HYDROGEN FUEL-CELL LOCOMOTIVE: SWITCHING AND POWER-TO-GRID DEMONSTRATIONS

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Abstract

An industry-government consortium has developed a prototype zero-emissions, hydrogen-fueled, fuel-cell hybrid switch locomotive for urban and military-base rail applications. With 130 t weight and maximum power of 1.5 MW from its proton-exchange membrane fuel-cell prime mover and auxiliary traction battery, the hybrid locomotive is currently the heaviest and most powerful fuel-cell land vehicle. The observed mean thermodynamic efficiency of the powerplant is 51 %. Compressed hydrogen fuel is stored in carbon-fiber composite tanks (maximum pressure of 35 MPa) located at the roofline. On an energy-content basis, hydrogen fuel produced on a large scale is comparable today in price to diesel fuel. Depending on the duty cycle of the railyard, onboard storage is sufficient for an 8-16 h operational shift. The locomotive successfully completed a rigorous yard-switching demonstration during 2010. The demonstration results show that use of hydrogen fuel cells in the harsh, heavy rail environment is technically feasible. The locomotive performed well in all respects and garnered good worker acceptance. The locomotive was also successfully demonstrated as a mobile backup power source on a military base. A large vehicle that is environmentally benign can operate as a mobile backup power source (power-to-grid) and provide energy security for critical applications.

1. INTRODUCTION

Issues of urban air quality and energy security are related by the fact that about 97 % of the energy for the transport sector in the US is based on oil and more than 60 % is imported. Because the sector's primary energy derives so predominantly from combustion of fossil fuels, it is one of the largest sources of air pollution, including greenhouse gases.

A public-private project partnership comprised of Vehicle Projects Inc, BNSF Railway Company, and the U.S. Army Corps of Engineers (through the Engineer Research and Development Center Construction Engineering Research Laboratory, ERDC-CERL) has developed a prototype fuel-cell-powered switch locomotive (see Fig. 1) for urban rail applications. This prototype is intended to evaluate this technology's feasibility to (a) reduce air and noise pollution in urban railyards, (b) increase energy security of the rail transport system by using a fuel, hydrogen, whose supply is independent of imported oil, (c) reduce atmospheric greenhouse-gas emissions, and (d) serve as a mobile backup power source for

Fig. 1. Fuel-cell switch locomotive: This is the largest fuel-cell land vehicle, photographed at a press conference in completed form on 29 June 2009.

critical infrastructure on military bases and for civilian disaster relief efforts. A large vehicle that is environmentally friendly opens up a new application: The locomotive can serve as a mobile backup power source, termed “vehicle-to-grid,” for critical infrastructure. Vehicle-to-grid applications include military bases and civilian disaster-relief operations.

Specifically, the fuel-cell-hybrid switch locomotive project was initiated to demonstrate that a fuel-cell locomotive is a technically feasible solution to reducing emissions and engine noise in urban areas such as Los Angeles, California. Because of its topography and its reliance on the automobile for transportation, Los Angeles has historically had air-quality problems. It is also the site of the adjacent ports of Long Beach and Los Angeles, the largest seaports in the United States, which contribute to air pollution from trucks, trains, and ships. The most significant emissions are diesel particulates and nitrogen oxides. The project also was initiated to demonstrate the important potential of power-to-grid to provide energy security to critical infrastructure.

Fig. 2. Locomotive under construction: Right-rear view of the locomotive with installed fuel-cell prime mover shown in the foreground (31 July 2008)

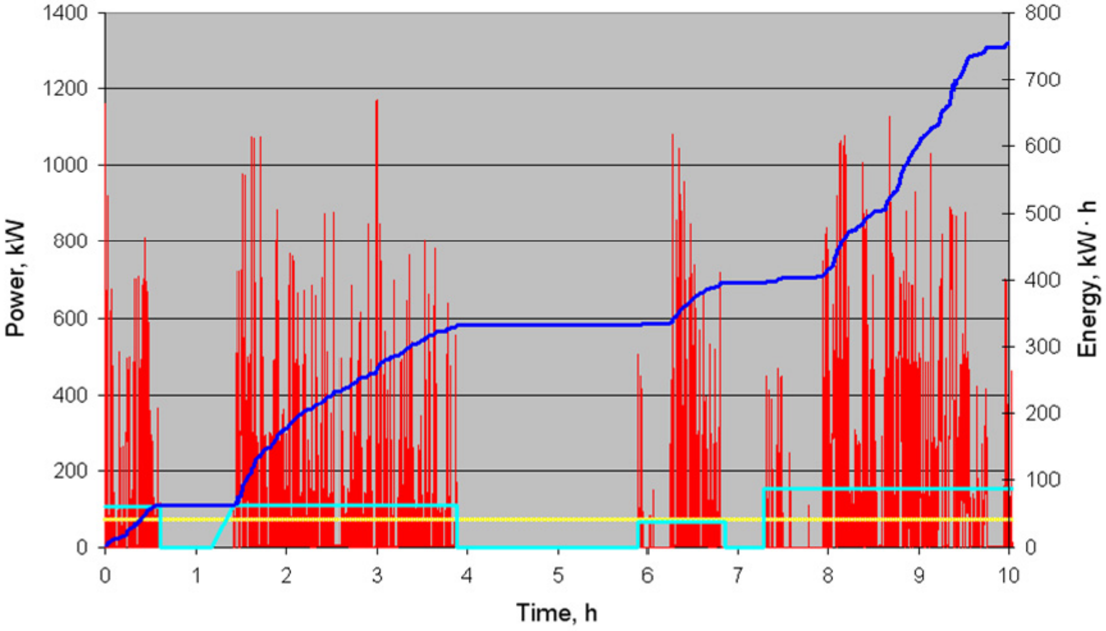
Previous papers have discussed the theory [1-3] and engineering design [4-6] of the hybrid locomotive. While the fuel-cell locomotive is the largest fuel-cell land vehicle to-date, it is not the first fuel-cell locomotive. The first was an underground fuel-cell (non-hybrid) mine locomotive successfully completed and demonstrated in a working gold mine by Vehicle Projects Inc during the period 1999-2002 [7, 8].

This paper focuses on operation of traction fuel cells in the harsh, heavy rail environment. Both its operation as a switch locomotive and in a power-to-grid application are discussed.

2. POWERTRAIN DESIGN

The rational starting point for engineering design of a fuel-cell-hybrid powertrain is the duty cycle [9]. Fig. 3 shows a typical duty cycle – that is, required vehicle power P as a function of time t – empirically recorded from a yard-switching locomotive. The vehicle’s required mean power, maximum power, power response time, and power duration may be calculated from continuous function P; its energy storage requirements are calculated from the integral of P. As shown, peaks of the function commonly reach 0.6-1.0 MW, but peak width is no more than several minutes, usually corresponding to acceleration of train cars or uphill movement. However, between the peaks, the power requirements are minimal, as when coasting a load, or zero when idling between move operations. The idle time for a switch locomotive, varying from minutes to hours between operations, usually accounts for 50-90 % of the overall operation schedule. Our analysis of multiple duty-cycle data sets from various railyards shows that the short duration of peak power and long periods of idle time result in mean power usage in the range of only 40-100 kW. The sharp peaks, low mean power, and long idle intervals of the duty cycle are ideal for a hybrid powertrain [1-3].

For a hybrid vehicle to be self-sustaining, the prime mover, a hydrogen proton-exchange membrane (PEM) fuel cell in this case, must be capable of providing continuously at least the mean power of the duty cycle. While our fuel-cell powerplant is capable of continuous net power of 240 kW, a thermal limitation of the onboard DC-DC converter limits *continuous* power to 200 kW. The auxiliary energy storage device, a battery in this case, must store sufficient energy to provide power, in parallel with the fuel cell, to allow the vehicle to scale any peak in the duty cycle. This power must be available while not exceeding a rather shallow depth of discharge, which significantly increases the size of the battery. Allowable depth of discharge is a function of acceptable battery cycle life and recharge rate. Our system maintains battery charge within 60-80 % of full capacity. The lead-acid traction battery, in parallel with the fuel-cell prime mover, allows transient power (maximum power) of 1.5 MW for about 5 minutes. For the power-to-grid application, power is taken from the main traction-motor bus and thus the load capacity of the locomotive should be the same as for traction (e.g., 1.5 MW for about 5 minutes). However, the off-board power inverter, providing three-phase AC at 440 V, limits the power into the grid to 250 kW.



F**ig. 3 – Duty cycle**: Sample switch locomotive duty cycle.

The fuel-cell powerplant consists of four primary subsystems; fuel-cell stack modules, air delivery, cooling, and power electronics. At the heart of the power module are two Ballard Power Systems P5 fuel-cell stack modules, which are each rated at 150 kW gross power at 624 V, for a total of 300 kW at 624 V. Each fuel-cell stack module includes the auxiliary components for air and hydrogen humidification, water recovery, hydrogen recirculation, and hydrogen purge. Hydrogen is supplied to the stack modules at a nominal pressure of 1.2 MPa. The cooling system rejects waste heat from the fuel-cell stacks as well as auxiliary motors and power electronics. The electrical distribution and control systems regulate power output, control various electrical devices, and monitor system parameters for faults.

The compressed-hydrogen storage system is also modular. In total, 14 carbon-fiber composite cylinders store 68 kg at 35 MPa. A thorough safety analysis highlighted two factors that led to packaging the hydrogen system above the battery: (a) Because of the buoyancy of hydrogen, roof-line storage allows harmless upward dissipation of hydrogen in the event of a leak. (2) Locating the hydrogen tanks at the roofline minimizes the likelihood of damage from events such as derailment, track debris, and impact from yard traffic. The roof location of the relatively light hydrogen storage tanks (95 kg empty for each) has minimal effect on vehicle center of gravity.

At 130 t weight and transient power of 1.5 MW for approximately five minutes, the hybrid locomotive is the heaviest and most powerful fuel-cell land vehicle yet built. The combined weights of fuel-cell powerplant and carbon-fiber hydrogen storage system are substantially lighter than the diesel engine-alternator and fuel tank they replace. Because a locomotive has a fixed operating weight to maintain wheel adhesion, a steel-plate ballast of 9 x10^3 kg was placed in the undercarriage bay.

A second-generation locomotive, with the capability of pulling short trains between railyards – in addition to the capabilities described above for the first-generation locomotive – is under construction. The modularity of the fuel-cell power system has enabled Vehicle Projects Inc to increase the steady-state net power to approximately 480 kW by adding a second 240 kW power module. To further improve system efficiency, the two modules can be operated together or independently. The second-generation power electronics hardware is expected to handle the entire net power on a continuous basis. Additionally, hydrogen storage is being increased to approximately 300 kg. This is accomplished by increasing hydrogen pressure to 45 MPa and utilizing more tanks. The key to packaging the larger storage tanks is use of a more energy-dense, compact lithium-ion battery under the hydrogen system.

3. OPERATIONAL TESTING

Extensive impact testing was performed to validate shock isolation design. Equipment isolation systems were designed with low natural frequencies, in the range of 3-7 Hz, which minimizes potential resonance with onboard equipment and track vibrations. Relatively soft mounts provide dynamic deflections up to 25 mm and enables maximum energy dissipation.

The fuel-cell locomotive then completed several weeks of operational testing at the BNSF Commerce and Hobart yards in the Los Angeles, California, metro area. The locomotive work schedule involved the movement and assembly of flat cars, tank cars, and hoppers within the Commerce yard, as well as a five-kilometer movement of short consists of 10-30 cars between the Commerce and Hobart yards. The fuel-cell locomotive performed all operational testing as a single-unit locomotive; thus, all work was provided solely by the fuel-cell prime mover. Trains pushed and pulled by the locomotive ranged in weight from 180 to 1600 t.

The locomotive performed the work well in all respects. The fuel-cell powerplant and associated cooling and fuel systems performed without issue during the repeated couplings to other rail equipment. During all work shifts, the fuel cell-battery hybrid powertrain was successful in providing adequate power to the traction motors.

Table 1: Fuel-cell Powerplant Performance

Gross power operating range of fuel-cell stacks	0 – 300 kW
Mean observed gross power	105 kW
Mean observed net power	87 kW
Mean fuel usage	5.6 kg/h
Usable onboard hydrogen storage at 20 °C	63.5 kg
Mean required refueling interval	11.3 h
Balance of plant parasitic losses	17 %
Mean powerplant thermodynamic efficiency	50-51 %

Interface between the train engineer and the locomotive is nearly identical to a conventional locomotive. Training of new operators took only a few minutes, which included an overview of unique circuit breakers, information screens, explanation of safety systems, and discussion of appropriate reaction to possible events. More than five train engineers operated the fuel-cell locomotive, and all left with an overall positive impression and expressed a consensus that it was pleasant to operate due to the lack of diesel emissions, lack of vibration, and low acoustic noise. The fuel-cell powerplant is virtually silent in the operator's cab, most of the noise being the noise of the steel wheels rolling on the tracks.

Several engineers commented favorably on the quick throttle response compared to the turbo-diesel engines they normally operate.

Operation of the fuel-cell powerplant was closely monitored, and data for key parameters were logged at one-second intervals. Of particular interest is the mean operating gross and net power levels, associated fuel consumption, and the resulting overall fuel-cell powerplant thermodynamic efficiency. Thermodynamic efficiency is defined as $E_{FC}/\Delta G_H$, where E_{FC} is the net electrical energy produced by the fuel cells during a 1 h time interval, and ΔG_H is the Gibbs free energy of oxidation to gaseous water of the hydrogen fuel consumed during the same time interval. The overall thermodynamic efficiency of the fuel-cell powerplant is thus calculated as 51 %. This computation is based on the free energy of forming *gaseous* water output of the fuel cells, the actual chemical output. Though not feasible in our PEM fuel cells, the thermodynamic efficiency would be 50 % if the chemical energy is taken as the free energy of hydrogen oxidation to *liquid* water.

Table 1 summarizes overall performance data based on preliminary operating data taken over the course of 16 days of switching operations. The observed mean net power requirement of the locomotive in switching operations was 87 kW. Observed mean fuel consumption for this power was 5.6 kg/hr. Total *usable* tank capacity is 63.5 kg at 20 °C, which yields an average mean shift duration of 11.3 hours. Therefore, for this application, daily refueling would likely be required. With a sufficiently large off-board hydrogen pump in the fueling station, refueling of the system would take 15-20 minutes. However, because of the long idle times in the duty cycle, during which refueling can take place, we use a relatively small pump, and the actual refueling time is about 45 minutes.

The locomotive has also completed its demonstration in the vehicle-to-grid application. It operated in this capacity at the US Army Defense Generator and Rail Center located on Hill Air Force Base, Utah, where it provided the sole source of power to the heavy-rail repair and rebuild shop. This shop serves as the only shop for the Army's fleet of switch locomotives, which are located at bases throughout the United States. The rail shop executes all major repairs, including diesel-engine rebuilding, rewinding of traction motors and traction alternators, and chassis repair.

Vehicle-to-grid testing at the base was performed over the course of six days. Fuel-cell DC output power was converted to 440 V three-phase AC power to the building by an off-board AeroVironment AV-900 inverter, which is limited to a maximum power of 250 kW. With a larger power inverter, the locomotive would be capable of providing power of 1.5 MW for short durations. Surge power exceeding the maximum continuous fuel-cell power of 240 kW would deplete energy from the locomotive battery, requiring the fuelcell to charge the battery at the next available opportunity. During the demonstration period, the mean facility power requirement was 65 kW. At this load, the hydrogen fuel consumption was 3.4 kg/h. With onboard usable fuel storage of 63.5 kg, the approximate runtime on one fueling would be 19 hours. Compressed hydrogen can easily be delivered or stored near the vehicle-to-grid point of use. A typical commercial hydrogen tube trailer contains approximately 300 kg of hydrogen, and the fuel cell run-time at a load of 65 kW using such a tube trailer would be about 88 hours. If the powerplant operated at maximum continuous power of 240 kW, the approximate fuel consumption rate would be 12.6 kg/h, yielding a run time of 24 hours.

4. DISCUSSION

These demonstrations, railyard switching and vehicle-to-grid backup power, have shown that use of fuel cells in a harsh, heavy-rail environment is technically feasible. The locomotive performed well in all respects and garnered good worker acceptance. The fuel-cell powerplant is virtually silent in the operator's cab, most of the noise being the noise of the steel wheels rolling on the tracks. Locomotive operators commented favorably on the quick throttle response compared to turbo-diesel locomotives. The locomotive routinely pulled trains weighing up to 1600 t. Operational data from the Los Angeles railyard show that a fuel-cell locomotive, being a zero-emissions vehicle, has the potential to reduce urban emissions of diesel particulates, nitrogen oxides, and noise.

Fuel-cell continuous net power is 240 kW, with transient maxima of about 1.5 MW. The very large power electronics devices for a locomotive, however, are the limiting factors in provision of continuous power. The onboard DC-DC converter limits continuous traction power to 200 kW and the off-board inverter for power-to-grid limited that application to 250 kW continuous net power. The second-generation locomotive, currently under construction, is expected to overcome this limitation. As locomotive fuel cell powerplants increase to the megawatt size, the potential will grow for use in emergency or contingency operations. A fuel-cell locomotive, because it is environmentally benign, can ensure a clean, quiet, mobile power source that can operate for extended periods in times of need.

Fuel-cell technology has a potentially significant role in the future of the rail industry. The operational data collected during the demonstration in Los Angeles will be invaluable in the development of future fuel-cell hybrid locomotives. It will assist in modeling their performance in order to optimize hybridization and maximize fuel economy.

5. CONCLUSIONS

These demonstrations, railyard switching and vehicle-to-grid backup power, have shown that use of fuel cells in the harsh, heavy-rail environment is technically feasible. Operational data from Los Angeles railyards show that a fuel-cell locomotive is a feasible machine, and by virtue of being a zero-emissions vehicle, has the potential to reduce urban emissions of diesel particulates, nitrogen oxides, and noise. A large vehicle that is environmentally benign, in combination with a hydrogen fuel source, can operate as a mobile backup power source (power-to-grid) and provide energy security for critical applications.

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