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A State of Charge Monitor for Sealed Lead-Acid Cells

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Chemistry and Physics Laboratory

20 July 1978

Prepared for
VICE PRESIDENT AND GENERAL MANAGER
THE IVAN A. GETTING LABORATORIES

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THE AEROSPACE CORPORATION
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ABSTRACT

Instrumentation has been designed for monitoring the state of charge of sealed lead-acid cells during discharge. This monitor utilizes the cell voltage during discharge, compensating for variations in load current and temperature. The discharge voltage is converted to a linear function of state of charge by a nonlinear amplifier. Statistics are given for the uncertainty in the monitor. Below 80% state of charge the monitor is accurate to better than $\pm 5\%$ state of charge at all currents in the C to C/10 range.

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INTRODUCTION

The relatively recent technological development of sealed lead-acid cells has led to the rapid proliferation of these cells in battery systems. In many applications sealed cells are replacing the more traditional wet cells such as those commonly used in automobile batteries. Along with the increased use of sealed lead-acid cells, there is a growing need to conveniently monitor properties of these cells such as their state of charge. Because they are sealed, it is not possible to measure acid concentration or density to indicate state of charge, as is commonly done for lead-acid wet cells. The open circuit voltage of a sealed cell currently serves to monitor state of charge on stand,¹ however a convenient function for monitoring state of charge during operation is not available. At present the state of charge during operation is typically estimated at any particular discharge current from both manufacturers data on rated capacity and the typical voltage discharge curve at that current. In applications where the current is not constant (conditions of constant power for instance), one must be armed with voltage discharge curves at a large number of currents, and must accurately know the actual capacity to estimate the state of charge. Since temperature variations as well as load variations also affect the voltage and capacity, practical state of charge monitoring for operating sealed lead-acid cells is qualitative at best under conditions of varying load and temperature, and automatic monitoring of state of charge has not been possible previously.

In order to utilize any property of a battery cell for monitoring state of charge, the dependence of this property on conditions such as operating current, capacity, and temperature must be taken into

account. The ideal state of charge monitor should either have little dependence on variables other than residual capacity, or these dependences should follow a relatively simple functional form which may easily be taken into account. In addition a monotonic, although not necessarily linear functional dependence on state of charge is desired. The specific property being used to follow state of charge should also be easily and reproducibly measured to a high degree of precision.

Studies of the impedance (phase angle) and voltage characteristics of operating sealed lead-acid cells are reported here with the objective of determining a single function which will quantitatively describe the state of charge of an operating cell over a range of useful currents and total capacities. The cells which were studied were commercially available 2.5 ampere hour sealed lead-acid cells produced by Gates Energy Products.

PHASE ANGLE AND IMPEDANCE MEASUREMENTS

The impedances of sealed lead-acid Gates cells have been previously reported² as a function of frequency at various states of charge. Figure 1 indicates the variation in phase angle with state of charge for a 5 ampere hour Gates X cell at a frequency of 10 Hz. This cell is being discharged at the C rate, i.e., the rate which will discharge the rated cell capacity in one hour. The phase angle appears to exhibit significant and reproducible changes with state of charge at this frequency. As the cell is discharged the phase angle becomes increasingly less capacitive, until near total discharge, where it rapidly becomes more capacitive. This lack of monotonic behavior becomes a serious problem at low states of charge. Figure 2 indicates the dependence of the phase angle on current passage through the cell at roughly 42% of charge and at a frequency of 10 Hz. This variation in phase angle with current cannot be described by a simple function even at this single state of charge. Because a simple function cannot be employed to correct for the current dependence, and because such a correction would necessarily have to be large (up to 50% of the phase angle value), the phase angle was not deemed suitable for use in a state of charge monitor.

Fig. 1. Phase Angle (—) and Voltage (---) of a 5.0 Ampere Hour Gates X Cell During Discharge at 5.0 Amperes. The phase angle is measured at a frequency of 10 Hz.

Fig. 2. Phase Angle of a 5.0 Ampere Hour Gates X Cell as a Function of Current. The state of charge is roughly 42%.

VOLTAGE MEASUREMENTS

Preliminary measurements of sealed cell discharge voltages combined with the information given in the manufacturer's data sheets,³ suggested that cell voltages could be used to monitor state of charge during discharge. However, several problems were encountered. At a particular discharge current the voltage serves as an excellent state of charge monitor if all cells being monitored are matched in capacity. The first problem was encountered when experiments on sealed lead-acid cells indicated that substantial capacity variations existed among these cells. It was therefore decided that a useful state of charge monitor utilizing voltage must operate on a percentage basis, that is, it must indicate the percentage of usable capacity remaining in the cell. This monitoring method assumes the shapes of the voltage discharge curves are identical irrespective of usable cell capacity, and thereby allows the problem to be factored into a fractional state of charge indicator and an a priori knowledge of cell capacity. Cell capacities only change gradually with cycling and aging and are therefore accurately known for an operating power system. The accuracy of factoring out the capacity variations will be experimentally evaluated in a later section.

A second difficulty is that the cell voltage at a particular state of charge depends on the discharge current. The functional form of this current dependence must be evaluated experimentally at all states of charge if the cell voltage is to be used to monitor state of charge. Sealed lead-acid cell discharge voltages were monitored at a variety of discharge rates ranging from C to $C/10$ in order to evaluate this current dependence. The data not only enable the feasibility of a voltage sensing state of charge monitor to be evalu-

ated, but also serve as a statistical data base for determining the accuracy of such a monitor.

The experimental data on sealed cell discharge voltages were obtained using the apparatus shown in Figure 3. This apparatus enabled a battery of six (6) 2.5 ampere hour Gates cells to be either charged or discharged in series. The voltage of any cell could be displayed by closing the appropriate switch. To simulate actual operating conditions, this 6 cell battery was charged for a minimum of 24 hours prior to discharge, using a Gates Energy Products 12 volt hybrid charger. This charger provides a charging current of 165 mA (C/15) until the battery voltage reaches 14.90 volts, then reduces to trickle charge at 6 mA (C/400) until the voltage falls to 13.80 volts, whereupon the higher rate is again supplied. After an interval ranging from 24 to 60 hours on such a charge scheme, the cells were held at full charge by a continuous trickle charge at 6 mA. This trickle rate was generated by switching a dummy cell into the charger circuit to hold the battery voltage above 14.90 volts. After trickle charging for 16 hours the charger was deactivated, the dummy cell switched out of the circuit, and discharge was begun at a constant current. During discharge the voltage of each cell was periodically recorded. When the voltage of any cell reached 1.500 volts, it was switched out of the discharge circuit. This 1.500 volt limit establishes the point of zero charge for each cell.

Before experimental voltage data were initially collected the entire 6 cell assembly was cycled three times with a 48 hour charge followed by discharge to 1.500 volts at 2.5 amperes. This preliminary cycling was intended to condition and match the cells by making their immediate past history identical. Experimental data were then

Fig. 3. Apparatus Used in Cycling Sealed Lead-Acid Cells. The six cells are 2.5 ampere hour Gates D cells, D1-D6 are switches for monitoring the voltage of individual cells, S1-S6 remove their respective cells from the current path, S7 initiates trickle charge, PS is the power supply for discharging the cell pack, and HL2-12 is a Gates Energy Products hybrid 12-volt charger.

obtained on the six cells at five different discharge rates: C (2.5 amperes), C/2 (1.25 amperes), C/3 (0.83 amperes), C/5 (0.5 amperes), and C/10 (0.25 amperes). The six cell assembly was discharged twice at each current, thus providing voltage data on 12 cell discharges at each current. All measurements were done at the ambient temperature of $24.5 \pm 1^\circ\text{C}$. The voltage data are summarized in the Appendix.

RESULTS AND DISCUSSION

The average cell voltages and capacities are tabulated in Table 1 at various states of charge for each discharge current. The uncertainties correspond to the standard deviations. Figure 4 graphically shows how the cell voltage during discharge depends on the discharge current. The curves in Figure 4 indicate that increasing discharge current shifts the curves to lower voltages without substantially altering their shapes. This relationship between voltage and current is indicated in Fig. 5, where current (in units of C) is plotted as a function of voltage at various states of charge. In Figure 5 we have assumed a linear dependence between voltage and current in fitting the data. This assumption implies that a purely resistive relationship exists between current and voltage at each state of charge, and therefore that the effects of cell polarization are nearly constant in this current range. The breakdown of this assumption is expected to lead to some deviations from linearity in Figure 5. These deviations are especially apparent near total charge, where significant curvature is obtained between the high and low discharge current extremes.

The parameters for the linear plots in Figure 5 are tabulated in Table 2. The resistance to which each line corresponds is also given, and varies from 0.015 to 0.028 ohms. Since this resistance

Table 1. Average Cell Voltages During Discharge at Various Rates.

Percent Charge	C/10	C/5	C/3	C/2	C
90	2.1092 ± 0.0035	2.0997 ± 0.0042	2.0852 ± 0.0057	2.0722 ± 0.0060	2.0457 ± 0.0082
80	2.0900 ± 0.0039	2.0812 ± 0.0036	2.0706 ± 0.0056	2.0588 ± 0.0059	2.0346 ± 0.0061
70	2.0685 ± 0.0040	2.0617 ± 0.0040	2.0527 ± 0.0061	2.0422 ± 0.0059	2.0200 ± 0.0054
60	2.0455 ± 0.0039	2.0405 ± 0.0039	2.0329 ± 0.0064	2.0227 ± 0.0065	2.0032 ± 0.0049
50	2.0212 ± 0.0035	2.0177 ± 0.0043	2.0111 ± 0.0070	2.0015 ± 0.0072	1.9834 ± 0.0047
40	1.9943 ± 0.0036	1.9921 ± 0.0039	1.9864 ± 0.0068	1.9784 ± 0.0073	1.9608 ± 0.0047
30	1.9647 ± 0.0036	1.9637 ± 0.0038	1.9575 ± 0.0064	1.9511 ± 0.0079	1.9333 ± 0.0047
20	1.9282 ± 0.0033	1.9276 ± 0.0053	1.9200 ± 0.0050	1.9147 ± 0.0083	1.8965 ± 0.0048
10	1.8722 ± 0.0035	1.8667 ± 0.0069	1.8605 ± 0.0054	1.8559 ± 0.0082	1.8238 ± 0.0060
0	1.500	1.500	1.500	1.500	1.500
Ampere Hour Capacity	2.530 ± 0.041	2.324 ± 0.052	2.164 ± 0.076	2.050 ± 0.071	1.766 ± 0.056

Fig. 4. Average Cell Voltages at Various Discharge Currents

Fig. 5. Dependence of Cell Voltage on Discharge Current at Different States of Charge. The number above each line indicates the state of charge to which that line corresponds.

Table 2. Least Squares Parameters for Results of Figure 5.

Percent Charge	Intercept a (C)	Slope b (C/V)	Slope (ohms)	Standard Voltage function Vo
90	29.63	-14.02	0.028	2.1020
80	34.03	-16.26	0.025	2.0874
70	38.38	-18.52	0.022	2.0699
60	43.02	-20.99	0.019	2.0502
50	47.06	-23.24	0.017	2.0286
40	52.09	-26.06	0.015	2.0044
30	54.21	-27.52	0.015	1.9762
20	52.57	-27.20	0.015	1.9395
10	34.86	-18.56	0.022	1.8766
0	---	---	---	1.500

is quite small, it only introduces a small correction to the cell discharge voltage for IR drop. We may use the average resistance of 0.0198 ohms to correct for IR drop at all states of charge without introducing much additional error in the state of charge monitor, except above 80% state of charge. This is not a serious problem since the voltage does not indicate state of charge very accurately immediately after the initiation of discharge (above about 90% state of charge), due to the initial polarization and passivation transients (see Figure 1).

A standard voltage discharge function for a 2.5 ampere hour sealed lead-acid cell may be determined by extrapolating the voltages at C/2 for each state of charge to zero current using a slope corresponding to 0.0198 ohms. This standard function is tabulated as V_o in Table 2 and plotted in Figure 6. The voltage function in Figure 6 is referenced to zero current, however the value of the function at any other current is obtained using Eq. 1.

$$V = V_o - 0.0198I \quad (1)$$

The standard function was obtained by extrapolating the voltages at C/2 to zero current because the C/2 rate is near the center of the range of useful discharge rates for these cells, and because this procedure leads to the minimum error at the current extremes.

A state of charge monitor for room temperature discharge may be obtained from a knowledge of the cell voltage, discharge current and the standard function V_o . To the measured cell voltage we add 19.8 mV per ampere of discharge current, and compare this result to the standard function to determine at what state of charge the function has this value. Since the standard function in general has no simple algebraic form, it is most convenient to make this comparison by appropriately calibrating an analog meter scale.

Fig. 6. Standard Cell Voltage as a Function of State of Charge Referenced to Zero Current (—). The dashed line is the cell voltage linearized and amplified by the device of Fig. 8. The right hand scale is for the linearized function and is measured at the output of IC5 in Fig. 8.

The voltage function in Figure 6 could be directly calibrated onto a meter scale, however the lowest 50% of the meter scale would display the state of charge in the range from 0 to 5%. Ideally we would like to linearize the voltage function in Figure 6 before using it to display the state of charge. This linearization may be accomplished by programming an amplifier for the appropriate gain function to linearize the voltage input and produce 0-10 volt output directly proportional to state of charge. The design parameters for such an amplifier are discussed in the section on the design and operation of a state of charge monitor. The linearized function which was used is illustrated in Figure 6.

A significant problem with the state of charge monitor described above is that the cell voltage varies with temperature, an effect which was not taken into account. The temperature coefficient for the voltage of lead-acid cells is relatively well known. The 1968 NBS value⁴ of 1.384 mV/°C is typical. The temperature coefficient for sealed lead-acid cells during discharge may be estimated from the discharge curves at several temperatures published by Gates Energy Products³ in their Battery Application Manual. At the C/10 and C/2.5 rates temperature coefficients of 1.3 and 1.7 mV/°C are estimated. These values are rough estimates at best, since the graphs from which they were obtained do not lend themselves easily to quantitative interpretation. Since these coefficients appear to be consistent with the NBS value, this value may be used to account for the effects of temperature variations on the state of charge monitor. A temperature correction may easily be introduced by using a thermistor to generate a rough voltage correction of 1.38 mV/°C relative to 25°C to compensate for the cell temperature coefficient.

ANALYSIS OF UNCERTAINTIES

There are a number sources of error which may contribute to uncertainty in the state of charge monitor. The first of these is the initial polarization transient obtained when discharge is initiated. (see Figure 1). The cell voltage initially drops sharply from the trickle charge voltage, goes through a minimum, and then peaks before going into the plateau region. This transient makes the state of charge monitor essentially useless above 95% state of charge. The effects of this transient which persist below 95% are considered in the calibration curve of Figure 6. Any non-reproducibility of this transient will be reflected by increased standard deviations near full charge.

A second source of error, which is probably the major one, is the basic cycle to cycle non-reproducibility of the discharge voltage. This non-reproducibility results from variations in charging times as well as internal cell structure and composition. To obtain realistic standard deviations in the cell discharge voltage, constant charge times were not employed in these experiments. Likewise no special efforts were made to match cells so as to minimize cell to cell voltage variations. In fact cells 1 and 5 were consistently low and high respectively compared to the other four cells in the battery, and in a high quality battery would not have been matched together. The standard deviations in the discharge voltages for 12 cycles are given in Table 1 at each current.

A third source of uncertainty is introduced by deviations from the 0.0198 ohm linearity in the current correction. Figure 5 and Table 2 indicate that these sources of uncertainty are typically less than those resulting from cell non-reproducibility, and are only impor-

tant at the current extremes and near full charge. Lastly the compensation for thermal voltage variation may introduce uncertainty. This uncertainty depends on the errors associated with the accepted thermal coefficient, as well as on its constancy over the range of discharge currents from C to $C/10$. These uncertainties while impossible to evaluate quantitatively from the available data, are likely to be quite small for up to 10°C temperature excursions from 24.5°C .

The uncertainties in state of charge which result from non-reproducibility effects and current variations are illustrated in Figure 7 at each discharge current. The increased uncertainties above 80% state of charge result from deviations from linearity in the near full charge voltage/current curves in Figure 5. At high currents these uncertainties are also increased by non-reproducibility arising from the transient subsequent to the initiation of discharge. Below 80% state of charge the error in the state of charge monitor is better than $\pm 5\%$. Below about 25% the error drops below $\pm 2\%$ due to the more rapid variation of voltage with state of charge.

STATE OF CHARGE MONITOR DESIGN

The design of a state of charge monitor basically involves four functions. The cell voltage must be offset 1.500 volts to set the point of zero state of charge. A further offset of 1.38 mV per degree above 25°C is required to compensate for temperature fluctuations. The voltage must then be increased 19.8 mV per ampere of discharge current. Finally this voltage must be amplified so as to obtain an output which is linear with state of charge and varies between 0 and 10 volts over the full state of charge range.

Fig. 7. Uncertainty in Percent State of Charge as a Function of Percent State of Charge at Various Discharge Rates

A schematic diagram is given in Figure 8 for an instrument capable of monitoring the state of charge of a lead-acid cell. IC1 is an operational amplifier which uses a 1.5 volt input reference and a thermistor to adjust the 1.500 volt zero offset for ambient temperature. The thermistor response is only roughly linear between 0 and 40°C, having the approximate form, $R = 1000 + 45(25 - T)$ ohms. For a more precisely linear temperature correction a platinum resistance thermal detector may be used in place of the thermistor. IC3 generates an output voltage of 19.8 mV per ampere of current flow through the current sensing resistor, R_7 . The output of IC3 is combined with the output from IC1 using op amp IC2. The output of IC2 is $1.500 + 0.00138(25 - T) + 0.0198i$. This voltage is subtracted from the cell voltage by IC4, and this difference is multiplied by 10. The circuitry associated with op amp IC5 forms a nonlinear amplifier designed to linearize the voltage discharge curve. The linearized result is shown in Figure 6. This linear 0 to 10 volt signal is then displayed on a 0-100mA ammeter as the percent state of charge.

Critical parameters are involved in obtaining the proper amplifier function for IC5 to linearize the cell voltage. This amplifier function is given in Figure 9. The values for $R_{13} - R_{16}$ which provide this function are determined by first measuring the response function of each IN914 diode using values of $R_{13} - R_{16}$ such that these response functions extrapolate to roughly 2 and 5.15 volts. The gain for each input diode is set to roughly produce the desired amplifier response. The values for $R_{13} - R_{16}$ which yield the desired response are then obtained by solving the equation

$$f(V) = \sum_i q_i(V) g_i \quad (2)$$

for the q_i , where $f(V)$ is the desired amplifier response at input

Fig. 8. Schematic Diagram for a State of Charge Monitor

Fig. 9. Amplifier Response Function (—) Required to Linearize the Standard Voltage Curve of Fig. 6. The response functions for D1 (----) and D2 (—·—) which produce this amplifier response are also presented.

voltage V , $q_i(V)$ is the diode response, and g_i is the factor by which the gain of each input diode must be multiplied to give the desired result.⁵ The values for $R_{13} - R_{16}$ given in Figure 8 were determined by calculating the g_i which reproduced $f(V)$ at 3 and 6 volts input. This approximation to $f(V)$ gave errors of less than 1% at voltages between 3 and 6 volts input, i.e., states of charge ranging from roughly 5 to 90%.

CONCLUSIONS

A state of charge monitor with an accuracy of better than $\pm 5\%$ state of charge over the range from 0% - 80% of charge has been designed for sealed lead-acid cells. This monitor compensates for discharge rate variations from $C/10$ to C , but can also be used at lower rates with some loss in accuracy. Compensation for temperature variations from 0°C to 40°C is also incorporated into the design.

While the monitor described above is designed to monitor the state of charge of a single cell, the method may also be applied to an entire battery. If the cells in a battery pack are matched in capacity to better than about 5%, the battery voltage may be divided down and the result will correspond to an average individual cell voltage. The single cell monitor should be ideally suited to utilize such an average voltage. If for some reason the cells are not very well matched in terms of capacity, the battery capacity will be determined by the cell with the lowest capacity. In this case the battery state of charge may be monitored by using the voltage of the lowest capacity cell as the input to the battery state of charge monitor.

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APPENDIX: Summary of Data

In this Appendix the discharge voltage data for 6 sealed lead acid cells are summarized. At each discharge rate 2 cycles are reported for each of the six cells. The 6 cells were charged as a single 12 volt battery.

Table A1. Cell Voltages on Discharge at 2.5 Amperes

<u>Percent</u>							
<u>Charge</u>	<u>Cell 1</u>	<u>Cell 2</u>	<u>Cell 3</u>	<u>Cell 4</u>	<u>Cell 5</u>	<u>Cell 6</u>	<u>Total</u>
90	2.056	2.047	2.049	2.057	2.047	2.051	12.307
80	2.042	2.036	2.037	2.044	2.034	2.039	12.234
70	2.027	2.022	2.022	2.027	2.018	2.024	12.140
60	2.009	2.004	2.004	2.009	2.000	2.005	12.031
50	1.989	1.984	1.983	1.989	1.980	1.984	11.909
40	1.966	1.961	1.961	1.966	1.959	1.962	11.775
30	1.939	1.933	1.933	1.939	1.933	1.933	11.610
20	1.902	1.895	1.897	1.902	1.897	1.897	11.390
10	1.825	1.825	1.820	1.819	1.813	1.824	10.926
0	1.500	1.500	1.500	1.500	1.500	1.500	9.000
<u>Capacity</u>							
(AH)	1.697	1.812	1.812	1.788	1.840	1.809	1.793

Table A2. Cell Voltages on Discharge at 2.5 Amperes

Percent							
Charge	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Total
90	2.050	2.046	2.036	2.043	2.030	2.036	12.241
80	2.036	2.034	2.027	2.033	2.024	2.027	12.181
70	2.023	2.021	2.013	2.019	2.011	2.013	12.100
60	2.008	2.007	1.997	2.003	1.995	1.997	12.007
50	1.989	1.988	1.978	1.983	1.977	1.977	11.892
40	1.967	1.965	1.956	1.960	1.954	1.953	11.755
30	1.939	1.938	1.928	1.932	1.928	1.925	11.590
20	1.902	1.900	1.891	1.895	1.894	1.886	11.368
10	1.831	1.831	1.822	1.826	1.833	1.817	10.960
0	1.500	1.500	1.500	1.500	1.500	1.500	9.000
Capacity							
(AH)	1.663	1.718	1.749	1.739	1.819	1.740	1.738

Table A3. Cell Voltages on Discharge at 1.25 Amperes

Percent							
Charge	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Total
90	2.074	2.068	2.069	2.074	2.064	2.070	12.419
80	2.059	2.057	2.055	2.058	2.051	2.055	12.335
70	2.042	2.041	2.038	2.041	2.033	2.038	12.233
60	2.023	2.022	2.018	2.022	2.012	2.018	12.115
50	2.001	2.000	1.996	2.001	1.990	1.995	11.983
40	1.977	1.977	1.974	1.977	1.968	1.971	11.844
30	1.951	1.950	1.947	1.950	1.940	1.943	11.681
20	1.914	1.912	1.910	1.912	1.904	1.907	11.459
10	1.852	1.955	1.849	1.849	1.849	1.847	11.101
0	1.500	1.500	1.500	1.500	1.500	1.500	9.000
Capacity							
(AH)	2.002	2.093	2.098	2.070	2.136	2.083	2.080

Table A4. Cell Voltages on Discharge at 1.25 Amperes

Percent							
Charge	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Total
90	2.081	2.084	2.073	2.075	2.064	2.071	12.448
80	2.067	2.070	2.061	2.063	2.051	2.059	12.371
70	2.050	2.054	2.044	2.047	2.036	2.042	12.273
60	2.032	2.035	2.025	2.027	2.016	2.022	12.157
50	2.012	2.015	2.005	2.007	1.996	2.000	12.035
40	1.990	1.992	1.982	1.984	1.973	1.976	11.897
30	1.962	1.967	1.955	1.956	1.944	1.948	11.732
20	1.927	1.931	1.921	1.920	1.908	1.910	11.517
10	1.867	1.871	1.865	1.862	1.852	1.853	11.170
0	1.500	1.500	1.500	1.500	1.500	1.500	9.000
Capacity							
(AH)	1.910	1.949	2.025	2.032	2.148	2.051	2.019

Table A5. Cell Volatges on Discharge at 0.83 Amperes

Percent							
Charge	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Total
90	2.093	2.097	2.084	2.087	2.081	2.085	12.527
80	2.076	2.082	2.072	2.074	2.067	2.072	12.443
70	2.060	2.065	2.054	2.057	2.050	2.054	12.340
60	2.041	2.045	2.035	2.037	2.030	2.035	12.223
50	2.020	2.025	2.013	2.015	2.009	2.012	12.094
40	1.995	2.000	1.988	1.990	1.985	1.988	11.946
30	1.967	1.970	1.957	1.959	1.957	1.958	11.768
20	1.926	1.930	1.920	1.920	1.919	1.919	11.534
10	1.866	1.870	1.855	1.852	1.861	1.855	11.159
0	1.500	1.500	1.500	1.500	1.500	1.500	9.000
Capacity							
(AH)	2.028	2.069	2.130	2.128	2.129	2.146	2.005

Table A6. Cell Voltages on Discharge at 0.83 Amperes

Percent							
Charge	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Total
90	2.088	2.085	2.079	2.086	2.077	2.081	12.496
80	2.072	2.072	2.064	2.069	2.062	2.065	12.404
70	2.053	2.053	2.046	2.050	2.043	2.047	12.292
60	2.033	2.034	2.026	2.030	2.023	2.026	12.172
50	2.012	2.012	2.005	2.008	2.000	2.003	12.039
40	1.987	1.987	1.980	1.983	1.976	1.978	11.891
30	1.959	1.959	1.952	1.955	1.948	1.949	11.722
20	1.923	1.923	1.915	1.918	1.914	1.913	11.506
10	1.866	1.865	1.858	1.861	1.860	1.857	11.167
0	1.500	1.500	1.500	1.500	1.500	1.500	9.000
Capacity							
(AH)	2.150	2.217	2.226	2.206	2.301	2.229	2.222

Table A7. Cell Voltages on Discharge at 0.50 Amperes

Percent							
Charge	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Total
90	2.102	2.108	2.100	2.102	2.098	2.103	12.613
80	2.083	2.087	2.081	2.083	2.078	2.084	12.496
70	2.063	2.067	2.062	2.063	2.058	2.064	12.377
60	2.042	2.045	2.039	2.042	2.036	2.042	12.246
50	2.020	2.022	2.017	2.019	2.012	2.018	12.108
40	1.994	1.995	1.990	1.993	1.987	1.992	11.951
30	1.966	1.966	1.960	1.964	1.959	1.963	11.778
20	1.928	1.927	1.922	1.924	1.922	1.925	11.548
10	1.862	1.860	1.858	1.858	1.864	1.864	11.166
0	1.500	1.500	1.500	1.500	1.500	1.500	9.000
Capacity							
(AH)	2.213	2.355	2.318	2.258	2.388	2.324	2.309

Table A8. Cell Voltages on Discharge at 0.50 Amperes

Percent							
Charge	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Total
90	2.100	2.102	2.095	2.098	2.092	2.096	12.583
80	2.082	2.085	2.078	2.081	2.074	2.079	12.479
70	2.065	2.067	2.058	2.061	2.054	2.058	12.363
60	2.045	2.046	2.038	2.040	2.033	2.038	12.240
50	2.022	2.025	2.015	2.017	2.010	2.015	12.104
40	1.997	2.000	1.990	1.991	1.987	1.989	11.954
30	1.970	1.970	1.963	1.963	1.959	1.961	11.786
20	1.938	1.938	1.928	1.928	1.924	1.927	11.583
10	1.878	1.878	1.870	1.870	1.870	1.868	11.234
0	1.500	1.500	1.500	1.500	1.500	1.500	9.000
Capacity							
(AH)	2.273	2.323	2.363	2.351	2.349	2.378	2.340

Table A9. Cell Voltages on Discharge at 0.25 Amperes

Percent							
Charge	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Total
90	2.111	2.113	2.106	2.109	2.102	2.110	12.651
80	2.092	2.094	2.088	2.090	2.082	2.090	12.536
70	2.070	2.073	2.066	2.069	2.061	2.067	12.406
60	2.048	2.050	2.043	2.046	2.038	2.044	12.269
50	2.023	2.025	2.018	2.021	2.014	2.018	12.119
40	1.998	2.000	1.993	1.994	1.988	1.993	11.966
30	1.969	1.970	1.963	1.965	1.959	1.963	11.789
20	1.933	1.933	1.927	1.928	1.925	1.927	11.573
10	1.878	1.878	1.873	1.872	1.869	1.871	11.241
0	1.500	1.500	1.500	1.500	1.500	1.500	9.000
Capacity							
(AH)	2.477	2.552	2.565	2.527	2.522	2.584	2.538

Table A10. Cell Voltages on Discharge at 0.25 Amperes

Percent							
Charge	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Total
90	2.111	2.114	2.108	2.111	2.105	2.111	12.660
80	2.092	2.095	2.088	2.092	2.084	2.093	12.544
70	2.070	2.074	2.068	2.071	2.062	2.071	12.416
60	2.047	2.051	2.044	2.047	2.040	2.048	12.277
50	2.023	2.026	2.022	2.022	2.017	2.025	12.135
40	1.996	1.999	1.993	1.994	1.989	1.995	11.966
30	1.967	1.969	1.963	1.964	1.959	1.965	11.787
20	1.929	1.932	1.926	1.925	1.923	1.930	11.565
10	1.868	1.875	1.869	1.869	1.870	1.874	11.225
0	1.500	1.500	1.500	1.500	1.500	1.500	9.000
Capacity							
(AH)	2.444	2.552	2.535	2.488	2.538	2.567	2.521

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