

EV Battery Life Extension in Field Testing

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ABSTRACT

Results of the Charger Test Project conducted by Arizona Public Service (APS) indicated the importance of the charger/charge algorithm/battery interface with respect to battery capacity. It also indicated that EVs rapidly charged demonstrated longer cycle life in field testing without reduction in capacity. Additional testing conducted by APS has shown that cycle life of the batteries is strongly related to the charging scheme utilized. Application of results of laboratory charging to the charge scheme utilized in this testing has been hampered by extremely long test periods in field tests designed to cycle batteries to the end of life. Development of a predictive method of cycle life extrapolation based upon microscopic analysis promises to reduce the time required for battery cycle life testing.

INTRODUCTION

Three phases of testing will be addressed. Phase I testing was performed on EVs in the field to evaluate the performance of Hawker Genesis[®] batteries with a variety of chargers. Based on the results of the Phase I testing, Phase II testing was initiated to examine battery performance in the field at various rapid charge rates. Phase III addresses microscopic analysis of batteries that have been cycled at different rates to determine if the end of useful life can be predicted.

PHASE I - EV AMERICA FIELD TESTING

The first round of *EV America* Performance Testing concluded in November 1994. Among the

numerous bench mark performance data collected was EV range at constant speed 72.4 km/h (SAE 227A), constant speed 96.5 km/h (SAE 227A), and per fuel efficiency drive cycle (SAE J1634). Over 225 EVs were purchased in the Phase I Program (Solectria E-10 pickups and Force sedans, and US Electricar [USE] ES10 pickups and sedans) by utilities and government agencies across the United States. The *EV America* Phase I range test results for the USE ES10 and the Solectria E-10 pickups are provided in Table 1. All of these vehicles utilized Hawker Genesis[®] 38 ampour VRLA AGM batteries, model G190W.

Table 1. *EV America* Performance Testing, Phase I Range Testing

EV Manuf	km at 72.4 km/h	km at 96.5 km/h	km at SAE J1634
USE ES10	113.8	76.1	110.7
E-10	117.1	63.6	93.2

In use, the Phase I EVs reported a significant loss in range with low battery cycles. Proving ground range testing (SAE 227A @ 72.4 km/h) in Phoenix confirmed an approximate 50% range reduction in a USE ES10, and a 37% range reduction in a Solectria E-10.

An evaluation by Hawker Energy Products (HEPi) concluded that an undercharge condition existed in the batteries. The USE ES10 was originally equipped with a 2 kW integral charger which charged a 52 battery module, useable 21 kilowatt hour pack. For this vehicle,

HEPi concluded that a minimum 12 kW charging rate was required to properly charge the battery pack. The Solectria E-10 was originally equipped with a 2 kW charger which charged a 36 battery module, useable 16 kilowatt hour pack. HEPi concluded, for the E-10, that an 8 kW charging rate was required at a minimum.

Based on the need for an acceptable charge protocol for the Hawker Genesis® batteries, a field test program was initiated in 1995 (Phase I) for the purpose of evaluating the performance of Hawker Genesis® batteries with a variety of chargers. The following chargers were evaluated; 150 kW Norvik Minit Charger, 2 kW Solectria Charger, 3 kW Solectria Charger, and 6.6 kW Delco Inductive Charger. Six electric pickup trucks were selected for the field test. None of the Phase I EVs were equipped with a battery management system to monitor modules during charge and discharge. Thermal management of the EV packs was limited to a few small muffin fans in half of the vehicles, while the other half had no devices. This test program began in May 1995 and terminated in January 1996. The EVs were driven on the streets and freeways in Phoenix where summer daytime temperatures can reach 49° C.

Table 2 describes the chargers for the Phase I vehicles. Fast charging demonstrated its value early in the test, by restoring the capacity of a battery pack which was believed to have been irreversibly damaged through long term undercharging. The Norvik Minit Charger was used to fast charge two of the EVs at an arbitrarily chosen rate of 3C, i.e. three times the one hour discharge rating of the Hawker battery. EVs charged by the Norvik charger had to undergo a periodic equalization charge. EV138 was equalized periodically with the Norvik charger. Other vehicles were equalized by using on or off board low rate overnight chargers.

Norvik charging used 2.45 volts per cell for the Genesis® battery and equalization was based upon 2.65 volts per cell. EV137 was equalized with the Delco inductive charger. The Delco charger conducted the main charge routine with a 2.45 volts per cell basis and the equalization routine was based upon 2.56 volts per cell. The Solectria chargers used a 2.45 volts per cell and cell equalization was accomplished with extensive overcharging at this voltage.

Table 2. Phase I Field Test EV Chargers and Charge Cycles

EV	Fast Charge Rate	Overnight Ind Rate	Overnight Cond Rate	Equalization Charge
133	N/A	N/A	3kW	Cond
134	N/A	N/A	2kW	Cond
135	2C	N/A	2kW	Cond
137	3C	6.6kW	N/A	Ind
138	3C	N/A	N/A	Fast
139	N/A	6.6kW	N/A	Ind

Ind-inductive, Cond-conductive

Table 3 provides a summary of battery pack performance in the EVs and the cause of battery module failure. Although the batteries were the same in each EV, the consequences of chargers and charge algorithms is dramatically demonstrated in cycle life. In considering the battery performance in this test it was evident that the Hawker Genesis® VRLA AGM battery could be easily damaged by low power charging, and the battery performed better as the charge power increased. It was also surprising that the summer heat in Phoenix did not impact battery performance in high rate charging. One pack was destroyed by a fire, apparently caused by loose battery interconnections. This event reinforced the importance of good battery pack assembly procedures.

Table 3. Phase I Battery Pack End of Life Cycles, Over the Road km, and Module Failure

EV	Charge Cycles	Pack km	Cause of Module Failure
133	197	12,067	grid corrosion, 12 modules
134	52	1,931	thermal run away, 12 modules
135	113	5,749	thermal run away, 36 modules
137	360	26,549	grid corrosion, 8 modules
138	140	6,838	pack fire due to loose connection, 52 modules
139	120	6,240	grid corrosion, 17 modules

From the results of the Phase I field test and autopsy of modules from the EVs, it was concluded that the Norvik 3C charging provided the best vehicle performance and longest battery cycle life. The abrupt failure of 17 modules in EV139 (Delco inductive charger), caused by grid corrosion, was hypothesized to be the result of equalization or overcharging at the elevated voltage portion of the implemented algorithm. (Reference A) Coincidentally, the same number of equalization cycles (120) on EV137, charged by the Norvik charger and equalized by the Delco charger, resulted in a similar failure mechanism in 6 modules. The Solectria 2 kW charger produced battery failure due to thermal run away

early in battery life. The Solectria 3 kW charger produced failure via grid corrosion.

PHASE II - FIELD TESTING

For years, laboratory testing has been performed to determine the effects of charging methods on battery performance in EV applications. Parameters such as battery capacity, life, and grid corrosion have been examined. Results of laboratory testing, to date, have indicated that the charging scheme utilized has a direct effect on battery performance. However, testing within laboratories, even when simulated drive cycles are used for discharge, does not accurately represent the environmental rigors of fleet use. Fleet vehicles do not operate under a controlled set of conditions. Traffic conditions, ambient temperature, and operator usage are just a few of the variant conditions with which the battery must contend.

Significant cycle life extension has been achieved using high charging rates in laboratory testing. Chang and Valeriote *et al* (References B-H) have demonstrated that sealed valve regulated lead acid (VRLA) batteries can be rapidly charged with higher energy efficiency than traditional charging without detrimental effect to the battery and with significantly extended cycle life. VRLA batteries in laboratory testing were given five to ten rapid partial charge cycles and fully recovered their capacity in an extended charge.

Therefore, based on the Phase I and laboratory test results, a new program (Phase II), was commissioned. Phase II focused on: 1) partial charging at 3C, 5C, and 9C rates; 2) determination of whether periodic fast charging would reverse the damage from traditional low rate recharge; 3) evaluation of the cycle impact caused by reduction in the frequency of pack equalization; 4) evaluation of laboratory test results to improve field results; and 5) evaluation of the performance of NiCad and Nickel Metal Hydride batteries in the field environment.

Table 4 describes the field test fleet used in the Phase II program. EVs 114, 130, 136, 137, and 333 were given multiple fast charges per day and operated by a dedicated driver. This method of accelerated aging of the EV compressed the testing time. All accelerated aging vehicles were operated and maintained in accordance with test procedures. The test procedures describe the drive route, the depth of discharge strategy, and the recharge strategy for each EV in the program.

The remaining EVs were driven on arbitrary routes. In fleet testing, the EVs were driven by Arizona Public Service (APS) employees performing a certain work mission. EVs 131 and 134 were driven by meter readers. At the end of the work shift, EVs 131 and 134 were charged by the Delco charger. Twice per month

these EVs were given one 3C charge on the Norvik charger.

The EVs used in Phase II Field Testing did not use battery management or battery module monitoring equipment. The thermal management equipment utilized varied between vehicles. The two EVs charged at the 9C rates (114 and 333) were equipped with module cooling systems. Specifically, EV333 was equipped with high air velocity, manually initiated, module cooling. EV114 was equipped with a phase change material provided by Shape. EVs 124, 130, 131, 133, 134, and 135 used small muffin fans, activated by battery temperature, to ventilate ambient air across the pack.

EV116 (Nickel Cadmium), used in the APS Property Construction Department, received almost 100% fast charges, with a minimal number of equalizations. The Nickel Metal Hydride vehicle (EV124) was charged by a Solectria 3 kW charger and given frequent opportunity charges in its fleet mission.

All of the EVs in Phase II were tested during the Phoenix summer, where day time ambient temperatures can be as high as 49°C. On six to eight week intervals, vehicles were given a 96.5 km/h range test (SAE 227A) to evaluate battery capacity.

Table 4. Phase II Field Test Vehicles

EV	EV Model	Modules In Pack	Battery Manuf	Fast Charge Rate	Equalization Charger
114	S10	42	Hawker	9C	Martin M
333	S10	26	Hawker	9C	Norvik
137	S10	52	Hawker	5C	Delco
136	S10	24	GNB	3C	Norvik
136	S10	24	Optima	5C	Martin M
130	S10	36	Hawker	3C	Solectria
131	S10	36	Hawker	3C	Delco
133	S10	36	Hawker	3C	Solectria
134	S10	36	Hawker	3C	Delco
135	S10	36	Hawker	3C	Solectria
124	Geo	15	GMO	N/A	Solectria
116	TEVan	30	Saft	3C	Norvik

The accelerated aging group required extensive use of fast charging. Fast charging occurred at the 3C, 5C, and 9C rates. Daily fast charge cycles varied from one to five. Battery equalizations were varied from every third to every tenth cycle, depending upon the specific EV. Therefore, the majority of EV charging and operation was with partial charge cycles including the overnight

charging. Equalization charge cycles were minimized because of the module failures due to grid corrosion identified in Phase I.

Figure 1 depicts typical rapid charges delivered at the 3C, 6C, and 9C charge rates by the Norvik charger, Model 150kW, manufactured by Norvik Technologies Inc., Mississauga, Ontario, Canada. This charger monitors the resistance free voltage by interrupting about five times per second and then adjusting the applied voltage to match the charge acceptance ability of the battery. An identifier is installed on each EV which permits the charger to uniquely identify its battery type and maximum charge rate. The Norvik charger has an equalization feature which is manually initiated. With the Hawker Genesis® battery in Phase II, charging is accomplished at 2.45 volts per cell. In addition, the battery is temperature compensated and the equalization stage is based upon 2.50 volts per cell.

Figure 1. Norvik Charger Profile

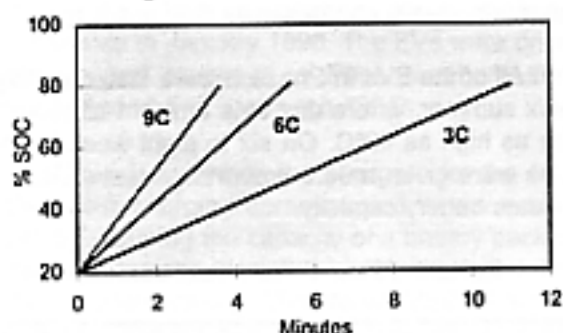


Table 5 provides the results of battery charger performance during the Phase II testing through December 1, 1996.

EVs 333 and 114 were primarily charged at the 9C rate. EV333 was equalized every sixth cycle by the Norvik charger. EV114 was charged overnight by the Martin Marietta 10 kW charger and equalized every fifth charge cycle by the Martin Marietta. Equalization voltage on the Martin Marietta charger was 2.50 volts per cell for the Hawker Genesis® batteries. During the overnight cycle on EV114, the Shape phase change material used for pack thermal stability, was frozen using a standard window air-conditioning unit to circulate air through the battery pack. Although a relatively large number of battery modules were lost by these high rate charges, the results are very promising due to the large number of modules which survived without the benefit of individual module charge control. Typical 9C charge rate module failures were observed to have a hot high rate venting of a module cell, which was detected by the Norvik charger and the charge was terminated.

Table 5. Battery Charger Performance Results Through December 1, 1996

EV	Days of Operation	Pack km	Pack Cycles	End of Life	Module Failures
114	78	2,851	108	no	2
333	165	7,413	200	no	9
137	247	16,064	251	yes	1
136/ GNB	279	6,318	97	yes	0
136/ Optima	175	4,277	137	no	4
130	367	18,008	399	no	1
131	414	6,024	140	no	0
133	610	18,270	427	yes	9
134	368	14,431	344	no	12
135	321	9,855	UNK	no	0
124	473	19,538	379	no	2
116	1,120	19,207	367	no	0

EVs 137 and 136 were charged at the 5C rate. EV137, which utilized Hawker Genesis® batteries, was charged overnight by the Delco inductive charger and equalized at 2.56 volts per cell on every third Delco charge. EV136, using Optima batteries, was equalized every sixth cycle by the Norvik charger. EV137 operated extremely well, incurring over 160.9 km (two partial 5C charges daily) in daily operation. At just under 16,090 km with no battery maintenance whatsoever, one module failed. At this point the test on EV137 was terminated. Problems with battery module interconnections in EV136 caused arcing and battery damage.

EV130 had very successful performance. The vehicle was predominately charged at the 3C rate. Overnight charges were accomplished with the Solectria 3 kW charger. EV130 showed no significant deterioration in range up to the time of its first module failure (17,915 km). The test protocol for EV130 was based on the protocol used for EV137 in Phase I. EV137, during Phase I, operated very successfully at the 3C charge rate using Delco overnight charges. While using this charge scheme, EV137 achieved about 26,549 km. In both cases, these EVs operated extremely well without battery management systems. If these systems were added to these EVs, their performance should improve. With this charge configuration, EV130 accumulated a total of 399 charge cycles and 18,008 km before incurring its first module failure. All of the fast charge cycles delivered achieved 80% State of Charge (SOC) in approximately 15 minutes.

EV131 and EV134 were driven daily in meter reading duty cycles (about 32 to 40 km per day) in Phase

II. EV134 was part of the Phase I testing where, using the Solectria 2 kW charger, 12 battery modules were lost due to thermal run away. These 12 modules were replaced and the pack charged using numerous fast charge cycles at the 3C rate. The vehicle was then moved into the Phase II program. Both EV131 and EV134, at the end of the work day, were charged with the Delco charger with equalizations occurring every fifth cycle. These EVs were fast charged once every other weekend with the Norvik charger at the 3C rate. Over the test period their range continued to deteriorate, until in the early part of November 1996 their range had dropped to about 37 km at constant speed 96.5 km/h. EV133 also continued from Phase I into Phase II field testing. In Phase I, EV133 accumulated about 12,550 km on its pack while being charged by the Solectria 3 kW charger, at which point the range had fallen to about 40 km. At this time the charging scheme for this EV was changed to being charged solely by the Norvik charger at the 3C rate. The range of the vehicle improved significantly and was then returned to fleet duty in construction where it continued to operate until abrupt pack failure at 18,270 km.

Phase II testing also included the evaluation of a Nickel Metal Hydride (NMH) battery and the Soft Nickel Cadmium (NiCad) battery provided with the Chrysler *TEVan*. The NMH is a prototype battery and is evaluated as being very promising. The NiCad battery has proven to be very durable. It has undergone a long period of partial fast charging at about the 3C rate. It has been in operation for three years. Fast charging dramatically reduced the amount of watering required by the battery. It has had extremely good reliability in the thirty months preceding December 1, 1996. There have been no battery modules replaced on this EV.

Preliminary results of the Phase II testing indicate that EVs charged at 3C and 5C charge rates perform extremely well, specifically EVs 130, 133, and 137. These EVs, with no battery management systems installed, achieved over 15,000 km on their battery packs without experiencing end of life of the batteries. In addition, charging at the 9C rate appears possible. However, further testing at the 9C charge rate is required using a battery management system.

Testing in Phase I and Phase II has extended battery life beyond the point which is reasonable to fully test in the field. The time and expense of operating vehicles in excess of 16,000 km dictates that a method be developed to predict remaining battery life such that testing to end of life is no longer necessary to evaluate the effectiveness of a particular charge protocol. In order to determine a means to predict remaining battery life, batteries with varying charge/discharge cycles were subjected to destructive analysis in Phase III of the test program.

PHASE III - ANALYSIS OF CYCLED BATTERIES

When a VRLA battery is cycled, i.e. repeatedly discharged then recharged, a host of largely irreversible processes occur internally. These processes impact the: a) morphology and crystallography of both the positive and negative active materials; b) corrosion and growth of the positive grid material; and c) electrolyte concentration and saturation level as both water loss and consumption of oxygen in the grid corrosion process occurs. Eventually, one or a combination of the above will result in unacceptable battery performance, i.e. end of useful life.

In order to correlate internal aging of the battery with use, a group of Hawker Genesis[®] G190W batteries were subjected to a number of cycles, as seen in Table 6, and subsequently analyzed. The batteries were cycled at the C/5 rate of discharge to an end point voltage of 1.67 volts per cell and recharged using a constant voltage regime (1U) of 2.45 volts per cell with a 0.4 C/5 (15A) current limit.

Table 6. Number of C/5 Cycles

Module	Number of 100% DOD C/5 Cycles Completed
A	0
B	5
C	40
D	62
E	157
F	286

Positive and negative plates from the above cycled modules were removed, washed so as to remove electrolyte, then dried and stored under inert conditions in order to prevent further changes prior to analysis. Active material samples were then carefully extracted from along the plate diagonal.

The analysis techniques employed for this study were BET Surface Area (BET SA), Particle Size Analysis, X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM).

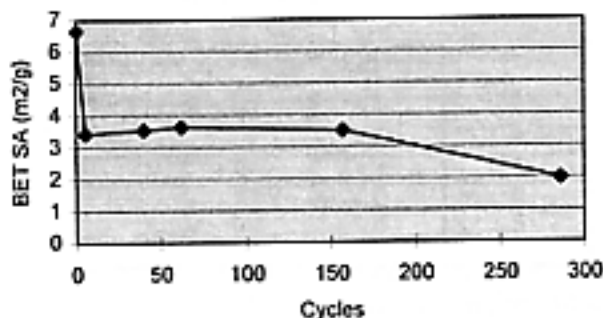
CYCLE LIFE CHANGES TO THE MORPHOLOGY AND CRYSTALLOGRAPHY OF THE POSITIVE ACTIVE MATERIAL - Table 7 summarizes the results for the positive active material (PAM).

Table 7. Morphological and Crystallographic Changes of the PAM During Life Cycling

Module	C/S cycles	BET surface area (m ² /g)	Median pore diam (nm)	XRD % α -PbO ₂	XRD % β -PbO ₂	XRD % PbSO ₄
A	0	6.66	24.9	12	81	7
B	5	3.42	35.8	8	88	4
C	40	3.55	28.8	2	96	1
D	62	3.64	49.1	1	97	2
E	157	3.52	4.9	0	100	0
F	286	2.00	4.2	1	99	0

As shown in Table 7, the first measured quantitative change to the PAM, throughout its cycle life, is the conversion from an initially high surface area crystalline material, immediately following formation, to a progressively lower surface area coraloid structure, as seen in Figure 2. (Reference 1)

Figure 2. PAM BET SA vs Cycles



This transition may clearly be seen in the following SEM pictures, Figures 3 through 5.

Figure 3. Bulk PAM from Module A, 0 Cycles, x2500

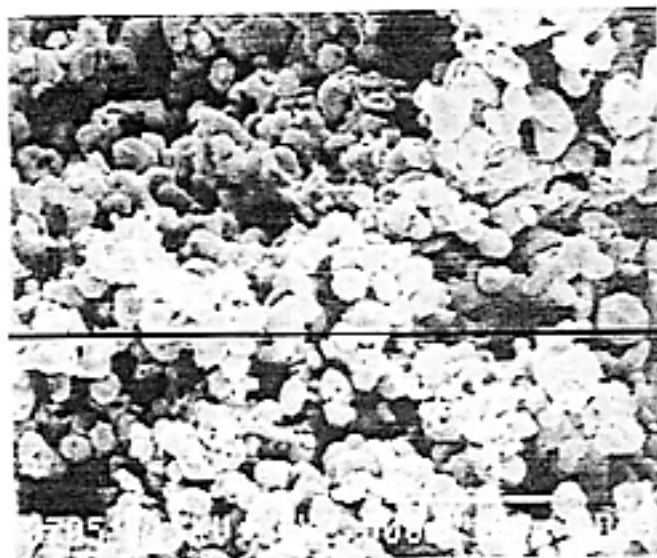


Figure 4. Bulk PAM from Module D, 62 Cycles, x2500

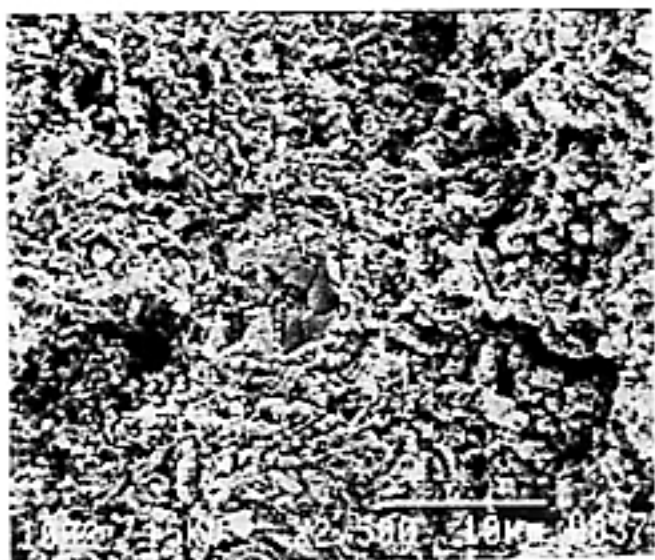
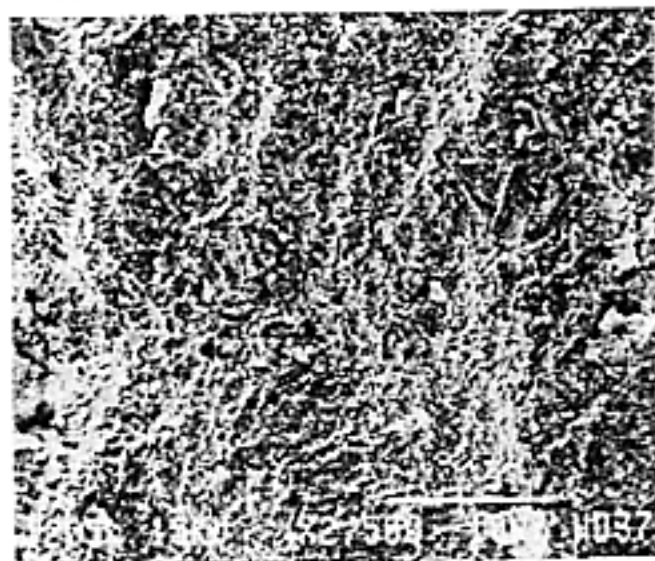


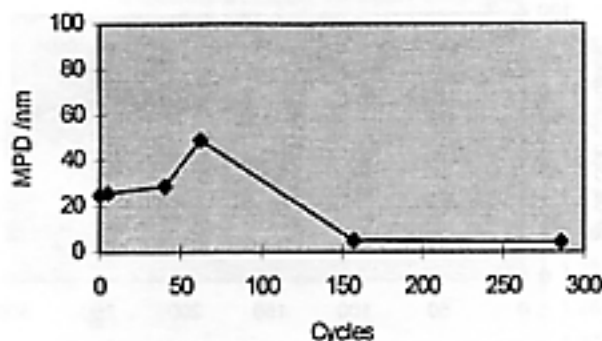
Figure 5. Bulk PAM from Module F, 286 Cycles, x2500



Healthy PAM is typically considered to possess a surface area (SA) of between 3-4 m²/g. Toward end of life the contraction of the active mass results in a reduced SA approaching 2 m²/g.

The second measured transition is the reduction in the median pore diameter (MPD) of the PAM, as shown in Figure 6.

Figure 6. PAM Median Pore Diameter

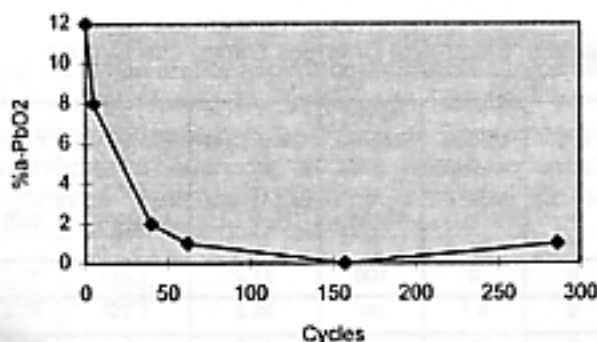


The median pore diameter referred to here is for PAM removed from the grid and gently broken-up, not left in-situ on the grid. It is thought that the in-situ PAM will have both very large pores left in the pellet, as the active mass consolidates, and small pores within the coralloid structure itself.

The MPD is a measurement of the degree of contraction of the PAM. In the above experiment Module E (157 cycles) exhibits a similar MPD to Module F (end-of-life) but still has 50% cycle life remaining. This anomalous behavior may be attributable to the high pack compression associated with the Genesis® technology. It is now recognized that high pack compression alleviates many of the shortfalls associated with cycling the positive plate by physically constraining the PAM. (Reference J)

The third measured quantitative change within the PAM is the transition of the α -PbO₂ component into β -PbO₂. This is shown in Figure 7.

Figure 7. Crystallography of PAM vs Cycles



This transition is generally a function of the battery design, specifically the degree of PAM utilization. For the Genesis® technology, this transition occurs early in life and, consequently, has no correlation with remaining useful cycle life.

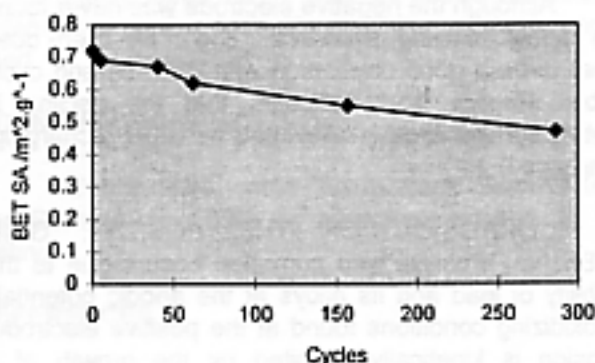
CYCLE LIFE CHANGES TO THE MORPHOLOGY AND CRYSTALLOGRAPHY OF THE NEGATIVE ACTIVE MATERIAL - Table 8 summarizes the results for the negative active material (NAM).

Table 8. Morphological and Crystallographic Changes of the NAM During Life Cycling

Module	C/5 cycles	BET surface area (m ² /g)	MPD (nm)	XRD % Pb	XRD % PbO	XRD % PbSO ₄
A	0	0.72	4.8	99	0	1
B	5	0.69	4.7	99	1	0
C	40	0.67	4.5	99	0	1
D	62	0.62	4.2	99	0	1
E	157	0.55	4.5	96	3	0
F	286	0.47	4.9	97	2	1

The only measured change found to the NAM during cycling is a gradual reduction in surface area, possibly as a result of the negative expanders losing activity. This reduction is shown in Figure 8.

Figure 8. NAM BET SA vs Cycles



SEM analysis of the negative plates, at the beginning of life and after 286 cycles, reveals little visual change, as seen in Figures 9 and 10.

Figure 9. Bulk NAM from Module A, 0 Cycles, x2500

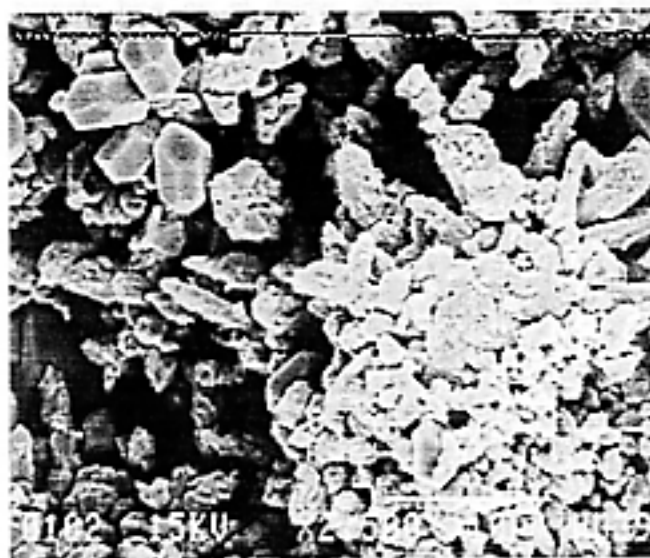
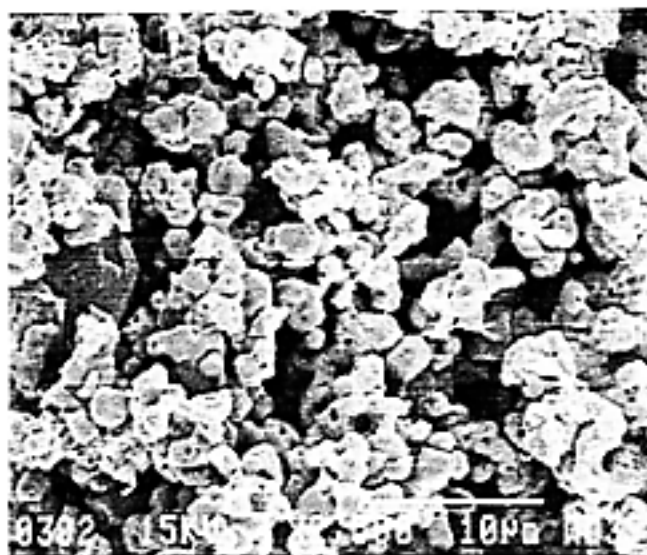


Figure 10. Bulk NAM from Module F, 286 Cycles, x2500

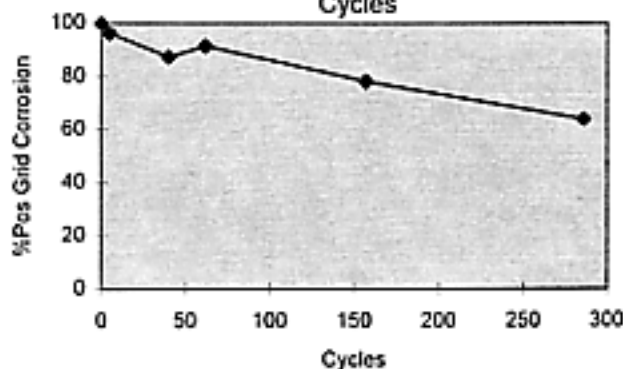


Although the negative electrode was never found to be capacity limiting, even at the end of life, there does appear to be a good correlation with BET SA and cycle number. Recent work indicates that the decline in negative surface area is alleviated by rapid recharging. (Reference 1)

CORROSION OF THE POSITIVE GRID MATERIAL - Positive grid corrosion occurs due to the instability of lead and its alloys at the anodic potentials and oxidizing conditions found at the positive electrode. Corrosion is kinetically inhibited by the growth of a passivating layer of PbO₂ on the grid surface. However, corrosion will eventually limit the capacity of the positive electrode by a combination of growth, caused by volumetric changes of the corrosion product at the grid surface and at the grain boundaries, and reduction of electronic continuity throughout the grid. Furthermore, it aggravates the situation by consuming much-needed water from the electrolyte, which in an acid starved system can be a major contributor to end of useful life.

Positive grid corrosion was estimated by mechanically removing the PAM, chemically stripping any residual PAM and corrosion product from the grid, and then finally weighing the residual lead grid. The difference in weight for the sample grid and the grid from Module A (0 cycles) yielded the amount of lead oxidized during cycle life. The results are shown in Figure 11.

Figure 11. %Positive Grid Corrosion vs Cycles



For the Genesis® technology, under these cycling conditions, there is a very strong correlation between % grid corrosion and remaining cycle life.

ELECTROLYTE CHANGES - Water loss is an inevitable consequence of cycling batteries. Water is electrochemically removed from the system by: a) charging inefficiencies resulting in electrolytic decomposition; and b) corrosion of the positive grid consuming oxygen from the electrolyte, according to:



The result is a progressive increase in electrolyte concentration and a reduction in saturation level.

These changes were evaluated by: a) measuring the total module weight loss over cycle life, b) removing and weighing the wet glass mat separator from one cell of each of the modules, and c) extracting the acid from the separator and measuring its concentration. These results are summarized in Table 9.

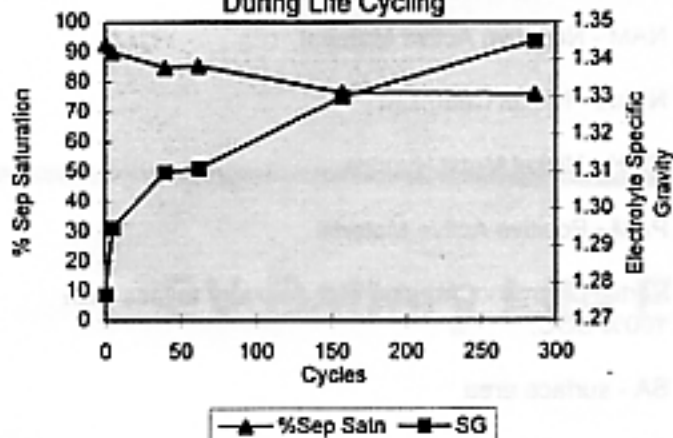
Table 9. Electrolyte Changes During Life Cycling

	C/S cycles	Module wt loss (g)	% wet sep wt comp to Module A	Electrolyte conc (% H ₂ SO ₄)	Electrolyte SG @ 15°C (kg/dm ³)	Calc sep % saln
A	0	0	100	37.2	1.277	92.9
B	5	5.7	95	39.2	1.295	90.2
C	40	12.2	87	40.9	1.310	85.0
D	62	15.8	87	40.9	1.311	85.5
E	157	67.9	82	43.1	1.330	76.5
F	286	88.4	70	44.8	1.345	75.9

Figure 12 shows the variation in % separator saturation and electrolyte concentration with cycle life.

predict remaining life in VRLA Hawker Genesis[®] batteries.

Figure 12. % Separator Saturation and Electrolyte Concentration Changes During Life Cycling



For Genesis[®] technology, a strong correlation between water consumption exists (measured as % separator saturation), and subsequently, electrolyte concentration and cycle life.

The results of the Phase III testing indicate that positive active material morphology or crystallography does not yield a good correlation to remaining cycle life. It is now recognized that high separator compression alleviates some of the problems associated with cycling the positive active mass. Therefore, high compression systems may continue to exhibit good cycling capability long after the PAM has transformed into a structure traditionally considered to be life limiting. In addition, positive grid corrosion and separator saturation (a measure of grid corrosion and dry out) exhibit a strong correlation to cycle life.

Therefore, based upon work completed to date, grid corrosion and/or separator saturation can be used to evaluate remaining life in Hawker Genesis[®] batteries. Additionally, measures to reduce grid corrosion/dry out will improve battery cycle life. This includes charge algorithms, particularly the amount of time the battery spends at high charging voltages.

CONCLUSIONS

Battery performance, in Phase I testing, indicates that Hawker Genesis[®] batteries can be damaged by low power charging. Both Phase I and Phase II testing results suggest that the utilization of a 3C fast charge rate, in vehicles not using battery management systems, provides good vehicle performance and extended battery life. In addition, charging of the Hawker Genesis[®] batteries at the 9C rate is possible, but a battery management system is required to reduce module failures. In Phase III, it was shown that grid corrosion and separator dry out may be used to

Through Phases I and II of the APS Charger Test Project substantial progress has been made in extending the life of VRLA batteries in fleet service and dramatically reducing the time required for charging. Additional work is required in Phase II testing to determine optimum charge protocols. However, the method of remaining battery life estimation pursued in Phase III is necessary to allow test work to be completed in a reasonable time period.

Future work will include continued Phase III evaluation of batteries cycled in Phase II to solidify the method of remaining life determination. Testing should then commence on batteries, charged between a 3C and 6C charge rate, using battery management systems to validate the preliminary results of Phase II. Testing should also continue using a 9C fast charge rate on batteries with battery management systems. In addition to this testing, other VRLA batteries should be tested to determine if similar cycle life predictive methods can be used.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AGM - Absorbed Glass Mat

ALABC - Advanced Lead Acid Battery Consortium

APS - Arizona Public Service

Battery management system - A system designed to manage the charge of each individual module.

C charge rate - The C rate of charging is defined to be the rated energy of a battery delivered over a one hour period. Fast charge rates are linear multiples of that one hour rating.

Comp - compared

Conc - concentration

Cond - conductive

Equalization Charge - Charging of the battery to 100% SOC.

Ind - inductive

Manuf - manufacturer

MPD - Median Pore Diameter

NAM - Negative Active Material

NiCad - Nickel Cadmium

NMH - Nickel Metal Hydride

PAM - Positive Active Material

Partial Charge - Charging of the battery to less than 100% SOC.

SA - surface area

Satn - saturation

SEM - Scanning Electron Microscopy

Sep - separator

SG - specific gravity

SOC - state of charge of the battery

UNK - unknown

VRLA - Valve Regulated Lead Acid

Wt - weight

XRD - X-ray diffraction