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Idaho National Engineering Laboratory

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Laboratory Testing of the (Japan Storage Battery) Traction Batteries GS E75A and GS E150H

Idaho National Engineering Battery Laboratory

EG&G Idaho

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Idaho National Engineering
Battery Laboratory

June 1993

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Idaho Falls, Idaho 83415

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ABSTRACT

This report describes the testing of the GS E75A and GS E150H flooded lead-acid 12-volt traction batteries and compares the selected batteries to U.S.-made electric vehicle batteries. The results and conclusions of the testing are presented.

SUMMARY

The Japanese-made flooded lead-acid 12-volt traction batteries were tested in the INEL Battery Test Laboratory to provide a basis for performance comparison with equivalent domestic products. Tests covered two different battery types (three modules each) and included:

- Constant-current discharges at specified rates
- Constant-power discharges at specified rates
- Variable power (simulated SFUDS)
- Peak power
- Ten-day open-circuit stand.

Test specifics are contained in referenced INEL Electric and Hybrid Vehicle Program Test Procedures. A glossary of related technical terms is included in this report as an appendix.

Test results in all categories were acceptable, but showed no substantial differences in performance from domestic products to justify their higher purchase cost.

LABORATORY TESTING OF THE (JAPAN STORAGE BATTERY) TRACTION BATTERIES GS E75A AND GS E150H

INTRODUCTION

The GS E75A and GS E150H batteries are manufactured in Japan by Japan Storage Battery Co., Ltd. and imported into the United States by GS Battery (U.S.A.), Inc. The GS E75A battery is shown in Figure 1, and the GS E150H in Figure 2.

The INEL ordered 3 modules of each type for initial evaluation testing at the Idaho National Engineering Laboratory (INEL) Battery Test Laboratory on August 1, 1990, and received the modules on January 15, 1991. Testing was completed in March 1992. No tear-down examinations or chemical analyses were performed. This report covers the results of the tests performed on these 3 modules.

Figure 1. Photograph of GS E75A battery.

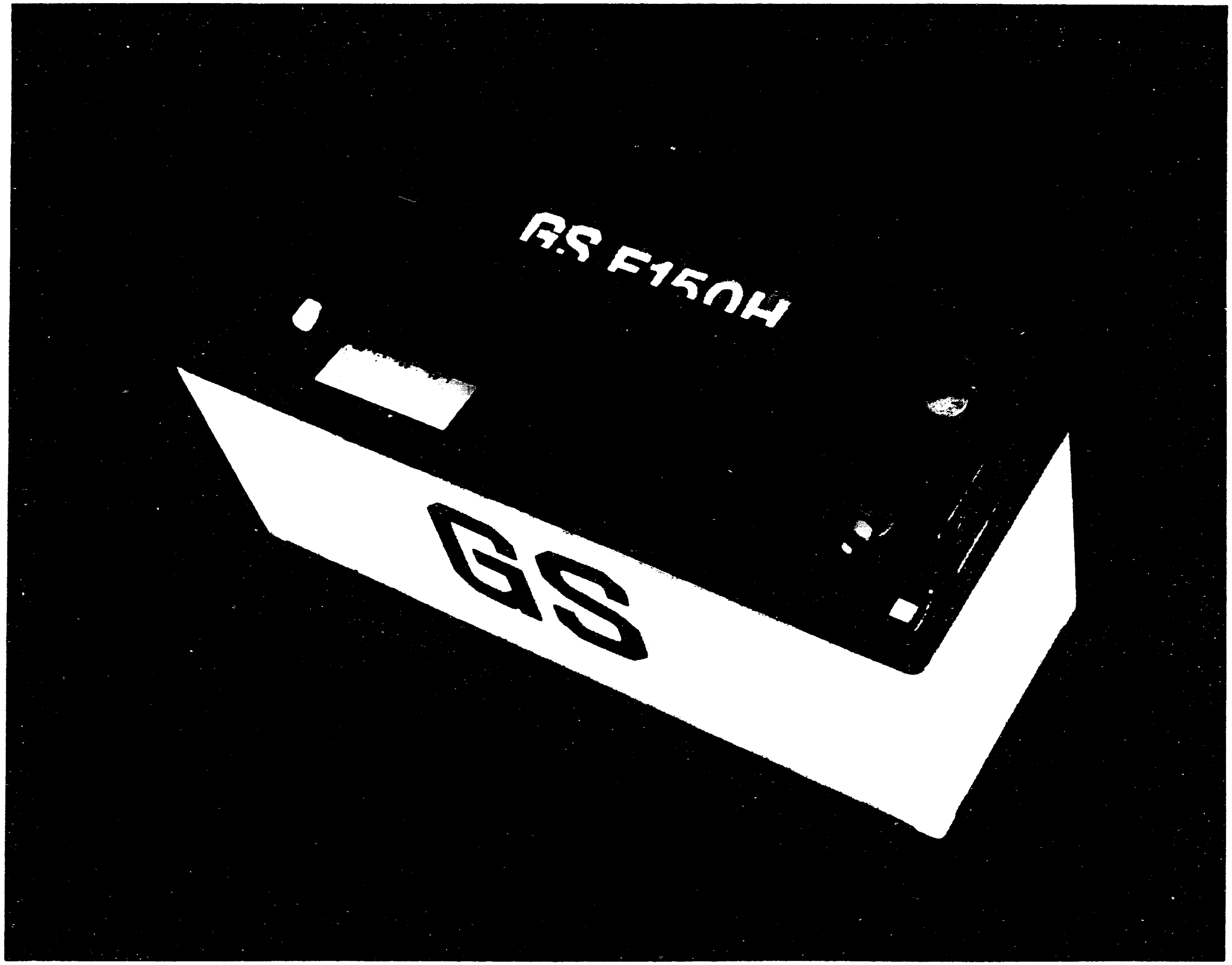

Figure 2. Photograph of GS E150H battery.

DESCRIPTION OF THE BATTERY

The GS E75A and GS E150H modules are of flat-plate design. Containers and covers are made of polypropylene. A single-point watering system is incorporated into the cover. Terminals on these modules are the SAE post type. The data recorded during receiving inspection of the batteries is given in Table 1.

Table 1. General battery information for GS E75A and GS E150H.

	GS E75A	GS E150H
Module weight dry (avg)	17.82 kg (39.21 lb)	32.38 kg (71.39 lb)
Module weight wet (avg)	24.98 kg (54.96 lb)	46.94 kg (103.5 lb)
Module weight variance	± 0.10 kg (0.22 lb)	± 0.40 kg (1.80 lb)
Module height (overall)	232 mm (9.05 in.)	258 mm (10.2 in.)
Module height (container)	207 mm (8.07 in.)	222 mm (8.79 in.)
Module width	172 mm (6.80 in.)	182 mm (7.21 in.)
Module length	304 mm (12.0 in.)	505 mm (20.0 in.)
Module cost (each)	$330.00	$590.00
Rated capacity at 3-hour rate	6.6 A·h	135 A·h

The modules were received in the dry-charged state. Upon receipt, the modules were weighed in the dry state, filled with 1.280 specific gravity sulfuric acid, and reweighed.

The batteries were configured into 2 packs, one for the GS E75A and one for the GS E150H. Each pack contained three 12-volt modules of the same type. The assigned pack numbers were:

Pack 66 . . . . GS E75A
Pack 67 . . . . GS E150H

TESTS PERFORMED

CONSTANT CURRENT

Constant current discharge tests were conducted as cycles 1-14 for the GS E75A and cycles 1-18 for the GS E150H: The purpose of this series of discharges is to assure that the battery capacity has stabilized and to establish the baseline actual capacity of the battery under test. Groups of three discharges are performed, approximating each of the following rates: $C_3/3$, $C_2/2$, $C_1/1$, and $C_3/3$, respectively (INEL Test Procedure ETV-BAT-984.)[1] Each discharge is terminated at the specified discharge cutoff voltage of 1.75 volts/cell. During this test series, the battery stands on open circuit before discharge for at least 1 hour (but no more than 24 hours) to allow the battery to reach test temperature. Additionally, the battery is allowed to stand at open circuit after discharge (prior to charge) for at least 1 hour (but no more than 6 hours) until the test temperature is reached. The initial $C_3/3$ discharge groups are normally repeated until three consecutive ampere-hour measurements are within 2% of each other. (In the work reported here, the ampere-hour measurements were not within this tolerance. However, the measurements were only a fraction of a percent outside the goal and thus the laboratory manager accepted the value in the interest of minimizing testing costs. Also the final $C_3/3$ tests were made later in the testing to combine the open-circuit stand test and tne $C_3/3$ tests in order to minimize testing costs.)

CONSTANT POWER

Constant power discharge tests were conducted as cycles 15-27 for the GS E75A and cycles 19-27 for the GS E150H (INEL Test Procedure EHV-BAT-688).[1] The purpose of this series of tests is to collect voltage-vs-current behavior of a battery as a function of depth-of-discharge under constant power discharge regimes. Constant power is chosen fur this analysis (as opposed to constant current) because it more accurately represents circumstances related to electric vehicle usage. A minimum of two discharges are performed at each of the following approximate power levels: 7 W/kg, 21 W/kg, and 42 W/kg based on the battery pack weight (i.e. the sum of the weights of the modules tested). Additional discharge cycles, at 60 W/kg, may also be performed. The cutoff voltage on the discharges of 42 W/kg and 60 W/kg is 1.3 volts/cell. There is no specified interval of time in which the battery must stand on open circuit prior to reaching the specified beginning-of-discharge temperature.

VARIABLE POWER (SFUDS)

Variable power discharges were conducted as cycles 28-29 for the GS E75A, and cycles 40-41 for the GS E150H. The Simplified Federal Urban Driving Schedule (SFUDS) battery test cycle represents the power profile which approximates the Improved Dual Shaft Electric Propulsion (IDSEP) vehicle performing the Federal Urban Driving Schedule (FUDS). The power profile of the SFUDS is segmented into discrete power steps (-10, 0, 10, 20, 50, and 79 W/kg of battery weight) of sufficient duration that the spectrum closely approximates the actual IDSEP vehicle driving the FUDS velocity-vs-time profile. The general profile of the SFUDS power-vs-time discharge for the IDSEP vehicle is shown in Figure 3. However, the battery test cycle that simulates dynamometer testing of an electric vehicle on the SFUDS was developed assuming a battery weight of 695 kg, and therefore cannot be directly applied to most batteries for determining the actual test power levels. The methodology used in determining the actual power profile used for this test was derived from Reference 2 and is summarized below.

1. The number of battery modules in series which will form an IDSEP battery pack is determined subject to the minimum and maximum voltage constraints of the IDSEP vehicle.

2. The total weight of these modules is then determined and 100 kg is added to the pack weight to arrive at the battery system weight.

3. The SFUDS power levels are then determined employing a formula which corrects the power requirements of the IDSEP vehicle for the variation in battery weight.

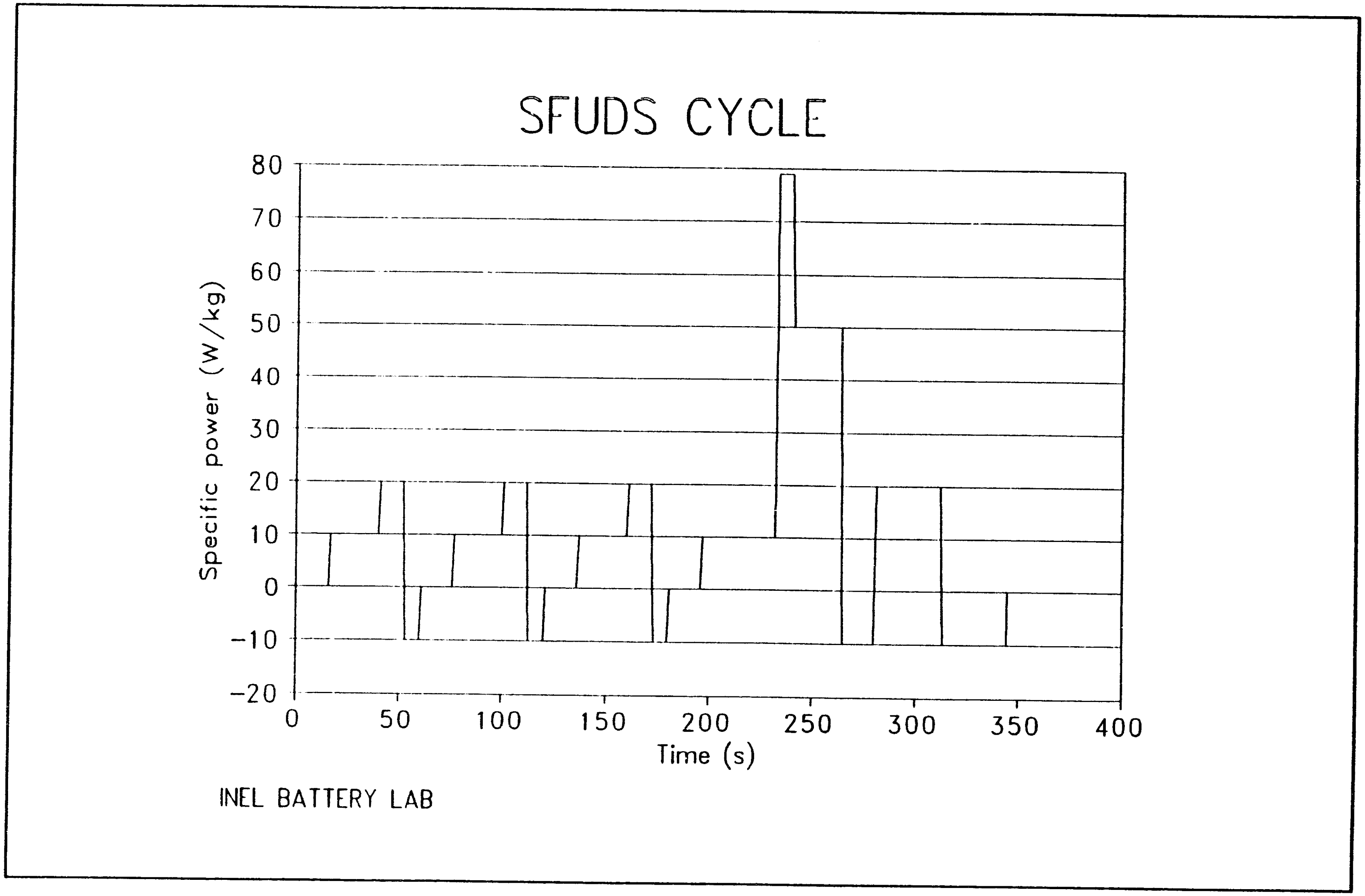

Figure 3. SFUDS profile.

4. The actual test power levels are then determined by multiplying the corrected IDSEP power levels by the ratio of the number of modules tested in series to the number of modules determined for the IDSEP vehicle in step 1.

The discharge profile is repeated in groups of four SFUDS cycles, with a ten-minute open-circuit rest period between each group. The test is controlled by the simulator. The voltage under load is clamped at 1.3 volts/cell minimum voltage (averaged over the pack) and the simulator limits power subject to this minimum voltage. When the test battery cannot produce 30 W/kg the test is automatically terminated. Thus, the results of variable power tests represent what would be expected if the test batteries were actually installed in an IDSEP vehicle and driven over the FUDS velocity-vs-time profile. Details of the test procedure can be found in Reference 2 and ETV-BAT-988.[1]

PEAK POWER

Peak power discharges were conducted as cycle 35 for the GS E75A and cycles 61-62 for the GS E150H. The purpose of this test is to determine the peak power capability from derived resistance calculations of a battery at various depths-of-discharge (i.e. 80% DOD, 50% DOD and 0% DOD, respectively). The method used is derived from a discharge schedule that emulates a portion of the SAE J227a D power profile for the IETV-1 vehicle. This procedure is identified in INEL Test Procedure EHV-BAT-885 (Method 2)[1] and is outlined as follows:

1. The battery is first discharged at 12 W/kg for ten seconds and then 44 W/kg for 60 seconds.

2. The battery is then discharged at the approximate $C_3/3$ rate to 50% depth-of-discharge where the 12 W/kg (for 10 s) and 44 W/kg (for 60 s) discharges are repeated.

3. The battery is then again discharged at the approximate $C_3/3$ rate to 80% depth-of-discharge and the 12 and 44 W/kg power-level discharges again repeated.

4. Steps 1-3 are repeated at least once to verify repeatability of test results.

5. The peak power capability is derived from the measured changes in battery voltage caused by changes in battery current at the 8- and 68-second points of the 12 and 44 W/kg power levels, respectively.

During the peak power portion of the test program, the peak power information at the selected DOD condition of the battery was obtained. Peak power discharges were performed on all modules of each type.

10-DAY STAND TEST

Stand tests were conducted as cycles 37-38 for the GS E75A and cycles 45-46 for the GS E15-H. The purpose of the stand tests is to measure the amount of capacity loss associated with extended periods of non-use storage at open circuit. For this test, the battery is fully charged and allowed to stand on open circuit at ambient temperature for 10 days. The capacity is measured under constant current discharges at the approximate $C_3/3$ rate before and after the open circuit stand period. This procedure is repeated a minimum of two times.

DATA ACQUISITION

Data were acquired using Neff 470 hardware and software. Parameters measured were: module voltages, battery voltage, charge/discharge amperes, module temperatures, and ambient temperature as a function of time. The raw data were then played back for subsequent analysis into a Lotus 123 spreadsheet. Calculations were then performed to provide analyses of the test data.

Typical calculated quantities include: standard deviation of module voltages and module temperatures; average module temperatures; maximum temperature; average battery voltage; average charge and discharge current; charge and discharge ampere hours; charge and discharge energy; power and specific power as appropriate to the test performed. A minimum of 50 data sets are taken during the course of any test to assure meaningful reported data. However, a much greater number of data sets are recorded for tests where it is judged appropriate. For instance, 10,000 or more time-specific data sets may be recorded during SFUDS testing.

CHARGING CONSIDERATIONS

The charge algorithm obtained from the battery distributor[3] was: 18 A constant current to 2.4 volts/cell, then 2.25 volts/cell to 125% return of previous A·h discharge for GS E75A, and 36 A to 2.4 volts/cell, then 2.25 volts/cell to 125% return for GS E150H. In practice, this algorithm would have required several days on charge as the current tapered to less than 0.3 A at approximately 105% return. The algorithm used during evaluation was 18 A for GS E75A and 35 A for GS E150H to 2.4 volts/cell, taper to 4 A, then 4 A to 125% return. This algorithm was acceptable to the Japan Storage Battery Field Sales Engineer.

RESULTS OF BATTERY LABORATORY TESTING

Complete test data are presented in Tables 2 and 3. **Constant current tests** were cycles 1-14 for the GS E75A and cycles 1-18 for the GS E150H.

1. The capacities determined by constant-current characterization tests were as follows:

	GS E75A	GS E150H
1-hour capacity	54 Ah	88 Ah
2-hour capacity	63 Ah	109 Ah
3-hour capacity	69 Ah	126 Ah

2. The battery reached rated capacity after 3 cycles for GS E75A, and after 9 cycles for GS E150H.

3. The coulombic efficiency was 80% for GS E75A and 79% for GS E150H.

4. The energy efficiency was 67% for GS E75A and 64% for GS E150H.

   The attached Peukert plot (Figure 4) compares the GS E75A and GS E150H modules with other batteries previously tested at the INEL.

5. The specific energy density at the 3-hour rate was 30 W·h/kg for GS E75A and 32 W·h/kg for GS E150H, which is average for commercially available lead-acid batteries.

6. The volumetric energy at the 3-hour rate was 62 W·h/ℓ for GS E75A and 66 W·h/ℓ for GS E150H, which is also in the average range for commercially available lead-acid batteries.

Constant power tests were cycles 15-27 for the GS E75A and cycles 19-27 for the GS E150H.

1. The Ragone plots (Figure 5) indicates these batteries have average performance for commercially available batteries. The Ragone plots were made using the constant power data.

2. Voltage behavior under load as a function of depth-of-discharge (DOD) at constant power is shown in Figures 6 and 7.

Variable power (SFUDS) tests were cycles 28-29 for the GS E75A and cycles 40-41 for the GS E150H batteries.

1. Voltage behavior under load as a function of DOD at variable power is shown in Figures 8 and 9.

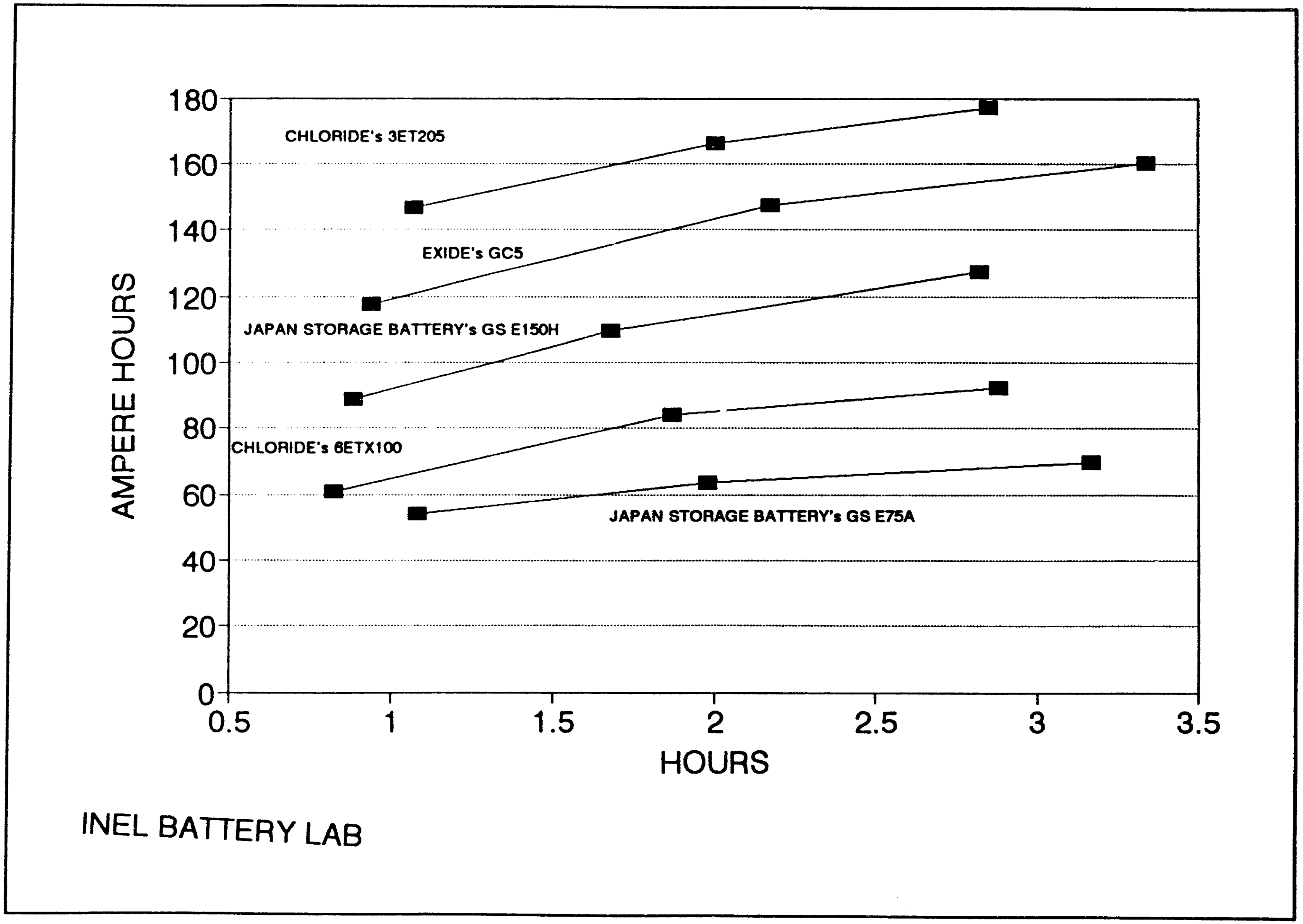

Figure 4. Puekert Plot for flooded lead-acid batteries.

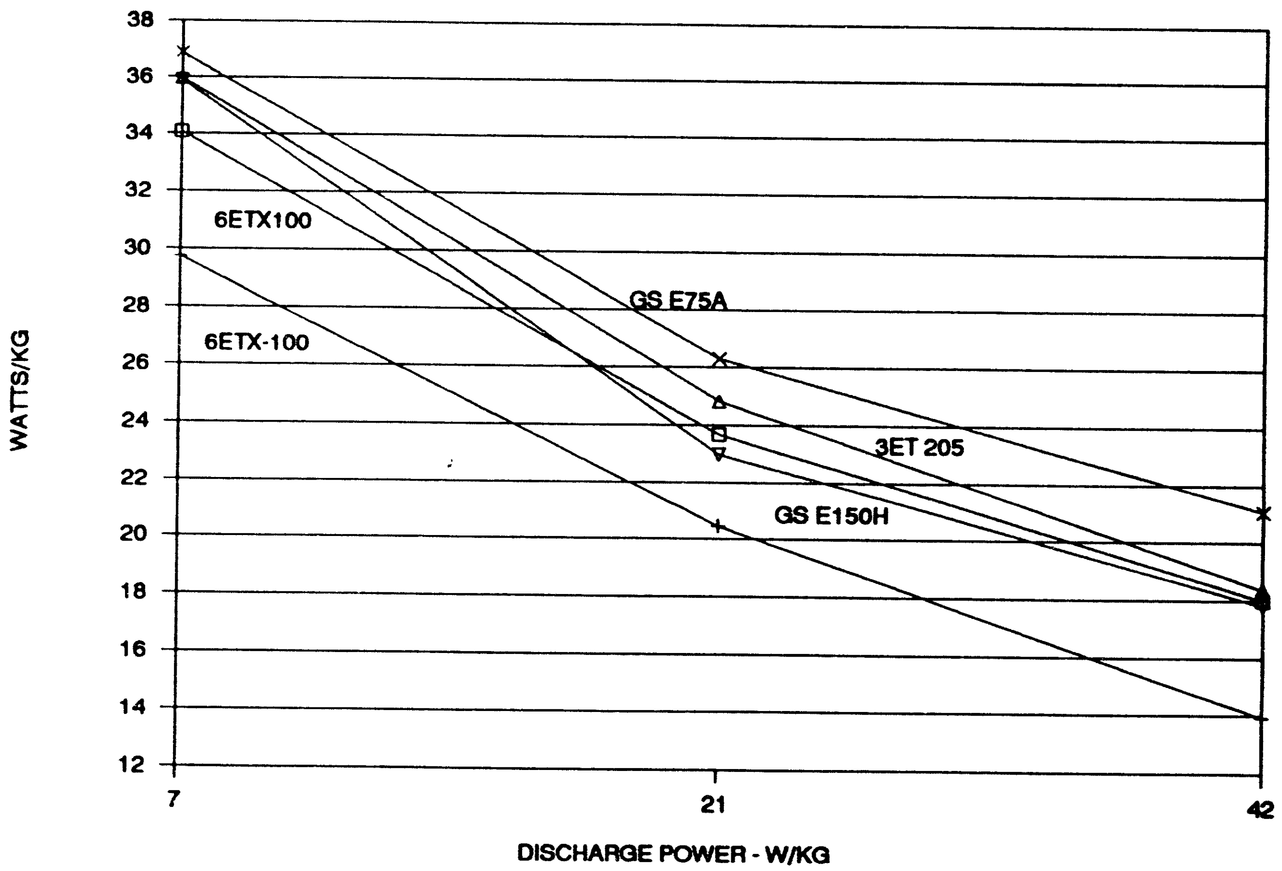

Figure 5. Ragone Plot for flooded lead-acid batteries.

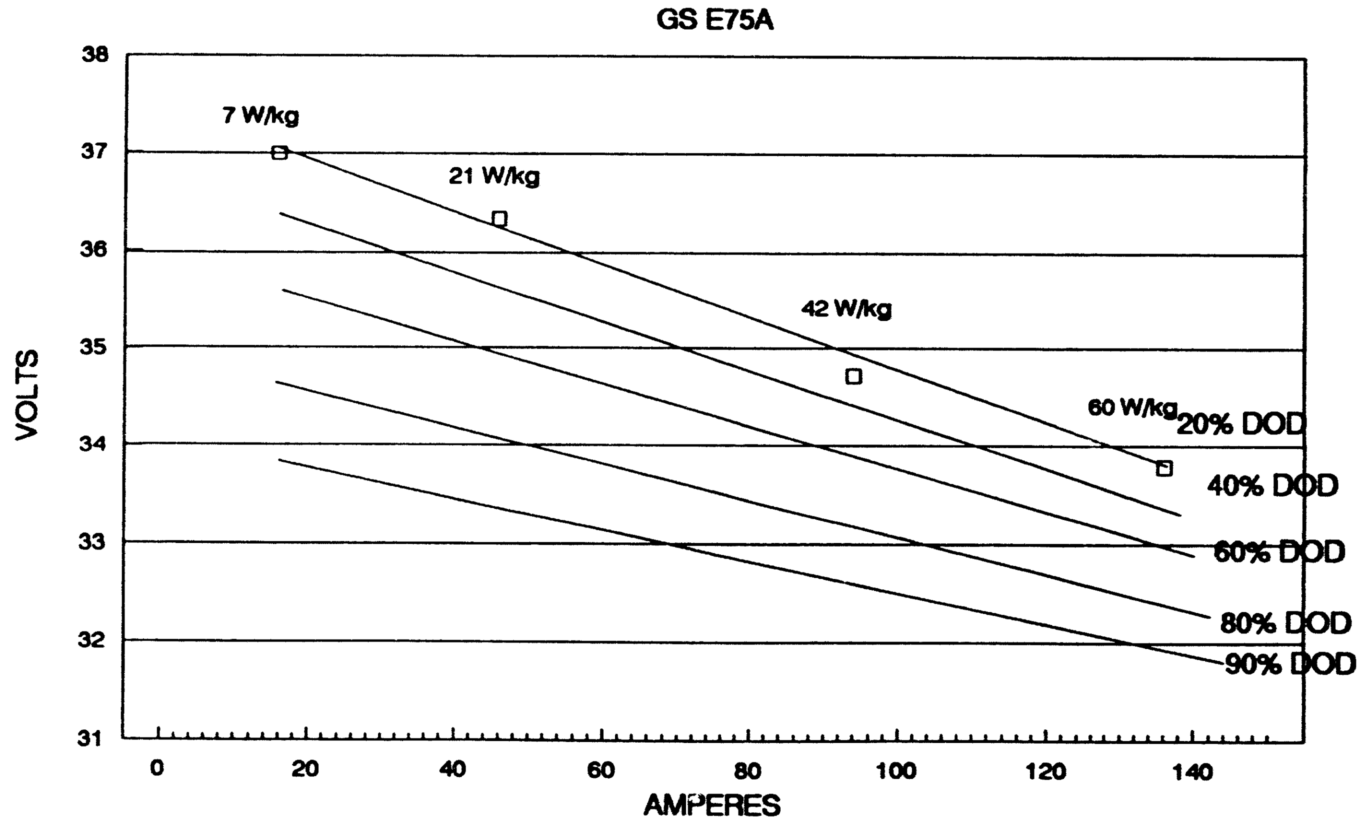

Figure 6. V vs. I at constant power for GS E75A battery.

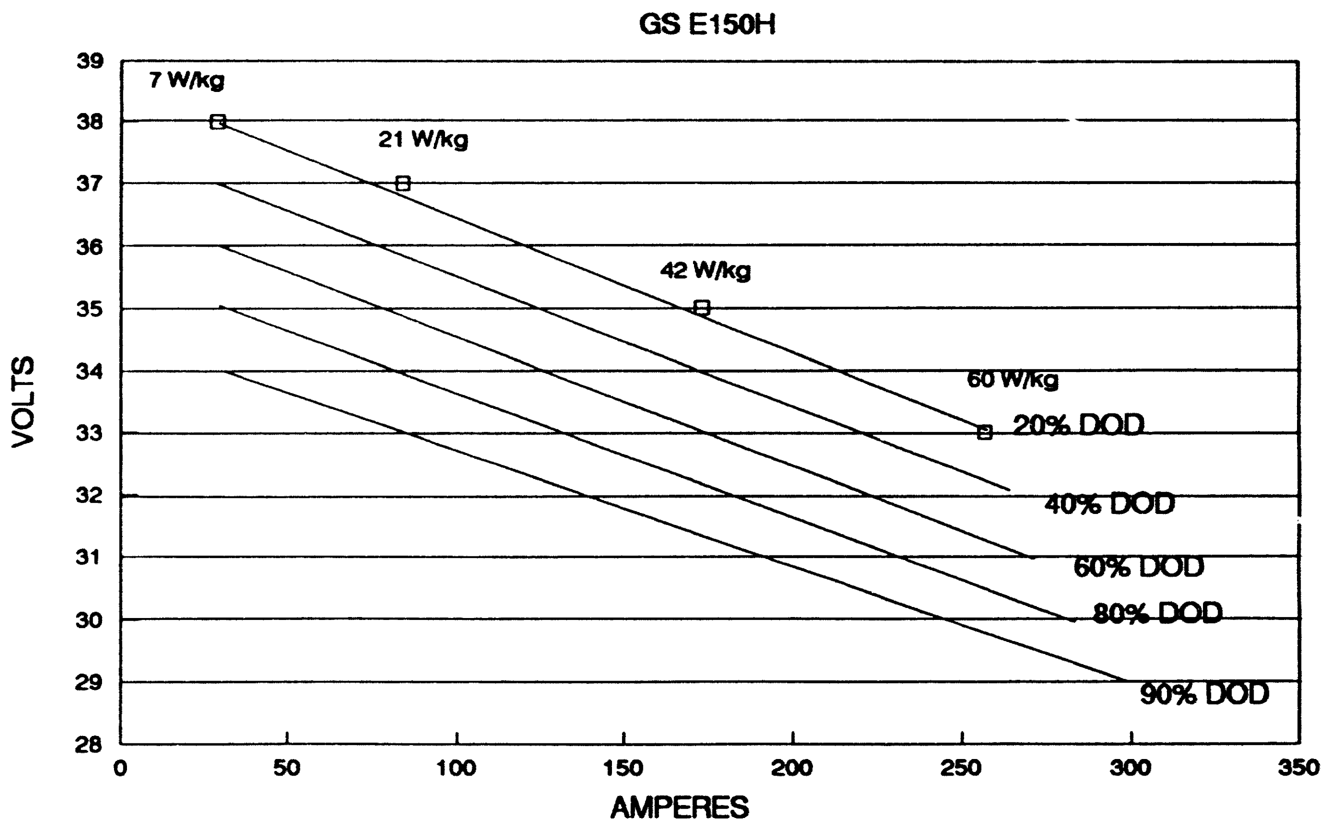

Figure 7. V vs. I at constant power for GS E150H battery.

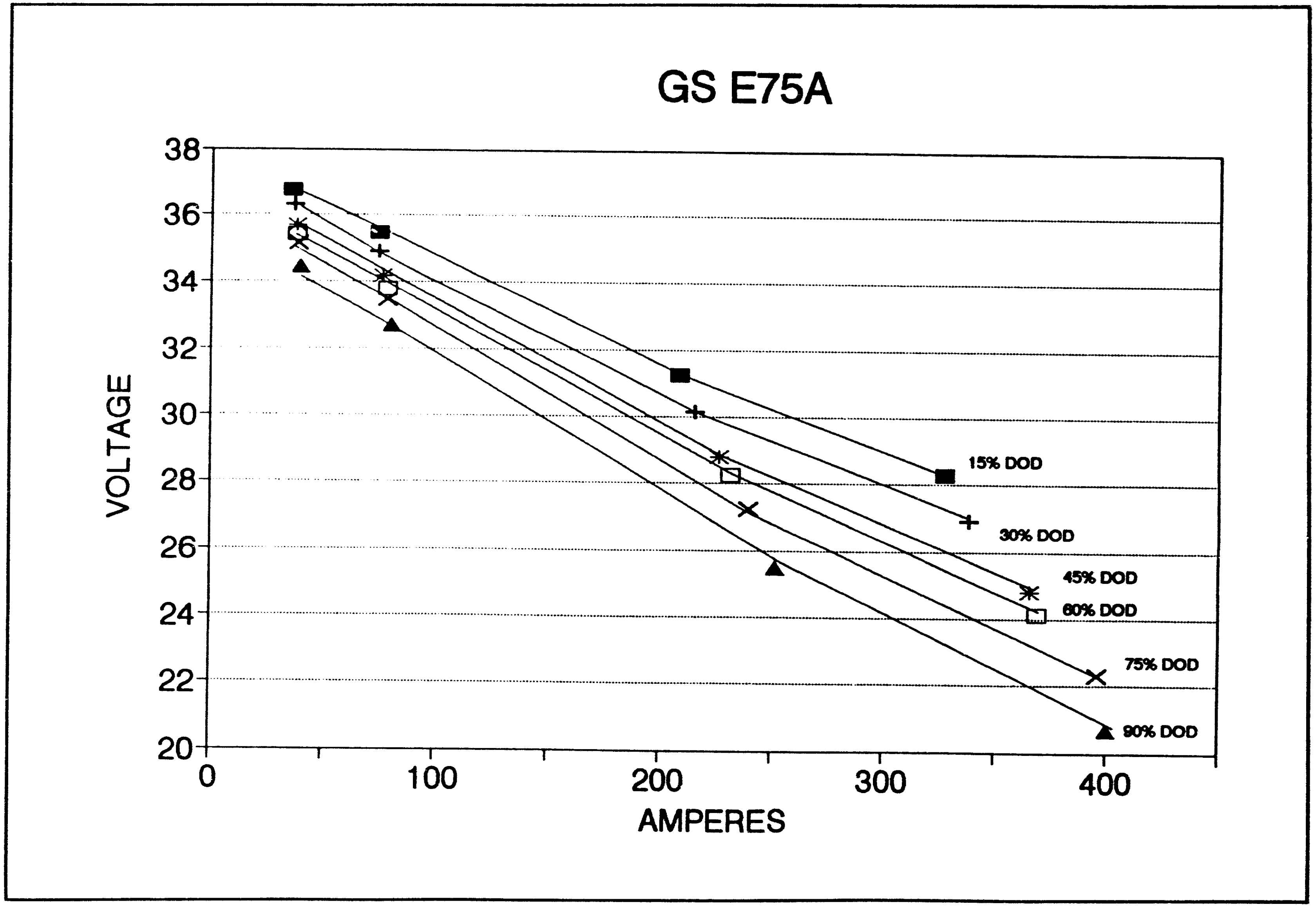

Figure 8. V vs. I at variable power (SFUDS) for GS E75A battery.

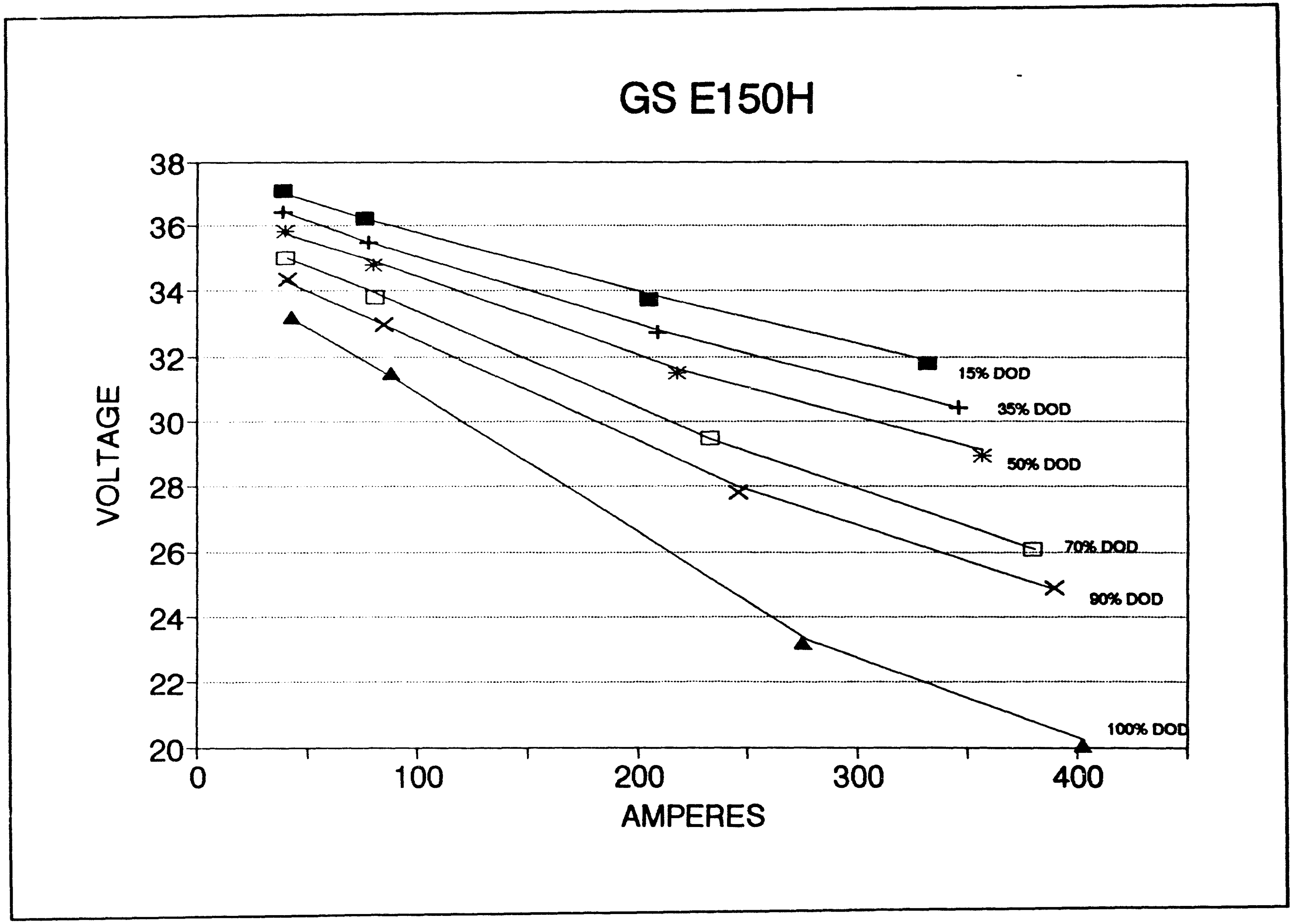

Figure 9. V vs. I at variable power (SFUDS) for GS E150H battery.

2. Voltage behavior as a function of time at variable power (SFUDS) for the respective batteries is shown in Figures 10 and 11.

3. The net specific energy density achieved during SFUDS tests was 22.3 W·h/kg for GS E75A and 20.9 W·h/kg for GS E150H.

Peak power performance was calculated from cycle 35 for the GS E75A and from cycles 61 and 62 for the GS E150H batteries.

1. Peak power capability was determined using method 2 as described in Procedure EHV-BAT-885.[1] This method emulates a portion of the SAE J227a D/ETV-1 power profile.

Peak Power	GS E75A	GS E150H
0% DOD	110 W/kg	98 W/kg
50% DOD	103 W/kg	85 W/kg
80% DOD	84 W/kg	47 W/kg

Peak power deals with the ability of the electric vehicle to accelerate. All other factors being equal, the greater the peak power the better the acceleration.

Stand tests were cycles 37-38 for the GS E75A and cycles 45-46 for the GS E150H batteries.

1. The battery retained 90% of its $C_3/3$ capacity following a 10-day stand test on the GS E75A, and 95% of its $C_3/3$ capacity on the GS E150H for an equivalent period.

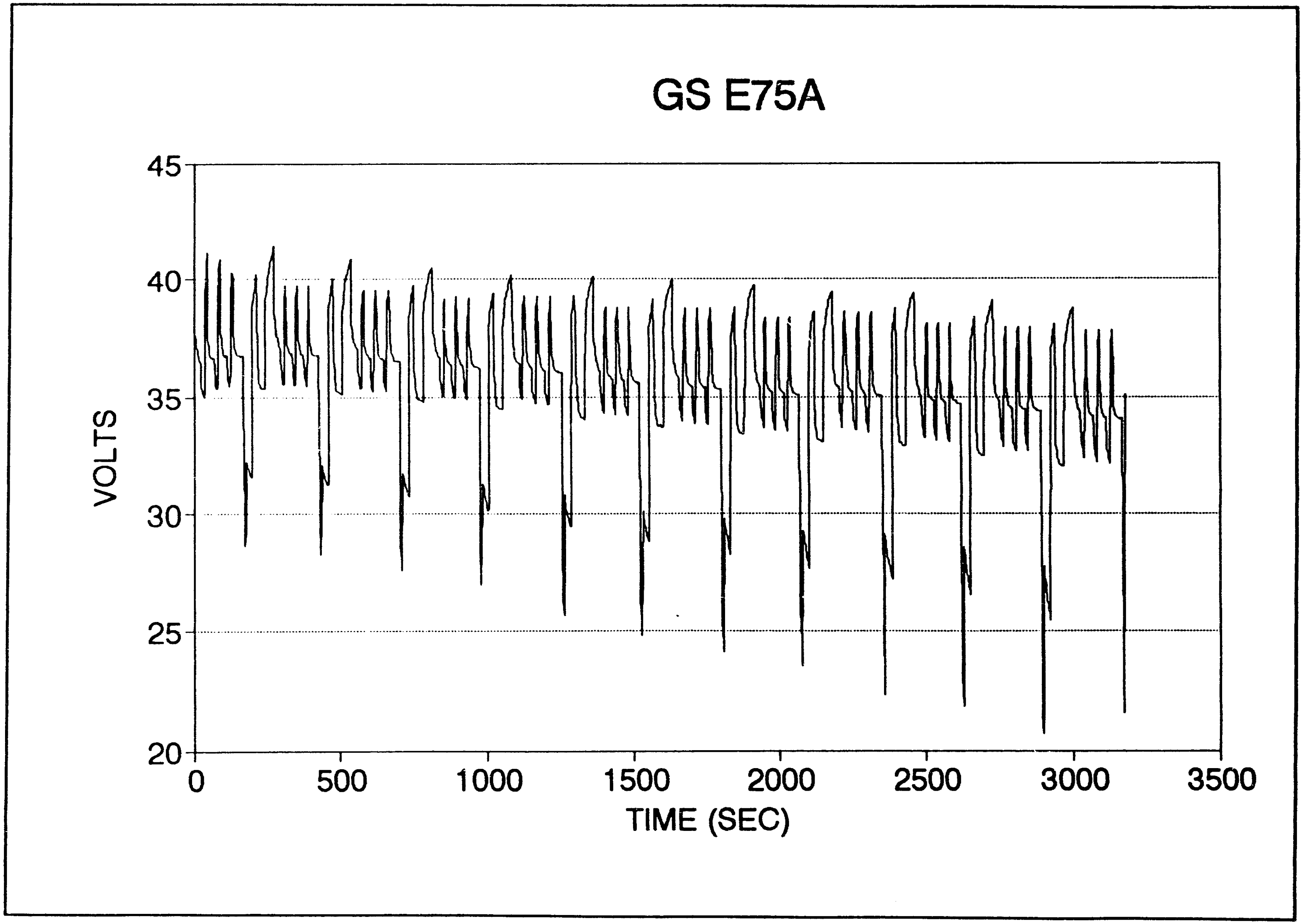

Figure 10. Voltage-vs-time variable power (SFUDS) for GS E75A battery.

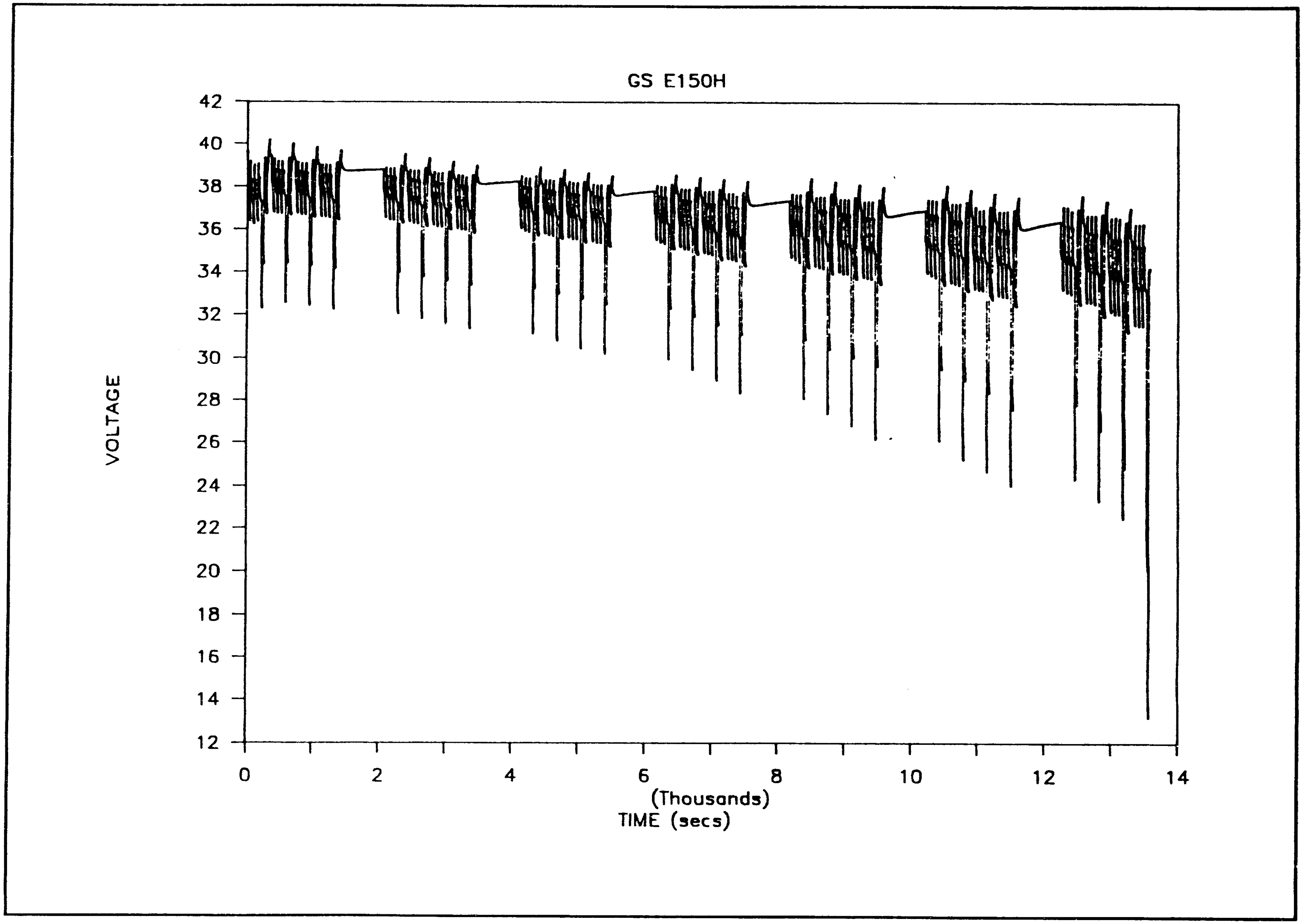

Figure 11. Voltage-vs-time variable power (SFUDS) for GS E150H battery.

Table 2. Summary data for GS e75A battery.

TOTAL SUMMARY BATTERY DATA SHEET PACK NO.66 GS E75A

	DISCHARGE							
	DATE	DR (A,P,F)	ABOD (Ah)	EBOD (KWH)	DCV$ (VOLTS)	EDT (AVG.)	MAX.TEMP. (C)	TTD
Cycle 1	07/31/91	21.82	58.18	2.01	31.45	25.83	26.45	2H 40M
Cycle 2	08/01/91	22.04	61.70	2.16	31.43	25.17	25.82	2H 48M
Cycle 3	08/02/91	22.02	65.31	2.29	31.40	25.13	25.52	2H 58M
Cycle 4	08/05/91	21.91	67.19	2.36	32.12	26.43	26.91	3H 04M
Cycle 5	08/06/91	21.95	67.33	2.37	31.92	25.04	25.31	3H 04M
Cycle 6	08/08/91	22.02	69.36	2.45	31.59	25.21	25.72	3H 09M
Cycle 7	08/12/91	21.99	70.37	2.48	31.93	25.61	26.48	3H 12M
Cycle 8	08/13/91	22.03	69.41	2.45	32.16	24.98	25.37	3H 09M
Cycle 9	08/14/91	32.06	63.05	2.21	31.75	26.20	27.02	1H 58M
Cycle 10	08/15/91	31.96	62.85	2.20	31.89	27.25	27.60	1H 58M
Cycle 11	08/16/91	32.05	64.10	2.24	31.68	26.42	27.21	2H 00M
Cycle 12	08/19/91	49.98	54.98	1.90	31.69	27.33	28.01	1H 06M
Cycle 13	08/20/91	49.98	53.32	1.84	31.58	25.97	26.41	1H 04M
Cycle 14	08/21/91	49.91	54.06	1.87	31.58	27.38	28.31	1H 05M
Cycle 15	08/22/91	7W/KG	75.29	2.69	32.35	24.71	25.79	4H 36M
Cycle 16	08/23/91	7W/KG	79.03	2.83	32.41	24.48	25.74	4H 51M
Cycle 17	08/26/91	7W/KG	77.68	2.77	32.34	25.23	25.58	4H 45M
Cycle 18	08/27/91	21W/KG	57.64	2.01	31.97	26.70	27.18	1H 14M
Cycle 19	08/28/91	21W/KG	55.74	1.95	31.99	28.26	28.61	1H 12M
Cycle 20	08/29/91	21W/KG	55.82	1.95	31.89	28.23	28.75	1H 12M
Cycle 21	08/30/91	42W/KG	37.39	1.27	31.87	28.04	28.42	23.5M
Cycle 22	09/03/91	42W/KG	35.16	1.18	31.78	27.11	27.72	22.0M
Cycle 23	09/04/91	42W/KG	34.15	1.16	31.90	26.69	26.78	21.5M
Cycle 24	09/05/91	60W/KG	23.73	0.78	31.63	26.01	26.73	10.25M
Cycle 25	09/06/91	60W/KG	21.99	0.73	31.66	24.86	25.46	9.50M
Cycle 26	09/09/91	60W/KG	20.00	---	31.66	24.49	25.23	8.83M
Cycle 27	09/10/91	60W/KG	20.01	0.66	31.73	23.51	24.16	8.67M
Cycle 28	09/11/91	SFUDS	45.10	1.67		24.00	34.80	70M
Cycle 29	09/12/91	SFUDS	44.82	1.67		22.10	32.90	70M
Cycle 30	09/13/91	42W/KG	47.91	1.57	24.10	28.45	28.73	29.25M
Cycle 31	09/16/91	42W/KG	48.40	1.59	24.51	30.95	31.19	29.67M
Cycle 32	09/17/91	60W/KG	41.73	1.32	25.19	30.93	31.56	17.50M
Cycle 33	09/18/91	60W/KG	41.31	1.31	24.72	30.15	30.60	17.17M
Cycle 34	09/19/91	22.01	71.52	2.53	31.87	25.38	25.50	3H 15M
Cycle 35	09/20/91	PEAK POWER @ 0. 50 & 80% DOD						
Cycle 36	09/23/91	21.93	75.65	2.69	31.84	26.96	27.11	3H 27M
Cycle 37	10/04/91	22.24	68.94	2.44	32.44	23.09	24.32	3H 06M
Cycle 38	10/14/91	22.01	67.14	2.38	32.48	25.66	25.98	3H 03M
Cycle 39								
Cycle 40								
Cycle 41								
Cycle 42								
Cycle 43								
Cycle 44								
Cycle 45								
Cycle 46								
Cycle 47								
Cycle 48								
Cycle 49								
Cycle 50								

	CHARGE									
	DATE	ABIR (Ah)	EBIR (KWH)	CC (amps)	% CHARGE	ECT (AVG.)	MAX.TEMP. ((C)	TTDC	WATER (ml)	NOTES
Cycle 1	07/31/91	74.94	3.13	4.11	128.81	27.38	28.02	7H 40M		CHARGE INTERUPTED AT 4 HRS. 5 MINS. FOR 3 HRS.
Cycle 2	08/01/91	80.30	3.38	3.97	130.15	29.00	29.90	9H 05M		
Cycle 3	08/02/91	82.90	3.50	3.95	126.93	27.23	30.31	9H 10M		
Cycle 4	08/05/91	87.54	3.70	3.95	130.29	29.11	30.12	9H 45M		
Cycle 5	08/06/91	86.77	3.67	3.97	128.87	23.84	30.77	9H 50M		INTERUPTED CHARGE - POWER FAILURE
Cycle 6	08/08/91	87.12	3.68	4.09	125.61	27.25	30.23	9H 30M		
Cycle 7	08/12/91	87.37	3.67	3.97	124.16	29.80	31.11	9H 10M		
Cycle 8	08/13/91	87.20	3.67	3.98	125.63	31.54	32.03	9H 20M	300	WATERED BATTERY
Cycle 9	08/14/91	80.91	3.43	3.96	128.33	31.67	32.08	8H 55M		
Cycle 10	08/15/91	90.56	3.90	4.97	144.09	32.52	32.88	9H 40M		CHARGER DID NOT FOLLOW INSTALLED PROGRAM
Cycle 11	08/16/91	82.61	3.53	4.10	128.88	27.71	29.08	9H 15M		TWO PART CHARGE
Cycle 12	08/19/91	71.06	3.03	3.96	129.25	28.82	30.42	7H 50M		
Cycle 13	08/20/91	68.90	2.94	3.98	129.22	31.43	31.93	7H 40M		
Cycle 14	08/21/91	68.76	2.93	3.94	127.19	31.10	31.94	7H 30M		
Cycle 15	08/22/91	98.60	4.19	3.99	130.96	33.29	34.87	11H 25M		
Cycle 16	08/23/91	97.58	4.11	4.02	123.47	34.08	34.67	10H 40M		
Cycle 17	08/26/91	97.60	4.12	3.95	125.64	30.44	31.55	10H 30M		
Cycle 18	08/27/91	74.81	3.21	3.97	129.79	31.61	32.03	8H 45M		
Cycle 19	08/28/91	74.63	3.22	4.12	133.89	31.78	32.34	8H 55M		
Cycle 20	08/29/91	72.71	3.12	4.06	130.26	31.89	32.45	8H 25M		
Cycle 21	08/30/91	47.58	2.06	3.98	127.25	30.38	30.56	5H 25M		
Cycle 22	09/03/91	48.18	2.10	4.09	137.03	29.99	30.60	5H 50M		
Cycle 23	09/04/91	43.75	1.90	3.99	128.11	33.28	33.55	5H 00M		
Cycle 24	09/05/91	29.98	1.31	3.98	126.34	28.66	29.31	3H 30M		
Cycle 25	09/06/91	27.00	---	---	122.78	29.65	30.25	3H 27M		CHARGE AMP/HRS ARE FROM MPG
Cycle 26	09/09/91	25.90	1.13	4.05	129.50	28.44	28.75	3H 05M		DISCHARGE AMP/HRS ARE FROM MPG
Cycle 27	09/10/91	26.58	1.17	4.04	132.83	31.15	31.31	3H 20M		
Cycle 28	09/11/91	55.58	2.37	4.03	123.24	29.84	30.19	6H 05M		
Cycle 29	09/12/91	50.29	2.12	4.15	112.20	28.51	28.95	4H 55M		
Cycle 30	09/13/91	59.19	2.53	2.73	123.54	23.58	31.33	6H 45M		
Cycle 31	09/16/91	61.02	2.61	4.05	126.07	31.51	32.11	6H 50M		
Cycle 32	09/17/91	54.12	2.34	4.20	129.69	31.29	31.88	6H 25M		
Cycle 33	09/18/91	50.04	2.15	4.08	121.13	30.28	30.77	5H 30M		
Cycle 34	09/19/91	94.48	4.03	4.13	132.10	31.77	32.21	11H 15M		
Cycle 35	09/20/91	77.96	3.36	4.08	---	31.17	31.71	9H 25M		
Cycle 36	09/23/91	99.76	4.26	4.13	131.87	31.77	32.35	11H 50M		
Cycle 37	10/04/91	89.04	3.72	4.27	129.16	29.18	33.84	9H 20M		10 DAY STAND TEST
Cycle 38	10/14/91	87.45	3.70	4.15	130.25	22.89	32.11	10H 05M		10 DAY STAND TEST
Cycle 39										
Cycle 40										
Cycle 41										
Cycle 42										
Cycle 43										
Cycle 44										
Cycle 45										
Cycle 46										
Cycle 47										
Cycle 48										
Cycle 49										
Cycle 50										

Acronyms:
ABOD Amps Battery Out Discharge
EBOD Energy Battery Out Discharge
EDT Avg. Ending Discharge Temperature
DR Discharge (A-Amps, P-Power Kw, F-FUDS Cycle)
Constant Current Discharges done per ETV-BAT-984
Constant Power Discharges done per ETV-BAT-688
Fuds Discharges done per ETV-BAT-988 and/or ETV-BAT-9013
Stand Tests done per ETV-BAT-888
Peak Power Tests done per ETV-BAT-885
DCV Discharge Cutoff Voltage ($ varies due to time interval spacing)
TTD Total Time of Discharge
ABIR Amps Battery In Recharge
EBIR Energy Battery In Recharge
CC End of Charge Current
ECT Avg. Ending Charge Temperature
TTDC Total Time of Charge

NOTE: 1. Module 1 weighs 24.91 kg (54.92 lbs)
Module 2 weighs 24.93 kg (54.96 lbs)
Module 3 weighs 25.11 kg (55.34 lbs)
Total Pack Weighs 74.95 kg (165.22 lbs)

Table 3. Summary data for GS E150H battery.

	DISCHARGE								CHARGE										NOTES
	DATE	DR (A,P,F)	ABOD (Ah)	EBOD (KWH)	DCV (VOLTS)	EDT (AVG)	MAX.TEMP (C)	TTD	DATE	ABIR (Ah)	EBIR (KWH)	CC (amps)	% CHARGE	ECT (AVG.)	MAX.TEMP (°C)	TTOC	WATER (ml)		
Cycle 1	05/22/91	45.29	84.54	2.93	31.50	26.43	26.94	1H 52M	05/22/91	111.95	4.63	4.14	132.42	27.88	30.10	12H 25M			
Cycle 2	05/28/91	45.18	91.11	3.17	31.50	26.82	26.94	2H 01M	05/28/91	119.74	4.99	1.84	131.42	26.36	32.63	12H 25M			
Cycle 3	05/30/91	45.08	105.19	3.67	31.50	28.58	28.76	2H 20M	05/30/91	123.56	5.42	1.32	117.46	26.99	33.28	14H 00M			
Cycle 4	06/03/91	45.06	114.16	3.98	31.50	28.03	28.28	2H 32M	06/03/91	136.01	5.68	1.51	119.14	27.55	31.85	13H 45M			
Cycle 5	06/05/91	44.87	110.68	3.78	32.50	26.56	26.97	2H 28M	06/05/91	144.15	6.11	4.00	130.24	24.44	34.26	13H 05M			
Cycle 6	06/10/91	45.16	115.91	4.03	31.50	27.99	28.35	2H 34M	06/10/91	138.67	5.80	4.00	119.64	25.55	30.38	SEE NOTE			FIRST 620 MINS. DATA ONLY
Cycle 7	06/11/91	44.99	119.98	4.19	31.50	26.54	26.82	2H 40M	06/11/91	134.71	5.62	4.00	112.28	34.15	35.99	SEE NOTE			FIRST 515 MINS. DATA ONLY
Cycle 8	06/17/91	45.16	124.95	4.34	31.50	27.06	27.56	2H 46M	06/17/91	156.99	6.66	4.00	125.64	27.54	29.42	15H 30M			CHARGE INTERRUPTED DUE TO POWER OUTAGE
Cycle 9	06/19/91	45.06	124.67	4.32	31.41	26.43	26.78	2H 48M	06/19/91	162.40	6.92	4.07	130.26	26.62	30.23	15H 15M	500		WATER ADDED AFTER CYCLE 9 CHARGE
Cycle 10	06/24/91	45.13	127.87	4.47	31.68	27.65	28.09	2H 50M	06/25/91	182.13	7.88	4.84	142.43	29.42	31.94	17H 15M			
Cycle 11	06/26/91	45.15	126.42	4.43	31.67	26.55	27.26	2H 48M	06/26/91	147.61	6.25	4.01	116.76	27.76	31.81	11H 35M			CHG INTERRUPTED AT 190M FOR THE NIGHT
Cycle 12	06/28/91	45.10	124.78	4.36	31.68	28.14	28.50	2H 48M	06/28/91	162.18	6.95	3.99	129.97	26.99	30.82	15H 20M			
Cycle 13	07/01/91	65.03	110.56	3.83	31.75	26.26	27.37	1H 42M	07/01/91	144.16	6.21	3.99	130.39	26.24	29.21	13H 35M			
Cycle 14	07/02/91	64.95	108.25	3.76	31.74	27.56	27.98	1H 40M	07/02/91	140.23	6.02	4.14	129.54	27.28	30.82	12H 40M			
Cycle 15	07/03/91	64.92	110.37	3.82	31.35	27.48	28.00	1H 42M	07/03/91	139.23	5.48	4.17	126.15	27.81	30.81	12H 35M			
Cycle 16	07/08/91	100.58	90.52	3.08	31.33	28.75	29.35	54M	07/08/91	116.77	5.03	3.99	129.00	28.69	30.22	11H 05M			
Cycle 17	07/09/91	100.31	87.77	3.00	31.23	29.11	29.41	52.5M	07/09/91	114.51	4.96	4.19	130.47	28.58	29.94	11H 20M			
Cycle 18	07/10/91	100.28	87.75	3.00	31.22	28.51	29.05	52.5M	07/10/91	114.07	4.94	4.16	129.99	28.48	30.07	11H 05M	750		WATER ADDED AFTER CYCLE 18 CHARGE
Cycle 19	07/11/91	7 W/KG	140.23	4.99	32.18	26.25	26.49	4H 45M	07/11/91	176.13	7.56	3.97	125.60	26.90	31.62	16H 40M			
Cycle 20	07/15/91	7 W/KG	142.30	5.06	32.01	25.55	26.03	4H 51M	07/15/91	175.51	7.49	4.11	123.34	26.72	32.55	15H 30M			
Cycle 21	07/16/91	7 W/KG	143.51	5.12	31.95	25.39	26.53	4H 54M	07/16/91	176.00	7.51	4.00	122.64	28.88	34.65	15H 40M			
Cycle 22	07/17/91	21 W/KG	96.05	3.33	31.93	28.87	30.23	1H 06M	07/17/91	124.24	5.39	4.00	129.35	28.70	30.62	12H 05M			
Cycle 23	07/18/91	21 W/KG	91.62	3.19	31.90	28.50	29.87	1H 03M	07/18/91	124.49	5.43	4.14	135.88	27.93	29.25	12H 55M			
Cycle 24	07/22/91	21 W/KG	91.99	3.19	31.90	27.93	28.28	1H 03M	07/22/91	118.69	5.16	4.00	129.02	26.59	28.88	11H 30M			
Cycle 25	07/23/91	42 W/KG	56.84	1.92	31.79	27.47	28.25	19.25M	07/23/91	73.59	3.22	3.99	129.47	27.68	28.56	7H 15M			
Cycle 26	07/24/91	42 W/KG	52.81	1.78	31.68	26.11	26.48	17.75M	07/24/91	74.00	3.27	3.97	140.12	25.47	26.41	8H 05M			
Cycle 27	07/25/91	42 W/KG	53.31	1.80	31.75	26.93	27.41	18.00M	07/25/91	73.79	3.24	4.08	138.42	27.45	28.70	7H 50M	700		WATER ADDED AFTER CYCLE 27 CHARGE
Cycle 28	07/26/91	45.01	126.04	4.41	31.66	26.04	26.65	2H 48M	07/26/91	159.35	6.88	3.99	126.43	27.07	28.59	15H 20M			
Cycle 29	07/29/91	44.96	131.89	4.64	31.60	27.02	27.49	2H 56M	07/29/91	166.30	7.17	3.98	126.09	25.81	30.09	15H 40M			
Cycle 30	07/30/91	44.97	128.93	4.55	31.91	26.37	26.90	2H 52M	07/30/91	164.68	7.09	4.13	127.73	27.41	30.23	15H 55M			
Cycle 31	09/25/91	45.06	114.90	3.99	31.97	26.12	26.42	2H 36M	09/25/91	157.42	6.70	4.57	137.01	29.72	31.32	14H 45M			9/24 MAINT CHG 23.22 AH'S
Cycle 32	09/26/91	44.45	124.46	4.35	31.49	27.00	27.29	2H 48M	09/26/91	161.40	6.88	4.10	129.68	27.57	31.16	15H 30M			
Cycle 33	09/27/91	45.06	126.17	4.43	31.89	27.26	27.64	2H 48M	09/27/91	162.61	6.94	4.22	128.88	22.05	30.35	15H 40M			
Cycle 34	09/30/91	42 W/KG	78.23	2.54	24.16	30.06	30.80	25.75M	09/30/91	101.33	4.36	4.10	129.53	21.69	29.74	9H 50M			
Cycle 35	10/01/91	42 W/KG	76.81	2.49	23.92	28.90	29.60	25.25M	10/01/91	100.69	4.35	4.25	131.09	22.79	29.04	10H 15M			
Cycle 36	10/02/91	42 W/KG	77.54	2.52	24.02	30.18	30.81	25.75M	10/02/91	100.18	4.32	4.10	129.20	22.34	28.99	10H 05M	600		
Cycle 37	10/03/91	60 W/KG	68.35	2.13	24.67	30.71	31.28	15M	10/03/91	87.93	3.80	4.10	128.65	22.40	29.45	8H 30M			
Cycle 38	10/07/91	60 W/KG	67.08	2.08	24.57	27.97	30.35	14.67M	10/07/91	86.74	3.74	4.10	129.31	22.89	29.32	8H 20M			
Cycle 39	10/08/91	60 W/KG	67.41	2.11	24.86	29.34	30.13	14.83M	10/08/91	85.83	3.70	4.13	127.33	23.73	29.24	8H 25M			
Cycle 40	10/09/91	SFUDS	113.00	2.91	—	—	—	166.4M	10/09/91	134.18	5.62	4.13	118.74	22.75	30.73	11H 35M			THREE PART CHARGE - ABOD FROM MPO

Table 3. (continued)

	DISCHARGE								CHARGE										
	DATE	DR (A,P,F)	ABOD (Ah)	EBOD (KWH)	DCV (VOLTS)	EDT (AVG.)	MAX.TEMP (C)	TTD	DATE	ABIR (Ah)	EBIR (KWH)	CC (amps)	% CHARGE	ECT (AVG.)	MAX.TEMP (°C)	TTOC	WATER (ml)	NOTES
Cycle 41	10/11/91	SFUDS	113 00	2 97	—	—	—	166.4M	10/11/91	145.27	6.21	4.10	128.56	26.47	30.44	14H 20M		ABOD FROM MPU
Cycle 42	10/16/91	44 85	125.99	4.46	32 05	27 26	27.97	2H 48M	10/16/91	157.68	6.77	4.10	125.15	29.69	30.35	15H 25M		
Cycle 43	10/18/91	44 95	121.37	4 31	31 89	27 26	28 36	2H 42M	10/18/91	148.19	6.36	4.05	122.10	27.21	31.02	14H 35M		
Cycle 44	10/28/91	44 58	114 63	4 05	31 71	26 93	28 21	2H 33M	10/28/91	141.38	6.05	4.05	123.34	29.08	33.69	11H 35M		
Cycle 45	11/07/91	44 90	112 64	3 98	31 54	28 49	29 75	2H 30M	11/07/91	146.56	6.30	4.15	130.11	28.51	32.60	13H 35M	750	10 DAY STAND TEST
Cycle 46	11/08/91	45 17	119.38	4 24	31 80	28 33	28 81	2H 39M	11/08/91	146.03	6.26	4.20	122.32	27.26	31.99	13H 05M		10 DAY STAND TEST
Cycle 47	01/06/92	44 80	81 11	2 86	32 52	27.75	28 53	1H 51M	01/06/92	85.41	3.57	9.58	105.30	31.89	32.55	3H 25M		POWER GLITCH
Cycle 48	01/07/92	44 64	76 33	2 69	32 04	27 59	28 34	1H 42M	01/07/92	103.43	4.37	4.12	135.50	29.17	31.62	7H 40M		
Cycle 49	01/08/92	44 74	90 06	3 18	32 12	26 87	27.38	2H 00M	01/08/92	115.80	4.19	4.10	128.58	28.06	31.08	10H 15M		
Cycle 50	01/09/92	44 69	98 87	3 51	32 01	27 65	28 46	2H 12M	01/09/92	128.90	5.50	4.14	130.37	28 64	31.31	12H 20M		
Cycle 51	02/18 92	45 06	67 59	2 38	32 69	26 55	27 06	1H 30M	02/18/92	89.48	3.79	4.27	132.39	30.75	31.66	5H 10M		
Cycle 52	02/19/92	45 04	76 57	2 71	32 19	26 53	27.06	1H 42M	02/19/92	98.50	4.16	4.13	128.64	29.35	30.37	9H 15M		
Cycle 53	02/20/92	45 07	81 13	2 88	32 37	26 49	26 85	1H 48M	02/20/92	104.40	4.37	3.98	128.68	27.85	29.14	9H 45M		
Cycle 54	02/21/92	44 85	87.46	3 05	32 22	26.59	26 85	1H 57M	02/21/92	112.40	4.72	4.10	128.52	28.43	29.46	10H 45M	650	
Cycle 55	02/24/92	45 12	94.76	3 31	32 16	26 38	26.55	2H 06M	02/24/92	122 15	5.14	4.15	128.90	27.89	29.17	11H 30M		
Cycle 56	02/25/92	44 98	101.22	3.53	31.81	26 89	27 25	2H 15M	02/25/92	130.02	5.48	4.00	128.45	27.75	29.76	12H 25M		
Cycle 57	02/26/92	44 99	105.73	3 69	31.60	27.06	27.57	2H 21M	02/26/92	136.65	5.76	4.03	129.24	27.87	30.03	13H 20M		
Cycle 58	02/27/92	44.83	107.60	3.77	31.87	27.41	27.70	2H 24M	02/27/92	136.64	5.75	4.13	126.99	27.40	30.06	12H 40M		
Cycle 59	03/02/92	44 94	107.85	3.77	31.82	26.66	26.99	2H 24M	03/02/92	137.79	5.81	4.13	127.76	26.16	30.13	12H 50M		
Cycle 60	03/03/92	45 01	108.02	3 78	31.79	26.38	27 06	2H 24M	03/03/92	137.86	5.81	4.20	127.62	26.79	30.28	10H 10M		
Cycle 61	03/04/92	PK PWR	91 20	3.16	—	—	—	—	03/04/92	112.36	4.75	4.08	123.20	26.71	26.68	10H 10M		
Cycle 62	03/05/92	PK PWR	91.48	4.22	—	—	—	—	03/05/92	111.86	4.72	4.10	122.28	27.58	28.68	10 H 00M		Peak Power = @ 0% 97.62 - @ 50% 85.49 - @ 80% 47.24 (W/kg)

Acronyms:

- ABOD — Amps Battery Out Discharge
- EBOD — Energy Battery Out Discharge
- EDT — Avg. Ending Discharge Temperature
- DR — Discharge (A-Amps, P-Power Kw, F-FUDS Cycle)
  - Constant Current Discharges done per ETV-BAT-984
  - Constant Power Discharges done per ETV-BAT-688
  - Fuds Discharges done per ETV-BAT-988 and/or ETV-BAT-9013
  - Stand Tests done per ETV-BAT-888
  - Peak Power Tests done per ETV-BAT-885
- DCV — Discharge Cutoff Voltage (* varies due to time interval spacing)
- TTD — Total Time of Discharge
- ABIR — Amps Battery In Recharge
- EBIR — Energy Battery In Recharge
- CC — End of Charge Current
- ECT — Avg. Ending Charge Temperature
- TTOC — Total Time of Charge

NOTE: 1. Pack weighs 140.83Kg (310.48lbs.)(three modules)

CONCLUSIONS AND RECOMMENDATIONS

Based on the data gathered during characterization testing, these batteries appear to have average performance for lead-acid type batteries for the criteria investigated. Additional tests (e.g., life expectancy) could provide a better overall appraisal of their merits. However, their relatively high cost (compared with similar products from domestic suppliers) would most likely be a deterrent when considering a decision to purchase.

REFERENCES

1. Idaho National Engineering Laboratory Electric & Hybrid Vehicle Program Test Procedures:

   ETV-BAT-984, Battery Characterization
   ETV-BAT-688, Constant Power Discharge
   ETV-BAT-988, Variable Power Discharge
   ETV-BAT-885, 30-Second Peak Power

2. Cole, G. H., "A Simplified Battery Discharge Profile Based on the Federal Urban Driving Schedule," 9th International Electric Vehicle Symposium, Toronto, Ontario, Canada, November 1988

3. GS Battery (U.S.A.), Inc. Technical Literature "Instruction, Filling, and Recharging of GS E75A and GS E150-H Dry Charged Battery".

APPENDIX A

GLOSSARY OF TECHNICAL TERMS FOR RECHARGEABLE BATTERIES

GLOSSARY OF TECHNICAL TERMS FOR RECHARGEABLE BATTERIES

average power (kW)	Total energy withdrawn (or returned) from (or to) a cell or battery divided by the time of discharge (or charge). May also be specified for test regimes that include both charge and discharge.
average voltage (V)	The ratio of the watt-hours delivered to the ampere-hours delivered for a given discharge or charge. Not a simple average of voltage over time.
baseline	The procedure used in the accelerated-aging tests that provides a common experimental measurement and analytical comparison basis.
battery	Electrochemical cells electrically connected in a series and/or parallel arrangement.
battery management subsystem	System that monitors and/or controls some or all battery functions (charge, watering, temperature, discharge, electrolyte flow, etc.). It may also provide an operator interface.
battery module	A grouping of interconnected cells that are treated as a single mechanical and electrical unit.
battery pack	The parts of a battery system that are physically contained in an enclosure that can be moved as a single unit.
battery package density (kg/L)	Battery system weight divided by battery system volume.
battery system	The battery plus all battery auxiliaries except the charger.
battery volume (L)	The volume of the battery. Cell, battery, or battery system should be specified.
battery weight (kg)	The weight of the battery. Cell, battery, or battery system should be specified
benchmark	The results of the characterization of the current status (both performance and life) and used in the actual-use simulation testing. These results will form a reference, or benchmark, point that can be employed in future determinations of development progress.
capacity (C) (Ah)	Generally, the total number of ampere-hours that can be withdrawn from a fully charged cell or battery under specified conditions.
available capacity (Ah)	The total number of ampere-hours that can be withdrawn from a fully charged cell or battery for a specific set of operating conditions including discharge rate, temperature, age, stand time, and discharge termination criteria.
C_i (Ah)	The capacity in ampere-hours obtained from a battery discharged at a constant current such that a specified minimum voltage is reached in precisely _i_ hours. _C_ is established once and is not adjusted as it changes with time.

gross capacity (Ah)	The cumulative ampere-hours removed from a battery operated on a test profile that can include regenerative braking or other source charging.
net capacity (Ah)	The gross capacity less any ampere-hours returned to the battery from, for example, regenerative braking or other charging.
rated capacity (Ah)	The manufacturer's specification of the total number of ampere-hours that can be withdrawn from a fully charged cell or battery for a specified discharge rate, temperature, and discharge cutoff voltage.
cell	An assembly of at least one positive electrode, one negative electrode, and other necessary electrochemical and structural components. It is used to store and provide electrical energy.
charge	Conversion of electrical energy into chemical potential energy within a cell by the passage of a direct current.
charge cutoff voltage {CCOV} (V)	The cell or battery voltage at which charge is terminated.
charge rate (A)	The current applied to a cell or battery to restore its available capacity. This current is commonly expressed in terms of the rated capacity of the cell or battery. For example, the 10-hour charge rate of a 500-ampere-hour cell or battery (rated at the 5-hour discharge rate) is expressed as: $\frac{\text{rated capacity}}{\text{charge time}} = \frac{\text{500 ampere-hours}}{\text{10 hours}} = 50\text{ ampere} = C_5/10\text{ rate.}$
commissioning	The process of preparing the test unit for testing. The manufacturer of products to be tested establishes specific instructions for the initiation, or commissioning, of use. For sodium-sulfur modules and batteries, these procedures can include such items as uncrating, heatup rates, break-in cycles, and control strategies.
constant current charging or discharging {C}	The charging or discharging of a cell or battery at a controlled, constant rate of electron flow.
current (A)	The rate of flow of electrons in a circuit. Also called rate.
cycle	The period commencing from the start of one charge/discharge to the start of the next charge/discharge where said period includes discharge time, open-circuit time, and charge time.
cycle life	The number of cycles, to a specified discharge termination criteria, such as depth of discharge, under a specified charge and discharge regime, that a cell or battery can undergo before failing to meet its specified capacity or efficiency performance criteria.
depth of discharge {DOD} (%)	The ratio of the ampere-hours discharged from a cell or battery at a given rate to the available capacity under the same specified conditions.
discharge cutoff voltage	The cell or battery voltage at which discharge is terminated. It is generally a function of discharge rate.
discharge rate (A)	The current during discharge of a cell or battery. This can be expressed in amperes, but more commonly it is normalized to rated capacity (C), and expressed as C_i/X, where i is the hour rate for the rated capacity, and X is a time specification, usually in hours. For example, the 10-hour discharge rate of a 500-ampere-hour cell or battery (rated at the 5-hour discharge rate) is expressed as: $\frac{\text{rated capacity}}{\text{charge time}} = \frac{\text{500 ampere-hours}}{\text{10 hour}} = 50\text{ amperes} = C_5/10\text{ rate.}$

end-of-discharge voltage {EODV} (V)	The cell or battery voltage when discharge is terminated.
energy density (Wh/L)	The ratio of energy output from a cell, battery, or battery system to its volume. Not the same as specific energy.
energy output (Wh)	The total number of watt-hours that can be withdrawn from a fully charged cell or battery. The energy output varies with temperature, rate, age, stand time, and discharge cutoff voltage.
equalization	The process of restoring all cells in a battery to an equal state-of-charge. This can consist of a prolonged charge or a complete discharge to a shorted condition, depending on the battery technology.
failure criteria	Specific cell or battery performance characteristics that indicate the cell or battery can no longer perform its intended duty cycle.
internal impedance (ohm)	The opposition to the flow of an alternating current at a particular frequency in a cell or battery at a specified state-of-charge and temperature.
internal resistance (ohm)	Opposition to direct current flow in a cell or battery. Its value may vary with the current, state-of-charge, age, and temperature. It is the sum of the ionic and electronic resistances of the cell components.
open circuit after charge {OCAC} (h)	The period during which the battery is placed on open circuit following a charge.
open circuit after discharge {OCAD} (h)	The period during which the battery is placed on open-circuit discharge following a discharge.
open-circuit voltage {OCV} (V)	The voltage of a cell or battery at a specified state-of-charge and temperature in the absence of charge or discharge current. It varies with the length of time following a charge or discharge. See also rated open-circuit voltage.
power profile test	A cell, battery, or battery system charge/discharge test that uses a sequence of different power levels applied for a defined time duration to simulate battery operation in a vehicle. For example, power profile tests have been derived from the FUDS and the J227aD driving profile tests.
rated open-circuit voltage (V)	The manufacturer's specification for the open-circuit voltage of a fully charged cell or battery.
rated power (kW)	The manufacturer's specification of the discharge power capability of a cell or battery.
reference performance cycle (RPC)	A specific cycle formulated to allow energy and power degradation of the subject test unit to be monitored and compared with that for other units.
segment	The repetitive portion of FUDS and GSFUDS discharge regimes. The duration of a segment is 1372 seconds for the FUDS regime and 360 seconds for the GSFUDS regime.
self-discharge	The process by which the available capacity of a cell or battery is spontaneously reduced by undesirable chemical reactions or electronic short circuits within the cell.
specific energy (Wh/kg)	The ratio of energy output to battery weight. Varies with rate of discharge.
specific peak power (W/kg)	The ratio of peak power to the cell, battery, or battery system weight

specific power (W/kg)	The ratio of rated power to the cell or battery weight.
test unit	A generic descriptor for any of the battery-hardware configurations being evaluated (e.g., cell, module, battery).
voltage depression	A transient voltage drop at the start of discharge of a fully charged cell or battery, with a subsequent recovery.

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