Fuel-Flexible Fuel Cell Systems for Military Power Generator

Paul George, Vince Contini, and Doug Thornton
Battelle
Columbus, OH

ABSTRACT

Fuel Cell Systems offer high efficiency, quiet, clean, low signature power generation. To be useful for military applications they must use commonly available logistic fuels: JP8 is the primary fuel of choice. This paper reports the results of 1000 hour tests of innovative hardware to desulfurize and reform JP8. Results from early testing of a 6 kW fully integrated PEM fuel cell system operating on JP8 are also presented.

BACKGROUND

In 2004 Battelle recognized that microtech fuel reforming technology could beneficially be applied to military fuel cell systems. We embarked on a program of spiral development to understand the system integration requirements through building and testing fully integrated polymer electrolyte membrane (PEM) fuel cell systems. PEM fuel cells were chosen because of their commercial maturity and their ability to start and react quickly to load changes. The initial systems used synthetic JP8 – a zero sulfur, low aromatic fuel produced from natural gas via the Fischer-Tropsch process. These systems were highly useful in elucidating the issues with integrating a compact fuel processor, a PEM fuel cell and the balance of plant hardware. Intellectual property created included developing effective control algorithms and hardware to allow a battery hybridized system to respond to uncontrolled load changes. The first system built (Gen1) was tightly packaged to fit a box mounted on the back of a combat vehicle and use vehicle power for start-up and load management. Both the fuel cell and the fuel processing system proved inadequate. To assist with technology maturation, Battelle's additional developments have focused on stand-alone units. Two Gen2 units were built, one as a traveling demonstration unit and one to demonstrate start from -20 C. Both used synthetic JP8 and the original microtech fuel processor design. The Gen2 systems were demonstrated a variety of venues including AUSA on several occasions. The Gen3 fuel processor was a variation on the original design intended to reduce the cost of the reformer hardware. Cost reductions were achieved by application of design for manufacturing principles with the assistance of Battelle's production and field support group. Significant cost reduction was achieved but it also became clear that achieving military and commercial targets with the basic design approach would be difficult. Gen3 performance was initially superior to both Gen2 units; but the lifetime was not acceptable, less than 100 hours were achieved before cleaning and regeneration were required. The short life may have been partially attributable to ~2 ppmw sulfur which was found in the synthetic JP8 used in Gen3.

For our Gen4 system we used hydrodesulfurization technology that had proven capable of desulfurizing JP8 fuel up to 2500 ppm without requiring selective distillation or other pre-processing. In order to integrate with the overall system we made some innovative system changes that allowed the use of either reformate or hydrogen as the desulfurizing reactant.

For Gen4 we concluded that a radical departure from the previous reformer designs would be necessary to achieve adequate lifetime and cost. In parallel with Gen4 development we had conceived a completely different approach to fuel reforming that was designed for small systems (2 kW or less) to support a solid oxide fuel cell system development program. That design approach was named the CFF reactor for convenience, Upon review we determined that the CFF concept could be scaled successfully to 6 kW and higher and that it would significantly reduce cost. The decision was made to emphasize cost over an extremely compact design – essentially a trade between cost and performance of the reactor. The new design increased passage size, eliminated some fine features required by the original design and, for one-off fabrication, could be built for approximately 20% of the original cost with production cost even more attractive. Performance

Acknowledgements: Battelle gratefully acknowledges the support of the US Army TARDEC the development of the Gen1, Gen2 and Gen3 systems and the JP8 desulfurization technology. The support of the Ohio Department of Development was critical to inventing and testing the Gen4 reformer concept. The Gen4 system design was supported by the US Air Force Research Laboratory Advanced Power Technology Office.

and life were unknown. Given the experience with short lifetimes in the previous designs it was clear that some form of long-term test would be needed to assess the performance and life of both the desulfurization and reforming hardware. This paper provides the results of 1000+ hour tests on the desulfurization system and the CFF reformer and also provides initial test results from a fully integrated 6 kW continuous output PEM fuel cell system operating on JP8.

TEST OBJECTIVES

The test objectives for both the hydrodesulfurization (HDS) and Gen4 reformer were similar – to determine performance degradation over a 500 hour test period which would allow extrapolation to 1000 hours or longer in a full scale system. Specific, well controlled conditions were developed for each subsystem. Although the desulfurizer and reformer were undergoing test simultaneously for most of the test duration (HDS testing began before reformer testing), the systems were not directly connected. Since one obvious aspect of HDS performance was that it should produce a fuel acceptable to the CFF reformer, the reformer was operated on fuel that had been desulfurized by the HDS test system. The clean fuel used by the reformer was tested for sulfur level prior to being reformed to avoid any incidental sulfur contamination and to avoid damaging the reformer if HDS performance degraded. Because both systems were performing at design levels after 500 hours of testing, the testing times were extended to 1000 hours. Reformer testing continued to 1200 hours.

TEST RESULTS

HDS Test System

Figure 1 is a schematic of the HDS test system. The HDS and ZnO reactors were housed in a heated air duct to simulate being closely integrated with a fuel processor. A conventional air heater provided heated air to surround the reactors. Fuel and hydrogen were introduced through a proprietary fuel vaporizer which fed into the HDS reactor. The output of the HDS reactor was routed through a ZnO reactor (adsorption bed) and then to a fuel condenser. Non-condensable gases were sampled for H_2S and then rejected to a vent. Condensed fuel was collected and samples submitted for testing by an outside laboratory.

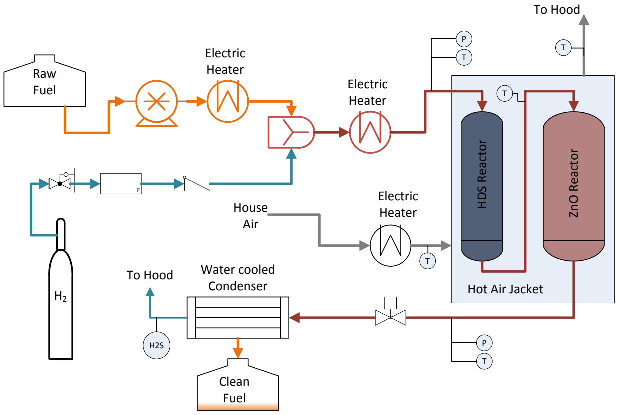

Figure 1. HDS Test System Schematic

Success criteria for this test were cleaned fuel residual sulfur level (less than 1 ppmw) and hydrogen sulfide gas concentration in the fuel condenser effluent stream (less than 10 ppmv). Testing was initially performed with commercially purchased JP8 (~150 ppmw sulfur). One drum of high sulfur (~2500 ppmw) JP8 was also available. After initial testing with the commercially purchased fuel, the high sulfur JP8 was blended with the commercial fuel to yield a fuel with 400 to 600 ppmw sulfur. At approximately 450 hours into the test, raw JP8 at 2500 ppmw was tested for one day with fuel segregated for residual sulfur testing. The remainder of the testing (500 hours and beyond) was conducted using flight-line grade JP8 provided by the Air Force Research Laboratory which had sulfur levels of between 500 and 600 ppmw (drum-to-drum analysis varied but remained within the 500 to 600 ppmw range). Initial plans were to test at full nominal fuel flow rate (10cc/min) for 500 hours and decrease flow rate if either success criterion was exceeded. Fuel residual sulfur showed virtually no change over the course of the test. Hydrogen sulfide levels reached the test termination/modification threshold at approximately 1000 hours and the test was terminated shortly thereafter having achieved twice as many hours as originally planned.

Figure 2 shows the measured residual sulfur in the fuel for the test duration. Note the single test point on 2500 ppm near hour 450. Sulfur levels prior to 200 hours were analyzed by an outside laboratory using a different, less sensitive method than samples after 200 hours. Pre-200 hour results are not reported here.

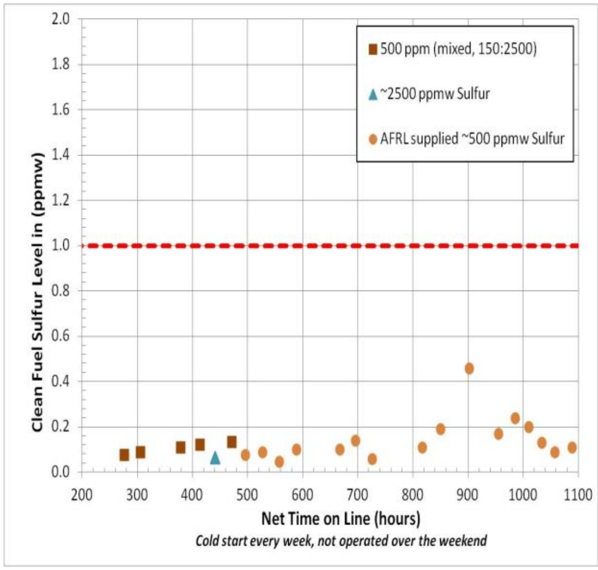

Figure 2. Residual Sulfur (by weight) in Clean Fuel as Measured by DCG Laboratories

Reformer Test System

Figure 3 is a schematic of the reformer test system. Superheated steam and fuel are mixed prior to the reformer; fuel is vaporized by injection into the hot steam. All fuel used was desulfurized JP8 from the HDS test system. Design flowrate for this sub-scale (~1 kWe) reformer was 4.5cc/min and most of the testing was performed at this flow rate. The test regimen varied over the 1200 hours of testing but included both daily start-stop cycles (cooled overnight) and continuous runs of over 100 hours (allowed to cool over the weekend). As noted above, most of the fuel began as flight-line JP8 with sulfur levels between 500 and 600 ppmw but was desulfurized to less than 0.5 ppmw. The steam/fuel mixture enters the reformer at approximately 450 C and passes over the reforming catalyst at a pressure between 150 and 300 psig. A burner provides heat to the reformer to provide the energy necessary for the endothermic steam reforming reaction and to increase the temperature to approximately 750 C at the outlet. For this test the burner operated on natural gas to allow independent control. In the fuel cell system described below, the burner uses reformate not consumed by the fuel cell. Reformate was sampled directly at the outlet of the reformer, pressure reduced, condensed to approximately 30 C, dried, and directed to a gas analysis system including quantitative measurements for Hydrogen, CO, CO2, total hydrocarbons (THC), CH4, and non-methane hydrocarbons (NMHC) by subtraction. Reformate not directed to the sampling system is air cooled, reduced in pressure and rejected to a vent. The gas analysis instruments were manually calibrated each test day using zero air and appropriate span gases.

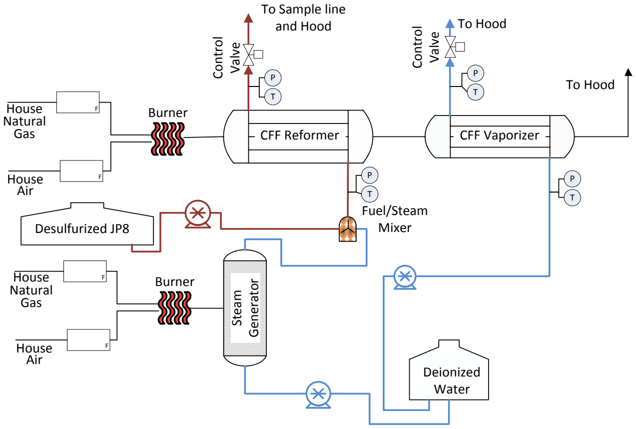

Figure 3. Reformer and Vaporizer Test Schematic

The criteria measurements for this test were NMHC level and condensate quality in the sample condenser. Specifically, NMHC levels above 1000 ppmv were considered to indicate a reduction in catalyst activity and fuel reformer capacity. While 5000 ppmv or higher (5X our threshold) would not be a problem in a our fuel cell systems (SOFC or PEM), an increase from below 100 ppmv to over 1000 ppmv would clearly indicate that catalyst activity was decreasing and could signal the onset of carbon deposition – a common failure mode for steam reformers. The other criterion was condensate quality at the sample point. We looked for evidence of any hydrocarbon film on the condensate. The presence of an oily film would indicate that some fuel or fuel derived higher molecular weight material was passing through the reformer but perhaps not reaching the THC analyzer because it remained in the sample condenser. The condensate was also checked for any telltale smell that could indicate the presence of hydrocarbons in the condensate that would not be detected by the THC analyzer.

At the nominal test target of 500 hours of full-load operation, NMHC levels remained below 500 ppm and sample condensate water was pristine. In the absence of significant change in criteria measurements, testing was continued under the same operating conditions. An increase in NMHC above 500 ppm was noted at approximately 600 hours. Because of significant variation and noise in NMHC levels prior to 600 hours we operated the system at a variety of loads to investigate the variability up to approximately 720 hours. Based on the results we determined that the hydrocarbon analyzer required repair and recalibration. Although the NMHC values between 400 and 720 hours may not be accurate, they are reported as recorded. At 729 hours the system was shut down for approximately one month for THC analyzer repair. At approximately 730 hours, after analyzer repair and a short shakedown test, testing continued with a fuel flow rate to the reformer of 3.5 ccm (78% of design load) to bring NMHC back below 300 ppm. Figure 4 shows the NMHC and hydrogen content of the reformate leaving the reactor and fuel flow rate into the reactor for the duration of the test. It is clear that reformer performance is decreasing over the final period of the test. As noted above, we would not expect to see a noticeable decrease in fuel cell system capacity unless NMHC values were much higher; but continued testing did not seem warranted based on the drop-off observed. No detectible increase in reformer pressure drop was noted throughout the test. We postulate that catalyst life is being affected by the residual sulfur in the fuel. Therefore catalyst life would be proportional to total fuel processed. To affect a longer run time for the 6 kW system the catalyst was proportionally greater on a grams of catalyst per liter/minute of fuel flow basis than used in this test.

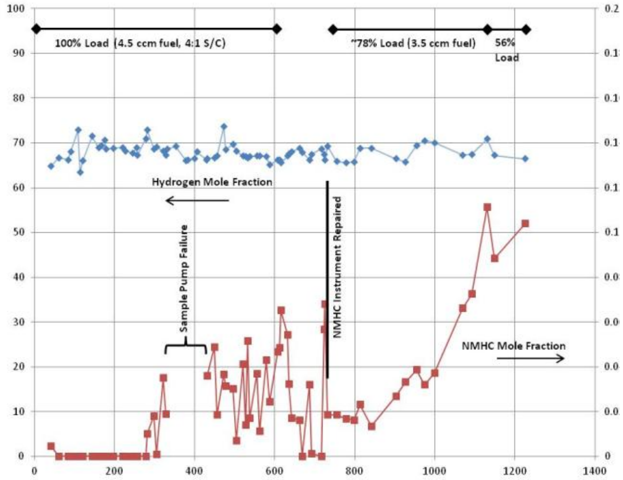

Figure 4. Reformate Composition During 1200 Hour Test

6 kW System Design

The results reported here provided the engineering information to allow designing and building a full scale (6 kWe continuous, 10 kWe peak) PEM fuel cell system capable of operating on any JP8. The PEM system, designated Gen4, includes up-scaled versions of both the reformer and desulfurizer. Reforming catalyst quantity (on a grams/ccm fuel basis) was increased in the scaled up reformer to provide longer run times before cleaning refurbishment. The fuel processor has been integrated with the remainder of the fuel cell system (See Figures 5 and 6) and operated to demonstrate:

- Continuous power of 5.8 kW
- Desulfurization of fuel at a faster rate than fuel is being consumed
  - This applies during steady state operation. Excess desulfurization is necessary to replenish the fuel used during start-up when clean fuel is not being produced.
- Desulfurized fuel with less than 0.1 ppmw residual sulfur. Initial fuel sample sulfur levels from Gen4 were below the detection limit of (0.1 ppmw). Based on the long term test results we expect that steady state values after catalyst conditioning may be somewhat higher – about 0.3 ppmw but still acceptable).

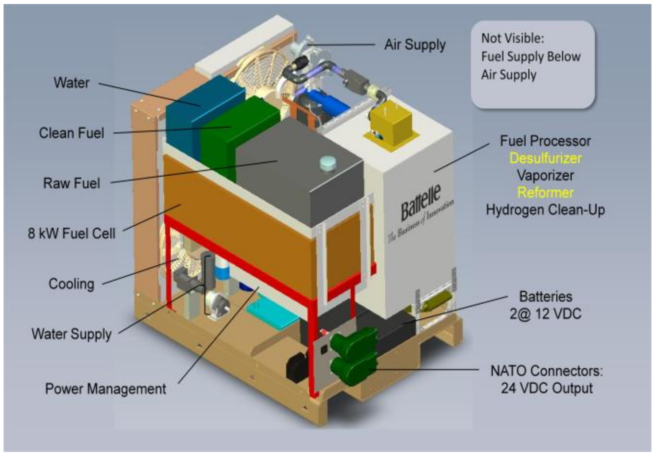

Figure 5. Annotated Rendering of Gen4 System Shown from Right Rear

As currently configured fuel desulfurization rate can be adjusted to balance or exceed the clean fuel consumption rate. All desulfurized fuel is condensed and stored in a clean fuel tank. Fuel to the reformer is taken from the clean fuel tank: start-up from room temperature requires approximately 2 liters of clean fuel which must then be replenished during operation. Typical operation is with fuel desulfurization approximately 10% greater than clean fuel usage until the clean fuel tank is full. At that point desulfurization is reduced to less than consumption until tank level drops to approximately 60% (assures enough fuel for two starts without desulfurizing any additional fuel.)

Figure 6. Gen4 System Photo with Test Instrumentation in Place. Shown from Left Front to Show Air System (black cylinders) and Fuel Supply System (immediately behind air system)

Figure 7 is a plot of output power and water tank level as a function of time during a test on July 18, 2012. Water level at the start of the test was 54% which declined to 40% during start-up. Two liters of water was added to the water tank at about 1.5 hours into the test according to the standard operating procedure for tests when the fuel cell is not in operation. After that point no more water was added from outside the system. At low fuel cell power levels water level is increasing slightly. As fuel cell power is increased, water recovery rate increases. During this test coolant temperature is controlled to 40 C by radiator fan operation. Radiator fans were at approximately 70% of capacity for the high power portion of the test (3 to 4 hours test duration). Laboratory ambient for these tests was 25 C.

The difference between the Power Management Module output (PMM) and fuel cell power output shown in Figure 7 is related to parasitic power. The primary parasitic power draw is for the radiator fans. Fan power increases as fuel cell power increases. There are two separate radiators – as shown in Figure 6. The smaller radiator is the main radiator that is responsible for water recovery. The larger radiator is responsible for fuel cell cooling. As noted above, main radiator fans were operating at an average of 70% power during the final hour of the test. The fuel cell radiator fans were cycling from off to 20% power (minimum for reliable start and run) at about 90% duty cycle during the same period.

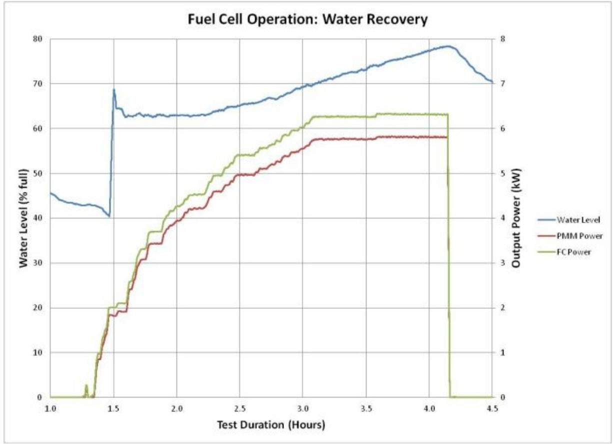

Figure 7. Water Recovery During Fuel Cell Operation on July 18, 2012

CONCLUSIONS

Fuel desulfurization and reforming are critical technologies to enable the use of fuel cell systems by the US Military. Sub-scale testing of these critical components showed that lifetimes in excess of 1000 hours could be achieved. In addition, the sub-scale testing provided the engineering information needed to design a 6 kW fully integrated PEM fuel cell system operating on flight-line quality JP8 – including sulfur levels potentially up to 3000 ppmw. A prototype system was built and tested briefly at Battelle with additional testing planned. Future testing has been proposed for the U.S. Army TARDEC GSPEL fuel cell laboratory where noise level, system efficiency, clean fuel quality, and extended run time operation will be evaluated.