TESTING AND EVALUATION OF BATTERIES FOR A FUEL CELL POWERED HYBRID BUS*

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ABSTRACT

Argonne National Laboratory conducted performance characterization and life-cycle tests on various batteries to qualify them for use in a fuel cell/battery hybrid bus. On this bus, methanol-fueled, phosphoric acid fuel cells provide routine power needs, while batteries are used to store energy recovered during bus braking and to produce short-duration power during acceleration. Argonne carried out evaluation and endurance testing on several lead-acid and nickel/cadmium batteries selected by the bus developer as potential candidates for the bus application. Argonne conducted over 10,000 hours of testing, simulating more than 80,000 miles of fuel cell bus operation, for the nickel/cadmium battery, which was ultimately selected for use in the three hybrid buses built under the direction of H-Power Corp.

INTRODUCTION

The battery evaluation effort described in this paper was conducted in support of the development and fabrication at three fuel cell/battery buses. A series of battery tests was conducted to establish a basis for selecting a battery to be used in these buses. The 25-passenger buses (30-ft long) are powered by a 50-kW, methanol-fuel, phosphoric acid fuel cell; a 216-volt battery pack provides additional power for bus acceleration and a means of storing energy recovered during regenerative braking of the vehicle. The net power is provided by the fuel cell, and the battery alternately delivers and accepts energy while maintaining a nearly constant nominal state of charge.

H-Power Corp. was the prime contractor and system integrator for development of these buses. The phosphoric acid fuel cell, based upon technology developed by Engelhard Corp., was supplied by Fuji Electric. Bus Manufacturing USA constructed the bus chassis and integrated the power-train components. The design of the buses has been fully described in a report (H-Power, 1996). Tests results on the performance of the buses have been previously reported (Fisher, 1995; Wimmer, 1996). The fuel cell power plants in these buses achieved an energy efficiency of greater than 44% (Lee, 1996). The three buses are currently being tested at three sites. The first test-bed bus (TBB-1) is at Argonne National Laboratory in Illinois, TBB-2 is at DOE's Energy Technology Engineering Center in Canoga Park, California, and TBB-3 is at Georgetown University in Washington, DC.

Battery requirements for the hybrid bus were defined early in the program. Vehicle simulation models, incorporating standardized transit coach duty cycles as well as measured data from actual bus routes, were used to define the battery requirements. The battery was expected to provide satisfactory performance and lifetime on the Georgetown University Transportation System (GUTS) cycle. The route includes numerous starts and stops, as well as uphill and downhill grades, with a resulting battery power requirement of up to 70 kW during discharge and over 55 kW of charging power imposed during regenerative braking. The battery power profile for this route is given in Figure 1.

For testing in the demonstration program, a battery with a lifetime of 1 year or 2,000 GUTS cycles, was required as a minimum for further consideration; however, a life of at least 5 years, or 10,000 GUTS cycles, was desired. In addition, the battery was expected to require little or no maintenance. These requirements, along with the basic requirement for the use of off-the-shelf components, narrowed the choice to lead-acid or

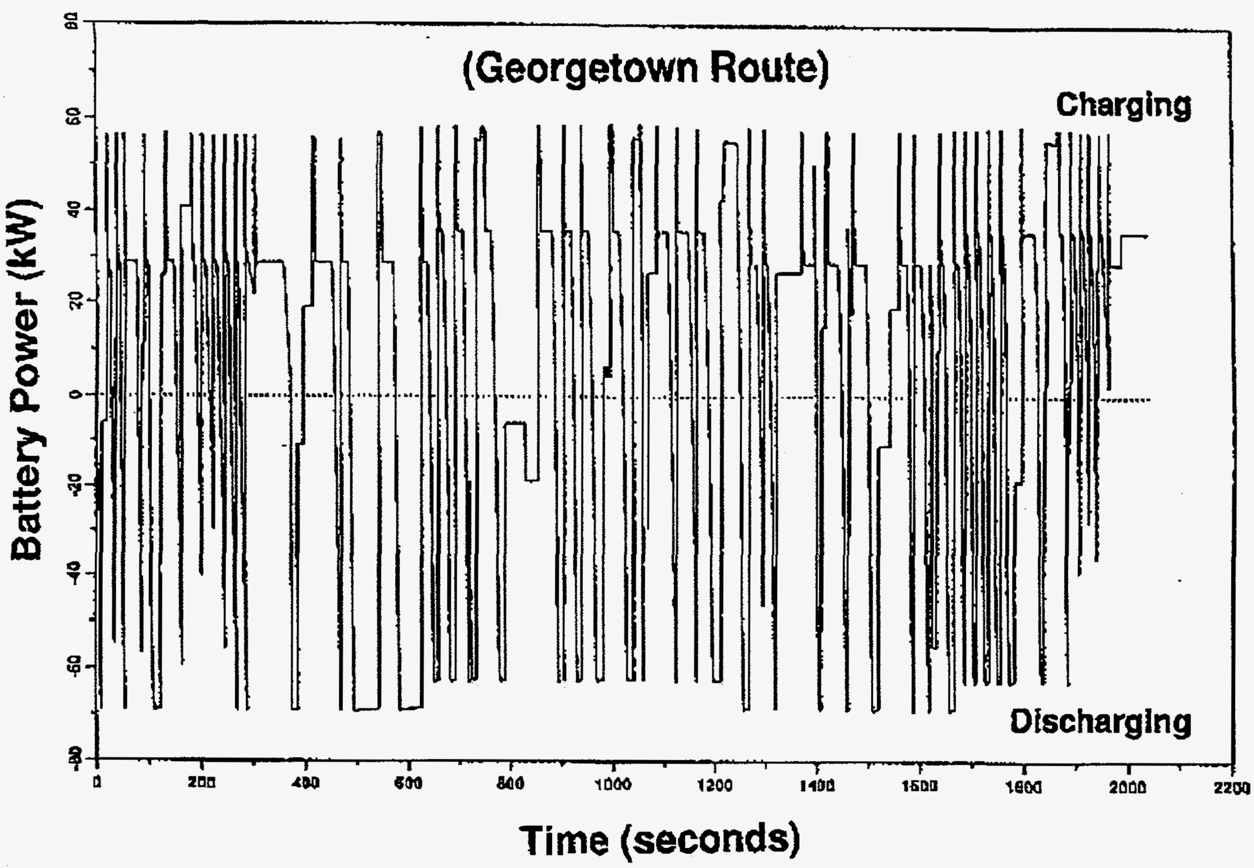

FIGURE 1: BATTERY POWER PROFILE BASED ON GEORGETOWN BUS ROUTE USED FOR LIFE- CYCLE TESTS.

nickel/cadmium batteries.

TEST RESULTS

Characterization, simulated operation, and life-cycle tests of lead-acid, vented nickel/cadmium, and sealed nickel/cadmium batteries were performed on 6- and 12-volt modules at Argonne National Laboratory's Electrochemical Analysis and Diagnostics Laboratory. The test laboratory and typical operating procedures have been described elsewhere (DeLuca, 1990).

Lead-Acid Batteries

The lead-acid batteries selected for these tests were chosen by the fuel cell bus developer and were tested by Argonne in support of the development effort.

Heavy-duty lead-acid batteries (Group 8-D) were procured by Argonne from two manufacturers as commercial off-the-shelf items representative of the state-of-the-art. These batteries had a 25-A reserve capacity rating of 390 min, equivalent to 162.5 Ah, and a cold cranking rating of 1155 A at 0°C. Battery dimensions for a 12-volt module were length of 19.5 in., width of 11.0 in., and an overall height of 10.0 in. to the terminal tops. Average battery weight was 58 kg. Initial tests were performed to determine battery capacity. The batteries displayed an initial capacity in excess of 165 Ah at the 25-A rate to a discharge cutoff of 1.75 volts per cell, thereby validating their acceptance as test articles. In addition, the batteries' peak power as a function of state-of-charge was determined by using standardized procedures developed from simulated driving profile discharges for electric vehicles. The 15-second peak power thus measured was 180 W/kg at 80% state-of-charge, and 120 W/kg at 20% state-of-charge. This measurement was repeated periodically during life-cycle testing as an indication of whether capacity or power degraded more severely under the simulated operating conditions, which involved very few deep discharges but a great deal of charge into and out of the battery at relatively high currents.

Life-cycle tests were conducted using the expected battery power demands on the fuel cell bus over the Georgetown route, which is shown in Figure 1. This one-hour test cycle includes

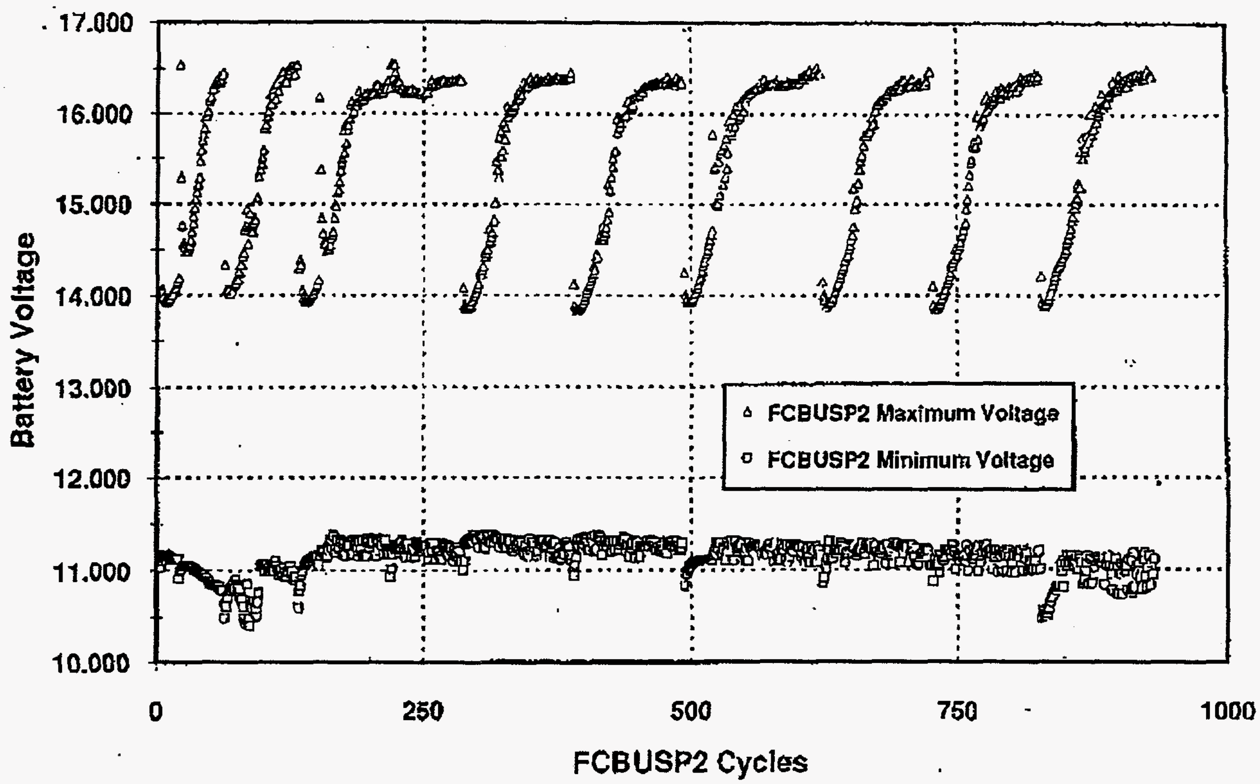

FIGURE 2: LEAD-ACID BATTERY VOLTAGE AS A FUNCTION OF TIME DURING LIFE-CYCLE EVALUATION

34 minutes of simulated route operation, followed by a 26-minute idle period, which allows some battery cooling and equilibration to occur. The cycle is adjusted so that the sum of ampere-hours discharged from the battery during the cycle (40 Ah) is equal to the ampere-hours from regenerative braking and excess fuel-cell power available for battery charging. This reflected the intended in-bus operation, where the fuel cell provides all of the tractive and bus accessory energy needs, and the battery only levels the power requirements. Tests were conducted with the battery at 65% initial state-of-charge. Each cycle, therefore, is roughly equivalent to a 25% depth-of-discharge for a 160-Ah battery, although the variation in actual state-of-charge is less than 5% around the starting point due to the interspersed charging.

Typical results showing battery voltage as a function of time during 900 hours of testing are shown in Figure 2. The results indicate that during the initial several cycles in each series of about 100 continuous cycles, battery peak voltages remained within an acceptable range; however, with continued cycling, battery peak voltages reached undesirably high voltages, up to 2.75 volts per cell, during the regenerative braking portions of the cycle. During this period, some battery gassing occurred, but the duration was short, and the net effect on overall columbic and water consumption was minimal. After each series of approximately 100 cycles, the battery was discharged to measure the remaining capacity in the battery and thereby determine its state of charge. The apparent ampere-hours lost as a result of a series of cycles, divided by the integrated total ampere-hours in/out of the battery, serves as a measure of the columbic inefficiency of the battery. For the lead-acid batteries, the columbic efficiency was found to be very small under these conditions, approximately 1%. The voltaic efficiency over the cycle was measured to be 86%.

Battery failures occurred after 1154 and 941 cycles for batteries from one manufacturer, and after 1310 cycles for the other manufacturer. Post-test teardown analyses of the failed batteries were conducted by Argonne and indicated that degradation and breakdown of the active material was the probable cause of failure. Sloughing of active material and loss of entire pellets from the positive plates were observed. Grid corrosion was not a cause of failure.

Nickel/Cadmium Batteries

Nickel/cadmium batteries, in several different design configurations and representing two manufacturers, were

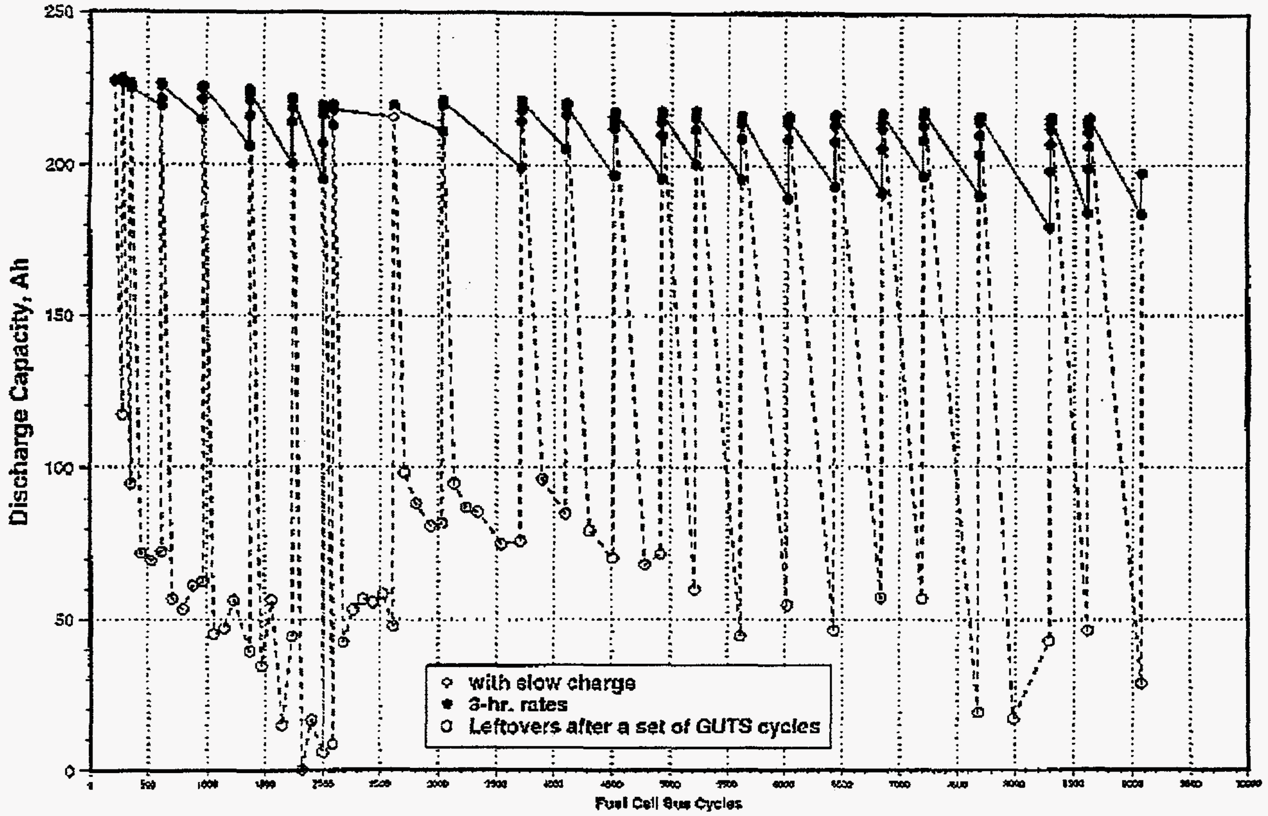

FIGURE 3: NICKEL/CADMIUM BATTERY CAPACITY AS A FUNCTION OF TIME DURING LIFE-CYCLE EVALUATION

chosen by the fuel cell bus developer for testing. Vented nickel/cadmium batteries from SAFT were procured in the STM-200, STH-800, and STH-1200 design configurations. Sealed nickel/cadmium batteries were procured from Hoppecke in the X-55 configuration. The STM-200 battery is a five-cell, six-volt, 200-Ah monoblock developed for electric vehicle applications. The STH-800 and -1200 designs were only available as 80-Ah and 120-Ah single cells, which were connected in series to form six-volt modules for testing. The STH series was developed as a higher power design than the STM series. After initial screening tests on all of these batteries, the STM-200 battery was selected for long-term life-cycle testing.

Although the STM-200 battery had a manufacturer's nominal rated capacity of 200 Ah, this rating proved to be conservative as the battery displayed significantly greater capacity during initial testing (223 Ah). The peak power of this battery when new was measured to be 195 W/kg at 80% state-of-charge, and 155 W/kg at 20% state-of-charge.

Life-cycle test results for the STM-200 battery during extensive simulated fuel cell bus operation are shown in Figure 3. More tthan 10,000 Georgetown route cycles, simulating over 80,000 miles of fuel cell bus operation, were imposed during the test period. When testing was discontinued after 10,000 cycles, the battery still maintained over 97% of its original capacity, but its power capability had degraded from 192 W/kg to 148 W/kg at 65% state-of-charge. From these data, it is impossible to accurately extrapolate to predict battery failure, but end of life occurring after about 20,000 cycles seems reasonable on the basis of the rate of capacity loss observed.

After each series of approximately 100 cycles, the battery was discharged to measure the remaining capacity in the battery (leftovers). Based on this analysis, the columbic inefficiency was found to be approximately 1%, which also correlated well with the amount of watering needed during the very infrequent topping off of the electrolyte levels.

The results also revealed a small memory effect whereby the battery's measured capacity after charging dropped slightly following these shallow discharges, but full capacity was regained after three deep-discharge cycles.

CONCLUSIONS

The test results indicated that the heavy-duty lead-acid batteries provided adequate power and charge acceptance to meet the mission requirements, but their lifetime under the duty cycle proved to be unacceptable. Less than one year of daily operation with the hybrid bus could be expected before replacement of these batteries would be required.

Nickel/cadmium batteries offered good performance and lower weight. Although these batteries are more expensive than lead-acid batteries, their much longer life should offset their higher initial cost. In addition, they have proven to be very reliable and rugged in other electric vehicle applications.

To ensure a wide margin of reliability, the STM-200 nickel/cadmium batteries were selected for the three test-bed buses, which were subsequently built. The batteries were installed on the bus in three trays, comprising a nominal 216-volt battery system. The battery tests determined the heat generated by each battery during the GUTS route. To maintain the internal temperature of the nickel/cadmium battery below 55°C (131°F) as specified by the manufacturer to meet battery life expectancy, thermostat-controlled blowers were installed on the bus to provide up to 600 cubic feet per minute of cooling air flow.

After three years of operation on the first bus, and approximately two years of operation of each of the second and third buses, none of the batteries on board these buses has failed, and none has been replaced. Each battery pack continues to perform well, and many additional years of successful operation is expected.

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