ACCELERATED CYCLE LIFE TESTING OF LEAD–ACID GOLF CAR BATTERIES AND THE INFLUENCE OF SEPARATOR TYPE ON BATTERY LIFE, ENERGY CONSUMPTION AND OPERATING COST

BRUCE S. GOLDBERG, ALEXANDER G. HAUSSER and BICH T. LE

Amerace Corporation, Technical Center, Ace Road, Butler, NJ (U.S.A.)

(Received in revised form November 22, 1982)

Summary

Commercial lead–acid golf car batteries containing five different separator materials were cycle life tested. An accelerated cycle life test was employed in which the battery temperature was allowed to rise as the batteries became less efficient in power utilization towards the end of life, and there was no rest period between charge and discharge during cycling.

The effects of continuous cycling and separator type on battery performance were monitored throughout the test together with battery temperature, end of charge current, energy balances, and capacity. Cycle life test data through correlation with actual expected life in the field allowed calculations to be made to determine the relative effective operating cost of various battery types.

The battery made with FLEX-SIL® rubber separators exhibited the best life and economics when compared with batteries containing ACE-SIL® rubber, polyethylene, cellulose (paper), and sintered PVC separators.

Introduction

There are many sophisticated procedures being employed to determine the performance characteristics of batteries under numerous cycle regimens and at various temperatures [1 - 4].

Laboratory testing, unless the cycle regimen reflects actual use conditions, does not give a good comparison with results obtained in the field. In order to obtain good correlative data, many laboratories attempt to simulate as closely as possible the actual conditions which a battery might experience in the field. Reasonable comparisons can be made to predict field behavior from results obtained in the laboratory [5]. Most commercially

FLEX-SIL® and ACE-SIL® are registered trademarks of Amerace Corporation, Microporous Products Division.

0378-7753/83/$3.00

produced industrial and automotive batteries are tested *via* the DIN (Deutsches Institut für Normen), the Navy WB-133, or the U.S. SAE (Society of Automotive Engineers) test procedures.

Currently there seems to be no standardized life cycle procedure for golf-car-type motive power batteries. The procedure used in this study, with some variations, is one of the interim procedures being considered by the Battery Council International.

The objectives of the work reported herein included the use of a test regimen which would continuously cycle golf car batteries, thus reducing the time required to reach end of life, and to allow the temperature of the cells to rise naturally, as they approach the end of life, without cooling to maintain a fixed temperature. Allowing the temperature to float simulates the real world situation where discharged golf car batteries are recharged and placed back in service without temperature regulation during the charge or discharge cycle.

Additional objectives of this study were to study the effect of various separators and their influence on the electrochemical performance of batteries and their cycle life capabilities.

Extrapolation of the laboratory data allowed estimation of what could be reasonably expected in actual field service. Thus, an estimated operating cost for these batteries can be obtained by using the energy consumption rates obtained in the laboratory.

Experimental

Five commercial 6 volt lead–acid golf car batteries containing nineteen 6% antimony alloy plates/cell were used for these experiments. The batteries were engineered to have a capacity of 100 min at a discharge rate of 75 amps. Each 6 volt battery was constructed with a different separator. The separators used were ACE-SIL microporous rubber; FLEX-SIL, a newly developed microporous rubber; microporous polyethylene; cellulose (paper), and sintered PVC. All separators incorporated a glass mat on the rib side. Table 1 presents the data on the above separators. ACE-SIL and paper are considered the two controls by the industry.

The batteries were tested on a commercially available electronic cycle life instrument incorporating automatic sequencing of charge and discharge without rest periods in the cycle regimen. Instrument design allowed control of current and voltage limits at 25 A and 7.3 V, respectively, during the charging phase and a discharge of 75 A. The cycling procedure employed was:

1. Discharge at 75 A for 1 h.
2. Recharge at 25 A current limit and 7.3 V limit for 12 h.
3. Repeat 1. and 2. continuously except when capacity tests are performed.

A capacity test was performed periodically throughout the test according to the following regimen.

TABLE 1

Initial properties of separators

	Cellulose	FLEX-SIL	ACE-SIL	Microporous polyethylene	Sintered PVC
Thickness (in.)					
Backweb	0.037	0.015	0.030	0.015	0.017
Overall	0.065	0.064	0.068	0.060	0.061
Glassmat	0.010	0.010	0.010	0.015	0.010
Electrical resistance (mΩ in.^{2})					
Standard method	35.2	—	45.0	—	20.0
Boiled method	—	35.0	—	27.0	—
Mullen strength (psi)	18	55	40	90	40
Total porosity (cm^3/g)	1.72	0.52	0.90	0.95	0.55
Pore diameter (μm)	19.0	0.03	0.35	0.2	14.0
% Over 20 μm	46.51	1.0	2.2	0.2	19.0

1. At end of charge, give an extra charge until the current is stable for 0.5 h.
2. Let the batteries stand on open circuit for 0.5 h to cool.
3. Discharge at 75 A. Record time required for voltage to reach 1.75 V per cell.
4. Recharge at 25 A current limit and 7.3 V limit for 12 h, then place back on cycle.
5. Failure occurs when the capacity drops below 80 min capacity and/or end of charge current reaches 15 A.

A Hewlett Packard 2240A data logger was used to automatically monitor the voltage and current relationships of the batteries to obtain energy balance data.

Results

Capacity as a function of cycle life

Figure 1 is a plot of retained capacity *versus* cycles for the test batteries. Most cycle test regimens usually consider end of life as the point where the battery will no longer deliver 75 A for 80 min. It will be noted that the battery built with FLEX-SIL® separators had the longest cycle life before its capacity dropped below 80 min.

Based on an 80 min capacity failure (Fig. 1), the batteries built with sintered PVC and cellulose separators had an early failure at 94 and 190 cycles, respectively. The cause of early failure was a combination of shorts across the bottom of the plates and poor performance of the separator as it affects plate potentials, overcharge, and loss of active material. A large

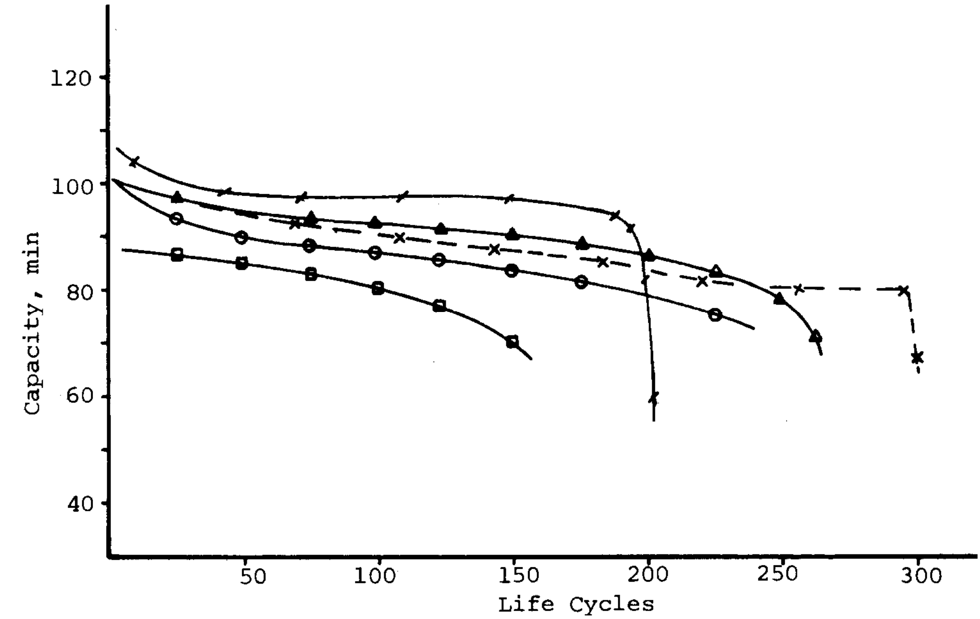

Fig. 1. Capacity (min to 1.75 Vpc at 75 A) *vs.* life cycles. ×, FLEX-SIL®; △, microporous polyethylene; ○, ACE-SIL®; □, sintered PVC; /, cellulose.

amount of lead was absorbed by the cellulose separator. Analysis of the cellulose separator after cycle life testing showed that the amount of lead absorbed was 51 times higher than the sintered PVC which absorbed 3.6 times more than the FLEX-SIL® separator.

The amount of lead absorbed by the cellulose separator and the high end of charge currents very early in life indicate that considerable lead treeing occurred. This resulted in numerous conductive paths through the separator, very high end of charge currents, and heat build-up. These factors may be attributed to the large pore size of a cellulosic separator.

Early failure of the battery with sintered PVC separators appears to have been the result of poor electrochemical performance of that product. The large pore size of the sintered PVC separator and its chemical composition may have contributed to this failure.

The battery containing ACE-SIL® separators failed to maintain 80 min of capacity after 167 cycles; however, it still exhibited a low temperature and end of charge current. Testing was therefore continued until the current exceeded 15 A, which occurred at 227 cycles due to sediment build-up and the resulting shorts at the bottom of the plates.

The battery containing microporous polyethylene failed to deliver 80 min capacity after 243 life cycles. It required 18% more power input and 2.7 times the water consumption of the battery containing FLEX-SIL® separators.

The battery built with FLEX-SIL® separators had an 80 min capacity cycle life of 294, which is three times longer than the one built with sintered

PVC separators and 49 cycles more than the one containing microporous polyethylene separators. Besides having a good life, the battery containing the FLEX-SIL® separators required less energy to recharge and required no water addition up to 240+ cycles.

End of charge current as a function of cycle life

Figures 2 and 3 illustrate battery end of charge currents and temperatures as a function of cycle life. It will be noted that as the end of charge current increases, the battery temperature increased and when the batteries reached end of life, the currents and temperatures increased rapidly. Based on energy consumption, failure occurred when end of charge current reached 15 A.

The results indicate that the battery built with sintered PVC separators failed at 133 cycles and 75 min capacity, that with ACE-SIL® separators failed at 227 cycles and 74 min capacity, and the one with microporous polyethylene separators failed at 247 cycles and 78 min capacity. The battery containing cellulose separators failed at 164 cycles and 96 min capacity, that with FLEX-SIL® separators failed at 290 cycles and 80 min capacity.

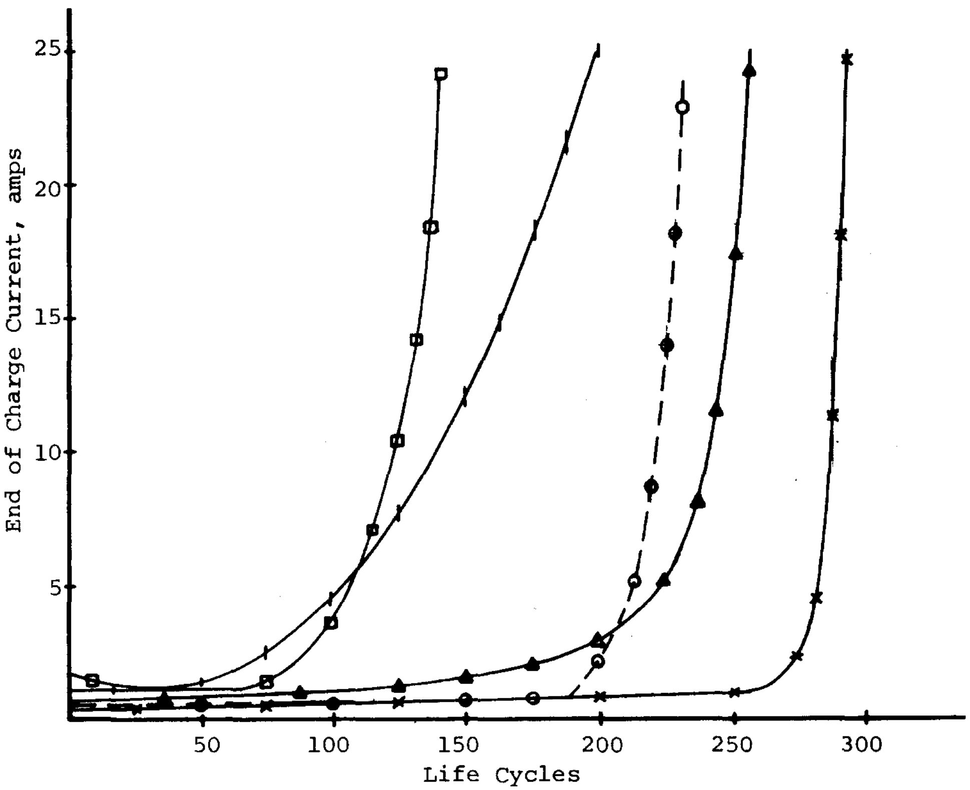

Fig. 2. End of charge current (A) *vs.* life cycles. ×, FLEX-SIL®; △, microporous polyethylene; ○, ACE-SIL®; □, sintered PVC; /, cellulose.

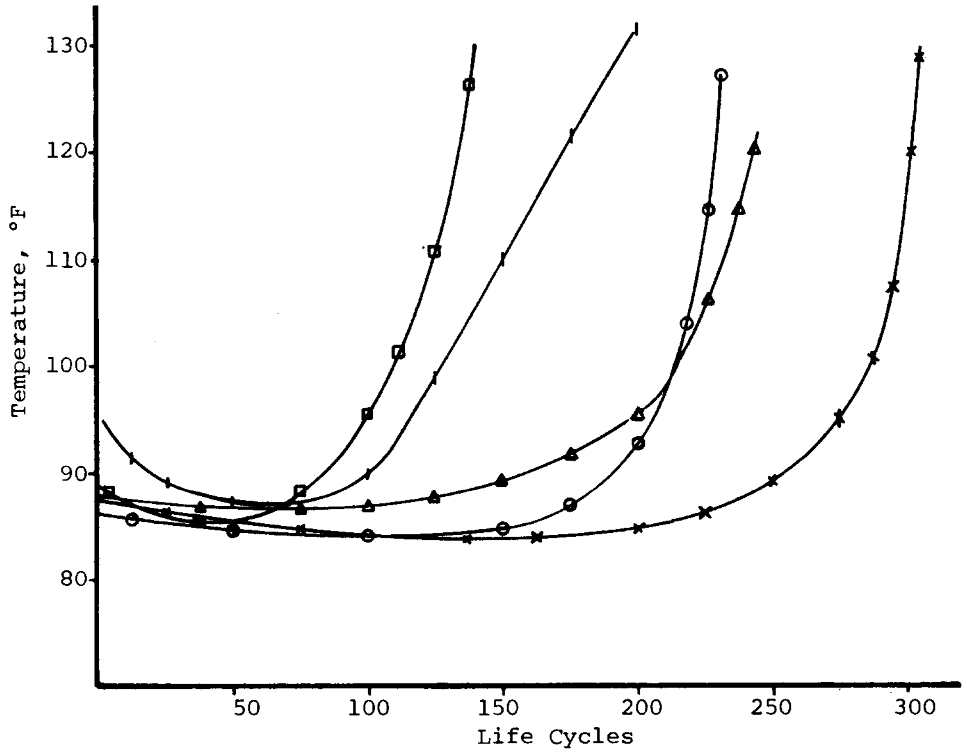

Fig. 3. Battery temperature (°F) *vs.* life cycles. ×, FLEX-SIL®; △, microporous polyethylene; ○, ACE-SIL®; □, sintered PVC; /, cellulose.

The end of charge currents increased rapidly at about 94 cycles (over 4 A) in batteries with sintered PVC and cellulose separators; and the battery with microporous polyethylene separators reached a high end of charge current at about 207 cycles, while the one with FLEX-SIL® separators still had an end of charge current of less than 1 A up to 230 cycles. The battery containing ACE-SIL® hard rubber separators reached an end of charge current of 4 A at 207 cycles as did the one with microporous polyethylene separators. Unlike the microporous polyethylene separators, the ACE-SIL® separators maintained a charge current of 1 A or less prior to initiation of failure due to bottom shorts. This resulted in a low energy consumption for the battery containing ACE-SIL® separators even though the rate of failure, once initiated, was more rapid. This indicates that the batteries containing sintered PVC, cellulose, and polyethylene separators required more recharge energy during cycling than the batteries with FLEX-SIL® and ACE-SIL® separators. The batteries containing ACE-SIL® and FLEX-SIL® separators exhibited a very low end of charge current through most of their lives until actual failure occurred, which was the result of sediment build-up and the resulting shorts across the bottom of the plates and not of performance failure of the separators.

Since failure due to a high rate of energy consumption occurred at 75 - 80 min capacity, or no more than 5 min less than the 80 min capacity specification, this difference is considered to be insignificant. Therefore, true end of usable capacity of the batteries is considered to be determined when excessive energy consumption or high end of charge current (> 15 A) occurs on recharge.

An interesting phenomena observed in Fig. 2 is the low end of charge currents required by the batteries containing the rubber separators (FLEX-SIL® and ACE-SIL®) as compared with the others, and that the battery with sintered PVC separators required the greatest amount of current for recharge.

Analogous with the current requirement is that of heat build-up. Here again, those batteries containing separators that drew the least current on recharge also maintained the lowest operating temperatures.

One could, therefore, set 15 A of recharge as a standard for failure instead of the 80 min capacity requirement. It should be noted that the rubber separators had an end of charge current which was 1 A up through 190 cycles, with the FLEX-SIL® going as long as 240 cycles.

Battery energy use and cost

Figure 4 is a plot of cumulative energy consumption during cycle life testing. Calculations can be made using various assumptions to determine the relative estimated cost of using batteries insulated with the various separators.

This calculation would need to include cost of energy to recharge the batteries, the usable number of cycles for which the batteries can be put through, as well as the cost of replacing the batteries after failure. Specifically, these are:

(1) 120 cycles on the above accelerated test regimen is equivalent to 300 cycles during actual use in the field and one year of service. This is based on the fact that an actual golf course season is about 300 cycle days/year and that the standard industry control battery containing ACE-SIL® will last 2 seasons in the field.

(2) The dollar replacement cost per battery is $75.00.

(3) The energy cost for recharging the batteries is $0.07 kW h.

Utilizing these assumptions, the following calculations can be made:

(A) The energy cost (\$ E) per year is given by the equation

$$\$ E = (A/B)(300)(0.07) \quad (1)$$

where A is the cumulative energy consumed in kW h during recharge of the batteries during life cycling, B is the total number of cycles under test as in (A), 300 is the average number of cycles of field use per year of operation, and 0.07 is the electrical energy cost per kW h.

(B) The battery replacement cost (\$ R) per year of operation is determined by

$$\$ R = (120/D) \$75 \quad (2)$$

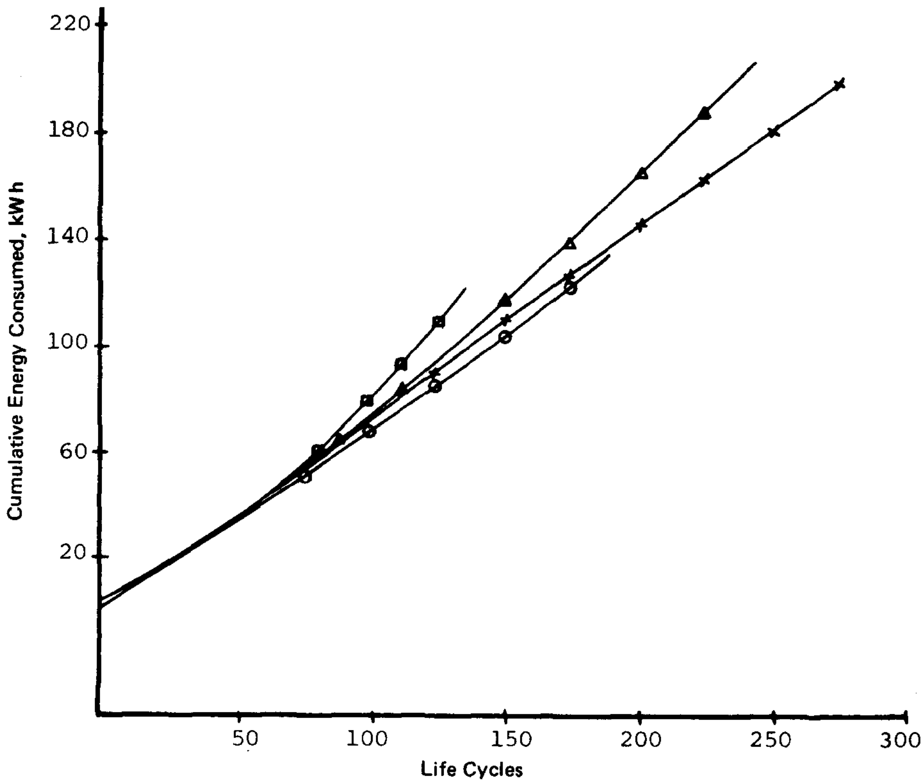

Fig. 4. Cumulative energy consumed (kW h) *vs.* life cycles. ×, FLEX-SIL®; △, microporous polyethylene; ○, ACE-SIL®; □, sintered PVC.

where 120 is the average accelerated cycle life which is equivalent to 300 cycles of field service, D is the number of cycles successfully completed by the batteries before failure, and \$75 is the battery replacement cost.

(C) For a specific battery type, the yearly operating cost ($\$P$) is given in the equation

$$\$P = \$E + \$R. \qquad (3)$$

Table 2 presents the estimated operating cost for each type of battery as determined by the above methods and assumptions.

Based on the above assumptions, the results indicate that FLEX-SIL® separators produce a cost effective battery having the potential for the lowest yearly operating cost of \$46.00. Sintered PVC separators which gave the highest operating cost had almost twice that value, \$86.00 per year. Batteries containing polyethylene and ACE-SIL® separators were found to have a yearly operating cost of \$54.00.

Water usage of batteries

If water use during cycle life is normalized on a per cycle basis, the battery containing the FLEX-SIL® separators required the least amount of

TABLE 2

Estimated yearly operating cost for batteries as a function of separator type

Separator type in EE-4 golf car battery	Estimated operating cost per year ($)
Sintered PVC	86.26
Polyethylene	54.27
Cellulose	*unknown
ACE-SIL®	54.44
FLEX-SIL®	46.10

*The unknown cost per year of the battery containing cellulose separators was due to equipment limitation during collection of energy consumption data. However, the total cost per year of the cellulose battery, based on the data available on the number of cycles and end of charge currents, could be similar to the battery containing the PVC separators since the end of charge current and the cycle life of these batteries are almost identical.

water to maintain the electrolyte level. ACE-SIL® required 10% more than FLEX-SIL®, microporous polyethylene used 270% more, and batteries containing cellulose and sintered PVC separators used 420% more than FLEX-SIL®.

Figure 3 shows that the temperature of the batteries containing the sintered PVC and polyethylene separators had begun to increase at mid-cycle life while those batteries containing ACE-SIL® and FLEX-SIL® still had a low temperature towards end of life. The temperature of the battery containing cellulose separators increased rapidly after 100 cycles. This indicates that the higher end of charge current resulting from lower plate potentials resulted in an increased temperature, greater evaporation, and higher gassing rates. These all combine to increase the rate of water consumption of the batteries containing sintered PVC, cellulose, and polyethylene separators.

Teardown analysis

Table 3 contains the teardown analysis for these batteries. Briefly, final failure of all batteries was the result of shorts across the bottom of the plates. The FLEX-SIL®, ACE-SIL®, and microporous polyethylene separators were generally in good condition after cycle life. The sintered PVC separators were in good condition but were discolored in areas where heat build-up was concentrated. This discoloration is a sign of polymer degradation. The cellulose separators had experienced severe degradation. The cellulose fibers were very weak. The sheet had become highly compressed, with overall thickness dropping from 0.065 to 0.043 in., deformed, and the original embossed ribs were only slight waves after cycle life. There were several shorts through the separators and there was evidence of extensive lead treeing through the separators.

Table 4 presents the data on the washed and dried separators after cycle life testing. One will note that the cellulose and sintered PVC separators had

TABLE 3

Teardown analysis of batteries after cycle life testing

	FLEX-SIL®	ACE-SIL®	Polyethylene	Cellulose	Sintered PVC
Battery type	← EE-4 Golf Car - 19-plate, antimony alloy →				
Cycle life	294	218	262	190	129
Acid gravity at end of life	1.268	1.270	1.268	1.125	1.268
Failure mode	← Mud build-up causing plate shorts →				
Mossing	← minimal →			← heavy →	← minimal →
CONDITION:					
Positive plate active material	Very soft at bottom of plate, some material lost in middle	Very soft at bottom of plate, top and middle slightly grainy	Very soft at bottom of plate, some material lost on top and middle	Very soft	Grainy
Spines	30% corroded	28% corroded	28% corroded	40% corroded	23% corroded
Negative plate	← Uniform, metallic →				
Separator	Intact, no cracks or holes	Excellent condition, like new	Good condition, short through one piece	Very degraded, ribs compressed, short through one piece, adhered to negative plate	Discolored due to heat at bottom, several burn marks

the highest lead retention, probably due to their larger pore sizes of 20 and 14 μm, respectively. Metals analysis on the separators was determined by standard atomic absorption techniques and the pore size was determined by mercury intrusion porosimetry.

The mode of failure in all cases was filling of the mud space by loss of active material to a level that caused shorts across the bottom of the cell. One may conclude that the life of these batteries was strongly influenced by the separators and their ability to reduce this active material loss. Separator pore size and composition influence the loss of active material.

TABLE 4

Extent of lead and antimony impregnation during cycle life testing

Separator	Cycle	Separator Pb (%)	Negative plate Sb (%)
ACE-SIL®	228	0.259	0.0037
FLEX-SIL®	294	0.087	0.0030
Polyethylene	262	0.096	0.0033
Sintered PVC	128	0.313	0.0016
Cellulose	190	4.483	1.233

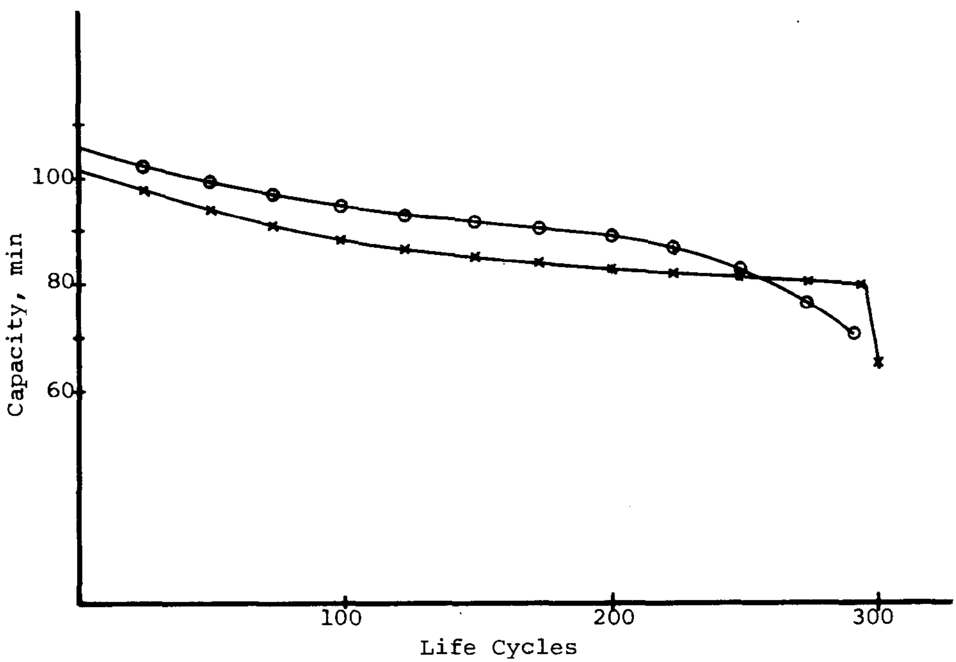

Fig. 5. Capacity of batteries containing FLEX-SIL® separators *vs.* life cycles. ×, 7.3 V limit on charge; ○, 7.4 V limit on charge.

Effect of recharge voltage

The best performing battery type at 7.3 V (FLEX-SIL®) was taken and run against another FLEX-SIL® battery but recharged at 7.4 volt limit. The purpose of this test was to see the effect of the higher recharge voltage on cycle life, capacity, end of charge current, and temperature. Figure 5 is a plot of the resulting data. It can be seen that by using the higher recharge voltage the capacity increased by about 5 - 8% for the first 200 cycles but the total cycle life is reduced by about 10%.

Conclusions

It is felt that the above described test procedure allows for the estimation of the actual field service life of a golf car battery in a few months rather than the 1 - 2 years required for complete field testing. The test also allows for the screening of separators to determine their effect on battery performance.

Based on the above data, the battery constructed with FLEX-SIL® rubber separators had the longest life, lowest operating current, temperature, and estimated yearly operating cost. The separator's size and its chemical composition will influence plate potentials, charge currents, and battery life.

References

1 H. G. Mueller, W. Schleuter and G. Wille, *ETZ Arch.*, *12* (1979) 359.
2 M. H. W. Visscher, W. Dezeeum and R. Van Der Graaf, *Symp. on Electric Vehicles, Philadelphia, PA 2-10-78*, Electric Vehicle Council, NY, NY, 5, pp. 1 - 10.
3 G. L. Wierschem, *Int. Conf. on Chemical Vapor Deposition, Los Angeles, CA, 14-10-79*, Electrochemical Society, Inc., Princeton, NJ, 7, pp. 249 - 253.
4 *DOE Contract Rep. #W-31-109-ENG-38, 31-109-38-3621* Journal Volume U7723 NO300, 1977.
5 G. E. Meyer, *Symp. on Electric Vehicles, Philadelphia, PA 2-10-78*, Electric Vehicle Council, NY, NY, 5, pp. 1 - 6.