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DESIGN AND PERFORMANCE OF SERC'S PROTOTYPE FUEL CELL POWERED VEHICLE

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Introduction

The Schatz Energy Research Center (SERC) is now engaged in the three year, $3.9M Palm Desert Renewable Hydrogen Transportation System Project. The Project involves a consortium which includes the City of Palm Desert, SERC, the U.S. Department of Energy, the South Coast Air Quality Management District, and Sandia and Lawrence Livermore National Laboratories. Its goal is to develop a clean and sustainable transportation system for a community. This goal will be accomplished by producing a fleet of fuel cell vehicles, installing a refueling infrastructure utilizing hydrogen generated from solar and wind power, and developing and staffing a fuel cell service and diagnostic center. We will describe details of the project and performance goals for the fuel cell vehicles and associated peripheral systems.

During the first stage in the project SERC has, in the past year, designed and built a prototype fuel cell powered personal utility vehicle (PUV). In this paper, we will describe each of the steps involved in this process:

- Designing, building, and testing a 4.0 kW proton exchange membrane (PEM) fuel cell as a power plant for the PUV.
- Designing, building and testing peripherals including the air delivery, fuel storage and delivery, refueling, water circulation, cooling, and electrical systems.
- Devising a control algorithm for the fuel cell power plant in the PUV.
- Designing and building a test bench in which running conditions in the PUV could be simulated and the fuel cell and its peripheral systems tested.
- Installing an onboard computer and associated input/output electronics into the PUV and debugging.
- Assembling and road testing the PUV.

PUV System and Fuel Cell Design

As the first step in the design and construction of the SERC prototype fuel cell PUV, we selected the E-Z-GO golf cart to serve as the platform because it was already established and accepted in the Palm Desert community and used an efficient motor and motor controller. We then acquired, instrumented, and tested an original, battery powered E-Z-Go Golf Cart. This provided information on the performance and power demands that the PUV fuel cell power plant would have to satisfy and allowed preliminary system design and sizing of the proton exchange membrane (PEM) fuel cell stack required for the prototype.

Based on these tests, we developed a parallel hybrid design for the system that incorporates three small lead acid batteries to provide power for acceleration and hill climbing. In this role, the batteries provide a small buffer for short term power demands and are recharged during normal cruising and idling conditions. Control of the system was assigned to an on-board computer that permits the PUV operator to start and drive the cart in a straightforward manner. The control computer also provides a lap-top computer with real-time information on the status of all PUV systems. The lap-top both displays and stores the data for further analysis later. The design of the PUV systems and the control software have been reviewed and revised to protect the operator and the PUV by the use of inherently safe hardware design and numerous software safety interlocks.

The PEM stacks developed and operated by SERC have been designed to be simple and to have high net efficiency. Consequently, they are designed to run efficiently on air at very low pressure. Although this entails some sacrifice in performance relative to high pressure fuel cells, a simple, low power blower (vs. a compressor) can be used to provide the air supply.

The fuel cell stack developed for and used in the prototype was designed:

- to operate throughout the entire range of driving conditions at a voltage compatible with the E-Z-GO motor controller,
- to provide sufficient power to cruise at constant speed up a mild incline and still charge the batteries,
- to require low parasitic loads for auxiliary systems such as air supply, water circulation, control computer, solenoids, sensors, etc., and
- to operate efficiently.

To meet these demands, the resulting fuel cell stack contains 64 cells with 300 cm^2 active area and delivers more than 4.0 kW peak power. During cruising conditions, the stack operates at 0.71 volts/cell which corresponds to a 57% stack efficiency (LHV). The required stack air inlet pressure is less than 2 psig.

Figure 1 provides a simplified schematic diagram of the prototype system. All of the energy to power the cart comes from the hydrogen stored onboard in two compressed gas cylinders that together hold about 0.16 kg H_2. The hydrogen plus air from a low power, high efficiency blower combine in the fuel cell stack and provide power to the traction bus through a DC-to-DC converter. The power to the PUV's 1.5 kW series DC motor is controlled by the driver via the E-Z-GO motor controller. Power from the traction bus also charges the batteries during normal idling and cruising conditions and power is provided to the traction bus from the batteries during periods of acceleration and hill climbing. Although the batteries store about 30 amp-hrs, only a small fraction of this capacity is normally utilized. Power for all of the auxiliary systems is drawn from the traction bus through a small DC-to-DC converter. The control algorithm for the fuel cell power plant in the PUV manages the power demand on the fuel cell stack plus the air flow, battery charging/discharging, and system heat management.

PUV Construction

Following testing of the original, battery powered cart and the design of the PUV system and fuel cell, the fuel cell stack was constructed and tested and the individual PUV auxiliary or peripheral subsystems were designed and individually tested and calibrated. The PUV peripheral subsystems include:

- air delivery,
- fuel storage, delivery, and refueling,
- water circulation and cooling,
- electrical systems, and
- on-board computer hardware and software.

In the design and testing of each of these subsystems, component safety, reliability, size, and parasitic power demands were important considerations.

Prior to assembly in the PUV, the complete system including the onboard computer was installed on a specially designed test bench so that PUV running conditions could be simulated and the fuel cell, the peripheral systems, and the control algorithm could be tested as they functioned in a complete system. The test bench incorporated duplicate and redundant data acquisition , safety checks, and system controls. This facilitated debugging of the system hardware and software and optimizing the control algorithms in a safe and convenient manner. A 12 kW programmable electronic load was used to impose on the traction bus different steady-state and transient loads that were patterned after those observed during the testing of the original golf cart. Near the completion of the bench testing, the actual cart motor controller and motor were used to load the traction bus while the cart was operated on a dynamometer.

As the component selection and later the bench testing were taking place, the original cart was stripped to the chassis and structurally modified. A fiberglass cover was designed and crafted to cover the fuel storage compartment and the air delivery, fuel storage/delivery/refueling, and the water circulation subsystems were installed. After bench testing, the electrical and on-board computer system were installed. While still in the lab, the PUV system was tested and debugged under idling and low power steady state conditions using a small dynamometer.

The development and testing of the PUV systems were greatly facilitated by the use of specially designed software that permitted real-time monitoring during bench, lab, and finally, on-road testing. Figure 2 shows the display screen provided by the Portable Cart Monitoring Tool (PCMT) software. PCMT displays fuel cell stack current, the average cell voltages for 4-cell blocks in the stack, the air flow to the stack, the stack temperature, the current to/from the battery, the hydrogen storage pressure, and many other useful sensor readings.

PUV Testing

After the lab evaluation was completed, the PUV was further tested at a nearby race track where the original cart trials had taken place. In a series of runs, the PUV would begin at a standing start, accelerate to its maximum speed, and then continue cruising through the remainder of the 0.25 mile course on a level track. Figure 3a compares the power provided to the motor controller during such a run in the original, battery powered E-Z-GO golf cart and the SERC fuel cell powered PUV. Under essentially identical conditions, both the original cart and the SERC PUV exhibit a sharp initial power demand of 6 to 9 kW in the first 1 to 2 seconds that then quickly drops over the next 8 seconds to a steady-state cruising power of about 1.5 to 1.6 kW. In Figure 3b, the scale of the power axis is expanded to show that during steady-state cruising the SERC PUV is providing about 100 W more power to the motor controller than the original battery powered cart. This is the result of maintaining the traction bus at a slightly higher voltage during cruising. As a result of the higher cruising power, the SERC PUV has a slightly higher cruising speed of 13 mph vs. the original 12 mph which causes the SERC PUV to finish the 0.25 mile course 7 sec. faster.

Figure 4 shows how the power demands to the motor controller and the parasitic loads are partitioned between the fuel cell and the battery during the test run. Before the start while the PUV is idling, the power is all coming from the fuel cell and is being used to support the parasitic loads and to recharge the battery. In the first 2 seconds of the run as the fuel cell output ramps up, the sharply peaking power demands of the motor controller are met by both the fuel cell and the battery but the majority is from the battery. After 2 seconds, the fuel cell has ramped up and the contribution from the battery falls quickly to zero by 10 seconds into the run. For the remainder of the run, the fuel cell again provides all of the power to the motor controller and the parasitic loads and also recharges the battery. After completing the 0.25 mile run at 70 seconds, the PUV returns to idle conditions.

Since one of the major objectives in the design of the fuel cell stack and the PUV subsystems was the minimization of parasitic loads, it was rewarding for us to examine the parasitic load observed during the test runs. Figure 5 presents the actual parasitic loads observed during the run vs. the power provided to the motor controller. Under idling conditions, the parasitic load is approximately 80 W. As the power to the motor controller increases up to about 2000 W, the parasitic loads remain approximately constant. Above 2000 W, the parasitic loads increase approximately linearly with power to the motor controller and reach a maximum of about 250 W. From about 2000 W to the maximum power point, the parasitic load is only about 4% of the power to the motor controller.

Table 1 summarizes the specifications for the prototype fuel cell powered (PUV) as built and tested.

Conclusions

On November 1, 1994, SERC submitted to the City of Palm Desert a report comparing fuel cell, battery, and gasoline powered golf carts and soon after agreed to design, build, and introduce a prototype fuel cell powered PUV at the November 5, 1995 Palm Desert Golf Cart Parade. The prototype PUV was completed on schedule and did debut on November 5, 1995 at the Palm Desert Golf Cart Parade. The cart performs well and meets our initial goals.

At present, we are completing the construction of the first PUV to be delivered to the City of Palm Desert as part of the Palm Desert Renewable Hydrogen Transportation System Project. By the end of this year, we will deliver at least two additional PUVs, have installed an interim hydrogen refueling station, be well into work on the first neighborhood electric vehicle (NEV), and have completed design of the photovoltaic hydrogen production system.

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Figure 1. Schematic of Prototype SERC PUV

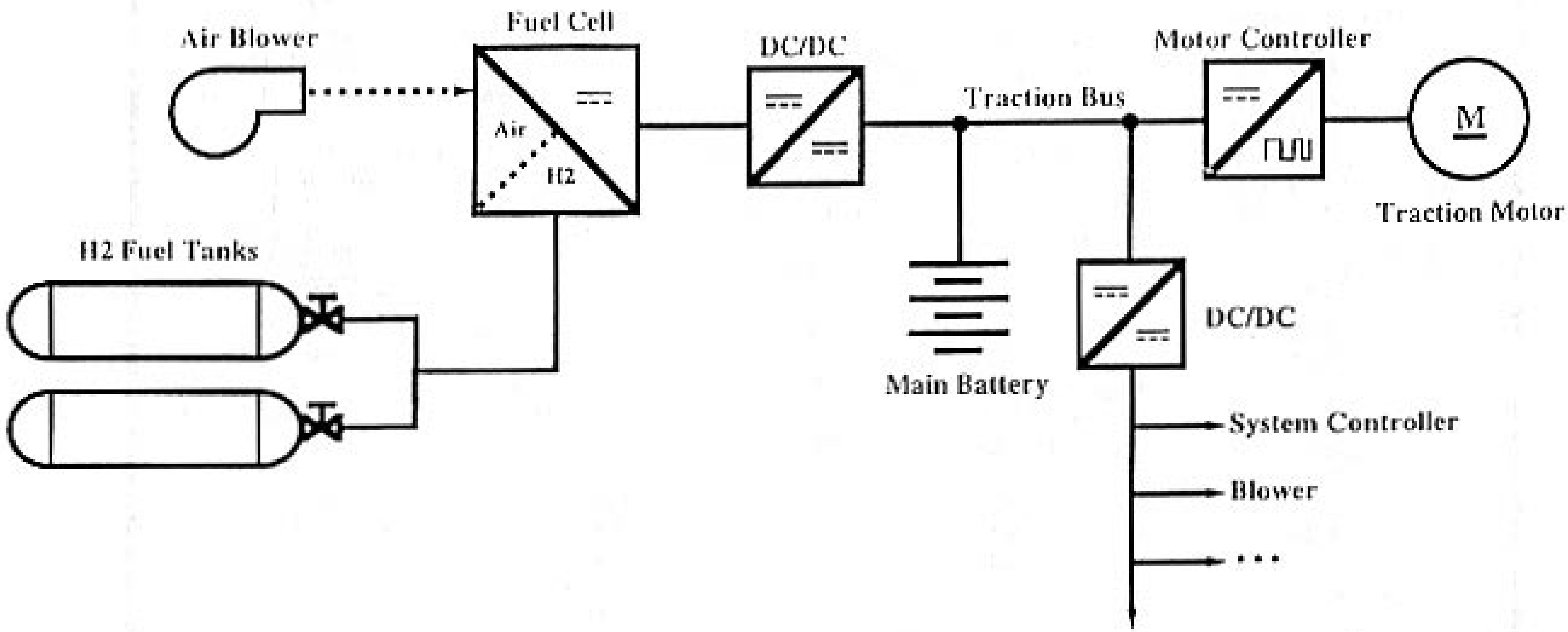

Figure 2. Display Screen for Portable Cart Monitoring Tool

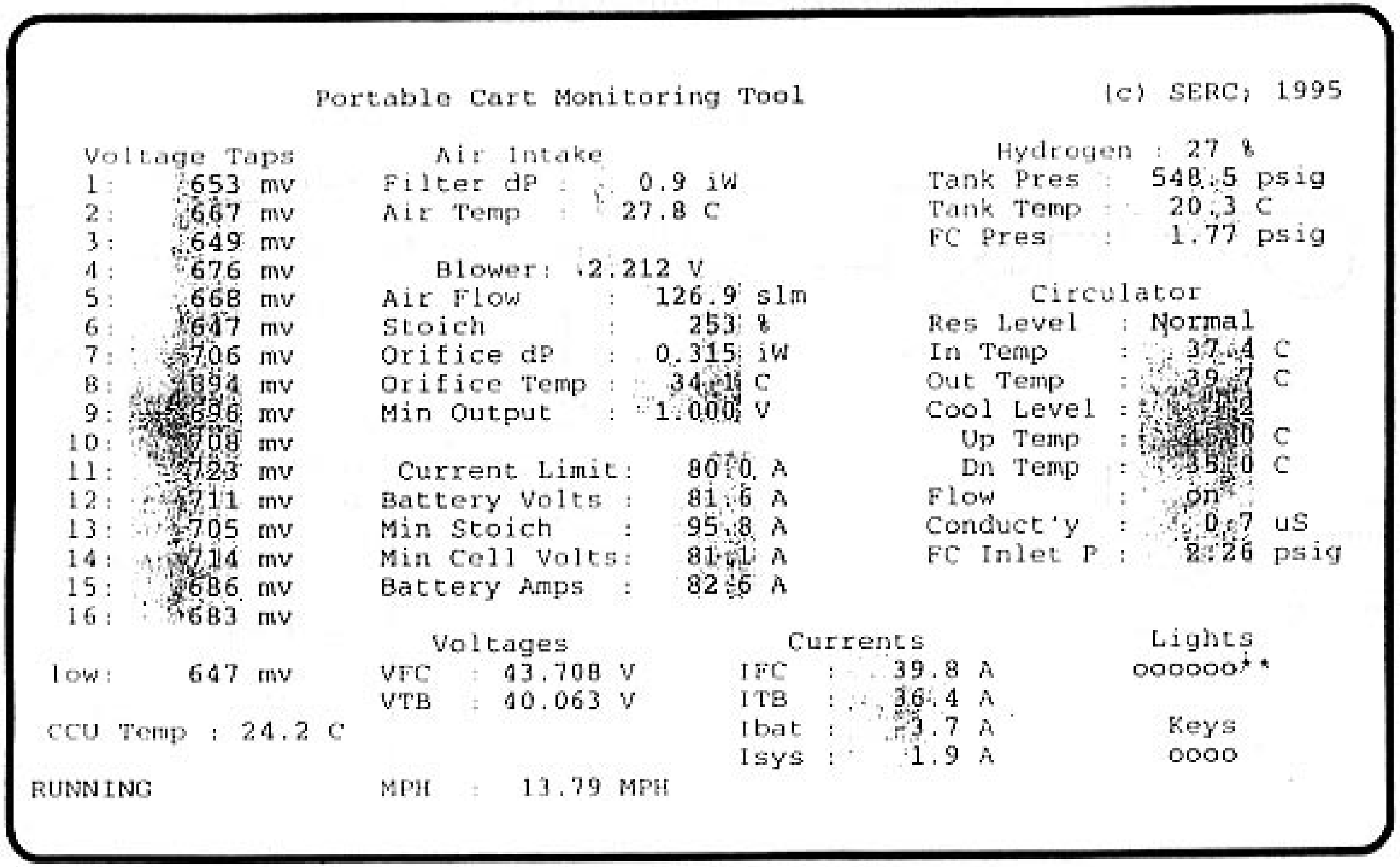

Figure 3a. Performance of SERC PUV vs, Original Cart

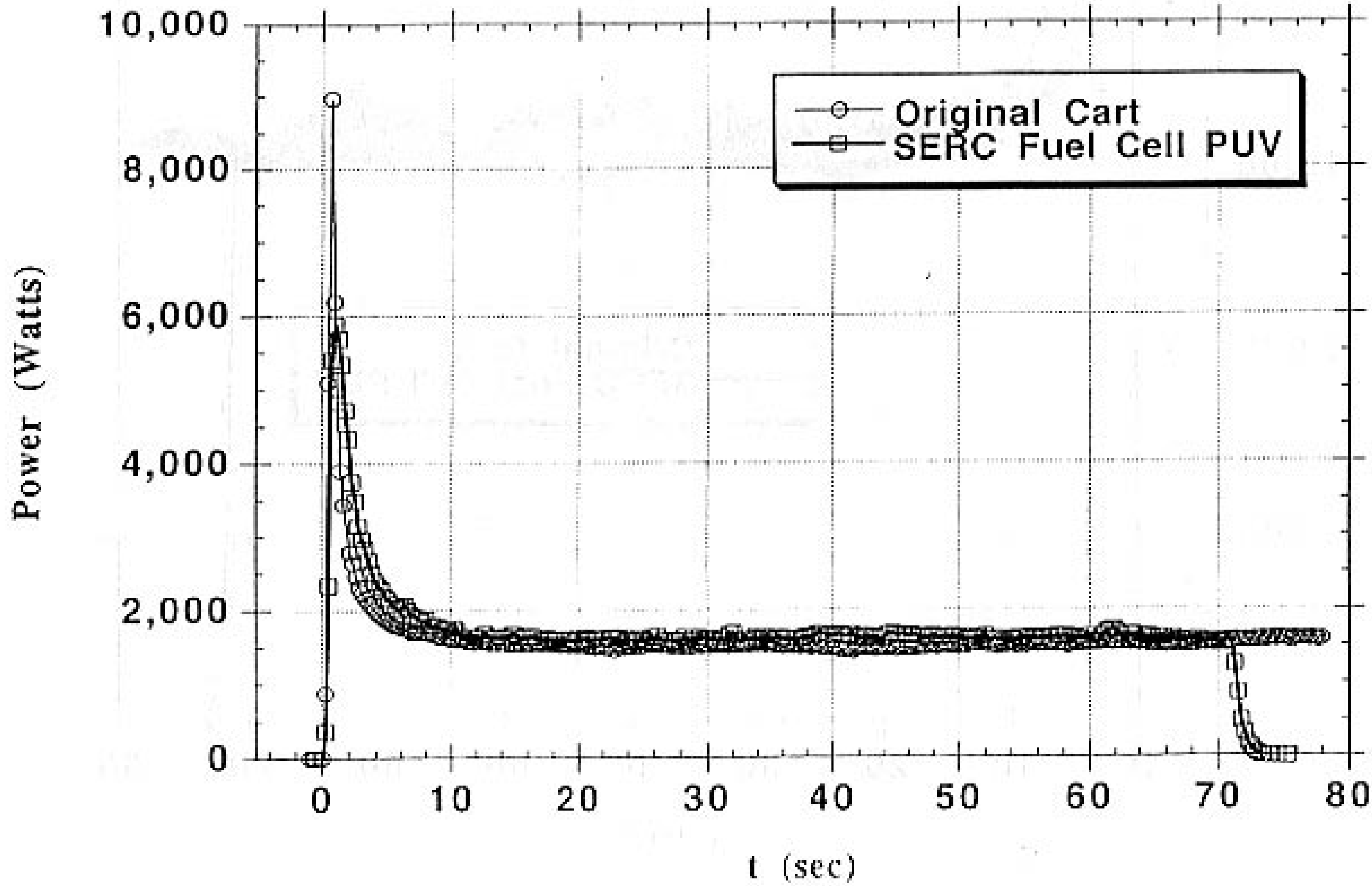

Figure 3b. Performance of SERC PUV vs. Original Cart

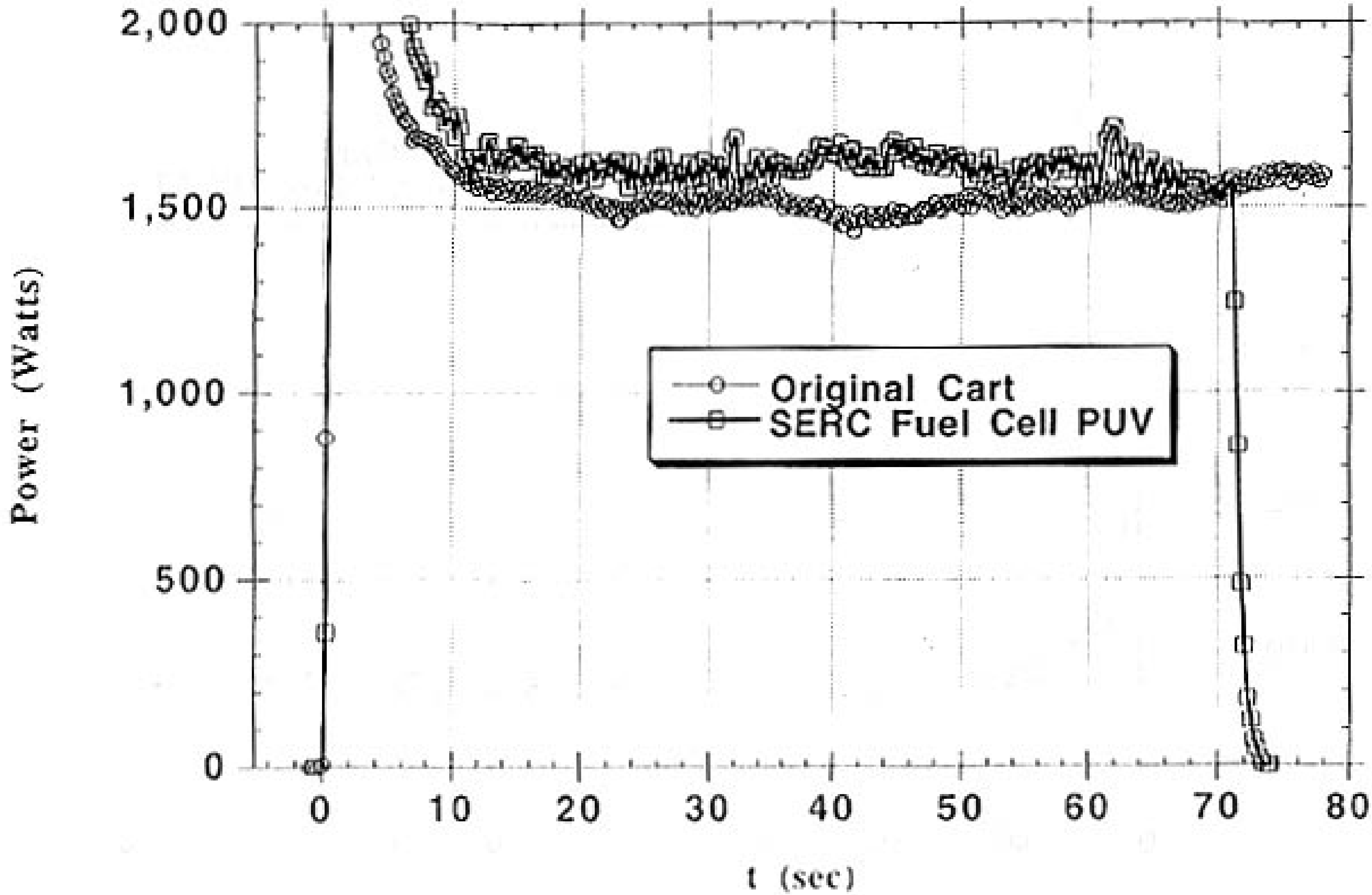

Figure 4. Fuel Cell Response during Acceleration

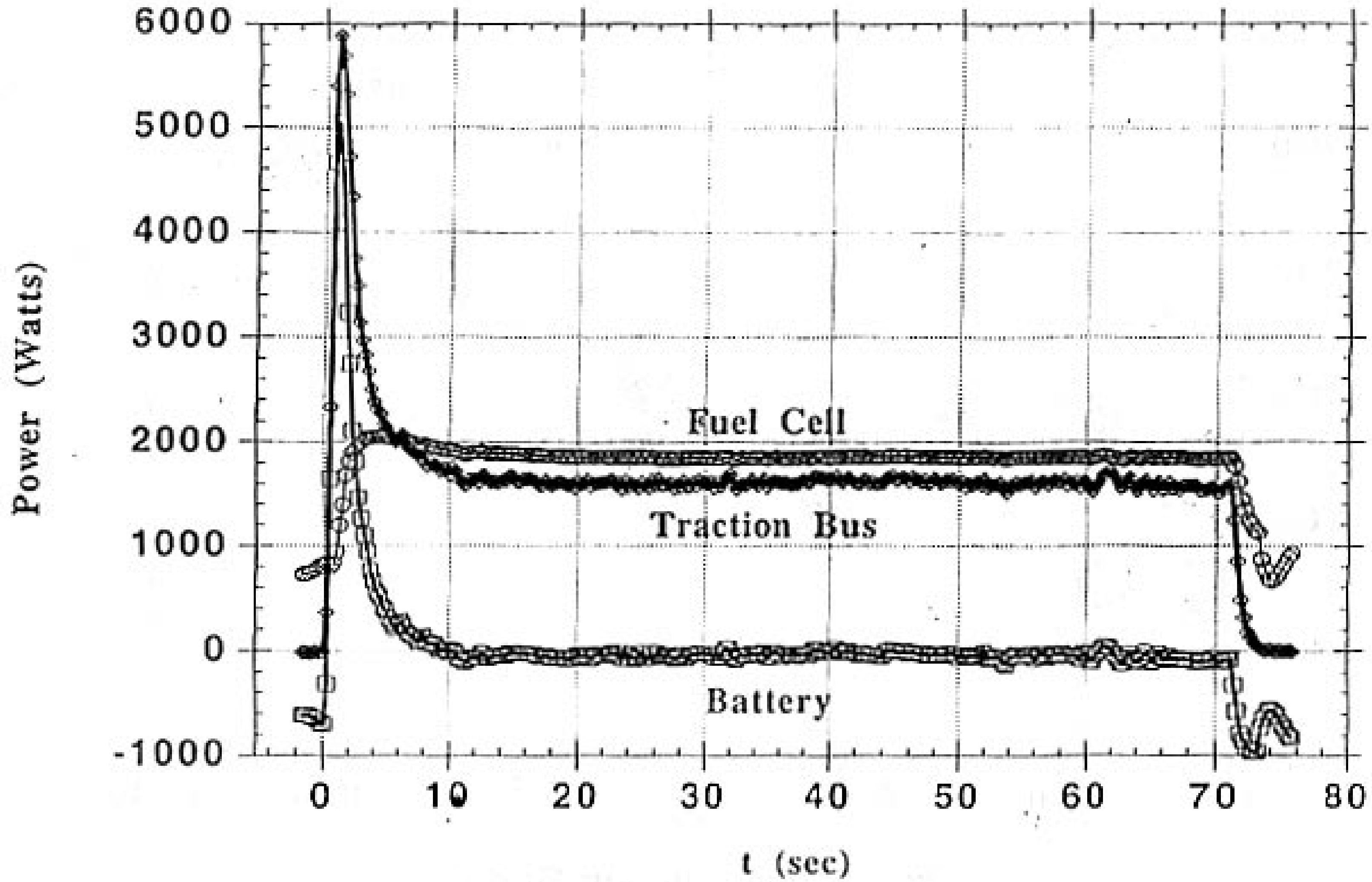

Figure 5. Parasitic Load vs. Power to Traction Bus

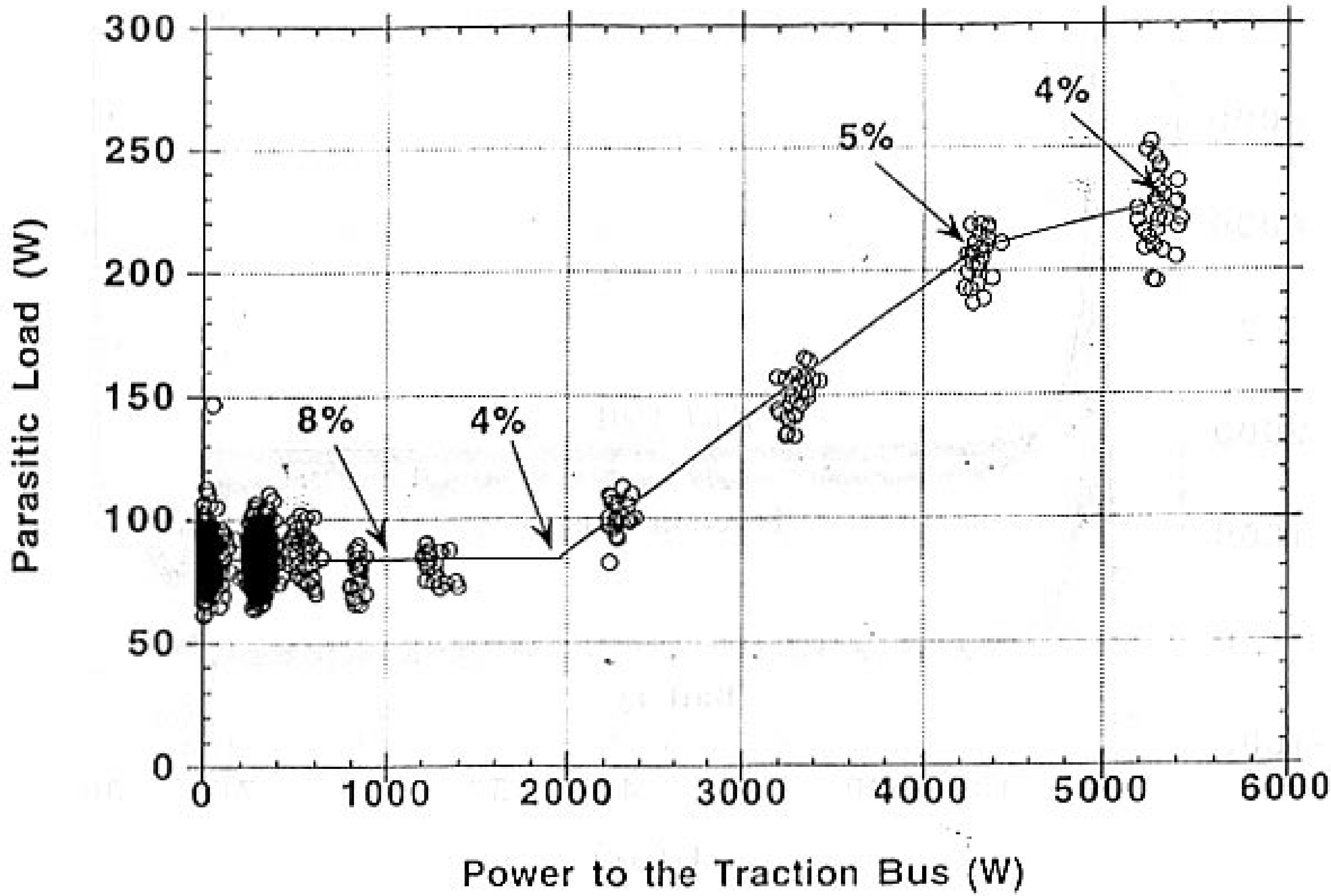

Table 1. Specifications for Prototype Fuel Cell Powered PUV

Characteristic	Value
Fuel cell type	proton exchange membrane (PEM)
Fuel cell stack power	4.0 kW (5.4 hp)
Number of cells	64
Hydrogen energy consumption	0.34 kWh/mile
Mileage (gasoline energy equivalent)	110 mpg
Fuel cell system weight	200 lbs
Traction bus voltage	36 volts (nominal)
Electric motor size	1.5 kW (2.0 hp)
Hybrid battery size	30 amp-hrs
Cruising speed	12 mph
Fuel cell net power at cruising speed	1.8 kW
Hydrogen tank volume	14 liters
Hydrogen gas storage pressure	2000 psig
Range	20 miles
Refueling time	2 minutes