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Results with advanced, in situ monitoring of electric-vehicle and stationary batteries

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Abstract

Battery energy systems for critical applications require monitoring techniques that properly inform equipment operators and maintenance personnel of battery integrity. While battery cells may appear as simple elements, a high voltage battery configuration has many complexities that must be monitored to ensure reliable performance. These include cell capacities, voltages, temperatures and interconnection resistances. Continuous data logging and evaluation of these parameters provide operating personnel with state of charge and alarm status for all relevant battery concerns. Long term data storage provides users and battery suppliers insight to battery performance under all conditions of use. Design and interfacing of data acquisition circuitry is critically important to ensuring reliable data measurements for assessment of the battery system. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Battery monitoring; Fuel gauges; Cell equalization

1. Introduction

Battery applications for critical needs providing standby power or power for electric vehicles require battery monitoring to ensure power system integrity when power is needed. Many monitoring products exist on the market which monitor battery operation, but only a few provide detailed cell information with sophisticated alarm functions and total battery performance history (Figs. 1 and 2).

The most highly developed battery monitoring systems provide the operator and maintenance personnel with the following information [1]:

1. Security of battery operation (alarm indication)
2. Indication of available energy (fuel gauge)
3. Maintenance indicator (cell repair, watering)
4. Battery performance (cycle life, capacity performance, maximum operating conditions, maintenance records)
5. Long term battery performance (cycle life, maximum operating conditions, maintenance records, end of life prediction)

Critical applications of standby power require advance information to maintenance personnel that the battery system is fully functional for the application requirement. Hospitals, airports, traffic control and telecommunications are but a few of such applications.

Battery monitoring electronics include the intelligence of all previously considered battery faults stored as limit conditions in on board memory. Limit conditions include values of cell voltage charge and discharge, ampere-hours charge and discharge, battery system or cell internal resistance, cell temperature and ambient temperature. Evaluating incremental changes, rates of change and limits of these parameters can in many cases provide advance warning of a critical maintenance requirement. In the most sophisticated monitoring systems ‘warning’ limits can be entered as limit values for the particular application. Alarm status may have multiple levels that allow maintenance intervention before critical status is reached or at minimum allow a judgement of battery use before critical status.

Charge/discharge data stored in memory for years provides a basis for end of life prediction. Long term cell

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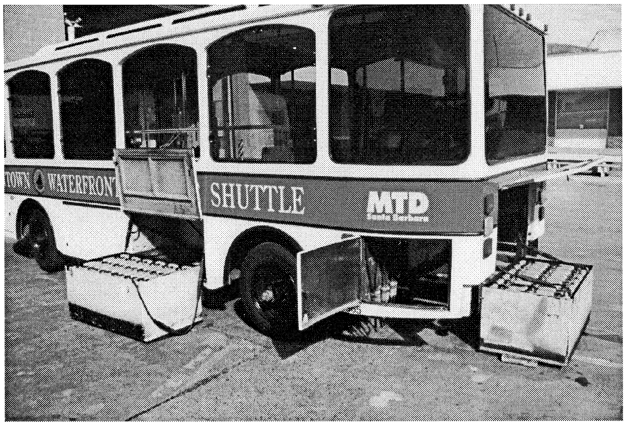


Fig. 1. Electric vehicle equipped with battery monitoring [4].

voltage data consisting of float and cell voltage variations during discharge are good indicators of remaining life [2].

Basic elements of a highly developed battery monitoring system consist of the following (Fig. 3):

Power supply—able to convert a high voltage battery system to a low level for logic circuits. The power supply must operate over a wide range of available battery voltage, often a 2:1 range.

Data acquisition circuitry—to measure cell or cell group voltages, system current and multiple temperatures, all with high accuracy.

CPU—a microprocessor that performs data handling according to programmed instructions with enough memory to hold lifetime data of the battery cells.

A sealed enclosure—designed to prevent acid, dirt and moisture from affecting circuit operation.

Remote PC with data analysis software—a laptop or portable PC which can transfer data from the monitoring system CPU to the laptop hard disk.

Interface and battery cells—a cabling system that connects cells to the data acquisition module. The cabling must be protected from abrasion and potential short circuit of cell voltages. This is especially important in electric vehicle applications, which should follow IEC and BCI standards for battery monitoring [5].

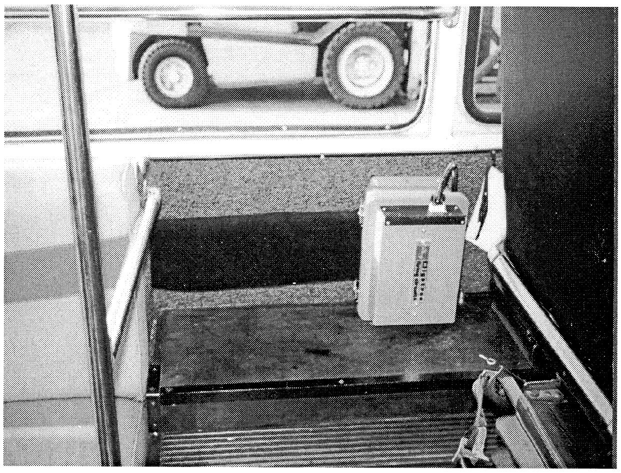


Fig. 2. Battery monitoring unit for electric vehicles.

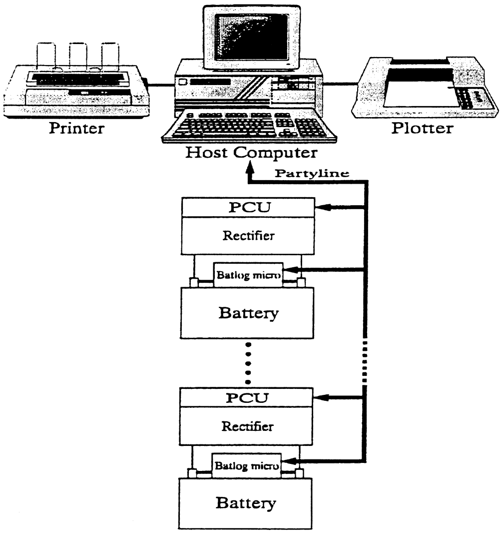


Fig. 3. Battery monitoring system overview.

2. Design of a monitoring system

As discussed earlier the power supply which converts battery power to logic level requirements must be very stable with the ability to operate over widely varying battery voltages. It is not unusual for battery voltage to contain positive and negative voltage transients which must be decoupled from the logic circuitry. Under deep discharge conditions battery voltage may dip to half its nominal value.

Data acquisition must be performed with high speed and high accuracy A/D converters which are synchronized for voltage and current measurements. Erratic noise peaks induced into channel measurements must be eliminated by software to eliminate transient voltage conditions that would otherwise produce an alarm status. In large battery systems the A/D measurements of many cells must be multiplexed from the cells. Single point connections to cells (one wire systems) include voltage drop information of intercell connectors which is an important component of cell voltage information for alarm status indication. The total elements of battery monitoring circuitry are shown in Fig. 4.

The CPU processes A/D measurements, output alarm indications, operator interface data, computer interface and storage of long term data. A 16-bit processor is required to process the large amounts of data. CPU functions are supported by an EPROM which contains the operating system for handling real time data, alarm conditions, out-

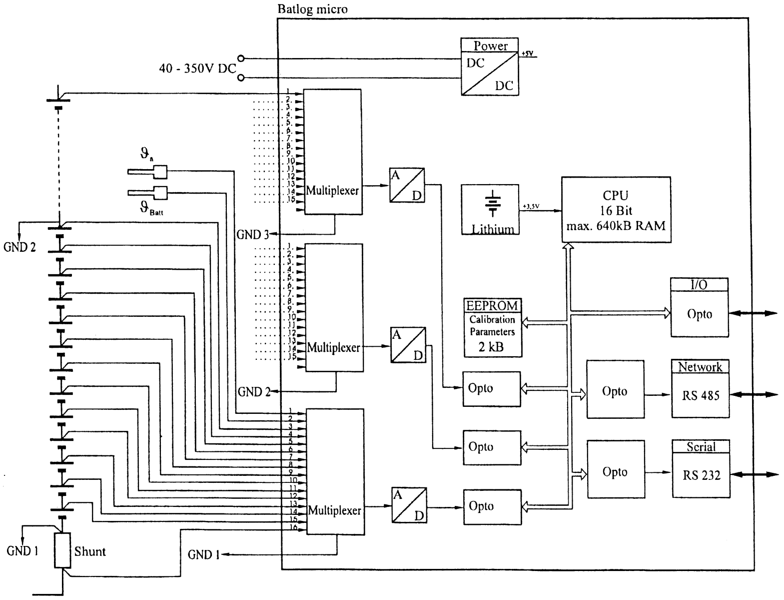


Fig. 4. Basic battery monitoring system configuration.

put functions and long term data storage. Actual and compressed long term data measurements are held in battery backed RAM. Most recent data values are used for real time display, then this information is data reduced by data compression instructions stored in the EPROM. The resulting, reduced data is held in the RAM for total service life of the battery. CPU functional flow is shown in Fig. 5.

3. Data processing and storage

The CPU processes data from A/D inputs as shown in Figs. 4 and 5, then outputs to LCD displays, off board chargers, external controls, a computer interface and long term data storage.

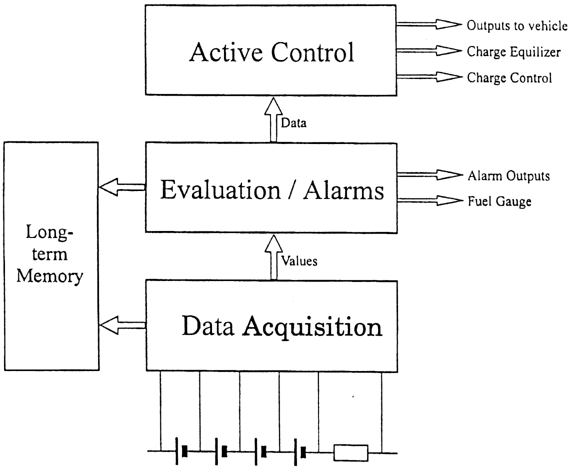
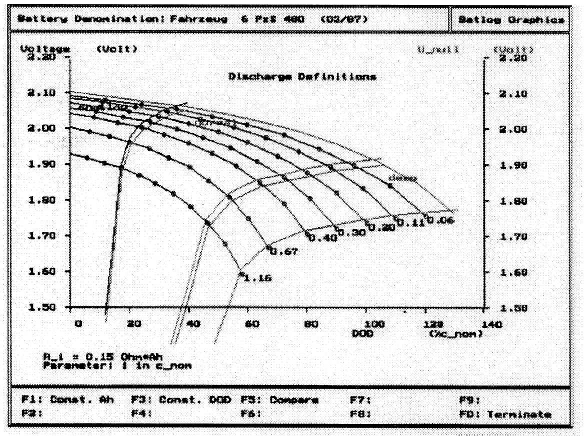


Fig. 5. CPU operating system.

- Real time data for the operator display interface. This data may vary depending on the battery application, but includes the following basic information:
  - –actual battery capacity
  - –actual state of charge
  - –residual discharge time in case of emergency power requirements or residual range required in the case of electric vehicles
  - –identification of weak or defective cells or intercell connections (alarm conditions)

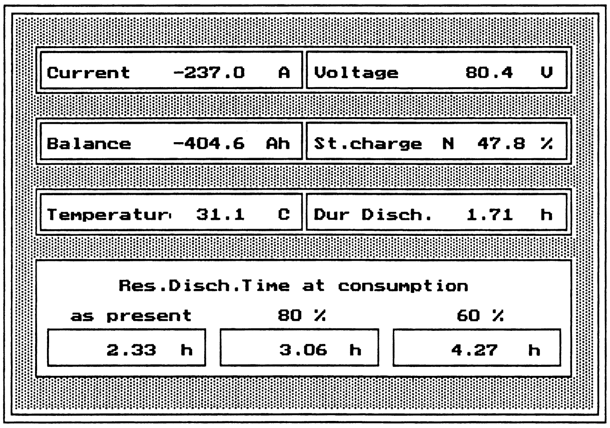
Actual battery voltage (less internal resistance losses) at the present rate of discharge in combination with the ampere-hour counter provides state of charge display and remaining time at the present rate of discharge. Refer to Figs. 6 and 7.

- Functional outputs to operate charging systems, cooling fans and other battery systems functions. Func-


Battery Denomination: Fahrzeug 6 PzS 400 (02/97)

R_i = 0.15 Ohm*Ah
Parameter: I in c_non

Fig. 6. Battery voltage defined for state of charge.



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Current     -237.0  A   Voltage        80.4  V

Balance     -404.6  Ah  St.charge  N  47.8  %

Temperatur   31.1   C   Dur Disch.    1.71  h

        Res.Disch.Time at consumption
   as present        80 %            60 %
     2.33  h       3.06  h        4.27  h
```

Fig. 7. Typical operator information.

tional outputs include contact closure to initiate external chargers that may further include a digital or analog signal which is a function of a charge algorithm. Additionally, contact closure outputs should be available to operate battery pack cooling systems in response to temperature measurement and programmed limits for cooling activation. Other outputs may include contact closures for protective devices. RS232 and 485 outputs are required for computer interfaces.

- Processing data for long term storage and total battery analysis. The fluctuations of battery current, due to load variations, provides an excellent opportunity to measure dynamic conditions of parameters. Information about cell voltage changes during load transitions allow calculation of actual capacity by comparing actual data to stored data.

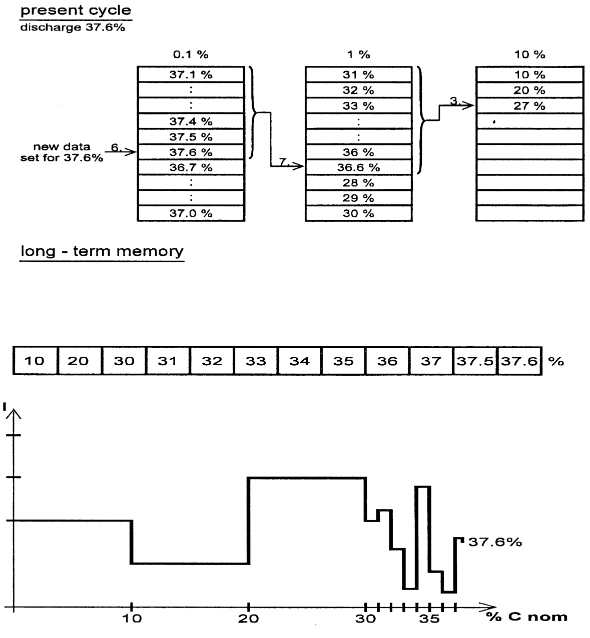
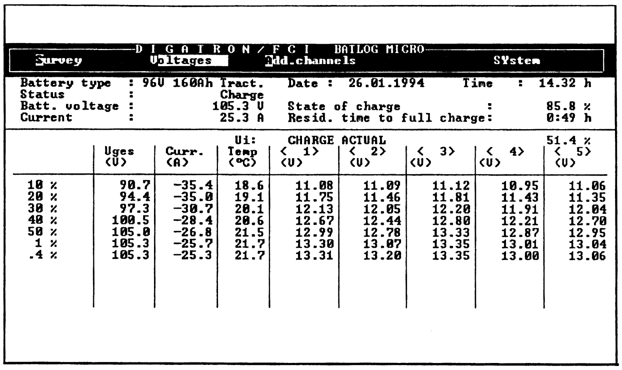


Fig. 8. Data reduction technique.



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———D I G A T R O N / F C I   BATLOG MICRO———
 Survey        Voltages        Add.channels            SYstem

Battery type  : 96V 160Ah Tract.   Date :  26.01.1994     Time    :  14.32 h
Status        :           Charge
Batt. voltage :          105.3 V   State of charge                :    85.8 %
Current       :           25.3 A   Resid. time to full charge:         0:49 h

                            Ui:    CHARGE ACTUAL                         51.4 %
              Uges  | Curr. | Temp | <  1>  | <  2>  | <  3>  | <  4>  | <  5>
              (V)   | (A)   | (°C) | (V)    | (V)    | (V)    | (V)    | (V)

 10 %         90.7  | -35.4 | 18.6 |  11.08 |  11.09 |  11.12 |  10.95 |  11.06
 20 %         94.4  | -35.0 | 19.1 |  11.75 |  11.46 |  11.81 |  11.43 |  11.35
 30 %         97.3  | -30.7 | 20.1 |  12.13 |  12.05 |  12.20 |  11.91 |  12.04
 40 %        100.5  | -28.4 | 20.6 |  12.67 |  12.44 |  12.80 |  12.21 |  12.70
 50 %        105.0  | -26.8 | 21.5 |  12.99 |  12.78 |  13.33 |  12.87 |  12.95
  1 %        105.3  | -25.7 | 21.7 |  13.30 |  13.07 |  13.35 |  13.01 |  13.04
 .4 %        105.3  | -25.3 | 21.7 |  13.31 |  13.20 |  13.35 |  13.00 |  13.06
```

Fig. 9. Data storage.

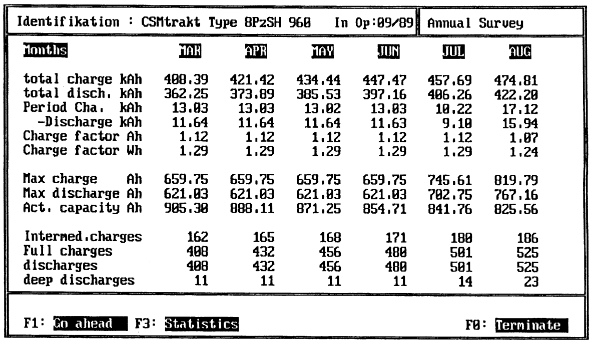
Actual data values are stored in an intermediate data storage area until a predetermined current conversion (A h) occurs. The mean values for this data set are then used for further long term data processing. A very beneficial effect of processing data from incremental defined data sets is accuracy. Transient noise conditions from electrical systems connected to the battery are completely filtered from meaningful data.

The key to accurate battery monitoring is accurate data acquisition which has already been established. Processing of data now looks to the data processing instructions which reside in the EPROM. The primary data necessary for all calculations are: battery voltage, individual cell voltages, battery current, pilot cell temperature(s) and ambient temperature. Actual values of these parameters are stored separately for charge and discharge operation and are stored as average values for an increment of nominal capacity. Typical storage of data sets is in 10%, 1%, and 0.1% values of nominal capacity as shown in Fig. 8 [3].

Fig. 9 shows actual battery parameters measured for each data set.

Remember that during a day data is stored in incremental values of C_{nom}. Following this level of data storage days are averaged from days to weeks, weeks to months and months to years for the entire service life of the battery.

Alarm conditions are especially important for daily and long term battery use. Cell voltages are constantly com-



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Identifikation : CSMtrakt Type 8PzSH 960   In Op:09/89 | Annual Survey

Months                 MAR      APR      MAY      JUN      JUL      AUG

total charge kAh    408.39   421.42   434.44   447.47   457.69   474.81
total disch. kAh    362.25   373.89   385.53   397.16   406.26   422.20
Period Cha.  kAh     13.03    13.03    13.02    13.03    10.22    17.12
  -Discharge kAh     11.64    11.64    11.64    11.63     9.10    15.94
Charge factor Ah      1.12     1.12     1.12     1.12     1.12     1.07
Charge factor Wh      1.29     1.29     1.29     1.29     1.29     1.24

Max charge    Ah    659.75   659.75   659.75   659.75   745.61   819.79
Max discharge Ah    621.03   621.03   621.03   621.03   702.75   767.16
Act. capacity Ah    905.30   888.11   871.25   854.71   841.76   825.56

Intermed.charges       162      165      168      171      180      186
Full charges           408      432      456      480      501      525
discharges             408      432      456      480      501      525
deep discharges         11       11       11       11       14       23

F1: Go ahead   F3: Statistics                            F0: Terminate
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Fig. 10. Annual survey.

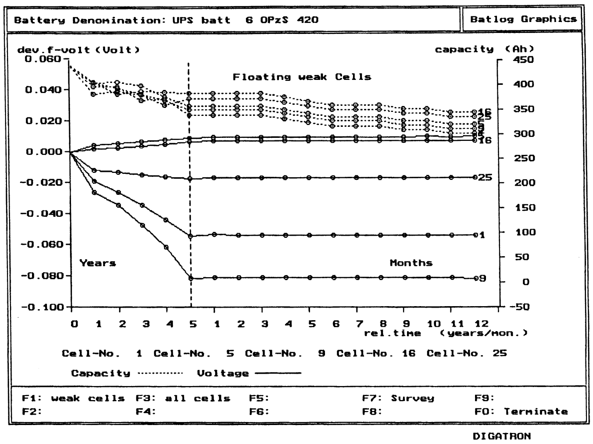


Fig. 11. Long term float charge variations.

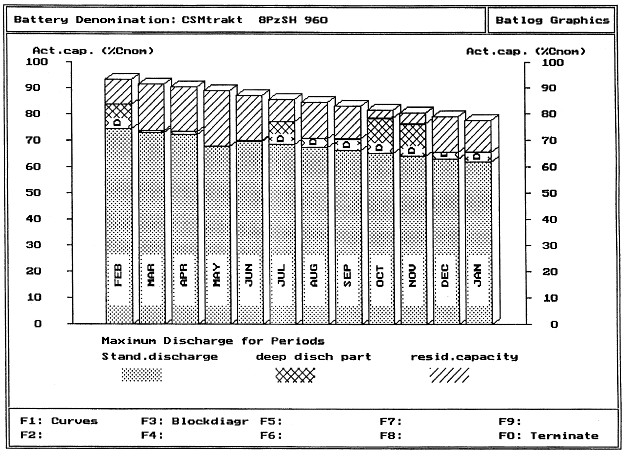


Fig. 13. Battery discharge history.

pared to programmed limits during discharge and charge. Long term cell voltage variations from the average of all cells show cell trends which may require equalizing to prevent cell capacities from falling below the average. Cell capacities which are allowed to fall below the average of all cells limit the total battery capacity. Typical alarm conditions include:

–Cell voltages which are 20% above the average during charge

–Cell voltages which reach a discharge limit

–Battery temperature which reaches an upper limit

–Battery current which exceeds a specified limit

–Floating voltages outside limit tolerances

Fault conditions are indicated by closure of relay contacts to energize indicators and may also be displayed on a local monitor available to the system operator.

4. Data evaluation

Long term data stored for days, weeks, months and years each show different operating concerns for the battery. Information for days and weeks provide short term maintenance requirements such as charge equalizing needs of specific cells or cell groups (Fig. 10).

In some cases cell variation may be linked directly to temperature variations during charge or discharge operation.

Figs. 11 and 12 show a long view of cell variations that can exist.

The above cell variations with respect to individual capacities allow further interpretation to provide a prediction of useful battery life to various discharge levels as shown in Figs. 13 and 14.

The information stored for each cell does not necessarily define the exact reason why a cell is in failure mode, but it does show the history of conditions which may have influenced the present cell status. These include the number of charge/discharge cycles, depths of discharge, peak discharge currents, float voltage values and operating temperatures of the cell.

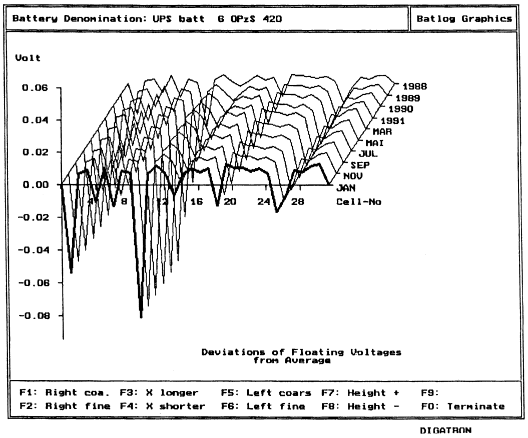
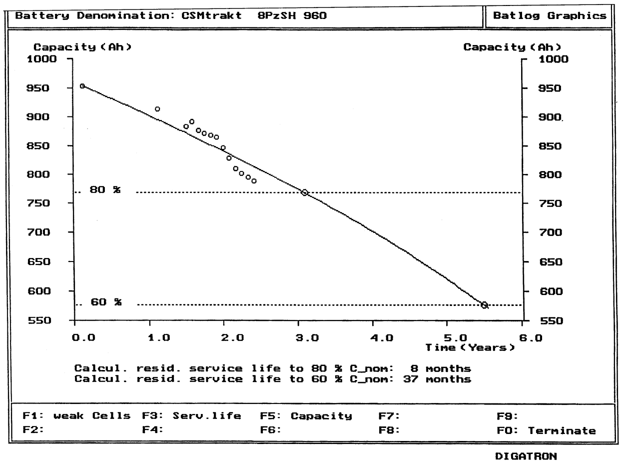


Fig. 12. Dimensional view of float voltage variations.



Calcul. resid. service life to 80 % C_nom: 8 months
Calcul. resid. service life to 60 % C_nom: 37 months

Fig. 14. Predicted service life for last 12 months.

5. Conclusions

Accurate battery monitoring relies on high accuracy A/D components measuring battery parameters, but it is equally important that data sets are averaged over small increments of C_{nom} to eliminate measurements of a transient nature. Real time data is useful for calculation of state of charge, remaining operating time (miles to go for EV use) and alarm conditions. Data stored over periods of days, weeks, months and years provide maintenance information for treatment of specific cells and provide a prediction of useful battery life.

References

[1] Advanced battery Monitoring and Control System, ALABC Rmc 004 (1994).
[2] Batlog UPS Digatron/Firing Circuits (1997).
[3] Batlog Micro Digatron/Firing Circuits (1997).
[4] Santa Barbara MTD Four-Year Report FTA-CA-26-0019-95-1 (1995).
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