PERFORMANCE AND LIFE EVALUATION
OF
NICKEL/IRON BATTERY TECHNOLOGY
FOR
DUAL SHAFT ELECTRIC PROPULSION VEHICLE

Electrochemical Technology Program
Technical Report for the
DSEP Technology Evaluation Period

March 1986 to October 1988

Prepared for

Eaton Corporation and
Idaho National Engineering Laboratory

May 1990

MASTER

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Printed in the United States of America

FOREWORD

Support for this work was provided by the US Department of Energy (DOE), Office of Transportation Systems (OTS), Electric and Hybrid Propulsion Division. For this effort, the DOE/OTS/EHP Program Manager was P. Brown, and the Project Manager was K. Barber. The tests were conducted at the ANL Analysis & Diagnostics Laboratory, which is operated under the auspices of the DOE.

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PERFORMANCE AND LIFE EVALUATION OF NICKEL/IRON BATTERY TECHNOLOGY FOR DUAL SHAFT ELECTRIC PROPULSION VEHICLE

ABSTRACT

As part of a cost-shared contract between the US Department of Energy (Office of Transportation Systems) and Eaton Corp. to develop an advanced dual shaft electric propulsion (DSEP) vehicle, several nickel/iron (Ni/Fe) batteries were designed and procured from Eagle-Picher Industries (EPI) for evaluation and vehicle use. In March 1986, two individual 5-cell Ni/Fe modules and a 140-cell (28-module) battery pack were delivered to Argonne for evaluation. Performance characterization tests were conducted on the two modules and life testing performed on the battery pack. Module performance testing was completed in early 1987 after about 215 cycles of operation. Each module still retained ~90% of its initial 180-Ah capacity at the end of testing (~163 Ah/970 Wh).

Life evaluation of the 168-V, 28-kWh battery pack was conducted with driving profile discharges. A 1377-s power profile that represented the battery load in a DSEP vehicle undergoing a Federal Urban Driving Schedule (FUDS) was used. Testing was temporarily suspended in October 1987 after the battery pack had accumulated 502 cycles (209 cycles in 1986). After a three-month trickle charge (~3 A), testing was resumed (January 1988) with driving profile discharges. In March 1988, battery performance was being limited by three modules. After 545 cycles, the three modules were removed from the pack. Battery performance, however, continued to decline and another four modules were removed in September 1988 (645 cycles). Several remaining modules started to exhibit a high self-discharge loss and a capacity of only 119 Ah (15.1 kWh) could be achieved. The life evaluation was halted in October 1988 after 661 cycles had been accumulated.

This report outlines the test activities and presents the performance results of the individual modules and the battery pack involved in this technology evaluation.

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I. INTRODUCTION

Several nickel/iron (Ni/Fe) batteries were designed and procured from Eagle-Picher Industries (EPI) for evaluation and use in an advanced dual shaft electric propulsion (DSEP) vehicle developed by Eaton Corporation. As part this program, two individual 5-cell Ni/Fe modules and a 140-cell (28-module) battery pack were delivered to Argonne in March 1986 for evaluation. The objective of this activity was to characterize the performance of the Eaton/EPI Ni/Fe battery technology for DSEP applications. Performance characterization tests were conducted on the two modules and life testing performed on the battery pack. Module performance testing was completed in February 1987. Each module retained ~90% of its initial 180-Ah capacity after completing about 215 cycles of operation (~163 Ah/970 Wh).

Life characterization tests for the 28-kWh DSEP battery pack were conducted with driving profile discharges. A 1377-s power profile that represented the battery load in a DSEP vehicle undergoing a Federal Urban Driving Schedule (FUDS) was used. After the battery pack accumulated 502 cycles in October 1987, testing was suspended for three months. Testing was resumed in January 1988 with the same driving profile discharge. After 545 cycles, three modules were removed from the pack (March 1988) because they were limiting battery performance. Battery performance continued to decline and another four modules were removed in September 1988 (645 cycles). Several remaining modules started to exhibit a high self-discharge loss and a capacity of only 119 Ah (15.1 kWh) could be achieved. The battery life evaluation was halted in October 1988 after 661 cycles had been accumulated.

A computer control and data-acquisition system was used to cycle and monitor the modules and battery during testing. The signals measured and recorded include battery voltage and current, individual module voltages and temperatures, battery pack cooling system airflow temperatures at the inlet and exhaust ports, and ambient temperature of the laboratory test enclosure. Temperatures were measured on the external surfaces of the module cases. The energy (Wh) and coulombic charge (Ah) transferred during each charge and discharge period were calculated by the computer using the voltage and current signals of the modules or battery. All the signals were quantified, computations performed, and data recorded at one-second intervals for driving profile discharges and about one-minute intervals for constant-current and constant-power discharges. Module internal resistance, IR-free voltage, and peak power vs. depth-of-discharge (DOD) data were derived from the measured values of voltage and current during specific driving profile discharges. These derivations were not performed during the battery life tests because of the special Eaton driving profile used in the evaluation. The driving profiles used in these performance and life evaluations are described below:

1. The Federal Urban Driving Schedule (FUDS) for the DSEP van (FUDS/DSEP), as shown in Fig. 1. It is a 1377-s profile with a maximum power of 57 kW and a minimum power load of 1.5 kW, which represents vehicle and system accessory loads. The

power profile is normalized to a battery weight of 818 kg. The energy consumed and distance traveled with each FUDS profile are 3.536 kWh and 7.43 miles, respectively (11.3 W/kg average discharge rate, and 19.5 mph average speed).

2. A 1381-s profile (Fig. 2) similar to that above but with a maximum power of 52 kW and a minimum accessory load of 0.75 kW (ECFUDS). The energy consumed and distance traveled with each ECFUDS profile are 3.107 kWh and 7.43 miles, respectively (9.9 W/kg average discharge rate, and 19.5 mph average speed). The ECFUDS discharges include a 20-s, 52-kW power pulse (current limited at 400 A) after 49.5 simulated driving miles. The power pulse represented a 0 to 50 mph acceleration period and was inserted 822 s into the seventh ECFUDS profile. The ECFUDS discharge was terminated immediately after the 20-s power pulse (total battery discharge energy of 21,273 Wh). A second version of ECFUDS discharges continued the FUDS profile after the 20-s power pulse (ECFUDSC). The ECFUDSC discharge was used to evaluate the modules. A third version of ECFUDS discharges had no power pulse at the 50-mile point (ECFUDSB). The ECFUDSB discharge was only used late in the life evaluation of the DSEP battery.
3. SAE J227aD urban driving schedule for the improved IETV-1 vehicle (J227aD/IETV-1), as shown in Fig. 3. This 122-s power profile represents the IETV-1 accelerating to a speed of 45 mph in 28 s, maintaining that speed for 50 s, coasting for 10 s, and then braking to a halt in 9 s. The profile is normalized to a battery weight of 488 kg and has a peak power of 48 W/kg, average power of 12 W/kg, and an average speed of 28.3 mph. Discharges with this profile are tested with and without regenerative braking to determine the benefits of this system capability.

The first two driving profiles were furnished by Eaton and the third by Jet Propulsion Laboratories. Each duplicates the power demand at the battery terminals in the specified vehicle when operated according to the indicated driving schedule. Each power profile is normalized to the weight of the battery used in the vehicle. To determine the discharge power levels that must be imposed on a single module, its mass is multiplied by the specific power profile. This method assumes that the total battery mass in the vehicle remains constant. For individual modules, an additional weight, or "burden," is added to the module mass to represent its fractional share of the weight for the battery enclosure and module interconnections. The measured weight was 24.5 kg for one module (No. 2) and was 24.4 kg for other (No. 3). For the profile discharges, a module weight of 29.21 kg was used (818-kg DSEP battery weight divided by number of modules it contained, 28) to include the 19% battery hardware burden.

This report outlines the test activities and presents the performance results for the two modules and the battery pack.

Fig. 1. A 1377-s power profile of the battery load (57 kW max.) in a DSEP vehicle undergoing the Federal Urban Driving Schedule (FUDS) with a 1.5-kW accessory load. (FUDS/DSEP)

Fig. 2. A 1381-s power profile of the battery load in a DSEP vehicle undergoing the FUDS with a 0.75 kW accessory load; 822 s into the seventh repeated profile (49.5 miles), a 20-s, 0-50 mph acceleration period (52-kW pulse with a 400-A current limit) was applied. (ECFUDS/DSEP)

Fig. 3. Battery power profile for an improved ETV-1 passenger vehicle on a SAE J227aD urban (to 45 mph) driving schedule. (J227aD/IETV-1)

II. MODULE EVALUATIONS

The two 5-cell modules underwent a set of standardized tests to characterize their performance for electric vehicle (EV) applications. The standardized tests were previously developed with aid and advice from the Standards and Procedures Subcommittee of the National Battery (ad hoc) Advisory Committee and the DOE/OTS/EHP Battery Test Working Task Force. Besides the verification of rated capacity, the tests measure:

1. available energy as a function of constant power discharge rate
2. available peak power for acceleration vs. DOD level
3. hill climbing capability (for 45 W/kg demand) vs. DOD level
4. capacity loss (self-discharge) for standtimes up to one week
5. projected range for various driving schedules and vehicles

When warranted, special characterization tests are also performed to acquire detailed performance measurements. In these tests, battery performance is recorded while a specific operating parameter is systematically varied over a range of values. In this manner, Ni/Fe battery charging studies were performed to assess the effect of recharge factor and initial discharge temperature on available discharge energy and operating efficiency. Module internal resistance, IR-free voltage, and peak power were derived as a function of DOD from the measured values of module voltage and current during specific driving profile discharges.

Module testing was initiated in May 1986 and completed in early 1987 after about 215 cycles of operation. A chronology of the testing activities for each module is given in Table 1. For testing, each module was set in a 25°C water bath to decrease the time needed to cool the module to room temperature after discharge. This significantly reduced the time needed to complete the set of performance characterization tests. Electrolyte maintenance was performed on each module at intervals of about five cycles. Water was added to the module electrolyte near the end of an open-circuit after charge (OCAC) stand time lasting one hour. The amount of water needed to fill the cells was dependent on the total overcharge applied since the previous maintenance period.

The manufacturer's recommended charge method and overcharge were used on the DSEP modules. The method was CI/CV/CI (45A/8.0V/20A) charging, where CI = constant current and CV = constant voltage. Charges were started at a CI rate of 45 A until a module voltage limit was reached, and then CV charging was used at that level. The CV charge level was 8.0 V (1.6 V/cell) minus 10 mV/°C above 20°C (-2 mV/cell/°C). CV charging was applied until the current tapered to 20 A, then, CI charging was resumed at a 20-A rate until the desired return was provided. Initially, a charge return of 120% was used (~206 Ah), but after about 60 cycles of operation, a fixed 220-Ah return (~129%) was used for recharges.

from 100% DOD. With this charge method, a charge time of ~6.5 h was needed to provide a 120% return and ~7.5 h needed to furnish a ~129% return.

The initial capacity of each module was ~181 Ah at the 2-h rate, but immediately started to decline at a rate of ~0.7 Ah/cycle. Electrolyte samples were taken for analyses after about 50 cycles of operation. Based on the results, the electrolyte in both modules was replaced in July 1986. After several conditioning cycles with 300-Ah charges, the modules achieved reproducible capacities of ~177 and ~165 Ah with 220-Ah charges (124% and 133% returns, respectively) and a 1-h OCAC time. The standardized performance characterization tests were initiated after the modules achieved stable operation. The purpose and results of each characterization test are discussed below.

Capacity Verification: A test was conducted to confirm that the modules achieved the manufacturer's rating under its specified charge and discharge conditions. For the DSEP Ni/Fe technology, the EPI modules were to provide a capacity of 170 Ah at a 2-h discharge rate (85-A) to a cutoff voltage of 5 V (1 V/cell) with a 120% charge return and 1-h OCAC time. The charge return was later increased to a fixed 220 Ah. Throughout the testing program, these operating conditions were replicated to establish a performance baseline for the tested modules. The capacity history of both DSEP modules for these cycling conditions is plotted in Fig. 4. The plots show the initial decline in capacity and the significant improvement after the electrolyte was replaced (about cycle 55). A slight decline in capacity was exhibited after ~160 cycles of operation, but at the conclusion of testing, both modules still retained >95% of their rated capacity.

Self-Discharge Loss: Tests were performed to assess the energy loss due to stand periods of 1 hour and 1 week. The self-discharge loss was determined by normalizing the measured 100% DOD module capacity with an OCAC stand time to that obtained with no OCAC. Each module was fully charged (220 Ah return from 100% DOD), placed on a OCAC, and then discharged to 100% DOD. Both modules exhibited a capacity loss of ~2.9% after a 1-h stand and ~15.2% after a 7-day stand. These losses are typical for Ni/Fe systems.

Partial DOD Operation: A test was performed to uncover any apparent "memory" effects and verify proper charging with partial DOD operation. In this test, each module was discharged 85 Ah (~50% DOD) and charged 110 Ah (~129% return) for ten cycles, and then discharged to 100% DOD to measure the available deep discharge capacity. The modules exhibited a capacity loss of 2.7% and 3.8% on the first deep discharge after partial DOD operation. The capacity of both modules on the second deep discharge (after a 220-Ah charge) was within 0.6% of that exhibited before partial DOD operation.

Hill-Climbing Capability: A test was conducted to determine the maximum DOD level at which the modules could sustain a hill-climbing constant-power (CP) level of 45 W/kg for 6

minutes. This CP level represents that required for the ETV-1 vehicle to negotiate a 7% grade at 30 mph. In this test, the modules were discharged at a 15 W/kg rate to DOD levels ranging from 40 to 90%, then a load of 45 W/kg was applied and the time to reach 100% DOD recorded. The test data, plotted in Fig. 5, show that both modules were able to sustain the 6-min hill-climb power to a DOD of 81.5%.

Energy vs. discharge rate: A test was performed to identify the change in available energy with discharge rate. These data, in conjunction with peak power data, allow EV range predictions for various vehicles and driving schedules. The test was performed after each module had been operated for about 120 cycles (from cycle 118 to 141). At this time, the capacity for 2-h rate discharges, 220-Ah charges, and no OCAC was 171 Ah/1057 Wh for module 2 and 176 Ah/1091 Wh for module 3. For this test, discharges were performed at CP levels ranging from 10 to 50 W/kg with the discharge cut off voltage (DCOV) varied to attain the same open-circuit volts at the end of discharge (EOD). Both modules satisfactorily completed the high rate discharges without exceeding the manufacturer-specified thermal or current limits. The measured module weights (24.5 and 24.4 kg for Nos. 2 and 3, respectively) were used to calculate the discharge specific power and the specific energy obtained. The lowest CP level (10 W/kg) is representative of that needed to provide an average vehicle speed of ~20 mph while the higher CP levels represent the powers needed for vehicle hill-climbing and acceleration. The results, plotted in Fig. 6, show that the available energy vs. discharge rate of the two modules is matched to within $\pm 2\%$, and module energy is decreased by less than 11% for a 10 to 50 W/kg increase in discharge rate.

Driving Profile Discharges: A test was performed to project EV range for each vehicle and driving schedule. Using the acquired voltage and current data from the J227aD/IETV-1 discharges, module peak power (sustained for ~30-s duration) vs. DOD data were derived. These data were compared with measured peak power data (discussed in the next section) to verify their accuracy. The driving profile discharge test was started after the modules had accrued about 142 cycles. Each module was discharged to 100% DOD with each driving profile after a 220-Ah charge and no OCAC. To determine the discharge power level imposed on a single module, its mass was multiplied by the specific power profile (Figs. 1, 2 or 3). For the FUDS profiles, a module weight of 29.2 kg and a DCOV of 4.0 V at 100% DOD were used. The module weight of 29.2 kg includes a 19% burden for the DSEP battery hardware and was derived by dividing the DSEP battery weight (818 kg) by the number of modules it contains (28). For the J227aD profile, the measured module weights were used, and the DCOV was raised to 4.5 V because of the lower power demand. The results listed in Table 2 give the simulated miles driven and the total and net Ah/Wh discharge. The net discharge was obtained by subtracting the Ah/Wh acquired by regenerative braking (charge) from the total. The net Ah obtained from each module with and without regenerative braking is about the same (to within 1%), but the net energy from

each module without regenerative braking (J227aD profile) is slightly more (~3%) than that obtained with it because of the module voltaic efficiency.

Peak Power vs. DOD: A test was performed to measure the capability of each module for up to 30 s of sustained power at various DOD's. The peak-power data indicate the capability of the battery to deliver power for vehicle acceleration as a function of DOD. Hence, the DOD at which the battery can no longer provide the power required to satisfy specific driving schedules can be identified. In this test, the module is discharged at a 3-h rate to specific DOD levels, after which a CI is applied to reduce the module open-circuit voltage (V_{OC}) by 1/3. The CI is maintained for 30 s and the average module voltage (V_{AVG}) is calculated. At each DOD tested, the module sustained peak power is defined as the product of the applied CI and derived V_{AVG} . The results of these peak power vs. DOD measurements are plotted in Fig. 7.

To obtain 2/3 of V_{OC} at the various DOD's, the magnitude of CI must be large and may exceed the manufacturer's recommended operating limits. For this reason, an alternative method was developed using the data from J227aD/IETV-1 discharges (with regenerative braking). In this method, the ΔV and ΔI are measured between the 25 and 75 s points of the driving profile. From the measured data for each profile in the discharge, module resistance (R) vs. Ah of discharge is derived ($R = \Delta V / \Delta I$). These R data for each DSEP module are plotted in Fig. 8. Using the R data and measured module voltage (V_M) and current (I_M) values, module internal IR-free voltage ($V_{IR-free}$) vs. discharge Ah (Fig. 9) can be derived from the equation $V_{IR-free} = V_M + I_M R$. Module sustained peak power (P_{PK}) vs. discharge Ah (Fig. 10) is then computed using the derived data and the equation: $P_{PK} = (0.667V_{IR-free})^2 / R$.

Because the power capability of a battery varies with discharge and age, it is beneficial to indicate peak-power data as a function of battery DOD (in terms of available capacity) instead of actual discharge Ah. The J227aD/IETV-1 discharges are not typically terminated at 100% DOD because of the high power demand (48 W/kg) during the acceleration period of the profile. Therefore, after completing the J227aD/IETV-1 discharge, the modules were immediately placed under a second discharge at the average power rate for the profile (12 W/kg) to measure the remaining capacity. In this manner, the termination DOD for the driving profile due to battery power vs. DOD limitations is identified. The peak power vs. DOD data derived using this methodology are also plotted in Fig. 7. The derived results are within 10% of those measured at the high CI rates.

Table 1. Chronology of DSEP Module Testing

Date	Accumulated Cycles		Activity
	Module #2 (EA05FN02)	Module #3 (EA05FN03)	
4-6/86	1-53	1-46	Capacity Verification Tests
6/86	54	47	Electrolyte Sampled for Analyses
7/86	55	48	Electrolyte Replaced
7/86	56-80	49-74	Conditioning Cycles followed by Capacity Verification Tests
8/86	81	75	7-Day Stand Test
8/86	82-95	76-89	Capacity Verification
8-9/86	96-124	90-117	Partial DOD Operating Evaluation and Capacity Verification
9/86	125-145	118-139	Energy vs. CP Rate Test
10/86	146-154	140-147	J227aD/IETV-1 Profile Discharges
10/86	155-164	148-152	Capacity Verification
10-11/86	165-183	153-179	DSEP FUDS Profile Discharges
11/86	184-192	180-188	Hill-Climbing Capability Test
11/86-1/87	193-212	189-207	Capacity Verification
1/87	213	208	Peak - Power vs. DOD Measurements
2/87	214-217	209-212	Capacity Verification

Fig. 4. Module capacity for 2-h rate discharges and 220-Ah charges with 1-h OCAC.

Fig. 5. Sustained hill-climbing capability of test modules

Fig. 6. Available specific energy vs. discharge specific power of test modules

Table 2. Projected Ranges for Four Simulated Driving Profiles

<u>Vehicle</u>				
- Type	DSEP-Van		IETV1-Car	
- Battery Weight, kg	818		488	
<u>Driving Schedule</u>				
- Profile	FUDS		J227aD	
- Option	W/O Pulse	W/Pulse	W/O Regen.	W/Regen.
-- Name	FUDS/DSEP	ECFUDSC	--	--
- Avg. Speed, mph	19.5	19.5	28.3	28.3
- Peak Power, W/kg	70	64	48	48
- Avg. Power, W/kg	11.3	9.9	15.0	12.0
<u>Module 2</u>				
- Range, miles	58.7	67.1	78.4	94.8
- Discharge, Ah/Wh				
-- Total	177/1075	176/1077	170/1029	204/1244
-- Regen.	9/62	11/73	0/0	36/254
-- Net	168/1013	165/1004	170/1029	168/990
<u>Module 3</u>				
- Range, miles	60.6	68.4	81.2	99.6
- Discharge Ah/Wh				
-- Total	180/1097	180/1102	173/1056	211/1294
-- Regen.	10/67	11/77	0/0	37/268
-- Net	170/1030	169/1025	173/1056	174/1026

Fig. 7. Measured and calculated specific peak power vs. DOD (derived from J227aD/IETV-1 discharge) for test modules

Fig. 8. Resistance vs. Ah DOD during a J227aD/IETV-1 discharge of test modules

Fig. 9. IR-free voltage vs. Ah DOD during a J227aD/IETV-1 discharge of test modules

Fig. 10. Peak-Power vs. Ah DOD during a J227aD/IETV-1 discharge of test modules

III. BATTERY PACK EVALUATIONS

The 168-V, 28-kWh DSEP Ni/Fe battery pack was delivered to Argonne for life evaluation in March 1986. This 140-cell (28-module) battery pack came with control unit and single-point watering system. A functional diagram of the battery interface control unit is given in Fig. 11. This unit provided control features for thermal management and safe operation of the battery. Thermal management was accomplished by ON-OFF control of heater power and adjustment of fan speed between three settings (based on detected temperature) to maintain a constant battery temperature. The safety features included monitoring the battery for hydrogen accumulation and loss of ventilation airflow. An alarm signal was connected to the ANL test system for continuous monitoring, whereby testing would be immediately halted should an alarm be issued. Although the feature was not used at ANL, the interface unit had a discharge/charge Ah meter that provided a charge ON-OFF control capability. A map of the battery pack is given in Fig. 12, which shows the location and designation of the 28 modules and 15 originally installed thermal couples (circle symbol). An additional 18 thermal couples (also shown in the figure) were installed in August 1987 to provide temperature monitoring of all modules.

To evaluate the heating capability of the thermal management system, a test was conducted at an ambient temperature of -18°C . This test was performed in June 1986 after the battery had completed 71 cycles. In this test, the battery was first stabilized at -18°C with the thermal management unit not energized. Power was then applied to the heater, blower, and battery temperature controller, and the power and temperature measurements were recorded. The blower was operated at a low speed power of 66 W and the heaters at 514 W. The total power consumed by the heater, blower, and controller electronics was 680 W. As a result, the pack temperature was increased 10°C (to -8°C).

Electrolyte maintenance was initially performed at the recommended EPI interval of every 10 cycles. The maintenance interval was decreased to 6-7 cycles as the applied overcharge was increased with battery life from its initial 20% to a maximum of 70% (300-Ah charges). Watering was started 3 h after finishing the charge and required about 1 h to complete. A water reservoir (placed 1.5 feet above the battery pack to establish flow pressure) was filled to the 14-gal level by using saved overflow fluids from the battery and additional distilled water. The battery single-point watering system used a valve sequence whereby the four module rows would be watered one at a time. After battery watering was complete, the amount of water used from the reservoir (less the amount in the overflow sump) was determined and recorded. Typically, about 6-7 gal of water was used to fill the battery pack modules.

Capacity verification tests were initiated on the battery pack in March 1986. Reference cycles were used to verify the availability of rated capacity and to establish a performance baseline. These cycles included 2-h rate (85-A) discharges to a minimum

DCOV for the battery pack or modules (140 V and 4.0 V, respectively) and CI/CV/C charges to a 120% return with a 1-h OCAC time. The charge return was changed to a specific Ah level, and 0-, 1- and 3-h OCAC times were used at various points during these battery life tests. The battery pack capacity vs. life obtained with reference cycle discharges is plotted in Fig. 13. The battery exhibited a capacity decline of less than 11% in more than 500 cycles of operation.

A chronology of the ANL battery testing activities is given in Table 3. A capacity of 189 Ah was attained on the first discharge (85-A, 2-h rate), but it decreased to less than 170-Ah in seven cycles. Operating parameters were adjusted (OCAC time, charge return, and temperature) in unsuccessful attempts to increase battery capacity. By cycle 63, battery capacity had declined to 147 Ah with 2-h rate, room-temperature discharges, 200-Ah charges, and 3-h OCAC times. At higher initial discharge temperatures (41°C), battery capacity decreased to ~145 Ah (Fig. 14). This result is primarily caused by increased self-discharge losses. After 71 cycles, the battery was returned to EPI (June 1986) for examination. EPI installed new electrolyte in all the modules and returned the battery to ANL in July 1986. After several conditioning cycles with 300-Ah charges, a reproducible capacity of ~164 Ah was achieved with 2-h rate (30°C) discharges, 220-Ah charges (~133% return), and no OCAC. At reduced temperatures (6°C), a capacity of 152 Ah was still achieved with the same charge and discharge conditions. These data are also shown in Fig. 14.

Battery life testing was to be conducted with FUDS/DSEP driving profile discharges to a minimum battery DCOV of 112 V or module DCOV of 3 V, and the current was to be limited to 400 A. Because of the additional capacity tests and the electrolyte exchange, about 90% of the first 150 cycles accumulated on the battery were reference cycle CI discharges. For the ~15 FUDS/DSEP driving profile discharges, a range of ~55 miles was achieved and the 400-A current limit was invoked after ~46 miles.

After 150 cycles, the FUDS/DSEP discharges were changed (November 1986) to include a 52-kW, 20-s power pulse after 49.5 simulated driving miles (ECFUDS). The ECFUDS still used a current limit of 400 A but had a lower average discharge rate and peak power demand than that of the FUDS/DSEP (Table 2). These discharges were terminated immediately after the power pulse was completed or if the power pulse caused the voltage to drop to a DCOV of 130 V. The ECFUDS provided a range of 49.5 miles and removed a total energy of 21.273 kWh from the battery. After only twenty ECFUDS cycles, the battery was unable to sustain the power pulse (reached the DCOV within 20 s) on the discharges following electrolyte maintenance. This was caused by increased capacity loss due to self-discharge and reduced temperature during the extended OCAC time (~4 h) needed to water the battery. Electrolyte maintenance was performed about every ten cycles. After completing ~190 cycles, the battery could only sustain the 20-s power pulse for about five of the ten cycles between maintenance periods.

A revised ECFUDS discharge, which continued the FUDS profiles following the 20-s power pulse (called ECFUDSC), was used after the battery had accumulated 213 cycles (January 1987). These discharges were initially terminated at a battery DCOV of 125 V or a module DCOV of 4.0 V. Because the current was limited at 400 A and the DCOV was 125 V, the 52-kW power pulse was allowed to drop below the prescribed level to only 50 kW at the DCOV. A range of ~57.5 miles was attained with the ECFUDSC. Testing was continued using both the ECFUDS and ECFUDSC driving profile discharges and reference discharges for capacity verification. The test results indicated that the power capability of the pack was decreasing at a higher rate than that of capacity. After about 200 cycles, the pack had difficulty completing the concluding 52-kW power pulse on all cycles without reaching the DCOV. The cooling pattern within the pack enclosure was found to cause thermal gradients that contributed to the power capability problem. The modules closest to the blower (Nos. 1, 14, 15, and 28) were operating at a lower temperature than the other modules. Insulation was installed on the surface of these modules closest to the blower. This resulted in a more uniform pack temperature and the battery was able to complete the power pulse.

Soon after the battery thermal gradient was corrected, the power problem returned. Adjustment of various parameters (DCOV, OCAC time, and overcharge) temporarily improved battery performance and allowed successful completion of the 20-s power pulse. After about 310 cycles (March 1987), the 400-A current limit was removed on the ECFUDS discharges (ECFUDS-NL). The EOD currents exceeded 500 A, and higher battery output powers were achieved to complete the 52-kW power pulse.

A test equipment failure in August 1987 resulted in an excessive overcharging of the battery. Following an ECFUDS discharge on a weekend (cycle 429) wherein 129 Ah (21.5 kWh) was removed from the battery, the minicomputer that applies the discharge profile malfunctioned and halted in a condition that continuously indicated successful completion of the discharge. The control computer then proceeded to provide five charges totaling 910 Ah over a ~48 h period before the problem was detected and remedied. Electrolyte maintenance was then performed, and 11.8 gal of water was needed to fill the battery. On the next discharge (cycle 430), a capacity of 186 Ah, 30.5 kWh was obtained at the 2-h rate. This was a 22% increase over the previous reference capacity of 153 Ah obtained on cycle 423. The increase, however, was only temporary and battery capacity returned to 154 Ah, 26 kWh on cycle 454 (24 cycles later). There was no apparent capacity loss or deterioration in performance that could be attributed to the excessive overcharge.

After 480 cycles, another version of the ECFUDS having no power pulse and no current limit (ECFUDSB-NL) was used. The ECFUDSB-NL maximized the DOD and range of the driving profile discharges. The battery specific energy (discharge Wh per kilogram) achieved with driving profile discharges that terminated at a selected DCOV and not a

specific value of energy (as in ECFUDS) is plotted in Fig. 15 as a function of battery life. The data show that the initial specific energy is similar to that achieved with the two modules characterized at ANL. The Ragone data (Fig. 6) indicate that the modules attained ~45 Wh/kg at the average driving profile discharge rate without the 19% weight burden (818 kg battery weight and 24.5 kg module weight) for the battery tray, enclosure, interconnections, etc. When the burden is included, the individual module specific energy decreases to about 37 Wh/kg. This result is also illustrated in Table 2, where the modules attained a specific energy of ~35 Wh/kg with FUDS/DSEP discharges. The battery attained over 35 Wh/kg on the first FUDS/DSEP discharge, but its specific energy decreased by about 10% after 110 cycles. Specific energy decreased to about 28 Wh/kg (~20% loss) after 400 cycles. After 550 cycles, the capacity of module 5 was limiting the discharges to ~24 Wh/kg.

Testing was temporarily suspended in October 1987 after the battery pack had accumulated 502 cycles (209 cycles in 1986). At that time, the battery was exhibiting a 2-h rate capacity of 153 Ah, 25.6 kWh (90% of rated) with a 220 Ah charge and a 1-h OCAC. The battery was placed on a CI trickle charge of about 3 A while awaiting further testing. After a three-month period, testing was resumed (January 1988) with ECFUDS-NL discharges. With this profile, the battery furnished 132 Ah (21.3 kW) before the discharge was terminated on low battery voltage (100 V) at about 7 s into the power pulse (current of ~520 A). The measured battery waveforms and discharge capacity were almost identical to those recorded the previous October (prior to the extended trickle charge period). Capacity verification cycles were also conducted using 2-h rate discharges to a battery voltage of 140 V (or module voltage of 4.0 V). A battery capacity of ~151 Ah (25 kWh) was obtained on these cycles. Based on these initial 1988 data, ANL concluded that (1) no improvement in module performance could be attributed to the extended trickle charge period; (2) only one module, No. 2, was clearly weak in power capability; and (3) removal of this module would make no significant improvement in battery performance.

In March 1988, battery performance after 545 cycles was being limited by three modules. A meeting between Eaton, EPI, and ANL resulted in a decision to remove the three weak modules from the battery. These modules were returned to EPI for conditioning and/or examination and included Nos. 2 (lowest power capability), 12 (lowest Ah capacity) and 26 (low power and capacity). The removed modules were replaced with water-filled module cases so that the pack airflow and watering systems could remain intact. After the pack was reassembled and charged, one of these module cases developed a leak (during watering) and had to be replaced with an artificial case. It was also determined that the pack thermal management unit was not operating properly, and this unit was shipped to EPI for repair. Reassembly of the pack was also delayed because water couplings were damaged and replacement couplings had to be fabricated by EPI.

Testing was resumed in April 1988 with 220 Ah charges and 19 kWh ECFUDS discharges (50 mile range with the reduced pack size) and no power pulse (52 kW) at the end of the discharges (ECFUDSB). These ECFUDSB discharges also used a 400-A maximum current limit and a 100-V DCOV. The pack successfully completed these 130-Ah, 19-kWh ECFUDS discharges. Because the 220-Ah charges resulted in an excessive overcharge (70%), the charges were reduced to 200 Ah (54% overcharge). The pack still successfully completed the ECFUDSB discharges under these conditions.

To evaluate the power capability of the individual modules, several discharges were attempted with the 52-kW power pulse (scaled to 46.4 kW) included at the end of the 50-mile driving schedule. These discharges were terminated because the voltage of module 5 decreased to less than 3 V as the current was increased (at ~350 A) during the power pulse. Time plots (in hours) of battery current (in amperes), voltage (in volts), and temperature (in degree Celsius) during an ECFUDSB discharge on cycle 593 are given in Fig. 16. The voltage of module 5 is also plotted. The data show that the voltage of module 5 drops to <3.0 V, causing the end of the discharge after providing a capacity of 131 Ah (19.1 kWh battery energy). A capacity of only 139 Ah/21 kWh (81% of its rated value) was obtained with 225 Ah charges, 1-h OCAC times, and 85-A CI discharges (DCOV of 140 V/pack or 4 V/module) due to the performance of module 5. The capacity increased to 146 Ah (22 kWh) with no OCAC. This result reflects a self-discharge rate for module 5 of 7 A.

The battery self-discharge loss was measured, and the results compared with those obtained earlier in the test program. Data from the early (28-30), middle (157-160), and late (599-612) test cycles are plotted in Fig. 17. The plots reflect the decline in battery capacity with life and an increase in self-discharge rate. The self-discharge loss in the first hour of OCAC increased by about a factor of three with life (~2.3, 4.0, and 6.5 Ah). The longer-term self-discharge loss late in life was excessive; the battery pack lost twice the capacity in one day (51 Ah, 35%) as the two DSEP modules lost in one week (~26 Ah, 15%). The impact of the increased self-discharge current on battery charge acceptance was also examined, and the results are given in Fig. 18. Early in life (<100 cycles), the increase in discharge capacity with overcharge (131 to 169%) reflects a battery charge acceptance of about 20%. In comparison, the charge acceptance has increased to >60% for a 145 to 153% change in overcharge late in life (>600 cycles).

The self-discharge loss of individual modules was examined at this time, and the rate of several appeared to be high based on the decline in module OCAD voltage. Four bad modules (Nos. 5, 7, 19, and 23) were electrically removed from the pack in September 1988 after 645 cycles. The pack subsequently achieved a capacity of only 119 Ah (15.1 kWh) because the performance of several other modules had deteriorated. Further data analyses showed that the weak modules were performing poorly due to high self-discharge rates. The life evaluation was halted in October 1988 after the battery pack had completed 661 cycles.

Fig. 11. Function diagram of the battery interface control unit

18 ADD.
THERMOCOUPLES
INSTALLED 14-AUG-87
(MOVED (10) to Mod* 23

Fig. 12. Module and thermocouple location map for the DSEP battery pack

Fig. 13. Capacity history of the DSEP battery pack for 2-h rate discharges

Table 3. Chronology of DSEP Battery Testing Activities

Date	Accumulated Cycles	Activity
3/86	1-6	Capacity Verification Tests with Reference Discharges
3/86	7-11	Driving Profile Discharges with FUDS/DSEP
3-5/86	12-71	Reference Discharges with Overcharge, OCAC, DCOV, OCAD, and Temperature Adjusted
6/86	--	Thermal Test at -18° C
6-7/86	--	Pack Returned to EPI for Electrolyte Replacement
8/86	72-76	Conditioning with 300-Ah Charges
8-10/86	77-151	Reference CI Discharges (63) and FUDS/DSEP Discharges (12)
11/86	152-155	New ECFUDS used with Power Pulse at 50 miles
11/86	156-160	Self-Discharge Test (0 and 1 h OCAC)
11/86	161-165	New ECFUDSC used that Continued FUDS after Power Pulse
11/86-3/87	166-310	ECFUDS (129) and ECFUDSC (16) Discharges with Charge Return Varied
3/87	311-313	ECFUDS used without 400 A Current Limit (ECFUDS-NL)
3-9/87	314-477	Reference CI Discharges (82), ECFUDS-NL (75), and FUDS/DSEP (7) Discharges with DCOV, Charge Return, OCAC, and Temperature Varied
9/87	478-481	New ECFUDSC with No Power Pulse or Current Limit (ECFUDSB-NL)
9-10/87	482-502	ECFUDS-NL (13) and ECFUDSB-NL (8) Discharges
10/87-1/88	--	Testing Suspended
1-3/88	503-545	Reference CI (6), ECFUDS-NL (19), ECFUDSB-NL (7), and ECFUDSB (11) Discharges
3/88	--	3 Modules Removed from Pack (#2, 12, 26)
4/88	546-556	Self-Discharge Test (0 and 1 h OCAC)
4-7/88	557-597	ECFUDSB (32), Reference (3), and ECFUDS (6) Discharges
7/88	598-604	Self-Discharge Test (0, 1, and 5 h OCAC)
7-8/88	605-645	ECFUDSB (15) and Reference (26) Discharges
8/88	--	4 Modules Removed from Pack (#5, 7, 19, and 23)
9-10/88	646-661	Reference (12) and ECFUDSB (4) Discharges
10/88	--	Battery Pack Testing Halted

Fig. 14. Battery capacity vs. temperature before and after the installation of new module electrolyte

Fig. 15. Specific energy history of the DSEP battery pack for driving profile discharges

11-JUL-88 09:50:23
 MCN 158 SET 98
 BATTERY ID=445
 TEST NUMBER=104
 29-JUN-88 13:34:17
 1.31E+02 AHR
 1.91E+04 WHR
 146.01 V-AVG

Fig. 16. Time plots of battery current, voltage, and temperature (along with the voltage of module #5) during an ECFUDSB discharge on cycle 593

Fig. 17. Self-discharge loss of the DSEP battery pack with life

Fig. 18. DSEP battery pack capacity as a function of applied charge with life

IV. CONCLUSIONS

Both DSEP modules exhibited good specific energy and maintained a good power capability at deep discharge. Based on measured module weight, these modules attained a specific energy of ~45 Wh/kg at a 10 W/kg discharge rate and a specific power of ~95 W/kg at 90% DOD. When the 19% weight burden for the battery hardware is included, module performance is reduced but remains at a high level: ~37 Wh/kg and ~81 W/kg, respectively. As a result, the modules were able to provide about 95% of their available energy with driving profile loads before their power capability limited the discharges. Both modules performed reproducibly, and their capacities remained constant to within $\pm 3\%$ during the ~100 test cycles after their electrolyte was replaced. Only after the peak power test did each module undergo a capacity loss of ~5%. These results indicated that the full-size battery pack would easily complete the proposed driving profiles.

The performance of the battery pack was not as good as anticipated. A capacity of 189 Ah was obtained on the first discharge, but this decreased to 151 Ah by cycle 50. After the electrolyte was replaced (cycle 71) in the battery's 28 modules, a maximum capacity of 165 Ah was achieved (97% of rating) with the same operating conditions as those used on the modules. The rate of battery capacity loss with life was small ($<0.02\%/cycle$) and a life of about 1000 cycles was projected. The power capability of the battery, however, was in question immediately after the electrolyte exchange. Because of its reduced power capability, a specific energy of only 32 Wh/kg (54-mile range) was obtained with FUDS/DSEP discharges (cycle 105), as compared to 35 Wh/kg (60-mile range) for the modules. The ECFUDS discharges to 49.5 simulated driving miles resulted in ~78% DOD operation. A charge return of 135% was used but may have been inadequate for that partial DOD condition. The subsequent difficulty in completing the 20-s, 52-kW power pulse in less than 30 cycles after its introduction also reflected the reduced battery power capability.

The DSEP modules and battery initially provided good performance and were able to satisfactorily complete profile discharge requirements. However, life performance for the battery pack did not meet expectations, and a reduced power capability and high self-discharge rates plagued its operation. Later post-test analyses of similar EPI nickel/iron modules showed that failure was caused by severe deterioration of the iron electrodes. The free iron material resulted in high self-discharge rates and nickel electrode contamination and capacity loss. It is believed that the capacity loss and reduced power capability in the first 300 test cycles are attributable to iron contamination of the nickel electrodes. The data presented above show the increased self-discharge loss with battery life. The excessive self-discharge rates caused by the buildup of loose iron electrode material with cycling resulted in battery end-of-life. Insufficient data are available to determine if the iron electrode deterioration is the result of a design or manufacturing deficiency.

Table 4. List of Abbreviations

ADL -----	Analysis and Diagnostics Laboratory
ANL -----	Argonne National Laboratory
CI -----	constant current
CP -----	constant power
CV -----	constant voltage
DCOV -----	discharge cut off voltage
DOD -----	depth of discharge
DOE -----	Department of Energy
DSEP -----	dual shaft electric propulsion
EHP -----	Electric and Hybrid Propulsion Division
EPI -----	Eagle-Picher Industries
EOD -----	end of discharge
EV -----	electric vehicle
FUDS -----	Federal Urban Driving Schedule
FUDS/DSEP ----	First Eaton battery power profile for the DSEP vehicle on a FUDS
ECFUDS -----	Second DSEP vehicle battery profile with concluding 52 kW, 20-s power pulse after 49.5 FUDS miles
ECFUDSB -----	Second DSEP vehicle FUDS without 52 kW pulse at 49.5 miles
ECFUDSC -----	Second DSEP vehicle FUDS that continues after 52 kW pulse
IETV-1 -----	Improve Electric Test Vehicle No. 1 (GE/Chrysler/DOE passenger car)
J227aD -----	SAE urban driving schedule with maximum 45 mph speed
Ni/Fe -----	nickel/iron
OC/ C -----	open circuit after charge
OCAD -----	open circuit after discharge
OTS -----	Office of Transportation Systems
Regen. -----	regenerative braking
SAE -----	Society of Automotive Engineers

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