrane (PEM) fuel cells provide an ideal candidate. They are commercially available and have been used in various applications (forklift propulsion, automotive and stationary) for several years. Furthermore, there is an established supply chain in the U.S., Canada, and Europe to produce such components. The fact that a chemical reaction (where hydrogen is combined with oxygen to produce electrons, with water as a byproduct) is at the heart of this technology makes it quiet and clean.

BAE Systems' power management experience, including fuel cell technology

Advanced power and propulsion systems support the critical need for higher mobility, better survivability, and lethality by providing a foundation to insert advanced weapon systems, electronic and information warfare systems, advanced sensor systems, and crew protection and comfort systems. An integrated approach to tactical and combat vehicle power subsystems must be provided to reduce the payload of the traditional sources of electric power (various gen-sets, micro-turbine and APU, etc). Hence, modern military vehicle-embedded power systems represent the optimum power management capabilities required to meet the safety and capability requirements for victory. Several challenges are presented in the development of these systems, which represent a paradigm shift to the methods employed to design and produce military vehicles. Balancing the intricate details involved in achieving the lowest weight, highest efficiency, highest reliability, and stringent military requirements to deliver a combat-ready embedded power system is paramount to success. The critical performance issues that must be addressed include: system fault protection, redundancy and graceful degradation, safety, serviceability, EMI/EMC, rugged packaging, human-machine interface, and silent watch operation. Finally, the overall system must be affordable. BAE Systems has a wide variety of experience in power and energy management applications and technologies. The company's expansion into the power management market began with its development of sophisticated systems for hybrid-electric transit buses. The continued tightening of already-stringent EPA emissions standards and ever-increasing fuel prices created market pull for hybrid propulsion technology. Over the past two decades, BAE Systems has developed its HybriDrive® system, which is now the leading hybrid propulsion and power management system in the demanding ground transportation market, and directly leveraged in tactical and combat military vehicles.

To date, more than 2,800 propulsion systems have been delivered to various markets, including the world's largest hybrid bus fleet in New York City (1,760 vehicles). Other fleets include Toronto, San Francisco, Houston, Ottawa, and London. Currently, BAE Systems propulsion systems have accumulated more than 150 million miles and have resulted in 10 million gallons in fuel savings, 100,000 tons of CO2 prevented, and 500 tons of NOx prevented.

In the military arena, BAE Systems has applied its hybrid propulsion and power management expertise to a number of applications. For the U.S. Army's Family of Medium Tactical Vehicles (FMTV) demonstration vehicle, BAE Systems' HybriDrive propulsion system demonstrated the ability to provide 100kW of AC export power. The FMTV demonstration vehicle completed more than 5,000 miles of endurance testing at Aberdeen Proving Grounds (APG) Churchill B course.

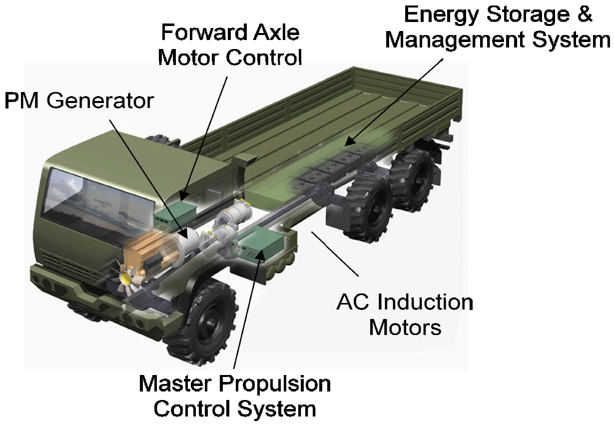


Figure 1: FMTV demonstration vehicle equipped with HybriDrive® propulsion system

BAE Systems' Common Modular Power System (CMPS) products were developed to support the U.S. Army Tank and Automotive Research, Development and Engineering Command, (TARDEC), Tank and Automotive Command (TACOM), and Program Engineering Office for Ground Combat Vehicles (PEO-GCS). This system is capable of providing 1,200 amps of 28Vdc power over the entire engine operating range, in addition to 30kW (208Vac) onboard and off-board AC power. The CMPS product supports fleet commonality (applicable to Stryker, Bradley, Abrams, and Paladin vehicles) and increasing power requirements.

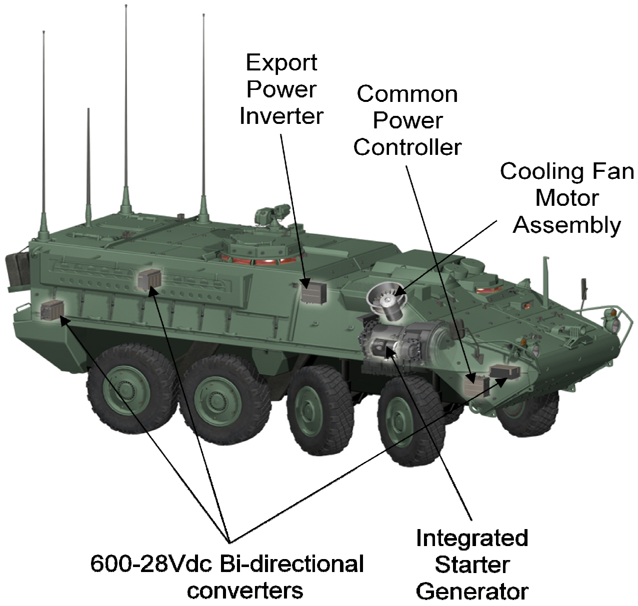


Figure 2: PM Stryker with Common Modular Power System (CMPS)

CALSTART COMPOUND FUEL CELL HYBRID BUS

BAE Systems, teamed with Daimler Buses North America, Hydrogenics, Lincoln Composites, Engineered Machine Products, San Francisco Municipal Railway, and WestSTART-CALSTART, is developing a compound fuel cell hybrid bus. The goal of this program is a comprehensive systems integration and component development effort that aims to achieve National Fuel Cell Bus Program (NFCBP) performance objectives. Additionally, the project expects to set the conditions for a commercially viable domestic fuel cell transit bus industry through the combined effort of developing and integrating fundamental requisite fuel cell bus technologies on a 40-foot heavy-duty Orion VII transit bus demonstrator. BAE Systems' approach integrates the hybrid-electric power system with a more-electric vehicle accessory system powered by the fuel cell technology. This holistic vehicle systems approach is clearly recognized by the NFCBP with the identification of these component technologies as focus areas "believed [by FTA] to be most important to the NFCBP."

Silent watch today

Modern military vehicles use the "prime mover" as the power source for propulsion, vehicle loads, mission loads, and to charge batteries, which are used during silent watch operations. A conventional belt-driven alternator supplies 28 Vdc power via a low-voltage distribution system to these various loads (see Figure 4). The implication related to the coupling of the internal combustion engine (ICE) to the alternator via a belt is that any electric power output requires the ICE engine to be running. Furthermore, any needs for additional vehicle loads, such as air conditioning, would require more power from the engine, leading to an increase in fuel burn, which in turn increases noise generation and the amount of rejected heat. In commercial applications such as transit buses and heavy-duty trucks, engine compartment acoustic levels can reach upwards to 100db, making the vehicle easily detectable. The sound propagation — particularly low-frequency harmonic content — is a major detriment to the success of a silent watch mission. Various mitigating steps can be taken to reduce such effects, including techniques to spread exhaust heat and sound damping. However, while these steps help reduce the amount of generated noise and heat, they do not completely suppress it and result in added cost and complexity to the vehicle. Another challenge that is increasingly impacting the ability of military vehicles to carry out their mission successfully is related to the severe power limitations of the belt-driven alternator technology. The inherent air-cooled field wound alternator technology performance is considerably de-rated by high ambient temperatures, such as the ones found in the desert. These devices have normal ambient efficiencies on the order of 70 percent, which affects the vehicle's overall fuel consumption. The lower efficiency at high temperatures impacts mission duration and the reduced output power capability is no longer sufficient to the demands of vehicle electrical loads and the ever-increasing mission loads. Some workaround solutions include the use of multiple belt-driven alternators to meet the vehicle power demand, further increasing vehicle overall fuel consumption, increasing engine parasitic losses (and heat signature), and reduced vehicle performance (mobility, lethality, and survivability). Recent development activities, led by DoD and leading industrial partners, have resulted in advanced embedded power systems that apply state-of-the-art generation, distribution, and management technologies. These modern systems make use of liquid-cooling combined with high-efficiency, power-dense electronics, and rotating machines to dramatically increase the available electric power on vehicles. Such power systems offer the flexibility to interface with other power and energy sources such as batteries, fuel cells, and flywheels, and provide the much-needed ability to support additional mission and weapon systems. Further, the overall mobility of the vehicle is improved with the integrated intelligent power management approach associated with these state-of-the-art power systems, by directing power and energy where needed and when needed depending on vehicle mode of operation. Such a holistic power system is depicted in Figure 5. In this type of system, the belt-driven alternator(s) and vehicle accessories are replaced with high-efficiency, power-dense, permanent-magnet-based machines that are directly or indirectly (through a power take-off) coupled to the crankshaft of the engine. The output power ranges anywhere between 40kW and 200kW+, and converts to various voltage formats, such as 28Vdc, 208Vac, 110Vac, 50/60 Hz, and 400 Hz. The basic capabilities of these systems address the current needs for military vehicle electrical power including improved system mobility, efficiency, advanced fault management, graceful degradation, intelligent power management, and reduced fuel consumption. The system architectures provide the built-in growth capability to support additional power sources directly to the common voltage link. As shown in Figure 5, the connection of fuel cells, energy storage systems, and pulsed power generators onto the DC link is now possible, making the system more versatile and able to provide:

- Enhanced vehicle mobility via electric propulsion assist: The electric machine that is now connected to the engine's crankshaft can be driven as a motor using a separate power source such as the energy storage system and/or the fuel cell to produce additional propulsion torque and supplement vehicle acceleration and/or grade-ability performance.
- Engine-off operation: The engine can be shut off for extended periods of time while all vehicle accessory loads,

as well as mission and silent watch loads, are powered via the fuel cell and/or the energy storage system.

- The vehicle engine can be shut off while the selected onboard loads and weapons ancillary systems can be supplied via the energy storage system and/or the fuel cell, and pulsed power generators can be brought online to support additional capabilities such as directed energy weapons and active armors.

The flexible architecture of such a system allows for its configuration to meet specific vehicle needs by eliminating or adding subsets of the full-up system discussed in this section. In the following sections, the specifics of the silent watch topology will be addressed.

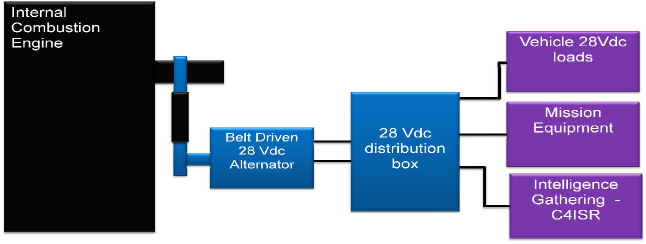


Figure 4. Conventional vehicle

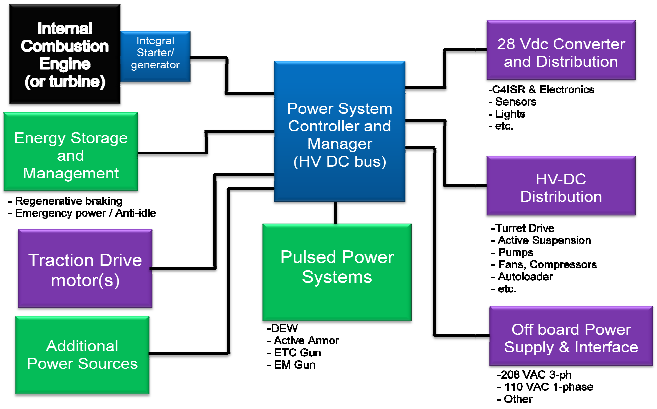


Figure 5. Advanced generic power system

A fuel cell APU-based silent watch approach

In the commercial transportation sector, hydrogen emerges as a particularly attractive option for the long term, with the following desirable characteristics:

- Hydrogen fuel cell vehicles have zero or near-zero tailpipe exhaust emissions, producing only water vapor.

- Hydrogen can be made from widely available primary energy sources, including natural gas, coal, biomass, wastes, solar, wind, and nuclear power (both solar and wind would be used to generate electricity for electrolysis). If hydrogen is made from fossil fuels, it would be possible to capture and sequester CO2.

- Greatly reduced full fuel cycle emissions of air pollutants and greenhouse gases is possible, if hydrogen is made from natural gas and used in hydrogen fuel cell or ICE vehicles. With hydrogen from renewable or de-carbonized fossil sources, full fuel cycle emissions could approach zero.

- Hydrogen fuel cell vehicles are undergoing rapid development worldwide and are projected to offer good performance and low costs in mass production. Hydrogen fuel cell vehicles are projected to reach life-cycle economic competitiveness with other advanced vehicle and fuel options at mass produced costs, if external costs are accounted for.

A fuel cell is a device that takes stored chemical energy and converts it into electricity through two electrochemical reactions. The chemical energy is stored in various fuels including gasoline, JP8, CNG, and other common fossil fuels. The main elements of a fuel cell are shown in Figure 6 and are a) the electrolyte, which also is a separator that keeps the various chemical reagents from mixing together, b) the electrodes, which are the catalysts where the electrochemical reactions take place, and c) bipolar plates, which collect the current and build the voltages in the cells.

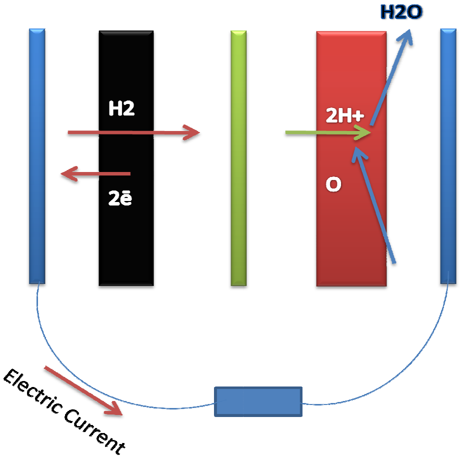


Figure 6. Fuel cell principle

Fuel cells have undergone several decades of development and maturity and have been in used in various applications for several years, including aerospace, space, stationary power generation, and motive/embedded power applications. The past decade has seen significant progress in terms of reducing the size and weight of these devices, increasing their power density, improving their dynamic response, and overall reliability and efficiency, while also reducing their cost and simplifying their manufacturing process. Various manufacturers of such devices are now well-established and supply production-grade fuel cell products to various markets, particularly to the material handling (forklifts and such), automobile, and heavy-duty transit bus industries. Today, several hundred material handling vehicles are in operation with fuel cell power plants, and similarly, a few hundred transit buses also are in revenue service where various fuel cells are used to generate their motive power. Such manufacturers include Ballard Power Systems, NUVERA, Hydrogenics, and others. In addition to the progress made on the actual fuel cell devices, a considerable effort was applied toward the development and maturation of hydrogen generators. As shown in Figure 6, hydrogen is the main fuel required to react with oxygen to produce electricity. While the hydrogen element is abundantly present in nature in a combined state, it does not commonly exist in a gaseous form, requiring a reformation process to obtain the fuel. Several methods can be applied to achieve this, including electrolysis, where water is separated into hydrogen and oxygen and the actual reformation of organic fuels such as JP8, gasoline, CNG, and others. This chemical process separates hydrogen gas, purifies it, compresses it, and supplies it to the fuel cell plant to produce electricity. Other components also are required to support the operation of a fuel cell, including the hydrogen supply system, humidifier, compressed reaction air, cooling system, and other elements that represent what is commonly known as the "balance of plant," or BOP.

Various architectures of interest are being developed in the commercial market for the purposes of improved vehicle fuel efficiency and providing zero-emissions-vehicle (ZEV) capability. In addition to the obvious use of fuel cells as the prime power plant in lieu of the combustion engine, an attractive scenario is one where it is used as an auxiliary power unit (APU) in conjunction with a prime power diesel engine (see Figure 4). Such topologies combine smaller, commercially available, 10-30 kW fuel cell APUs and a standard, diesel-fueled ICE. In this scheme, during normal operation, the diesel-fueled engine provides the main vehicle propulsion power, and during the "silent" mode, where the diesel engine is turned off, the APU is used to supply power to vehicle accessories such as air conditioning, 28 Vdc hotel power, power steering, air compressors, and such. This system implementation offers a variety of advantages for a military silent watch operation — where, in addition to vehicle accessories, the fuel cell APU also supplies power to the onboard mission equipment for intelligence and data gathering. Other advantages also can be gleaned from such a topology, including the ability to operate vehicle air conditioning without the need for the engine to be on. This is very important when the vehicles are in the depot or garage undergoing maintenance actions. Similar to commercial applications, directing the fuel cell output to the propulsion system provides additional torque boost to enhance acceleration and speed-on-grade, improving vehicle mobility in the battlefield.

Figure 7 and Figure 8 show system architectures that were implemented and demonstrated in the commercial market with subsystems also demonstrated in various military platforms. Figure 7 depicts a topology that combines a conventional ICE engine providing propulsion power to the vehicle while also providing prime power to a small, high-power-density, high-efficiency generator via a PTO-type interface. The generator provides variable voltage and variable frequency electric power on the order of 40kW to 60kW that then gets conditioned and managed via an auxiliary power supply (APS) module. The APS includes three power stages: a) an inverter that controls the generator and actively rectifies its power to a 600Vdc bus internal to the module, b) a DC-DC converter that converts the 600Vdc link to 28Vdc power, and c) an inverter that converts the 600Vdc link to 208 or 110 Vac (50 or 60Hz). Since the output voltage of today's off-the-shelf fuel cell products is in the 50-350 Vdc range, a fourth converter is required to boost this voltage for compatibility with the power system (600Vdc nominal). This converter usually is a separate module used only when a fuel cell is part of the system. However, there is no reason to keep this converter from being packaged in the APS. The outputs of both electric power sources are combined in the APS, converted to the required voltages, and then distributed to various loads via power distribution units (AC-PDU and DC-PDU) that also house various protection components such as fuses and contactors and others. Hence, the system can be made redundant by supplying power from the PTO-driven generator and the fuel cell APU, and provisions can be made to shut down either, depending on mission profile and need. Figure 8 shows the resulting power system where the PTO-driven generator is turned off or entirely eliminated from the system. In a silent-watch mode, the engine is turned off and the fuel cell supplies all the necessary electric power with an acoustic performance that is orders of magnitude lower than that of the ICE. Furthermore, the fuel cell efficiency is on the order of 45 percent to 55 percent, which is far superior to the ICE at idle or low-power conditions. However, the fuel cell stack, where most of the heat is generated, is liquid-cooled and packaged inside a metal container that spreads any emanating heat, resulting in a much lower (negligible) heat signature. The only components that generate acoustic noise are the electric pumps and fans used for the cooling of the fuel cell stack. Such components are packaged in the fuel cell with the appropriate sound-isolation measures, making them nearly undetectable when in operation.

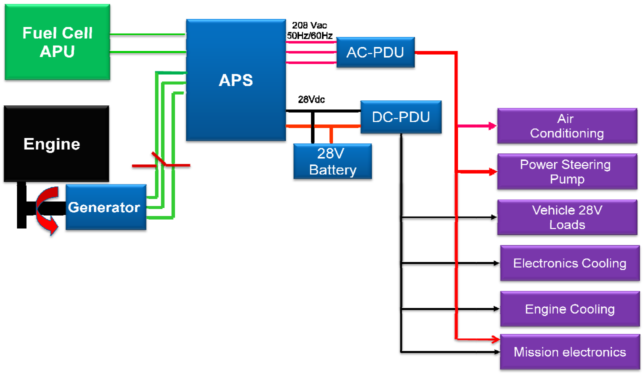


Figure 7.

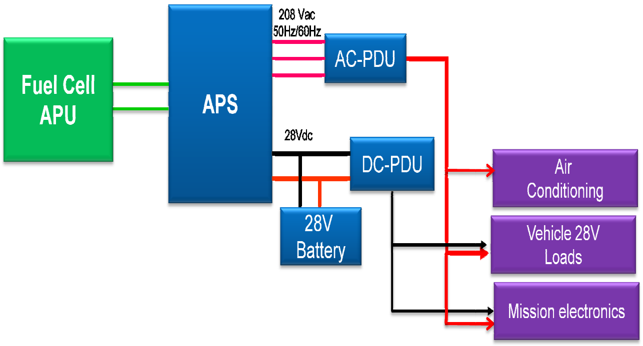


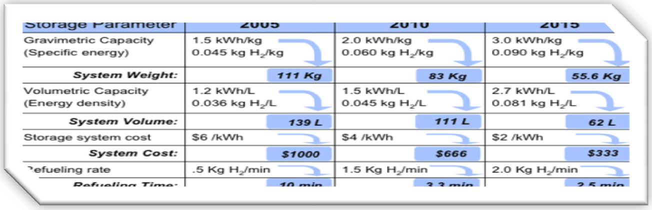
Figure 8.

Fuel cells perform best when supplied with compressed hydrogen. In today's mobile commercial applications, hydrogen is stored in tanks carried onboard the vehicles, similarly to CNG. (see Figure 4). Depending on the size of the fuel cell and required autonomy and mission profile and the amount of hydrogen, the size and number of tanks required for its storage are determined. While the weight of the hydrogen itself is inconsequential, that of the tanks (usually made of carbon-fiber) can be considerable. In the material handling market (forklifts and such), the hydrogen tanks are embedded in the fuel cell enclosure itself, resulting in a compact and easily transportable unit. Considering the possibly tremendous benefits and advantages of the fuel cell in a military environment when dealing with silent watch operation, the potential drawbacks of transporting hydrogen tanks are outweighed by the resulting enhanced performance. Other approaches to the onboard hydrogen storage tank solution also are viable. The challenge of accessible hydrogen needed for fuel cell operation can be solved via the use of vehicle embedded reformer technologies and/or centralized portable production stations where several reformers can be used to produce this fuel, which will then be stored in portable reservoirs on standard diesel fuel tanker trucks. When the combat vehicle is having its diesel fuel replenished, the hydrogen for the fuel cell can simultaneously be transferred during a combined refueling process. The technologies to produce, store, and distribute hydrogen to vehicles are more and more commercially available today:

- Hydrogen produced from natural gas in a large, centralized steam-reforming plant, and delivered via truck as a liquid to refueling stations, or hydrogen produced in a large, centralized steam-reforming plant, and delivered via small-scale hydrogen gas pipeline to refueling stations.
- Hydrogen from chemical industry sources (such as excess capacity in ammonia plants, refineries that recently have upgraded their hydrogen production capacity, etc.).
- Hydrogen produced at the refueling station via small-scale steam-reforming of natural gas, or by reforming of a more readily available liquid "hydrogen carrier" such as methanol or ammonia.
- Hydrogen produced via small-scale water electrolysis at the refueling station.
- In the longer term, hydrogen might be produced via gasification of coal, biomass, or wastes electrolysis powered by wind or solar electricity.

As stated above, vehicle-embedded reformers that reform JP8 fuel (for example) to hydrogen are available. This approach eliminates the need for storage tanks and the need to refuel the vehicle with two different fuels. However, generally speaking, reformers produce hydrogen at low pressure, and not necessarily with the purity required for the proper operation of the fuel cell. Hence, a compressor and a hydrogen purification system will be required. Other approaches being examined include the use of liquefied hydrogen. In this form, the energy content of hydrogen is several orders of magnitude higher than its gaseous form. However, in its liquid state, hydrogen is very volatile and must be kept at very low temperatures, which requires additional sub-zero chillers to eliminate boil-off. Table 1 shows the evolution of hydrogen storage used onboard commercial vehicles in the last several years. As shown, between 2005 and 2010, the weight of the system was reduced by more than 30 percent and the projection is that by 2015, the weight will be half of that in 2005, while reducing volume by the same factor, reducing refueling time by a factor of 4, and system cost by a factor of 3.

Table 1. Evolution of hydrogen storage technology (courtesy Wikipedia)



Storage Parameter	2005	2010	2015
Gravimetric Capacity (Specific energy)	1.5 kWh/kg 0.045 kg H_2/kg	2.0 kWh/kg 0.060 kg H_2/kg	3.0 kWh/kg 0.090 kg H_2/kg
System Weight:	***111 Kg***	***83 Kg***	***55.6 Kg***
Volumetric Capacity (Energy density)	1.2 kWh/L 0.036 kg H_2/L	1.5 kWh/L 0.045 kg H_2/L	2.7 kWh/L 0.081 kg H_2/L
System Volume:	***139 L***	***111 L***	***62 L***
Storage system cost	\$6 /kWh	\$4 /kWh	\$2 /kWh
System Cost:	***\$1000***	***\$666***	***\$333***
Refueling rate	.5 Kg H_2/min	1.5 Kg H_2/min	2.0 Kg H_2/min
Refueling Time:	***10 min***	***3.3 min***	***2.5 min***

In addition to the advancements achieved in onboard reformers, stationary hydrogen generators also are widely available in the commercial sector. Such stations are modular and can produce upwards of equivalent capacity 100kW. Several modules can be used to increase the amount of hydrogen produced as needed. It is conceivable that a mobile hydrogen station can be transported and implemented in a military camp or base. The produced hydrogen will then be carried via re-fueling vehicles the same way other fuels are transported and delivered in the battlefield.

Example of a small fuel cell APU power plant

In this example, continuous silent watch power demand of 10kW for 10 hours is assumed. Also assuming an 85 percent electrical conversion efficiency, 45 percent fuel cell efficiency and a 90 percent fuel use potential results in a requirement for 7½ kg hydrogen at 39.4 kW-hrs/kg energy content. Using the above 2015 advanced hydride storage metrics, the storage system weight would be 85 kg (~190 lbs) with a volume 95L (3.4 ft3). The fuel cell itself would be 80 kg (~175 lbs) and 105L (3.7 ft3).

Conclusion

In this paper, the authors discussed the viability and the benefits of applying fuel cell technology advancements achieved in the commercial sector to the military market. In particular, the potential benefits of using fuel cell auxiliary power units for the purposes of silent watch were highlighted, and various implementation approaches discussed. Beyond the stealth operation of these systems (reduced acoustic and thermal signatures), they can further enhance military vehicle mobility and reliability in the battlefield.