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Cycle Life Considerations for Batteries in Electric and Hybrid Vehicles

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ABSTRACT

Field experience with electric vehicles has shown in a significant number of cases, the performance of the batteries starts to degrade in a few months or a few thousand miles resulting in unhappy vehicle owners. This has occurred even for batteries for which the manufacturer has claimed a cycle life of several hundred deep discharge cycles. In this paper, the reasons are explored for this large difference between the expected and experienced battery cycle life and what life cycle testing should be done to greatly reduce the uncertainty in battery pack life. Test procedures for battery life testing are discussed and it is shown that there is a large difference in the cycle life that would be inferred from test results for one or two modules compared to that from testing a pack of many modules (at least ten). Measurements of the module–to–module variability in terms of the standard deviation of the module voltages showed that the increase of these module imbalances signals the degradation of the performance of the pack and they must be controlled through quality control in the manufacturing process and monitoring of module voltages during charge and discharge in the vehicle. Test data for packs of sealed lead–acid batteries discharged at constant power (10 W/kg) and on the SFUDS cycle indicated the module–to–module variability was much greater on the transient power SFUDS cycle and accordingly, the battery pack cycle life on the SFUDS cycle was much shorter than on the constant power cycle. The effects of load leveling on the initial and life cycle costs of the energy storage system in electric and hybrid vehicles as a function of vehicle acceleration and range characteristics were studied using spreadsheet models that related cycle life, $/kWh, average depth–of–discharge, energy density, battery peak power density, and load leveled battery power density. The load leveling was done using ultracapacitors having an energy density of 10 Wh/kg. The spreadsheet results show that the advantages of load leveling the batteries are largest for hybrid vehicles with relatively short all– electric range (less than 50 km) and for electric vehicles with 0–60 mph acceleration times of 10 seconds or less. The over–riding factor in assessing the operating cost of all the vehicles is battery cycle life and how it is affected by the maximum working power density of the battery and the average daily depth–of–discharge it experiences over its life.

INTRODUCTION

The uncertainty surrounding the cycle life of batteries for electric and hybrid vehicles is much greater than the uncertainty concerning their performance or initial cost. Battery performance can be determined from a relatively short series of tests in a few days or a week with a few modules and the results can be used to estimate with good confidence the performance of a battery pack in a vehicle consisting of a fairly large number of modules (15–30). As a result, the vehicle performance (range, acceleration, and energy consumption) when the batteries are "new" can be predicted and road tests of vehicles have consistently demonstrated close to the predicted performance. Initial cost ($/kWh) of batteries produced in large quantities is somewhat uncertain (maybe to within a factor of two) primarily because the manufacturing facilities required for their production have not yet been designed and built. Once the unit price of the batteries is set by the battery company, however, the initial cost of the batteries in a vehicle is known to the vehicle developer and can be included in establishing the price of the vehicle. Hence the initial performance and price of the vehicle can be stated with good confidence. The answer to the question of how long (miles or months) the electric or hybrid vehicle will continue to maintain its initial performance and what the life cycle operating cost (cents/mile) of the vehicle will be are much less certain, because they depend on the cycle life of the batteries. Field experience with vehicles has shown that in a significant number of cases, the performance of the batteries starts to degrade in a few months or a few thousand miles resulting in unhappy vehicle owners. Even laboratory tests of battery packs have often shown surprisely short cycle life. Short cycle life in practice has occurred even for those batteries for which the manufacturer has claimed a cycle life of several hundred deep discharge cycles. In this paper, the reasons are explored for this large difference between the expected and experienced battery cycle life and what cycle life testing should be done to greatly reduce the uncertainty in battery pack life.

In the next section, test procedures for battery cycle life testing are reviewed and how the life cycle test data can be analyzed is discussed. Next the effects of the discharge power profile on battery degradation are considered using life cycle data for packs of sealed lead–acid batteries. The paper is concluded with a discussion of vehicle and battery design and cost trade–offs that are inherent in the relationships between battery sizing (kWh and kW) and vehicle use–patterns and what test data are needed to evaluate these trade–offs.

TEST PROCEDURES AND DATA ANALYSIS

TEST PROCEDURES - In performing life cycle tests of batteries, one must select a discharge profile (power or current vs. time), a cut–off voltage or Ah/Wh criteria to terminate a given discharge cycle, and a charging algorithm that results in the batteries being completely recharged after each discharge cycle. In addition, there is the question of thermal management during the life cycle testing. The life cycle testing is usually terminated when the Ah/Wh capacity of the battery has degraded to 80% of the rated value or the value at the beginning of the testing. Every part of the test procedure can have a significant effect on the measured cycle life of a battery and even under laboratory conditions, it is difficult to maintain careful control of each of the test factors during a cycle life test that could last many months. If the capacity of the battery at periodic times during the cycling is to be determined using a different test than the cycling discharge profile, there can be questions concerning the effect of those tests on the cycle life of the battery. In addition, there is the question of how to relate cycle life under laboratory conditions to cycle life under real world driving conditions. The United States Advanced Battery Consortium (USABC) is developing test procedures (Reference 1) for the life cycle testing of batteries, including accelerated aging tests, but there has been little experience with the USABC procedures and no examples of how to relate their laboratory test results to real world experience with battery packs in vehicles.

Most battery manufacturers include information on cycle life in the brochures for their batteries. In nearly all cases, the basis for these cycle life claims is at best laboratory tests of single modules using constant current discharges (usually at the C/5 or C/3 rate) to at most a 80% depth– of–discharge. Field experience with batteries in electric vehicles has shown the claimed cycle life to be greatly optimistic in almost all cases. There are several reasons for the much shorter cycle life in vehicles. First, in vehicles the battery pack consists of many modules in series or parallel. Control of the discharge and charge of the pack in the vehicle is based on the behavior of the average module in the pack and as a result, individual modules, whose behavior can vary significantly from the average, can be overdischarged and/or undercharged. The module–to– module variability that results from differences in the manufacturing of the individual modules gradually causes imbalances in the capacity of the modules and results in a degradation of the pack performance over a relatively few cycles (often less than 100 cycles). Second, there are temperature differences throughout the pack especially in packs that have no thermal management system. These temperature differences result in significant module–to–module variability and imbalances in the pack after a number of charge/discharge cycles. Third, the battery pack is subjected to almost random discharge cycles both in terms of discharge profiles (power vs. time) and depth–of–discharge before recharge. These random charge/discharge cycles further enhance module–to–module variability and imbalances in the pack in real world use of the battery in a vehicle.

In light of these large variations in charge/discharge conditions, it is not surprising that a pack of many modules would exhibit a much shorter cycle life than if the average module were life cycle tested alone using a simple, repeated discharge cycle under carefully controlled conditions as is done by most battery manufacturers. It would appear that several steps must be taken to improve battery life and to insure a much better correspondence between claims of battery life based on laboratory testing and real world experience. First, the quality control in the manufacture of battery modules must be improved to reduce the inherent module–to–module variability in capacity and resistance. Second, thermal management of the battery pack must be instituted to reduce temperature differences in the pack. Third, battery pack monitoring and control systems must be developed that sense module–to–module imbalances and can correct them before they result in battery pack degradation. Fourth, test procedures must be developed that more closely simulate real world charge/discharge conditions for batteries in the laboratory. The present test procedures that utilize simple repetitive charge/discharge cycles to the same depth–of–discharge for all cycles are not adequate. Automated, computer controlled test equipment is presently available that will permit more generaic life cycle testing of complete battery packs after the real world test cycles are better defined.

DATA ANALYSIS - The results of a carefully planned and performed life cycle test of modules are reported in Reference 2 for the Sonnenschein DF 6V–160 sealed lead–acid battery. The tests were run on two modules using the SFUDS cycle (Reference 3) to approximately 100% depth–of–discharge based on characterization of the modules prior to beginning the life cycle tests. Each SFUDS discharge cycle during the life cycle tests was terminated based on a specified kWh (100% DOD) from the modules or the inability of the modules to sustain the 30 W/kg power step on the SFUDS cycle with the voltage above the 1.3V/cell cut–off voltage. The tests were done in an environmental chamber at 22 deg C. Recharge was done using a constant current (35A) to a clamp voltage (2.35V/cell) followed by a current taper to .2A or a return of 108% of the AH taken from the modules in the previous discharge. The condition of the modules was tracked by performing a C/3 discharge after every twenty SFUDS cycles. Life cycle testing was terminated after 383 cycles when the kWh capacity on the SFUDS cycle fall below 80% of the initial capacity of the modules. The modules maintained essentially 100% capacity on the SFUDS cycle for 279 cycles. The modules had 88.5% of their kWh capacity at the C/3 rate when the life cycle test was terminated. These two modules had a long cycle life on a very rigorous test – 100% discharge on the SFUDS cycle. It seems safe to say that the modules met the cycle life claim of the manufacturer.

The question is whether one should conclude from the test results that a pack of 20–30 modules of the batteries would have a cycle life of several hundred cycles in an electric vehicle in real world use. The answer to that question can be derived from test data for the seven module pack from which the two modules that were life cycle tested were selected. Data for C/3 and SFUDS discharges of the pack are shown in Figures 1 and 2 as plots of the standard deviation of the module voltages (sdv) vs. net Ah out of the modules for cycles 20 and 29. The rapid increase of the sdv near the end of the discharge is typical for battery packs consisting of a number of modules. One of the seven modules in the pack was very weak, having a voltage of 1.48V on the high power step of the SFUDS, when the discharge of the pack was terminated with an average module voltage of 3.9V. The sdv data for the C/3 discharge shows the same rapid rise, but the rise starts at a larger value of Ah out. If testing of the seven module pack had been continued, even greater module–to–module imbalances would have developed and the useful capacity of the pack would have decreased and life cycle testing would have been terminated at a relatively low number of cycles – much less than 300.

The life cycle data from this seven module pack illustrates how life cycle data from one or two modules can lead to misleading conclusions reguarding the life cycle characteristics of a pack of the modules in a vehicle. Further, it shows how the standard deviation of the voltages at various depths–of–discharge can be used to track the module–to–module variability in the pack and thus the presence of module imbalances as the pack is cycled. These imbalances are evident in both discharging and charging of the batteries. They will continue to increase unless something is done to correct them.

DISCHARGE PROFILE EFFECTS ON THE CYCLE LIFE OF A BATTERY PACK

Life cycle tests of two 10 module packs of Sonnenschein 8G24 12V–52 Ah batteries were performed in the Battery Test Laboratory of the Idaho National Engineering Laboratory as part of a study to determine the effect on battery cycle life of using ultracapacitors to load level the battery in an electric vehicle. One of the packs was discharged at constant power (10 W/kg) to simulate a load leveled battery pack and the other one was cycled on the SFUDS cycle to simulate the pack in a vehicle in city driving without load leveling. The data from those tests are summarized in detail in Reference 4. In this paper, the results of the tests are discussed in terms of their meaning with regard to life cycle testing of battery packs.

Twenty–eight modules of the 8G24 batteries were purchased and divided into two packs of fourteen modules each with the intent of selecting the ten of the fourteen in each pack that were the best matched for the life cycle tests. Characterization tests (Reference 1) of each pack were started to determine the baseline capacities for 10 W/kg constant power and SFUDS discharges. During the characterization testing, the individual module voltages were measured and recorded. The results of the first few tests of one of the packs indicated that it contained seven modules that were significantly weaker (exhibited lower voltages near the end of discharge) than the others. These modules were removed from the pack and characterization testing was continued. The capacities of the packs on the two discharge cycles of interest stabilized after only a few cycles and it was possible to assemble two packs of ten modules each that had essentially the same capacity and module–to–module variability on the cycles. Pack A, the pack that was to be cycled at a constant power of 10W/kg, had a capacity of 49.1 Ah on the constant power discharge and 48 Ah on the SFUDS. Pack B, the pack that was to be cycled on the SFUDS, had a capacity of 50 Ah on the constant power discharge and 48 Ah on the FUDS. The standard deviation of the voltages at the end of the constant power test for Pack A was .3385 V and for Pack B, it was .1985V. Hence, the characteristics of the two packs were quite similar. Both packs were charged using the same algorithm. The initial current was 30A to a clamp voltage of 2.36V/cell. The current was then tapered to a finishing current of .2A or an ampere–hour overcharge of 2% to 5%. Both battery packs seemed to meet the manufacturer's capacity specifications and module–to–module variability in each pack was relatively small after the weaker modules were sorted out in the characterization tests. The expectation was that both packs would have a relatively long cycle life with that of the one being cycled at constant power being somewhat longer based on previous experience at INEL and elsewhere.

LIFE CYCLE TESTS OF THE PACK AT CONSTANT POWER - Pack A was life cycled (see Table 1) at a constant power of 10 W/kg with each discharge cycle terminated at an average module voltage of 10.5 V (105 V for the pack). This resulted in a 100% discharge for each cycle. The capacity of the pack remained constant for the first 45 cycles at 50–52 Ah and 6–6.2 kWh. As shown in Figure 3, the module–to–module variability of the pack as given by the variation of the sdv with Ah out of the pack also remained unchanged for the first 45 cycles at constant power. Figure 4 shows that the characteristics of pack A for discharge on the SFUDS on cycle 46 was unchanged from earlier cycles. Hence one can conclude that the 10 module pack had a cycle life of at least 45 cycles for constant power discharges to 100% DOD.

The data for subsequent cycles indicated that the pack began to degrade after cycle 45 as the Ah capacity decreased slowly and the module–to–module variability increased significantly between cycles 45 and 49. It was not realized at the time that this was a critical period in the degradation of the pack and cycles 50–54 were done at temperatures below ambient (down to –10 deg C). All cycles after cycle 54 showed a much lower Ah capacity and larger module–to–module variability (Figure 4) than was the case before the low temperature testing of the pack. It is not known why the low temperature testing of the pack so greatly accelerated its degradation.

LIFE CYCLE TESTING OF THE PACK ON THE SFUDS CYCLE - Pack B was life cycled (see Table 2) on the SFUDS cycle with each discharge cycle terminated when the average module voltage fell to 7.8V (78V for the pack) on the 30 W/kg step of the SFUDS cycle. This resulted in a 100% depth–of–discharge for each discharge cycle. The capacity of Pack B on the SFUDS cycle remained near the initial value of 48 Ah for only ten cycles after the completion of the 13 characterization cycles. The variation of the sdv with net Ah out of the modules for cycle 17 is shown in Figure 5. Note that the sdv remains relatively small even for the high power step on the SFUDS until near the end of the discharge. The useful Ah capacity of the pack on any cycle corresponds to the Ah value at which the sdv shows a sharp increase on the high power steps. After cycle 23, the capacity of the pack on the SFUDS cycle started to steadily decline and it become evident that there were several weak modules in the pack. Those modules were removed after cycle 25 and SFUDS cycling was resumed with seven modules. Cycle 24 was a 10 W/kg constant power discharge of Pack B and even though the pack had significantly degraded for SFUDS cycling, its capacity of 49 Ah at constant power and its sdv variation (see

Figure 6) were nearly the same as at the beginning of the life cycle testing. Life cycle testing of Pack B was continued through cycle 70 (Table 2) periodically removing the weak modules as they exhibited voltages that were well below 7.8V at the end of the SFUDS discharges. After cycle 57, only two modules remained from the original ten modules in Pack B and those modules had an Ah capacity of less than 40Ah. The sdv variation on cycle 49 for six modules is shown in Figure 7. A useful capacity of only about 35 Ah on SFUDS is evident from the figure.

The cycle life of Pack B on the SFUDS cycle was very short being at most 25 cycles including 13 characterization cycles. Testing of Pack B also showed the value of looking at the sdv variation with net Ah out as a means of determining the useful capacity of the pack on cycles having transient high power steps. As a battery pack degrades the sdv increases and shows a sharp rise at smaller and smaller values of Ah out. Determination of the sdv variation over the life of the pack and identification of those modules responsible for its increase are essential to understanding degradation of packs and developing methods of extending battery cycle life. This work suggests that tracking the sdv variation in all battery testing is a good approach to monitoring quality control in battery manufacturing since the smaller the sdv variation at the beginning of life, the less difficulty will be encountered in controlling increases in the sdv variation as the battery pack degrades.

DESIGN, CYCLE LIFE, AND COST TRADE–OFFS

This section of the paper is concerned with the effect of load leveling on the initial and life cycle costs of the energy storage system in electric and hybrid vehicles as a function of vehicle acceleration and range characteristics. Load leveling the battery permits it to be designed to maximize energy density and cycle life with the peak power being provided by a pulse power unit, such as ultracapacitors. Key considerations in this study of the energy storage system costs are the trade–offs between battery peak power density, average depth–of–discharge, and cycle life. The magnitudes of these trade–offs are highly dependent on the acceleration performance (0–60 mph acceleration time) and the all–electric range of the electric and hybrid vehicles. The trade–offs are calculated using two spread sheet models in which the size, cost, and cycle life of batteries are estimated for various vehicle designs. One of the spreadsheets treats the case of a load leveled system using a battery, ultracapacitors, and interface electronics. The second spreadsheet treats the case of a single battery (a primary energy storage unit) that is designed to provide both the energy and the power for the vehicle. In both cases, the energy storage requirement (kWh) is calculated from the vehicle range on the FUDS driving cycle and the maximum power requirement is calculated from the 0–60 mph acceleration time of the vehicle (Reference 5). The use–pattern of the vehicle is described in terms of the average daily travel. Print outs of the spread sheets are shown in Tables 3 and 4. Each of the spreadsheets can be run for either an electric or a hybrid vehicle. The inputs are listed on the right side of the spreadsheets and the outputs are shown on the left side. In all the cases considered, battery cycle life is the key factor in determining the operating cost of the vehicle.

In order to formulate the spreadsheet models, it was necessary to express analytically the functional relationships (tradeoffs) between the energy density, peak power, initial cost, cycle life, and average depth–of–discharge. Unfortunately, at the present time, little information or data are available to describe these trade–offs for batteries being used in electric vehicles. Hence in this study, functional relationships (models) were assumed for these trade–offs based on what little information is available and on physical intuition about batteries. The form of the relationships and the constants used are shown below.

Relationship between cycle life and average
depth–of–discharge
Cycle life = cycle life at 80 DOD*DOD*exp(C4*(1–DOD)),
C4=3
where DOD is the average daily depth–of–discharge

Relationship between energy density and
battery peak power density
(Wh/kg)PR = (Wh/kg)LL*exp–B1*(PR–1)
where PR=(W/kg)req./(W/kg)LL, B1=.075

Relationship between density (gm/cm3) of a high power
battery and a load leveled design
(DSPR–DSMX)/(DSLL–DSMX) = exp–B2*(PR–1)
where B2=.242, DSLL=2.5, DSMX=3.1

Relationship between the cycle life of a high power battery
and a load leveled battery
(Cycle life)PR = (Cycle life)LL*exp–B3(PR–1), B3=..173

Relationship between the cost ($/kWh) of a high power
battery and a load leveled battery
(Cost)PR = ($/kWh)LL*expB4*(PR–1), B4=.156

The exponential form of the relationships was selected because it was compatible with the concept that the functional behavior of the effects being modeled was of the threshold type and was highly non–linear. The constants shown with each of the relationships yield values that are reasonable compared with available data or with the best estimates of the expected magnitude of the various effects. The values of the constants shown are for lead–acid batteries (40 Wh/kg). Slightly different values (see Tables 3 and 4) were used for nickel–metal hydride batteries (70 Wh/kg). Further analysis and much laboratory testing of batteries are needed to explore these functional relationships as they are critical in assessing the important battery design trade–offs identified in this paper.

Summaries of the spreadsheet results for a number of electric and hybrid vehicle designs are given in Tables 5–10. The effects of vehicle performance and whether or not the battery is load leveled are clearly shown in the tables. In all cases, improving the acceleration performance of the vehicle increases the operating cost (cents/mile) of the vehicle. However, load leveling the battery significantly reduces the variation with acceleration time (8–15 seconds) of all the vehicle design and cost parameters. In principle, as shown in Tables 5 and 9, load leveling should make battery cycle life and energy density independent of the acceleration performance of the vehicle. The volume and initial cost of the load leveled battery systems are higher than those using only a high power density battery, because of the added cost and volume of the ultracapacitors and interface electronics. The greater cycle life of the load leveled battery more than compensates for their higher initial cost resulting in a lower vehicle operating cost in the high performance vehicles. The variation in cycle life with vehicle performance shown in Table 5 is due to differences in the average depth–of–discharge of the battery and its maximum power requirement in the case of the batteries that are not load leveled. The baseline cycle life of the lead acid batteries was 300 cycles to 80% DOD and for the nickel metal hydride batteries, 600 cycles to 80% DOD.

The spreadsheet results show that the advantages of load leveling the batteries with ultracapacitors are largest for hybrid vehicles with relatively short all–electric range and for electric vehicles with 0–60 mph acceleration times of 10 seconds or less. The over–riding factor in assessing the operating cost of all the vehicles is battery cycle life and how it is affected by the working maximum power density of the battery and the average depth–of–discharge that the battery experiences over its life.

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Table 1: Summary of the tests of Pack A (10 W/kg discharges)

Cycles 1 thru 12	Characterization tests	14 modules
Cycle 13	10 W/kg, 49 A-h	14 modules
Cycle 14	SFUDS, 48 A-h	10 modules
Cycles 15 thru 45	10 W/kg, 50 A-h	10 modules
Cycle 46	SFUDS, 46 A-h	10 modules
Cycles 47 thru 49	10 W/kg, 49 A-h	10 modules
Cycles 50 thru 54	Low temperature test at 10 W/kg	10 modules
Cycles 55 and 56	10 W/kg, 40 A-h	10 modules
Cycle 57	10 W/kg, 33 A-h	10 modules
Cycles 58 thru 60	10 W/kg, 37 A-h	6 modules
Cycles 61 thru 70	10 W/kg, 40 a-h	4 modules

Table 2: Summary of the tests of Pack B (SFUDS discharges)

Cycles 1 thru 4	Characterization tests	14 modules
Cycles 5 thru 12	Characterization tests	7 modules
Cycle 13	10 W/kg, 50 A-h	10 modules
Cycles 14 thru 23	SFUDS, 46 to 48 A-h	10 modules
Cycle 24	10 W/kg, 49 A-h	10 modules
Cycle 25	SFUDS, 43 A-h	10 modules
Cycles 26 thru 33	SFUDS, 45 to 47 A-h	7 modules
Cycles 34 thru 39	SFUDS, 40 to 45 A-h	7 modules
Cycles 40 thru 45	SFUDS, 40 to 42 A-h	6 modules
Cycle 46	10 W/kg, 45 A-h	6 modules
Cycles 47 thru 56	SFUDS, 36 to 42 A-h	6 modules
Cycles 57 thru 70	SFUDS, 36 to 40 A-h	2 modules

Table 3: Spreadsheets for Load-leveled Battery Systems

Electric Vehicle

CHARACTERISTICS OF A N EV DRIVELINE WITH LOAD LEVELED ENERGY STORAGE
VEHICLE TYPE - COMPACT CAR

ALWAYS SET FLAG=0 TO START THE CALCULATION: CHANGE THE FLAG=1 TO CONVERGE ON THE FINAL RESULT

FLAG	1	0
		0 FOR EV
		1 FOR HV

VEHICLE CHARACTERISTICS	
CD	0.22
AREA FT2	19
FR	0.005
REFERENCE WEIGHTS KG	
VEHICLE	1227
EN STOR UNITS	200
VEHICLE RANGE (KM) AND ENERGY USE	
RANGE (80%DOD)	160
WH/KM	110
AV DAILY KM	48
CHARACTERISTICS OF THE LOAD LEVELED PRIMARY ENERGY STORAGE UNIT	
WH/KG	40
WH/L	95
KG/L	2.3
W/KG MAX	60
CYCLE LIFE	300
COST $/KWH	100
CHARACTERISTICS OF THE PULSE POWER UNIT	
WH/KG	10
WH/L	13
STORED WH	500
COST $/WH	1
ROUND TRIP EFFIC	0.925
CHARACTERISTICS OF THE INTERFACE ELECTRONICS	
KG/KW	0.5
L/KW	0.4
COST $/KW	16
DRIVING CYCLE CHARACTERISTICS	
FUDS	
MAX VEH KW/KG	0.025
AV VEH KW/KG	0.003
EN USE WH/KM	110
HWAY	
MAX VEH KW/KG	0.021
AV VEH KW/KG	0.005
EN USE WH/KM	90
CONST SPD 65 MPH	
AV VEH KW/KG	0.006
EN USE WH/KM	87
GRAD 65MPH ON 3%	
AV VEH KW/KG	0.014
EN USE WH/KM	200

	SPECIFIED 0-60 MPH ACCELERATION TIME -SEC			
	8	10	12	16
TOTAL STOR UNIT WGT	810.2934	772.0836	745.068	730.8562
VEHICLE WGT	1837.293	1799.084	1772.068	1757.856
ENERGY USE WH/KM	141.7333	139.7466	138.3412	137.5924
BATTERY WGT	664.3747	656.0616	648.4748	644.9643
BATTERY VOL	279.7367	276.2164	273.0419	271.5639
MAX VEH KW/KG	0.1	0.07	0.048	0.036
MAX VEH ACCEL KW	183.7293	125.9369	85.05876	63.27852
PULSE POWER UNIT WGT	64.06406	64.05405	64.05405	64.05405
PULSE POWER UNIT VOL	41.58004	41.58004	41.58004	41.58004
PULSE POWER UNIT KW/KG	3.396983	2.329813	1.573668	1.170599
BAT + PULSE POW WGT	718.4287	709.1157	702.5296	699.0184
BAT + PULSE POW VOL	321.3168	317.7956	314.622	313.144
MAX FUDS KW	64.48365	63.85043	62.01308	61.04491
AV FUDS KW	6.51188	6.397251	6.316174	6.272969
MAX HWAY KW	65.08721	62.92976	61.42976	60.63919
AV HWAY KW	9.186467	8.995418	8.85029	8.788291
POW AT 65 KW	14.59835	14.39267	14.17646	14.06126
GRAD AT 65 KW	33.01469	31.88092	31.09064	30.67323
SYSTEM WGT	810.2934	772.0836	745.068	730.8562
SYSTEM VOL	394.8085	357.7698	340.6466	330.4642
SYSTEM COST	5643.742	4974.283	4369.285	4031.867
HYBRID MILEAGE COR.	1	1	1	1
AVERAGE DOD	0.32	0.32	0.32	0.32
CYCLE DEPTH FACTOR	2.460996	2.460996	2.460996	2.460996
SYS LIFE VEH MILES	68772.6	68772.6	68772.6	68772.6
OPERAT CST CENTS/MI	8.497207	7.232926	6.336704	5.862178
BATTERY COST	2657.499	2620.247	2593.898	2579.857

WEIGHT CORRECTION FACTORS	
ENERGY USE	
FUDS	0.58
HWAY	0.31
65 MPH	0
GRADE	0.67
MAX POWER	
FUDS	0.9
HWAY	0.86
65 MPH	0
GRADE	0.67

CYCLE LIFE AT SHALLOW DISCHARGES LESS THAN DOD=.8
CYCLE =CYCLE-80%*DOD*EXP (C4*.(1-DOD))

C4	3

HYBRID MODE USE FACTOR 1+EXP (C5*RANGE/160)

C5	6

Lead-acid Battery

Electric Vehicle

CHARACTERISTICS OF A N EV DRIVELINE WITH LOAD LEVELED ENERGY STORAGE
VEHICLE TYPE - COMPACT CAR

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REFERENCE WEIGHTS KG	
VEHICLE	1227
EN STOR UNITS	200
VEHICLE RANGE (KM) AND ENERGY USE	
RANGE (80%DOD)	160
WH/KM	110
AV DAILY KM	48
CHARACTERISTICS OF THE LOAD LEVELED PRIMARY ENERGY STORAGE UNIT	
WH/KG	70
WH/L	220
KG/L	2.5
W/KG MAX	60
CYCLE LIFE	600
COST $/KWH	175
CHARACTERISTICS OF THE PULSE POWER UNIT	
WH/KG	10
WH/L	13
STORED WH	500
COST $/WH	1
ROUND TRIP EFFIC	0.925
CHARACTERISTICS OF THE INTERFACE ELECTRONICS	
KG/KW	0.5
L/KW	0.4
COST $/KW	16
DRIVING CYCLE CHARACTERISTICS	
FUDS	
MAX VEH KW/KG	0.025
AV VEH KW/KG	0.003
EN USE WH/KM	110
HWAY	
MAX VEH KW/KG	0.021
AV VEH KW/KG	0.006
EN USE WH/KM	90
CONST SPD 65 MPH	
AV VEH KW/KG	0.006
EN USE WH/KM	87
GRAD 65MPH ON 3%	
AV VEH KW/KG	0.014
EN USE WH/KM	200

	SPECIFIED 0-60 MPH ACCELERATION TIME -SEC			
	8	10	12	16
TOTAL STOR UNIT WGT	459.0859	432.0898	412.9079	402.856
VEHICLE WGT	1486.086	1459.09	1439.908	1429.856
ENERGY USE WH/KM	123.4716	122.0679	121.0705	120.5376
BATTERY WGT	330.7276	326.9676	324.296	322.8682
BATTERY VOL	105.2315	104.0352	103.1861	102.7306
MAX VEH KW/KG	0.1	0.07	0.048	0.036
MAX VEH ACCEL KW	148.6086	102.1363	69.11558	51.46762
PULSE POWER UNIT WGT	64.06406	64.05405	64.05405	64.05405
PULSE POWER UNIT VOL	41.58004	41.58004	41.58004	41.58004
PULSE POWER UNIT KW/KG	2.749269	1.989521	1.270638	0.952161
BAT + PULSE POW WGT	384.7816	381.0217	378.3501	376.9222
BAT + PULSE POW VOL	146.8116	145.6152	144.7651	144.3106
MAX FUDS KW	44.21249	42.68702	41.61936	41.06427
AV FUDS KW	4.458258	4.377263	4.319724	4.290968
MAX HWAY KW	36.8749	35.62627	34.76038	34.29724
AV HWAY KW	7.43043	7.295449	7.199539	7.14828
POW AT 65 KW	11.88869	11.67272	11.51926	11.43726
GRAD AT 65 KW	23.30927	22.62966	22.15252	21.89946
SYSTEM WGT	469.0869	432.0898	412.9079	402.856
SYSTEM VOL	206.255	186.4697	172.4114	164.8979
SYSTEM COST	6731.917	6016.657	6508.431	6236.809
HYBRID MILEAGE COR.	1	1	1	1
AVERAGE DOD	0.32	0.32	0.32	0.32
CYCLE DEPTH FACTOR	1.477817	1.477817	1.477817	1.477817
SYS LIFE VEH MILES	82595.17	82595.17	82595.17	82595.17
OPERAT CST CENTS/MI	8.160497	7.284514	6.869193	6.340334
BATTERY COST	4051.413	4006.353	3972.626	3956.136

WEIGHT CORRECTION FACTORS	
ENERGY USE	
FUDS	0.58
HWAY	0.31
65 MPH	0
GRADE	0.67
MAX POWER	
FUDS	0.9
HWAY	0.86
65 MPH	0
GRADE	0.67

CYCLE LIFE AT SHALLOW DISCHARGES LESS THAN DOD=.8
CYCLE =CYCLE-80%*DOD*EXP (C4*.(1-DOD))

C4	2.25

HYBRID MODE USE FACTOR 1+EXP (C5*RANGE/160)

C5	6

Nickel Metal Hydride Battery

Table 4: Spreadsheets for Non-load-leveled Battery Systems

Electric Vehicle

CHARACTERISTICS OF A N EV DRIVELINE USING PRIMARY ENERGY STORAGE							
VEHICLE TYPE - COMPACT CAR							
ALWAYS SET FLAG=0 TO START THE CALCULATION: CHANGE THE				FLAG	1	1	
FLAG=1 TO CONVERGE ON THE FINAL RESULT						0 FOR EV	
						1 FOR HV	
			SPECIFIED 0-60 MPH ACCELERATION TIME -SEC				
				8	10	12	16
VEHICLE CHARACTERISTICS		TOTAL STOR UNIT WGT		365.3682	316.4683	278.1612	257.326
CD	0.22	VEHICLE WGT		1392.369	1342.469	1306.161	1284.326
AREA FT2	19	ENERGY USE WH/KM		118.8987	116.004	114.0641	112.961
FR	0.005	ENERGY DENSITY		24.34369	27.57889	30.75486	32.329
		BATTERY WGT		365.3916	316.4683	278.1612	257.326
		WH/L		74.5156	84.05612	93.05704	99.035
REFERENCE WEIGHTS KG		BATTERY VOL		119.2104	103.5071	91.93003	85.842
VEHICLE	1227	MAX VEH KW/KG		0.1	0.07	0.048	0.036
EN STOR UNITS	200	MAX VEH ACCEL KW		139.2369	93.97278	62.64774	46.23573
		BATTERY KW/KG		0.381068	0.297083	0.225221	0.179678
VEHICLE RANGE (KM) AND ENERGY USE		POWER RATIO		7.621356	5.957658	4.504418	3.593566
RANGE (80%DOD)	80	MAX FUDS KW		39.03258	36.40424	34.49963	33.45823
WH/KM	110	AV FUDS KW		4.177169	4.027405	3.915484	3.862977
AVERAGE DAILY KM	48	MAX HIWAY KW		32.82971	30.47244	28.9099	28.06451
CHARACTERISTICS OF THE LOAD LEVELED		AV HIWAY KW		6.961946	6.712342	6.525806	6.421628
PRIMARY ENERGY STORAGE UNIT		POW AT 55 KW		11.13911	10.73976	10.44129	10.27481
WH/KG	40	GRAD AT 55 KW		20.99116	19.90271	18.93672	18.45838
WH/L	90						
KG/L	2.3	PRIMARY BATTERY SYSTEM CHARACTERISTICS					
W/KG MAX	80	CYCLE LIFE		96.41998	127.2439	163.5183	191.5401
CYCLE LIFE	300	INITIAL COST $		2498.856	1885.454	1477.884	1288.828
COST $/KWH	100	HYBRID MILEAGE COR.		1.153366	1.153366	1.153366	1.153366
		AVERAGE DOD		0.8	0.8	0.8	0.8
CHARACTERISTICS OF THE PULSE POWER UNIT		CYCLE DEPTH FACTOR		1.58124	1.58124	1.58124	1.58124
WH/KG	10	BATTERY LIFE IN MILES		6977.393	7970.94	10249.35	11996.85
WH/L	13	OPERATING COST CENTS PER MILE		41.80612	23.65409	14.4181	10.58392
STORED WH	500	BATTERY UNIT COST $/KWH		280.9289	216.7114	172.7524	149.8686
COST $/WH	1						
ROUND TRIP EFFIC	0.925						
CHARACTERISTICS OF THE INTERFACE ELECTRONICS							
KG/KW	0.5						
L/KW	0.4	BATTERY TRADE-OFF DESIGN FACTORS					
COST $/KW	19	ENERGY DENSITY (WH/KG)PR=EXP-B1(PR-1)*(WH/KG)LL					
		B1	0.076				
DRIVING CYCLE CHARACTERISTICS		DENSITY (KG/L) (DS-DSMX)/(DSLL-DSMX)=EXP-B2(PR-1)					
FUDS		B2	0.242				
MAX VEH KW/KG	0.025	DSLL	2.6				
AV VEH KW/KG	0.003	DSMX	3.1				
EN USE WH/KM	110	(CYCLELIFE)PR=EXP-B3(PR-1)*(CYCLELIFE)LL					
HIWAY		B3	0.173				
MAX VEH KW/KG	0.021	COST($/KWH) (CST)PR=EXP(B4)*(PR-1)*($/KWH)LL					
AV VEH KW/KG	0.006	B4	0.156				
EN USE WH/KM	90						
CONST SPD 55 MPH		CYCLE LIFE SHALLOW DISCHARGES LESS THAN DOD=.8					
AV VEH KW/KG	0.008	CYCLE=CYCLE-80%*EXP(C4*(.1-DOD)					
EN USE WH/KM	97	C4	3				
GRAD 55MPH ON 3%							
AV VEH KW/KG	0.014	HYBRID MODE FACTOR 1+EXP- (C5*RANGE/160)					
EN USE WH/KM	200	C5	5				

Lead-acid Battery

Electric Vehicle

CHARACTERISTICS OF A N EV DRIVELINE USING PRIMARY ENERGY STORAGE							
VEHICLE TYPE - COMPACT CAR							
ALWAYS SET FLAG=0 TO START THE CALCULATION: CHANGE THE				FLAG	1	0	
FLAG=1 TO CONVERGE ON THE FINAL RESULT						0 FOR EV	
						1 FOR HV	
			SPECIFIED 0-60 MPH ACCELERATION TIME -SEC				
				8	10	12	16
VEHICLE CHARACTERISTICS		TOTAL STOR UNIT WGT		494.0982	432.4119	387.0426	362.038
CD	0.22	VEHICLE WGT		1521.080	1459.412	1414.043	1389.038
AREA FT2	19	ENERGY USE WH/KM		125.2916	122.0847	119.7256	118.426
FR	0.005	ENERGY DENSITY		47.64653	62.93765	68.0002	61.333
		BATTERY WGT		494.0982	432.4119	387.0426	362.038
		WH/L		146.0291	160.3827	174.322	183.194
REFERENCE WEIGHTS KG		BATTERY VOL		161.9626	142.7266	128.7763	121.209
VEHICLE	1227	MAX VEH KW/KG		0.1	0.07	0.048	0.036
EN STOR UNITS	200	MAX VEH ACCEL KW		152.1068	102.1568	67.87406	50.00636
		BATTERY KW/KG		0.307858	0.236264	0.175366	0.138122
VEHICLE RANGE (KM) AND ENERGY USE		POWER RATIO		6.157182	4.72507	3.507316	2.762436
RANGE (80%DOD)	160	MAX FUDS KW		46.23015	42.70507	40.20106	38.85329
WH/KM	110	AV FUDS KW		4.563266	4.378236	4.242128	4.167116
AVERAGE DAILY KM	48	MAX HIWAY KW		36.52709	35.64005	33.56782	32.48268
CHARACTERISTICS OF THE LOAD LEVELED		AV HIWAY KW		7.606441	7.29706	7.070218	6.945182
PRIMARY ENERGY STORAGE UNIT		POW AT 55 KW		12.16871	11.6753	11.31234	11.11231
WH/KG	70	GRAD AT 55 KW		24.20465	22.83771	21.61678	20.91037
WH/L	220						
KG/L	2.6	PRIMARY BATTERY SYSTEM CHARACTERISTICS					
W/KG MAX	80	CYCLE LIFE		245.8561	314.9748	388.0364	442.3176
CYCLE LIFE	600	INITIAL COST $		9190.902	7162.56	6606.94	6116.616
COST $/KWH	175	HYBRID MILEAGE COR.		1	1	1	1
		AVERAGE DOD		0.32	0.32	0.32	0.32
CHARACTERISTICS OF THE PULSE POWER UNIT		CYCLE DEPTH FACTOR		1.477617	1.477617	1.477617	1.477617
WH/KG	10	BATTERY LIFE IN MILES		33644.07	43350.99	53526.96	60909.83
WH/L	13	OPERATING COST CENTS PER MILE		27.15661	16.51941	10.95236	8.4014
STORED WH	500	BATTERY UNIT COST $/KWH		391.2324	312.9042	250.7669	230.378
COST $/WH	1						
ROUND TRIP EFFIC	0.925						
CHARACTERISTICS OF THE INTERFACE ELECTRONICS							
KG/KW	0.5						
L/KW	0.4	BATTERY TRADE-OFF DESIGN FACTORS					
COST $/KW	18	ENERGY DENSITY (WH/KG)PR=EXP-B1(PR-1)*(WH/KG)LL					
		B1	0.076				
DRIVING CYCLE CHARACTERISTICS		DENSITY (KG/L) (DS-DSMX)/(DSLL-DSMX)=EXP-B2(PR-1)					
FUDS		B2	0.242				
MAX VEH KW/KG	0.025	DSLL	2.6				
AV VEH KW/KG	0.003	DSMX	3.1				
EN USE WH/KM	110	(CYCLELIFE)PR=EXP-B3(PR-1)*(CYCLELIFE)LL					
HIWAY		B3	0.173				
MAX VEH KW/KG	0.021	COST($/KWH) (CST)PR=EXP(B4)*(PR-1)*($/KWH)LL					
AV VEH KW/KG	0.006	B4	0.156				
EN USE WH/KM	90						
CONST SPD 55 MPH		CYCLE LIFE SHALLOW DISCHARGES LESS THAN DOD=.8					
AV VEH KW/KG	0.008	CYCLE=CYCLE-80%*EXP(C4*(.1-DOD)					
EN USE WH/KM	97	C4	2.25				
GRAD 55MPH ON 3%							
AV VEH KW/KG	0.014	HYBRID MODE FACTOR 1+EXP (C5*RANGE/160)					
EN USE WH/KM	200	C5	5				

Nickel Metal Hydride Battery

Table 5: Summary of Spreadsheet Result for Battery Cycle Life

	Battery Cycle Life			
0-60 mph acc. time	8 sec	10 sec	12 sec	15 sec
EV Primary Storage				
Pb-Ac, 150 km	413	499	583	640
Pb-Ac, 100 km	308	388	472	528
Pb-Ac, 80 km	232	300	374	428
Ni Mt Hy, 150 km	362	465	575	652
EV Load Leveled				
Pb-Ac, 150 km	738	738	738	738
Pb-Ac, 100 km	685	685	685	685
Pb-Ac, 80 km	598	598	598	598
Ni Mt Hy, 150 km	886	886	886	886
HV Primary Storage				
Pb-Ac, 100 km	321	405	493	552
Pb-Ac, 60km	160	213	276	322
Pb-Ac, 48 km	98	133	176	210
Ni Mt Hy, 48 km	not viable	....	....	....
HV Load Leveled				
Pb-Ac, 96 km	705	705	705	705
Pb-Ac, 60 km	504	504	504	504
Pb-Ac, 48 km	367	367	367	367
Ni Mt Hy, 40 km	768	768	768	768

Table 6: Summary of Spreadsheet Result for Vehicle Operating Cost (cents/mile)

	Vehicle Operating Cost (cents/mile)			
0-60 mph acc. time	8 sec	10 sec	12 sec	15 sec
EV Primary Storage				
Pb-Ac, 150 km	11.9	8.0	5.8	4.8
Pb-Ac, 100 km	17.3	10.8	7.3	5.8
Pb-Ac, 80 km	24.8	14.9	9.6	7.4
Ni Mt Hy, 150 km	27.2	16.5	10.9	8.4
EV Load Leveled				
Pb-Ac, 150 km	8.5	7.2	6.3	5.9
Pb-Ac, 100 km	10.2	8.6	7.4	8.3
Pb-Ac, 80 km	13.0	10.8	9.1	8.3
Ni Mt Hy, 150 km	8.1	7.3	6.7	6.3
HV Primary Storage				
Pb-Ac, 100 km	16.5	10.3	7.0	5.5
Pb-Ac, 60km	41.8	23.7	14.4	10.6
Pb-Ac, 48 km	79.0	42.6	24.7	17.5
Ni Mt Hy, 48 km	not viable	....	....	....
HV Load Leveled				
Pb-Ac, 96 km	10.1	8.5	7.3	6.6
Pb-Ac, 60 km	18.1	14.7	12.4	11.1
Pb-Ac, 48 km	28.6	23.1	19.2	17.1
Ni Mt Hy, 40 km	17.0	14.1	12.0	10.9

Table 7: Summary of Spreadsheet Result for Battery Life in Vehicle Miles

	Battery Life in Vehicle Miles			
0-60 mph acc. time	8 sec	10 sec	12 sec	15 sec
EV Primary Storage				
Pb-Ac, 150 km	38524	466592	54418	59646
Pb-Ac, 100 km	19198	24188	24374	33040
Pb-Ac, 80 km	11623	15004	18664	21344
Ni Mt Hy, 150 km	33844	43358	53526	60888
EV Load Leveled				
Pb-Ac, 150 km	68772	68772	68772	68772
Pb-Ac, 100 km	42555	42555	42555	42555
Pb-Ac, 80 km	29689	29689	29689	29689
Ni Mt Hy, 150 km	82595	82595	82595	82595
HV Primary Storage				
Pb-Ac, 100 km	20041	25251	30668	34492
Pb-Ac, 60km	5977	7971	10249	11999
Pb-Ac, 48 km	2904	3973	5247	6264
Ni Mt Hy, 48 km	not viable	....	....	....
HV Load Leveled				
Pb-Ac, 96 km	42072	42072	42072	42072
Pb-Ac, 60 km	18793	18793	18793	18793
Pb-Ac, 48 km	10937	10937	10937	10937
Ni Mt Hy, 40 km	19174	19174	19174	19174

Table 8: Summary of Spreadsheet Result for Energy Storage System Cost

	System cost ($)			
0-60 mph acc. time	8 sec	10 sec	12 sec	15 sec
EV Primary Storage				
Pb-Ac, 150 km	4586	3729	3158	2866
Pb-Ac, 100 km	3311	2614	2149	1910
Pb-Ac, 80 km	2882	2233	1799	1577
Ni Mt Hy, 150 km	9190	7162	5808	5115
EV Load Leveled				
Pb-Ac, 150 km	5843	4974	4359	4031
Pb-Ac, 100 km	4370	3649	3138	2865
Pb-Ac, 80 km	3862	3192	2715	2460
Ni Mt Hy, 150 km	6731	6016	5508	5236
HV Primary Storage				
Pb-Ac, 100 km	3311	2614	2149	19.10
Pb-Ac, 60km	2498	1885	1477	1269
Pb-Ac, 48 km	2293	1694	1298	1096
Ni Mt Hy, 48 km	not viable	....	....	....
HV Load Leveled				
Pb-Ac, 96 km	4265	3555	3051	2781
Pb-Ac, 60 km	3393	2768	2324	2086
Pb-Ac, 48 km	3129	2529	2102	1874
Ni Mt Hy, 40 km	3259	2701	2304	2092

Table 9: Summary of Spreadsheet Result for Battery Energy Density

	Energy Density - Wh/kg			
0-60 mph acc. time	8 sec	10 sec	12 sec	15 sec
EV Primary Storage				
Pb-Ac, 150 km	31.1	33.8	36.1	37.6
Pb-Ac, 100 km	28.3	31.3	34.1	35.8
Pb-Ac, 80 km	26.6	29.7	32.7	34.7
Ni Mt Hy, 150 km	47.5	52.9	58.0	61.3
EV Load Leveled				
Pb-Ac, 150 km	40	40	40	40
Pb-Ac, 100 km	40	40	40	40
Pb-Ac, 80 km	40	40	40	40
Ni Mt Hy, 150 km	70	70	70	70
HV Primary Storage				
Pb-Ac, 100 km	28.3	31.3	34.1	35.8
Pb-Ac, 60km	24.3	27.6	30.8	32.9
Pb-Ac, 48 km	22.5	25.7	29.1	31.4
Ni Mt Hy, 48 km	not viable	----------	----------	----------
HV Load Leveled				
Pb-Ac, 96 km	40	40	40	40
Pb-Ac, 60 km	40	40	40	40
Pb-Ac, 48 km	40	40	40	40
Ni Mt Hy, 40 km	70	70	70	70

Table 10: Summary of Spreadsheet Result for Energy Storage System Volume

	Energy System Volume - Liters			
0-60 mph acc. time	8 sec	10 sec	12 sec	15 sec
EV Primary Storage				
Pb-Ac, 150 km	289	259	237	226
Pb-Ac, 100 km	187	166	150	143
Pb-Ac, 80 km	152	133	120	113
Ni Mt Hy, 150 km	161	143	129	121
EV Load Leveled				
Pb-Ac, 150 km	394	367	348	338
Pb-Ac, 100 km	271	249	234	226
Pb-Ac, 80 km	235	215	201	194
Ni Mt Hy, 150 km	206	186	172	165
HV Primary Storage				
Pb-Ac, 100 km	187	166	151	143
Pb-Ac, 60km	119	104	92	86
Pb-Ac, 48 km	100	86	76	70
Ni Mt Hy, 48 km	not viable	----------	----------	----------
HV Load Leveled				
Pb-Ac, 96 km	271	250	235	227
Pb-Ac, 60 km	194	176	163	156
Pb-Ac, 48 km	171	154	141	134
Ni Mt Hy, 40 km	115	100	89	83

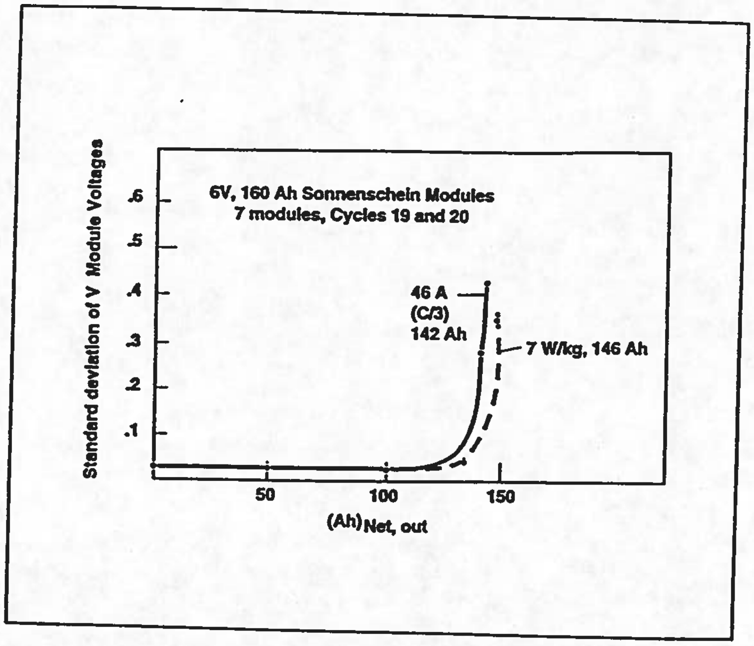

Figure 1: Module variability for the 46 A (C/3) and 7 W/kg discharges of the 7-module pack of Sonnenschein 6 V, 160 A-h batteries,

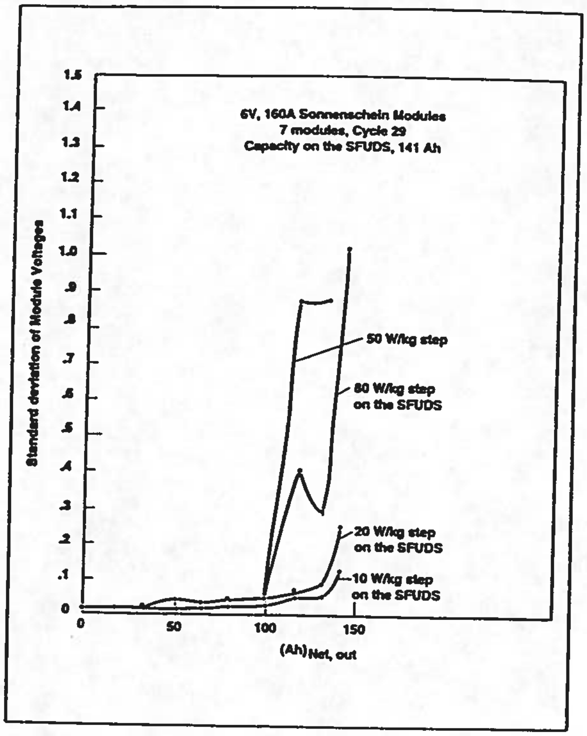

Figure 2: Module variability on the SFUDS for a 7-module pack of 6 V, 160 A-h Sonnenschein batteries (Cycle 29)

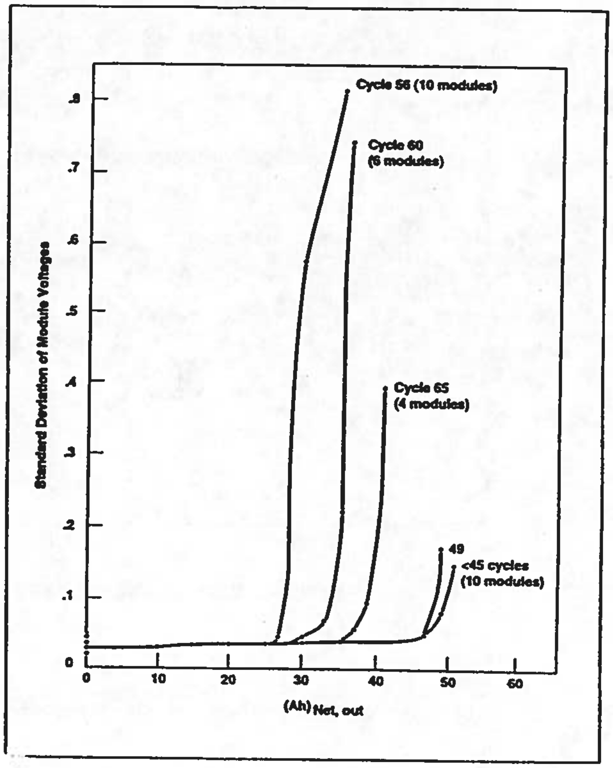

Figure 3: Module variability for 10 W/kg discharges for various cycles - Pack A.

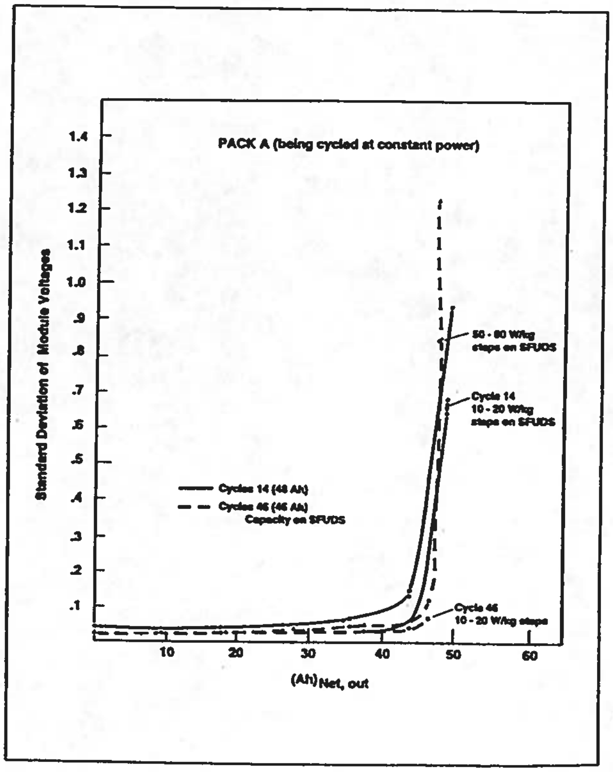

Figure 4: Module variability on the SFUDS of Pack A (10 modules), Cycles 14 and 46.

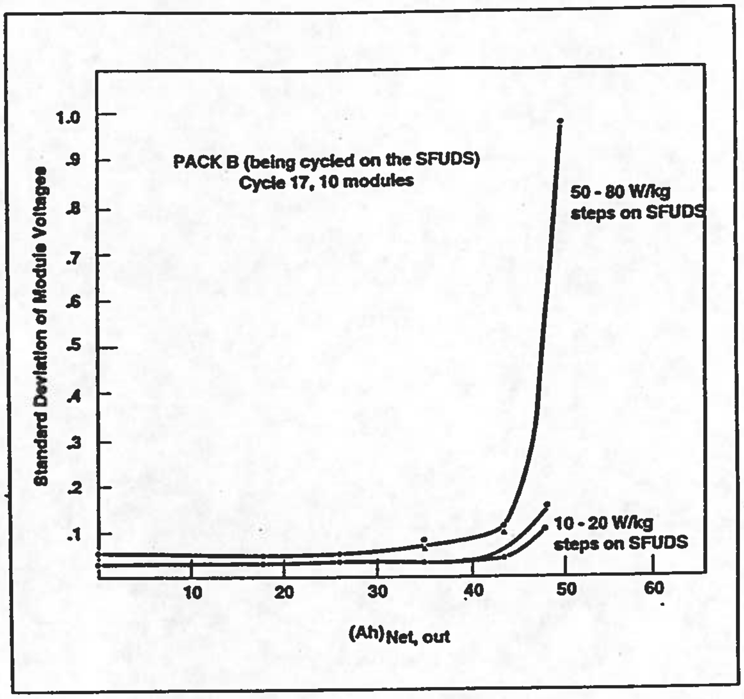

Figure 5: Module variability of Pack B on the SFUDS for Cycle 17.

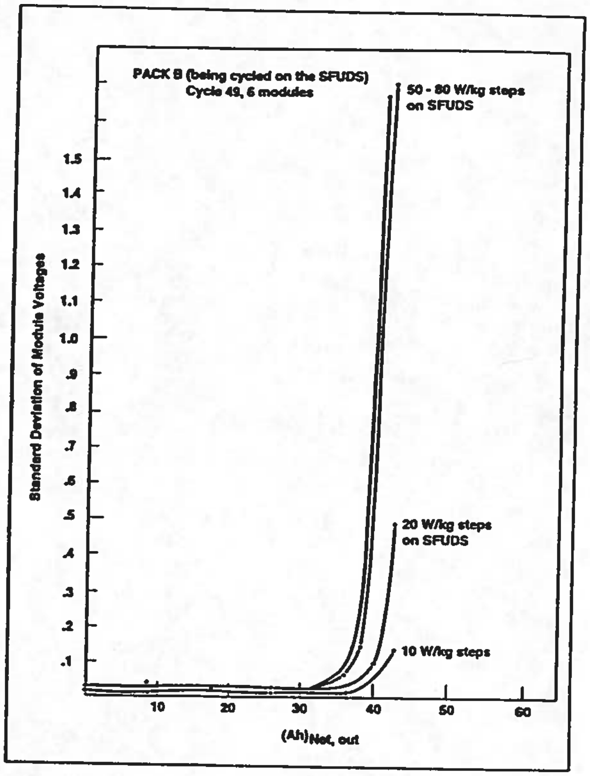

Figure 7: Module variability on the SFUDS of Pack B for Cycle 49, 6 modules.

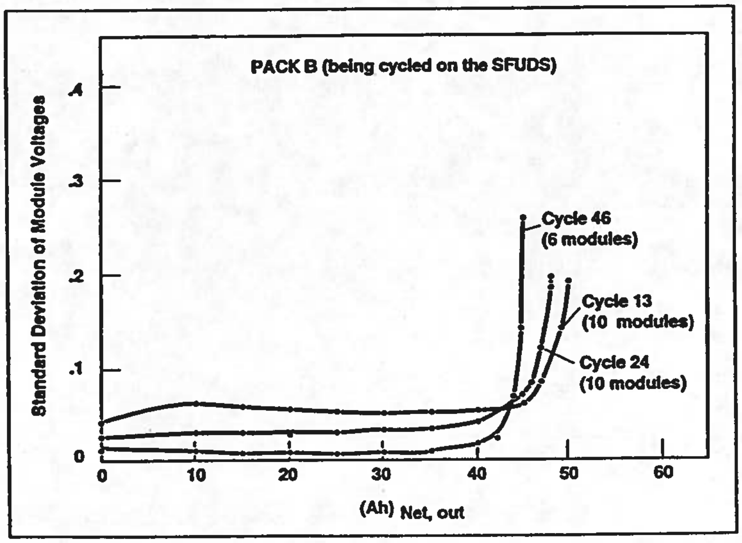

Figure 6: Module variability for 10 W/kg discharges for various cycles - Pack B, Cycles 13, 24, and 46.