# LIFETIME EXTENSION OF VALVE REGULATED LEAD ACID (VRLA) BATTERIES UNDER HYBRID VEHICLE DUTY.

**P. Bentley*, D.A. Stone.**

The University of Sheffield, UK.

Fax: +44(0)11426665196 *e-mail: elp98pb@sheffield.ac.uk

**Keywords:** Battery; Cell; Traction; Hybrid-vehicle.

## Abstract

This paper presents some of the results of a Foresight Vehicle Link research project, exploring the possibility of lifetime extension of Valve Regulated Lead Acid (VRLA) batteries under hybrid-vehicle duty cycles. The work shows that by the addition of a second set of terminals to a commercially available spiral wound cell, during manufacture, it is possible to improve the cells performance to a degree whereby it can meet the needs of a hybrid-electric vehicle.

It is then shown that by the periodic application of a simple conditioning routine the lifetime of a pack of these modified cells may be dramatically improved. Results from a long-term test of a pack of modified cells are presented outlining cell-to-cell variation and capacity loss. The paper gives an in depth analysis of the whole test series including comparisons of the VRLA results with those from the standard Nickel Metal Hydride (NiMH) battery pack removed from the test vehicle and installed on the test bench.

## Introduction

One major obstacle against the adoption of hybrid electric vehicle (HEV) technology is the cost of the peak power buffer. Currently NiMH, LiIon, NaNiCl batteries, supercapacitors and combinations of these are all proposed as peak power buffers, however, the cost of such systems is relatively high. VRLA battery technology would however provide a significantly cheaper alternative, provided problems of lifetime degradation under partial state-of-charge (PSoC) cycling can be addressed. Previous studies have shown that VRLA batteries possess the required specific power and energy ratings, but operation under PSoC leads to a truncated service life. Work carried out at CSIRO [1], highlights the build up of inactive sulphate crystals within the negative electrode structure, leading to premature cell failure.

This work was undertaken as part of the Foresight Vehicle Link 'RHOLAB' (Reliable, highly optimised lead acid battery) project, details of which have been presented elsewhere [2]. The main project aim was to create a reliable VRLA cell based battery pack to replace the standard NiMH pack fitted to the Honda Insight hybrid electric car.

To this end, power demand test cycles for the replacement battery pack were derived from the existing Honda Insight pack power requirements, when driven relatively aggressively around test tracks at the Millbrook proving ground, UK. Data collected from the instrumented car was used to create a typical 'Rholab' driving power demand profile, which included sample motorway, urban and hill routes. The profile is therefore significantly more demanding than standard published hybrid-vehicle test profiles. It was also hoped that when employed on the test bench, this cycle would accelerate the lifetime tests to a point where they would fit within the time constraints of the project, whilst still remaining representative of actual vehicle operation. The cells selected for the project, to replace the Insight's NiMH cells, were 8Ah (5hour discharge rate) Cyclon spiral wound VRLA cells supplied by Hawker (Enersys), as part of the project. This gives a comparable pack capacity to that of the NiMH cells, measured at the 1hour rate. Four 36V modules are to be employed to replace the full 144V NiMH pack. Each module containing 18 VRLA cells.

## Test Equipment

The experiments were performed using two main pieces of custom-built test equipment. The first, a pack-testing rig, is used to apply current or power demand cycles to the battery packs. It utilises a 14kVA Ward-Leonard motor/generator set as an active load/power supply. Voltages and temperatures of individual cells within the pack under test are logged, whilst pack current and voltage may be sampled at up to 1kHz. During test cycling, the pack/cells are held within a thermally controlled chamber. The cells are thus operated under set ambient conditions. Test control, and data acquisition is via Labview. A detailed description of this test rig is given in [3].

The second piece of custom test equipment was a 16-cell, conditioning rig. This allowed the simultaneous charge and discharge of 16 individual cells. Again, the cells were held within a thermally controlled chamber, to ensure repeatable conditions. This rig is able to accurately measure individual cell charge capacities, and pre-condition cells prior to testing. Cell charge and discharge was achieved via analogue controlled, MOSFET loads. Individual cell temperatures, voltages and currents were sampled at 100Hz. Data acquisition and control was once again performed under Labview.

## Pack Cycling

The cells used for this study were selected at random from within large batches of cells (200-400cells). The selected cells were then pre-conditioned, according to the manufacturers instructions, to bring them to full capacity. The pre-conditioning routine utilised, consisted of four applications of the following cycle:

1. Soak at 25°C to achieve thermal equilibrium.
2. Discharge at 1.53A (nominal 5-hour rate) at 25°C to a low voltage limit of 1.70V.
3. Charge for 16 hours with a current limit of 10A and a voltage limit at 2.45V, at 25°C.

Subsequent to pre-conditioning, packs were formed from the 18 cells, and placed within the thermally controlled chamber of the pack-testing rig, to be thermally 'soaked' at 25°C and then discharged at 1.53A to 80% of the cells' mean capacity, the target state-of-charge for the required PSoC operation. Subsequent to this, the pack was then pre-heated to 40°C, the desired operating temperature, and held until thermal equilibrium was achieved. The previously discussed power profile, scaled to represent the demand for one Rholab module, is shown in Fig. 1, and is referred to as the Rholab power profile. Positive power represents battery recharge, and negative discharge, for the module. This power demand profile was then applied to the assembled module.

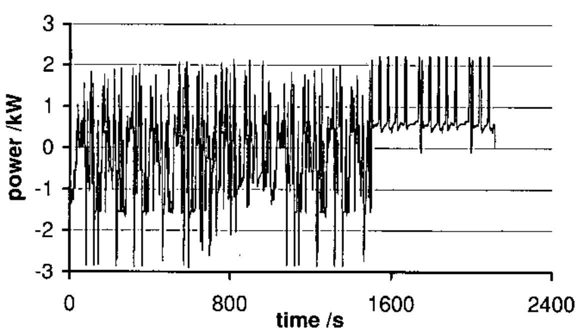


Fig. 1 Power profile scaled four one Rholab module (1/4 of Insight pack).

Cycling was continued until set limits on low/high voltage/current were exceeded, terminating the test. The pack was then recharged, and re-set to the target 80% SoC where a further attempts to re-start the cycling were made.

### Standard Cyclon cell test

Initially, a pack of standard Cyclon cells was subjected to the Rholab power profile. A photograph of the instrumented pack within the test chamber is given below, Fig. 2. The terminal voltage response of the pack is shown in Fig. 3. It can be seen that the pack fails to complete the 2400s power profile, after only 1083s. At this point the current demand exceeded the 100A trip limit, at which time the pack voltage was less than 5V, for a nominal 36V Pack. The maximum allowed test current was set at ±100A, the maximum allowed by the Honda Insight's onboard management system. It was therefore concluded that standard cells were incapable of replacing the NiMH cells under the HEV power duty demand recorded on the Honda Insight.

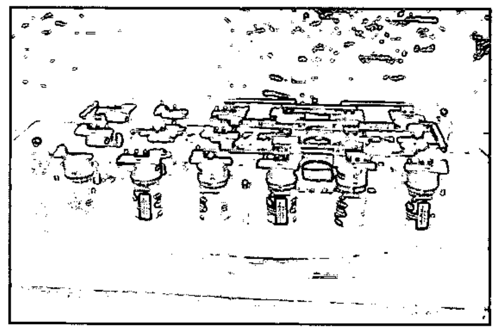

Fig. 2 Pack of standard Cyclon cells within test chamber

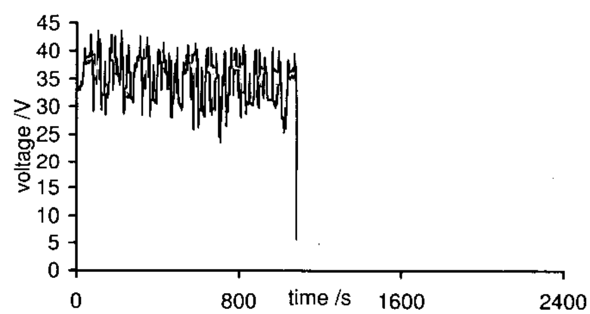


Fig. 3 Voltage response of a pack of standard Cyclon cells on power profile testing.

### Double terminal cell tests

To overcome the standard cell's low power capability, Hawker (Enersys) developed a novel double terminal cell, based on the same plates as the standard Cyclon cell, but with two pairs of current take off terminals. One pair was at the top of the cell whilst the second pair was at the bottom. These terminals also have a higher current carrying capacity than the spade terminals on the standard cell, being M5 threaded studs. This 'double terminal' approach leads to lower current densities in the plate grids, accompanied by lower thermal gradients within the cells, and better utilisation of active material area.

A pack of double-terminal cells was then installed in the pack test rig, shown in Fig. 4, both top and bottom bus bars being visible. The test conditions were established as before, and the power profile applied. The pack terminal voltage for one cycle is shown in Fig. 5, illustrating the double terminal cells can successfully complete the demanded power profile.

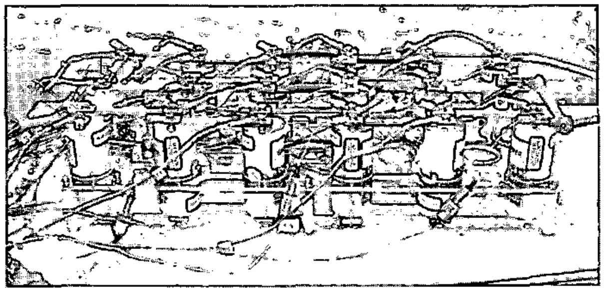

Fig. 4. Pack of double terminal cells in test chamber.

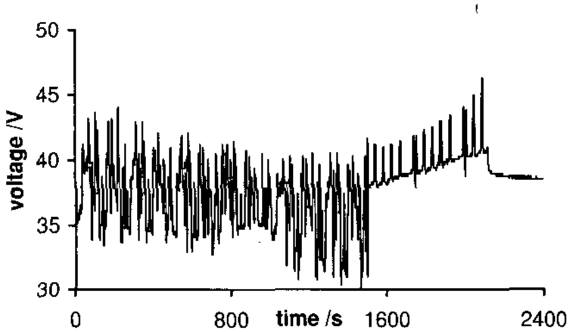


Fig. 5. Voltage response of a pack of double terminal cell on power profile.

Two such packs were cycled until they could no longer complete the power profile. The packs were then disassembled and the capacities of the individual cells' measured on conditioning rig. A typical test run is illustrated as Fig. 6, showing 65 consecutive 'Rholab' power cycles. The voltage divergence seen towards the end of the test is typical of VRLA cells under PSoC cycling [1].

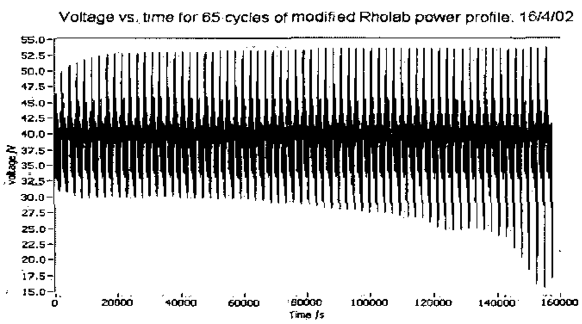


Fig. 6 Double terminal pack, on Rholab power profile, illustrating the voltage divergence with cycling.

The pre- and post-test cell capacities for one pack are shown in Fig. 7. This illustrates the loss in charge capacity for each cell during the test. The mean loss in cell charge capacity for both packs, during testing, are summarised in Table: 1. It can be seen that both packs achieved similar numbers of cycles, and incurred a similar cell capacity loss of approximately 0.01Ah per cycle.

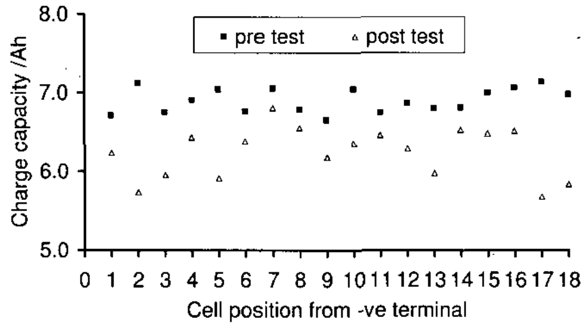


Fig. 7 Comparison of pre and post test cell charge capacities for double terminal pack B.

| | no. of cycles | Mean cell charge capacity loss (Ah) | Mean cell energy capacity loss (kJ) | Mean cell charge capacity loss per cycle (Ah/cycle) |
|---|---|---|---|---|
| Double-terminal pack A | 77 | 0.66 st.dev. 0.38 | 4.28 st.dev. 2.70 | 0.01 |
| Double-terminal pack B | 74 | 0.78 st.dev. 0.40 | 5.26 st.dev. 2.74 | 0.01 |

Table: 1 Summary of mean cell capacity losses for test packs.

## Effect of conditioning during cycling

In an attempt to increase cell lifetime, a periodic conditioning routine was applied during power cycling. This raises the cells to full SoC from the PSoC set-point, to attempt the removal of lead sulphate from the plates before it forms into large 'un-reactive' crystals due to continuous crystal growth. This, in-turn, would then prevent capacity loss caused by the loss of active material. The conditioning routine was:

- Full discharge to measure remnant cell capacity
- Fully recharge
- Full discharge to measure cell capacity
- Fully recharging and returning to the 80% SoC set-point.

This was applied to individual cells at intervals of every 10 Rholab power cycles. The measured cell charge capacities, recorded on the second discharge, being taken as each cell's new charge capacity. The test was run in this way for approximately 1 year, during this time the cells in the pack were subjected to 291 full Rholab power cycles.

Fig. 8. Illustrates the evolution of the mean cell charge capacity, as measured after each 10 power cycles, during the test. The steep drop in mean cell charge capacity seen during the first 20 cycles could be due to an insufficient/inappropriate cell pre-conditioning routine. The subsequent recovery in capacity is promising both with respect to the conditioning procedure, and the conditioning interval. The mean charge capacity then rose to a peak, at around 100cycles. At the end of the test the mean charge capacity was not dissimilar to that at the start of testing.

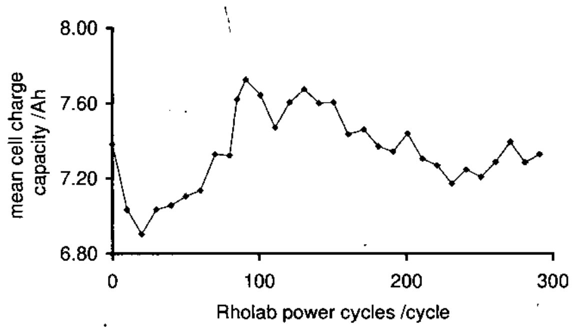


Fig. 8 Evolution of mean cell charge capacity over 291 Rholab power cycles.

Fig. 9 illustrates the evolution, of the standard deviation of cell charge capacities, with power cycling. It demonstrates an initial increase in the spread of charge capacity values. This peaks slightly before the peak mean charge capacity exhibited in Fig. 8. The standard deviation then falls rapidly to assume a roughly constant value till the end of the test.

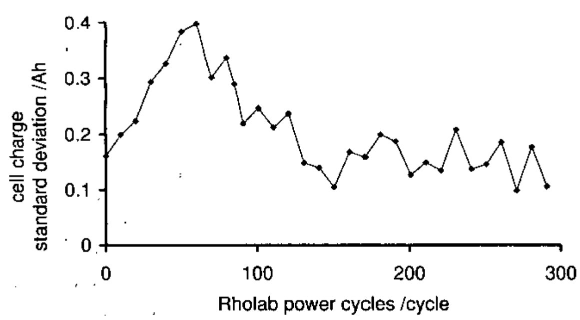


Fig. 9 Evolution of standard deviation of cell charge capacity over 291 Rholab power cycles

Over the 291-cycle test a there was a significant increase in the amount of charge accepted by each cell during the recharge periods of the conditioning. Towards the end of the test period, the cells drew a higher current for a much longer time, whilst on the 2.45V constant voltage charge, than they did at the start of the experiment.

This is illustrated by the mean trend observed in Fig. 10. It should be noted that measurements from several cells are excluded from the average readings towards the end of the testing period, as their surface temperatures exceeded, the 56°C temperature limit during recharge, causing charging to be prematurely terminated.

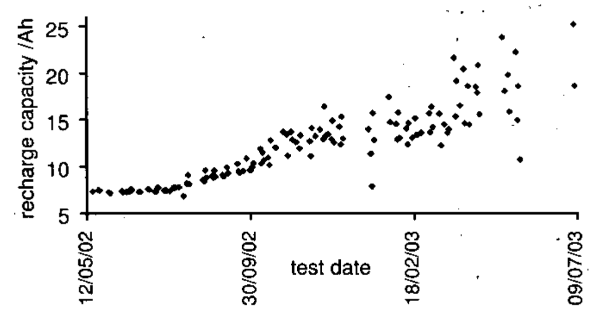


Fig. 10 Mean cell charge input during conditioning.

Further tests were conducted to examine the effects of the conditioning routine alone on cells. In particular the extended 16 hour constant voltage charge at 2.45V, which may have contributed to electrolyte loss. Two cells were individually cycled 30 times using only the conditioning routine, the results being shown in Fig. 11.

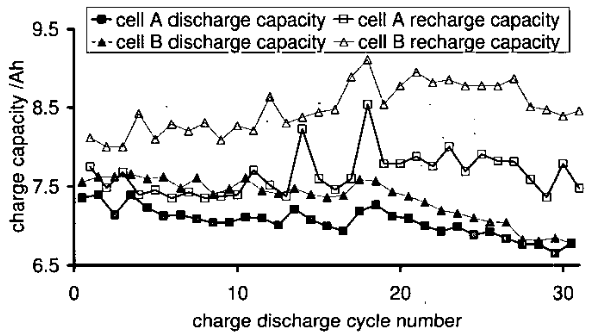


Fig. 11 Charge discharge cycles.

It can be seen that after 18 cycles the cell capacity falls steadily, but there is no evidence of the increase in charge returned on recharge as displayed by cells over the power cycling tests. This points to the power cycling and not the conditioning routine, being responsible for the increase in capacity returned on recharge.

## Discussion

High cell voltages, above 2.45V, displayed during the recharge portion of the power cycles may have led to loss of electrolyte through gassing. The gassing reaction becomes dominant over the charging reaction at voltages above 2.45V. The elevated operating temperature would also hasten the onset of gassing.

The gradual rise in recharge capacity, due to increased recharge currents, as displayed in Fig. 10, can be explained by gradual dry out of the cell plate separators. This makes the oxygen recombination reaction easier due to the increased permeability of the separator sheet.

## NiMH pack

The NiMH pack was removed from the Honda Insight for comparative testing with the VRLA module on the pack-test rig. The pack was installed in the testing chamber and instrumented. The 10 string voltages and 4 thermistor connections provided on the pack, and accessible via pack connectors were wired to the pack-testing rig. A centrifugal fan was attached to the pack to force air between the cells to mimic the cooling system of the vehicle. A photograph of the instrumented pack within the testing chamber is given below, Fig. 12.

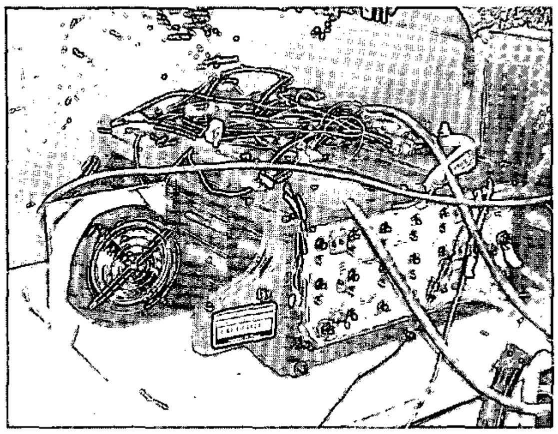

Fig. 12 Honda Insight NiMH battery pack in test rig

The pack was run on the Rholab power profile, at around 80% SoC, to allow comparison with the lead acid pack. Voltage profiles for the two packs are given in Fig. 13. The voltage of the lead acid pack has been scaled by a factor of four to represent a full pack rather than a single Rholab module. The voltage difference between the two packs over the power profile, are then illustrated in Fig. 14. The main difference in voltage response is seen during the recharge portion of the cycle. Initially, the NiMH pack voltage rises rapidly between recharge pulses. This rise then assumes a gradient equal to that shown by the VRLA pack. The VRLA pack voltage, however, displays an almost constant rate of rise between pulses. Furthermore, the voltage pulses seen during the VRLA recharge increase in amplitude towards the end of this recharge period. This leads to both packs attaining almost the same maximum voltage at the end of the cycle. The NiMH pack ends the cycle, after a 300s rest period, with a voltage approximately 9V higher than the VRLA pack.

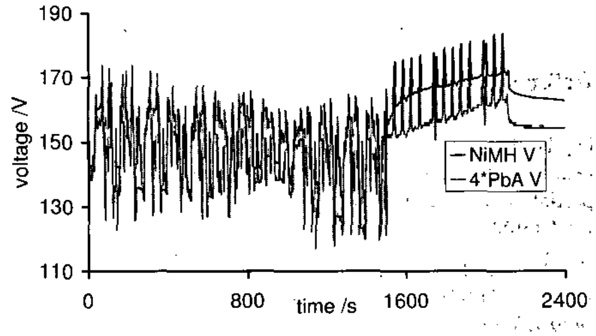


Fig. 13 Comparison of NiMH pack voltage and VRLA module voltages (×4) on power profile.

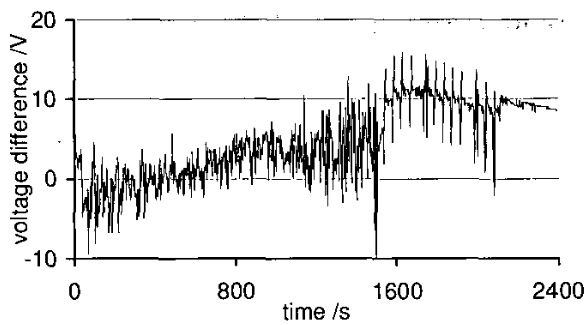


Fig. 14 Voltage difference between NiMH pack and VRLA module (×4) on power profile.

## Conclusion

This paper has shown that by the use of double terminals on a standard cell plate, the cell power handling capacity may be improved so as to enable its use within a hybrid vehicle. Also, the application of sustained hybrid vehicle driving cycles, under PSoC operation, leads to a rapid voltage divergence between the cells. The cells may therefore achieve only a limited useable lifetime, due to a severe and rapid loss of capacity. Furthermore, the paper shows that this rapid capacity loss is prevented by the periodic application of a periodic conditioning routine at cell level. The optimisation of this routine, and its application, are the subject of an on-going study.

## Acknowledgements

The authors would like to acknowledge the financial assistance provided by the UK's DTI Foresight Vehicle Link Program and the EPSRC who have funded this RHOLAB project jointly with the European Advanced Lead Acid Battery Consortium and Hawker Batteries. They would also like to acknowledge the support given by the other partners in the project namely, Provector Ltd, the University of Warwick and Hawker Batteries (now part of Enersys Inc.).

## References

[1] Hollenkamp, Baldsing, Lim et al. (2001). Overcoming negative-plate capacity loss in VRLA batteries cycled under partial state-of-charge duty. ALABC Investigation report ET/IR398R.

[2] M.J. Kellaway, P. Jennings, D. Stone, E. Crowe, A. Cooper. (2003) *Early results from as systems approach to improving the performance and lifetime of lead acid batteries.* Elsevier. Journal of Power Sources. Vol.116. p 110-117.

[3] P. Bentley, D. Howe, D. Stone. (2001). *Test bench for lifetime testing of electric and hybrid vehicle battery packs.* Conference proceedings PCIM 2001, Nuremberg, Germany.