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JP-8 Fuel Cell Electric Vehicle

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ABSTRACT

This paper summarizes development and demonstration of F-24/JP-8-fueled Fuel-Cell Electric-Vehicle that offers silent-mobility, silent-watch, and export-power. The prototype electric vehicle was fueled with MIL-SPEC F-24/JP-8. It can potentially be operated with other logistic fuels and does not require on-board hydrogen storage. An onboard fuel reformer with integrated sulfur trap was used for processing MIL-SPEC F-24/JP-8. The 10-kW electric (kW_e) generator included a solid oxide fuel cell and balance of plant components (oxidizer, pumps, blowers, sensors, power and control electronics). It was hybridized with a rechargeable battery for startup, peak loads, and load following. Water neutrality and silent operation (i.e., ~60 dBA at 1-meter) was confirmed. The power produced was sufficient for vehicle propulsion and export power. Both 28-32 VDC and 110 VAC for charging batteries and supporting external load demands were available onboard. Initial off-road demonstrations were conducted at PCI and Detroit Arsenal. System design and performance data are shared in the paper.

1. INTRODUCTION

Precision Combustion, Inc. (PCI) has developed multiple turnkey, standalone Solid Oxide Fuel Cell (SOFC)-based power generation systems (including for various fuels e.g., F-24/JP-8, Sasol IPK, etc.). The systems include (i) fuel reformers, (ii) sulfur cleanup, (iii) SOFC from various OEM, (iv) power electronics, (v) water recovery, (vi) start/tail-gas burners, (vii) heat exchangers, (viii) balance of plant (BOP) components (e.g., pumps, blowers, sensors), (ix) controls, and (x) packaging. Figure 1 highlights the approach. The generators developed range in size from 100 W_e to 10-kW_e. Components for larger MW-scale applications have also been developed. Fuel reforming approaches have included steam reforming (SR), catalytic partial oxidation (CPOX), and auto-thermal reforming (ATR). Systems have been developed for various fuels, and pressurized operation for high efficiency UAV, APU, and vehicle platforms.

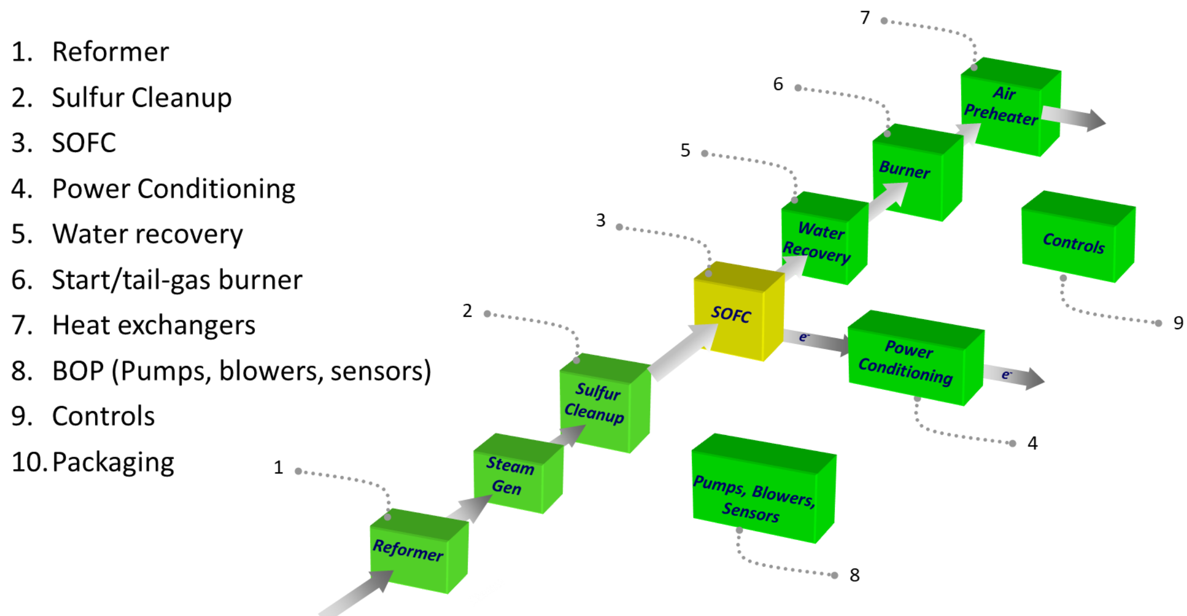

Figure 1: Key components for a complete Solid Oxide Fuel Cell Generator.

A photograph of the battery hybridized SOFC vehicle prototype delivered to the US ARMY DEVCOM GVSC is shown in Figure 2.

Figure 2: F-24/JP-8 fueled, electric SMET prototype developed at PCI with US ARMY DEVCOM GVSC support. It is self-charging and provides 10-kW$_e$ export power.

A semi-autonomous, off-road vehicle, Squad Multipurpose Equipment Transport (SMET), was chosen for this demonstration. It is designed to lighten infantry soldier load by carrying an array of supplies and gear. It was developed by General Dynamics Land Systems (GDLS). The original vehicle (Figure 3) was used as a mule for the prototype developed at PCI. The original vehicle only had a rechargeable battery which required charging from an external power source. PCI's prototype does not require external charging during operation, was designed for 10 kW$_e$ export power, and is fueled by F-24/JP-8. It is analogous to a plug-in hybrid, but without range anxiety.

Figure 3: Multi-Utility Tactical Transport developed by GDLS. It requires external charging and provides 3 kW$_e$ export power. (https://www.gdls.com/ products/ tracked-combat /MUTT. html)

2. SYSTEM DEVELOPMENT

The key hurdles limiting implementation of SOFC power generators in military applications include sulfur in F-24/JP-8, F-24/JP-8 reformation without carbon precursors in the product stream, water neutrality, and requirement of high gravimetric and volumetric power densities. Development of efficient and robust F-24/JP-8 reformers and sulfur cleanup systems for supplying stack-quality reformate preceded the current development and has been reported elsewhere.

Development of a battery hybridized SOFC system required component design and fabrication, process modeling and simulation, system integration, and operational optimization. Interface requirements between sub-systems and sub-components, thermal and flow management, power conditioning, packaging, controls, user interface, safety, and environmental compliance, were carefully considered and were supported by process intensification and multiple innovations.

2.1. JP-8 Reformer and Sulfur Cleanup

PCI's patented and trademarked Microlith® catalyst and reactor technology used process intensification that combined F-24/JP-8 atomization, mixing, reformation, steam generation, and sulfur cleanup, resulting in an extremely compact and lightweight footprint. For example, a 10 kW_e process intensified F-24/JP-8 reformer is shown in Figure 4, with reference to a standard coffee mug. The reformer was integrated with a quick-connect, field replaceable, sulfur filter that is currently designed for ~250 hours of operation with typical, unmodified F-24/JP-8 fuel. The filter can readily be made larger for longer operation, via a trade-off with weight and volume. The reformer operation was validated for >1000 hours of operation with F-24/JP-8 and other fuels with the added benefit of fuel-flexibility (gasoline, diesel, biofuels, etc.) for 'dual-use', i.e., commercial applications.

Figure 4: 10 kW_e F-24/JP-8 reformer.

2.2. Balance of Plant Components

In addition to the F-24/JP-8 reformer, sulfur filter, and SOFC stack, the system includes fuel/water pumps, air blowers, sensors, heat exchangers, burner, water recovery system, control and power electronics, and MIL-SPEC compliant packaging. PCI has developed a single burner that can operate both on liquid fuel (for system startup) and anode tail gas (for steady state operation). The pumps, blowers, sensors, and heat exchangers were selected for low parasitics, availability, and durability. System optimization vis-à-vis thermodynamic considerations, via CHEMCAD process simulation software, was used to identify components specifications, and achieve high system efficiency via effective thermal and flow balancing.

2.3. Power Electronics

PCI's power conditioning system was developed to provide output control (maintain required voltage range and power quality to the electrical loads), charge management of hybridized batteries, and fuel cell stack protection from overload, current surge, ripple, and load distortion. This feature not only allowed hybridization with MIL-

SPEC rechargeable batteries but also included flexibility for microgrid integration and direct battery charging. Battery hybridization for load balancing and maintaining power quality required development of custom algorithms and hardware for matching load and fuel cell transients.

2.4. Controls

Control algorithms were first developed for each subcomponent and its operation. For example, algorithms for burner operation (startup, steady state, shutdown), reformer/steam generator/sulfur trap, and SOFC (anode/cathode flow rate/pressure drop/rates of temperature rise/differentials) were developed independently. In addition to these three major components, user load characteristics, including hybridization protocols were identified. The individual control schemes were then integrated and programmed into the control hardware. Master control architecture was developed and used to communicate with each of the sub-controllers using National Instruments control and data acquisition hardware programmed with Labview software. Additional custom control boards were also designed, fabricated, and programmed to allow fail-safe and user interface operation. The control algorithm consisted of a fully automated operation capable of single push button start/stop and continuous self-monitoring and adjustment to accommodate user-loads.

2.5. Packaging

Effectively packaging within the SMET vehicle of the fuel reformer, sulfur filter, fuel cell, and associated BOP components to account for efficient flow, thermal integration, and space claim management was critical towards meeting form factor requirements. This includes separation of hot and cold zone components, adding insulation, designing for shock, vibration and environmental conditions, resistance to electrical interference, material selection, manufacturability, and cost-effectiveness. Multiple iterations were performed to optimize the system packaging, including component layout and thermal management configuration, and update the component drawings. Many of the system components were upgraded, including the flow manifolds, heat exchangers, to reduce the overall size and weight of the fuel cell system. Finite Element Analysis (FEA) of the primary components was completed to determine the structural strength and requirements for the enclosure frame and supporting hardware and vibration testing to meet the packaging requirements. This analysis was used to identify the required materials of construction and thickness to support the components, sub-systems, and the complete fuel cell system and source vibration isolators, tailored for the SMET vehicle. Several design options were iterated to meet light-weighting requirements.

Efforts are ongoing with packaging the system in a robust, compact, and lightweight configuration with ruggedization to meet MIL-SPEC targets.

3. SYSTEM PERFORMANCE

The SOFC system produced up to 10 kW_e of variable/continuous electrical power (Figure 5). The generated power was used to charge onboard batteries, power external components (i.e., user load), and provide for BOP parasitics. During vehicle operation, rapid transient demands (e.g., acceleration and turning) were managed via battery hybridization (Figure 6) Note that the instantaneous surges to 15 kW_e, necessary to execute vehicle maneuvers, were seamlessly provided by the battery/fuel cell hybrid setup. Vehicle demonstrations (stationary and mobile) were completed at PCI facilities as well as at Detroit Arsenal.

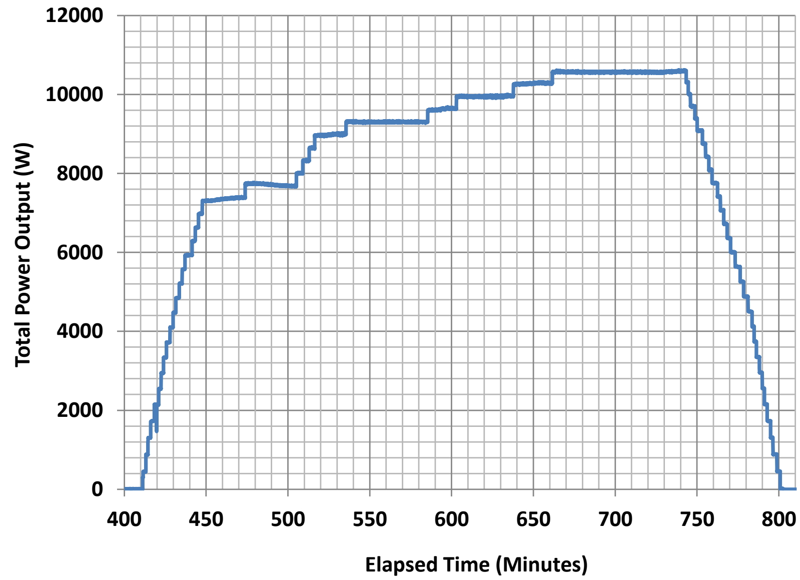

Figure 5: PCI's battery hybridized SOFC vehicle concept demonstrator prototype produced 10.7 kW_e (gross) with room for higher power output (~10 kW_e [net]).

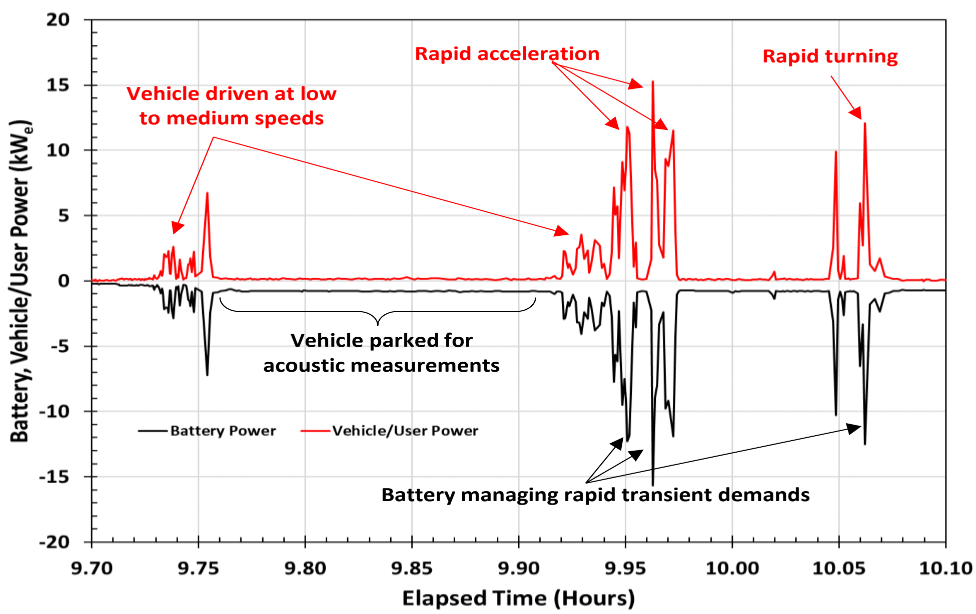

Figure 6: A window of the power profile of the battery hybridized SOFC vehicle prototype during drivability testing.

The vehicle was transported over public highways and subjected to ~1600 miles worth of on-road vibrations with no impact on system performance.

Unlike generators or other internal combustion engine-based systems, PCI's SOFC system was capable of silent operation for combat environments. When operating at power, the system registers at only ~60 dBA from 1 meter away. The measured background noise at the time of testing was also ~60 dBA. In comparison, a diesel generator producing 1.5 kW_e was experimentally measured at ~91 – 95 dBA from 1 meter away at the same background noise conditions.

4. FUTURE DEVELOPMENT

Efforts towards optimizing the weight, efficiency, and faster startup as well as adaptability to other vehicles are ongoing.

5. CONCLUSIONS

A F-24/JP-8 fueled, fuel cell based, electric-semi-autonomous vehicle integrated system was developed and successfully demonstrated. It was able to achieve strategic benefits of silent-watch, silent-mobility, and MIL-SPEC quality export-power with standard logistic fuels. This was the first demonstration of a long-envisioned goal and highlighted the potential of using a “solid state” power generation technology for a range of DoD applications – auxiliary power, propulsion, unmanned platforms, portable generators, sensors, etc. This advance has also created interest for commercial applications. Transition to field applications will require significant work.