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Early results from a systems approach to improving the performance and lifetime of lead acid batteries

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Abstract

Lead acid batteries offer important advantages in respect of unit cost and ease of recycling. They also have good power and low temperature performance. However, for hybrid electric vehicle (HEV) duty with their extreme rates and continuous PSoC operation, improvements are required to significantly extend service life. The Reliable Highly Optimised Lead Acid Battery (RHOLAB) project is taking a radical approach to the design of a lead acid HEV battery pack to address this issue, taking a systems approach to produce a complete pack that is attractive to vehicle manufacturers. This paper describes the project at an intermediate stage where some testing has been completed and the construction of the complete pack system is well under way.

Keywords: Lead acid; Battery pack construction; Battery management; Hybrid electric vehicles

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1. Introduction

For a significant number of years lead acid battery development has concentrated on the internals of a typical monoblock without as much consideration being given to improvements in the way a complete battery pack is constructed. The most common applications (outside the specific requirements of SLI batteries) have been in float or relatively low-rate cyclic situations. The move to a higher voltage battery in more demanding electrical applications such as EVs has not led to a significant level of innovation in whole-pack engineering in spite of the extremely cost-conscious and demanding automotive customer base. The lead acid battery industry has largely left pack engineering to the customer. This is in stark contrast to the suppliers of batteries such as NiMH, Li-ion and Na-based systems who have directly addressed this issue. Whilst it could be argued that much of this is down to the special requirements of these chemistries for thermal and battery management, in reality lead acid batteries have similar requirements, particularly when the demands increase further still, as in hybrid electric vehicle (HEV) and 36/42 V applications.

There is a large potential demand for lead acid HEV and 36/42 V batteries as ultimately first cost is the dominant driver in the automotive industry. However, significant improvements are required before this potential can be translated into business [1]. The key factors are considered to be as follows:

- Significantly improved service life, coupled with a need for the elimination of failures that stop the vehicle (36/42 V batteries will almost certainly be used to power some safety-critical systems).
- Modular whole-pack design which allows the vehicle developer to view the batteries as a self-contained system which interfaces with the rest of the vehicle through industry-standard protocols such as Controller Area Network (CAN).

2. RHOLAB project

The Reliable Highly Optimised Lead Acid Battery (RHOLAB) project was conceived as an approach to addressing these issues. The project has several main steps:

- Identification of the requirements of a battery in PSoC HEV duty.

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- Identification of the mechanisms that are likely to cause early failure and cell lifetime scatter.
- Design and development of a Cyclon cell optimised for long lifetime in HEV duty.
- Bench testing of this as individual cells and in 36 V strings.
- Design and development of an integrated battery pack including thermal management, active battery management and all power and signal interconnect.
- Vehicle testing of the pack on a modified Honda Insight as a 'clean' installation, i.e. replacement of the Honda Battery Management System (BMS) and interfacing at the electronics level rather than simulating the signals for a NiMH battery.
- Endurance testing to test pack performance over an extended period of up to 80,000 km.

3. Project team

The main project team comprises:

- EALABC: Allan Cooper—project management.
- Enersys: Eliot Crowe—cell development.
- Sheffield University: Paul Bentley, Dr. David Stone—bench testing.
- Warwick University: Stephen Wan, Dr. Paul Jennings, Ivor Davies—BMS cell and module software, pack physical construction.
- Provector Limited: Mike Kellaway, Dr. Roger Thornton, Jon Green—overall system design, BMS hardware development, BMS pack level software, vehicle testing.

Dr. Andrew Loyns and Robert Ball also made significant contributions earlier in the project.

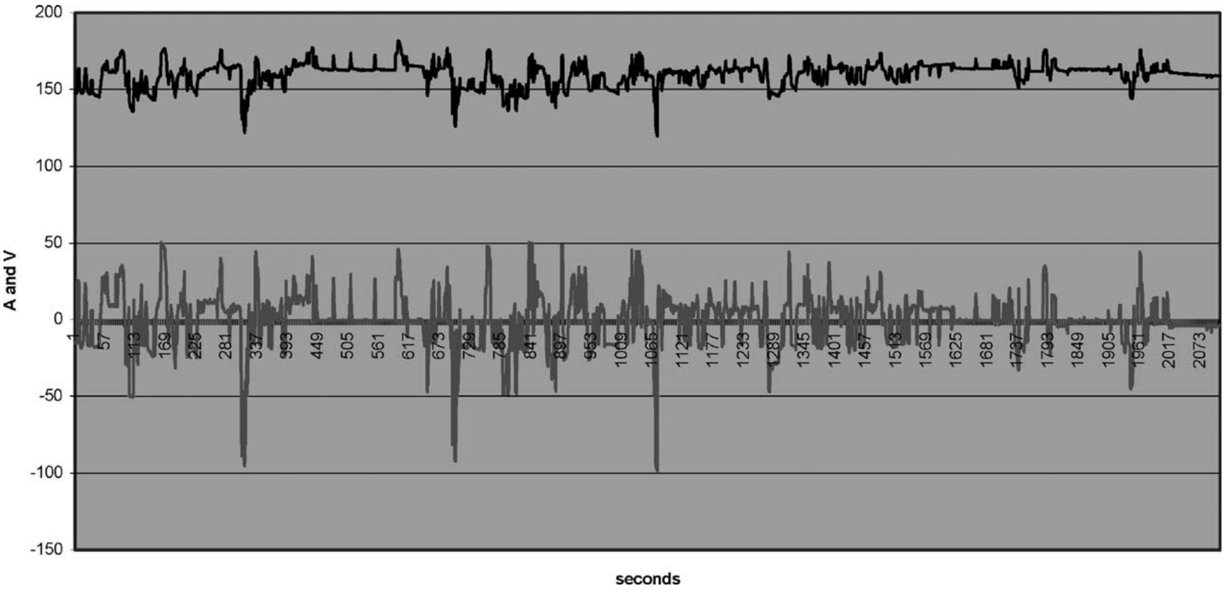

Fig. 1. Mixed route string voltage (V) and current (A).

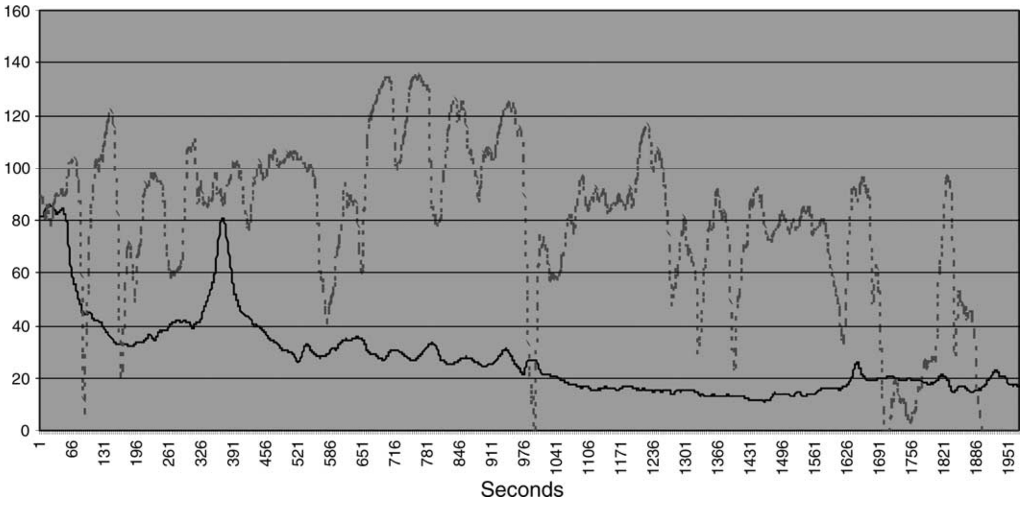

Fig. 2. Speed (km/h) and altitude (m, above GPS datum) data.

4. Pack requirements

These have been described elsewhere [2] but are illustrated by Fig. 1 which shows typical current delivery requirements measured on a Honda Insight operating over a mixed route including both motorway, rural and hill-climbing duty. Fig. 2 shows the speed and altitude data for the route. It can be seen that the pack has to deliver very high rates of up to 15 C in normal driving, generally associated with the motor-assist system supporting the vehicle during high acceleration, high speeds or hill-climbing.

The RHOLAB pack is a nominal 144 V, 8 Ah design.

5. Cell design

The cell developed (Fig. 3) has also been described elsewhere [2]. It uses takeoffs at each end to optimise the power flow into/out from the cell and has a chemistry optimised for high rates and PSoC duty. The cell detailed design was developed in conjunction with the pack design to optimise the benefits that could be obtained by this approach.

Fig. 3. RHOLAB cell.

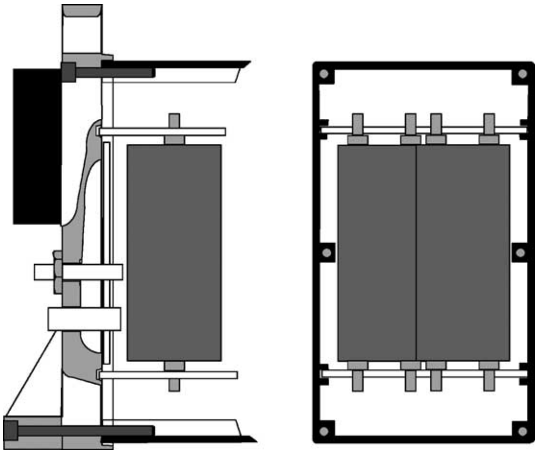

Fig. 4. Module sections.

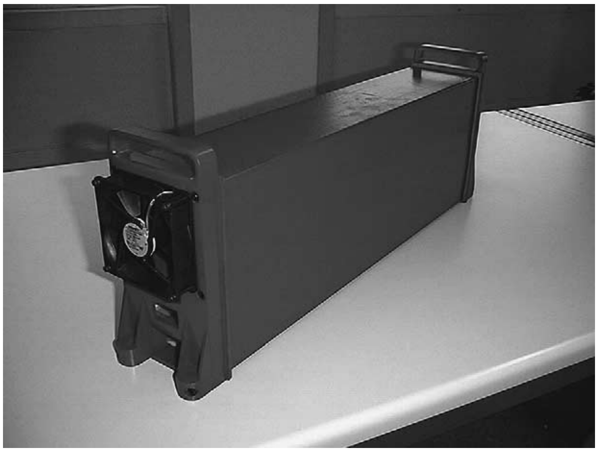

Fig. 5. Prototype module.

6. Pack physical design

Two main objectives have driven the pack physical design:

- keeping each cell in the same thermal environment throughout the pack to help reduce lifetime scatter;
- elimination of wire interconnects so that the pack construction can be highly automated and reliability improved.

6.1. Pack construction

The final design of the modules that go to make up the pack is illustrated in Figs. 4–7. The main elements are as follows:

- An extruded plastic outer case which supports the ends and top and bottom printed circuit boards PCBs.
- Moulded plastic ends (one part number being used for both ends) which support the front and rear PCBs and power terminals.

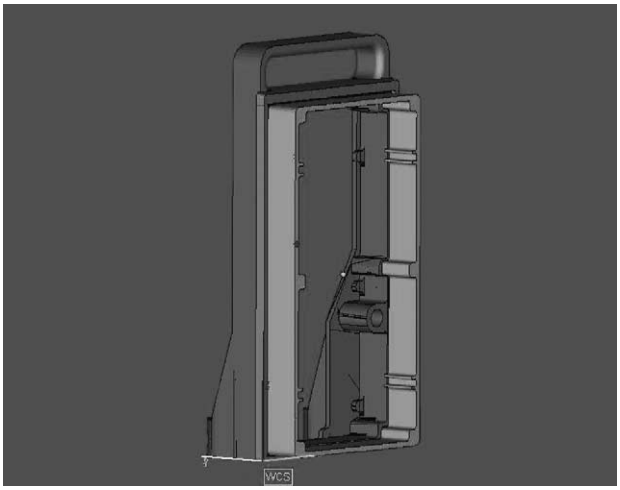

Fig. 6. Plastic parts.

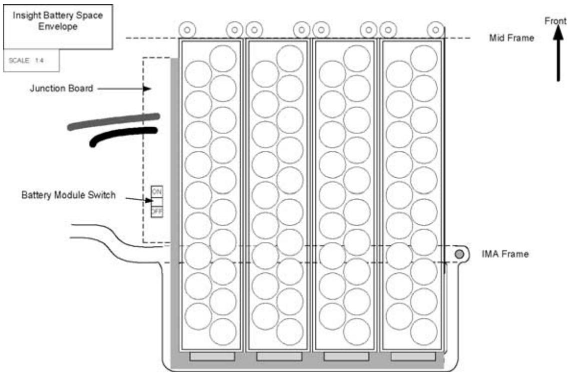

Fig. 7. Pack constructed from four modules.

- End-specific cover plates.
- Top and bottom 'heavy' printed circuit boards that support the cells, carry the power through thick tracks and integrate all BMS components.
- A rear PCB which carries most of the power converters used for cell conditioning and inter-module balancing.
- A front PCB which carries the module and power management controllers.
- Side insulation/air control guides.

This approach is clearly easily scaleable in both module length and number of modules. In the test vehicle the Honda Junction Board will be re-used mounted on the end of the pack to provide the pack electrical functions.

6.2. Thermal management

The parallel-flow air cooling shown in Fig. 8 illustrates the method chosen to cool the modules. Air is drawn in from one end of the module into a bottom plenum chamber from which it passes through controlled air paths to the top plenum before passing through the fan at the opposite end to the air inlet. Using this configuration it is possible to equalise the flow of air over each cell with the objective of equalising cell temperature across the pack. Bottom air entry also gives some fault tolerance as the air will thermosyphon if the fan fails. The fan operation is electronically controlled so that the cell temperatures can be controlled to an ideal level. At low temperatures a small heater is used to bring cell temperatures up to the required point. A simple foamed plastic moulding is used (Fig. 9) to both act as part of the air path control and to limit heat flow out of the cells when the vehicle is not being used. This slows down the overnight cooling of the pack considerably and helps to shorten the period until full performance is available in the morning.

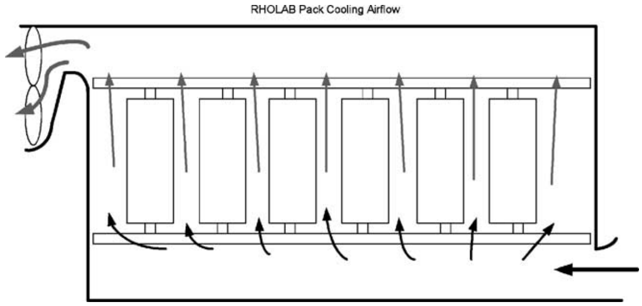

Fig. 8. Cooling flow.

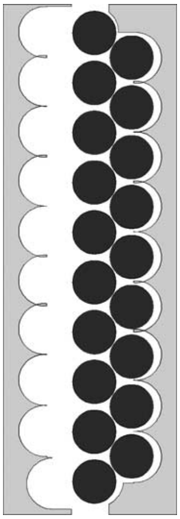

Fig. 9. Flow control/insulation.

6.3. Battery management

By integrating the Battery Management System on the main PCBs supporting the cells it has been possible to eliminate all wire interconnects. The prototype design uses multiple microcontrollers to simulate a custom application specific integrated circuit (ASIC) production implementation. This has allowed additional channels of data collection to be used on the prototype so that detailed cell level information can be recorded whilst in operation as part of a long string.

Part of the design requires all cell voltages to be sampled at the same instant. This allows cell voltages to be more accurately compared than with the more common sequentially sampled approach. Whole module cell spectrographic analysis is also possible using this technique in the same time normally taken to measure a single cell.

An important facility included in the BMS is the ability to move charge around the battery. This is used to balance the operating point of all cells in a module, and to equalise the charge between modules. The same system can also condition individual cells using a fully programmable algorithm.

This system is coupled to the cell bypass system which allows a number of cells to be removed from the string in each module. Each module has an extra cell which allows one cell at a time to be bypassed and conditioned while the battery is in use without any performance disadvantage. It is also possible to remove a faulty cell from the string, initially for attempts to recover the cell using cell conditioning so that it can be returned as an operational cell. If this fails the cell

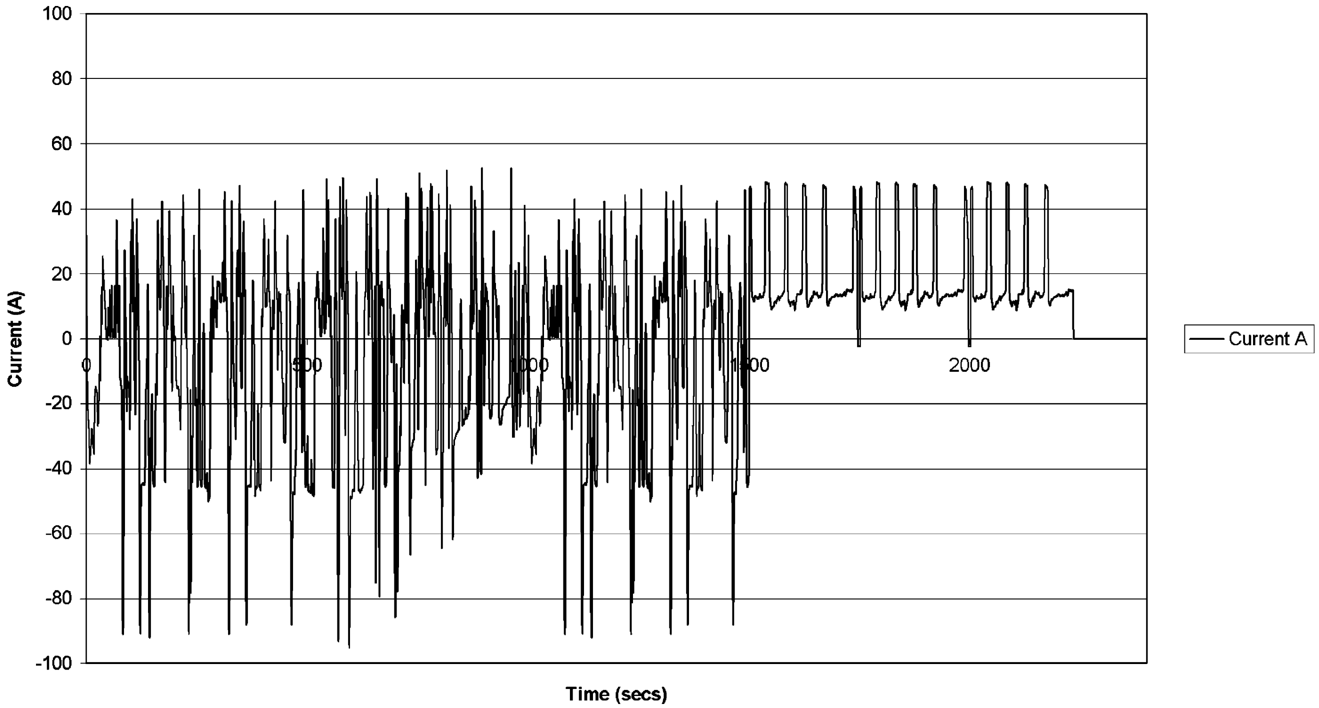

Fig. 10. RHOLAB bench test cycle.

can remain bypassed, but the battery can still be used with a small performance reduction. This is much better than the present situation in which a failed cell prevents the battery being used at all.

The BMS is designed to integrate directly with the Honda Insight electronic systems, replacing the Honda BMS. An automotive standard CAN interface is also available that offers extensive diagnostic functionality. Detailed design is well advanced and it is hoped to have the system working in the test vehicle this year.

7. Bench testing

Life testing is an inherently long process, but care must be taken not to over-accelerate the test process in case this emphasises different failure modes. The RHOLAB project is investigating the influence on life of a number of test parameters such as SoC operating point, cell operational temperature and conditioning strategy and algorithms. The project decided to use real vehicle data rather than standard test cycles as it was felt that these would give a more accurate view of cell performance. The project Honda Insight car was driven over a wide range of operating conditions at the Millbrook Proving Ground to seek the most aggressive demands on the battery. This was found on the hill circuit. Some regeneration data from a different part of the track was added to the hill circuit data to form the test cycle shown in Fig. 10.

The test rig shown in Fig. 11 is used to cycle a test string using the RHOLAB test cycle. Fig. 12 shows a comparative test of a standard Cyclon and the RHOLAB Generation 1

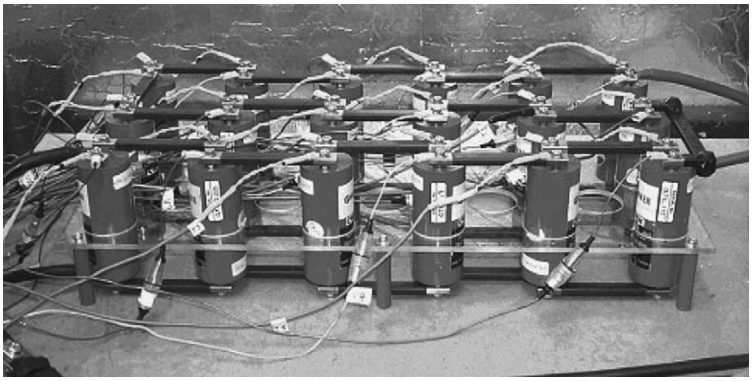

Fig. 11. Bench test string rig.

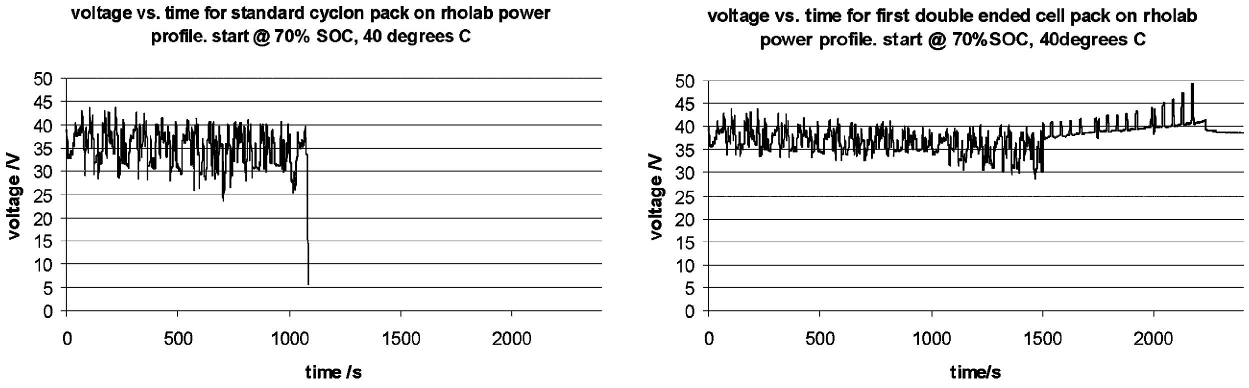

Fig. 12. Comparative performance standard Cyclon vs. RHOLAB Generation 1 cell.

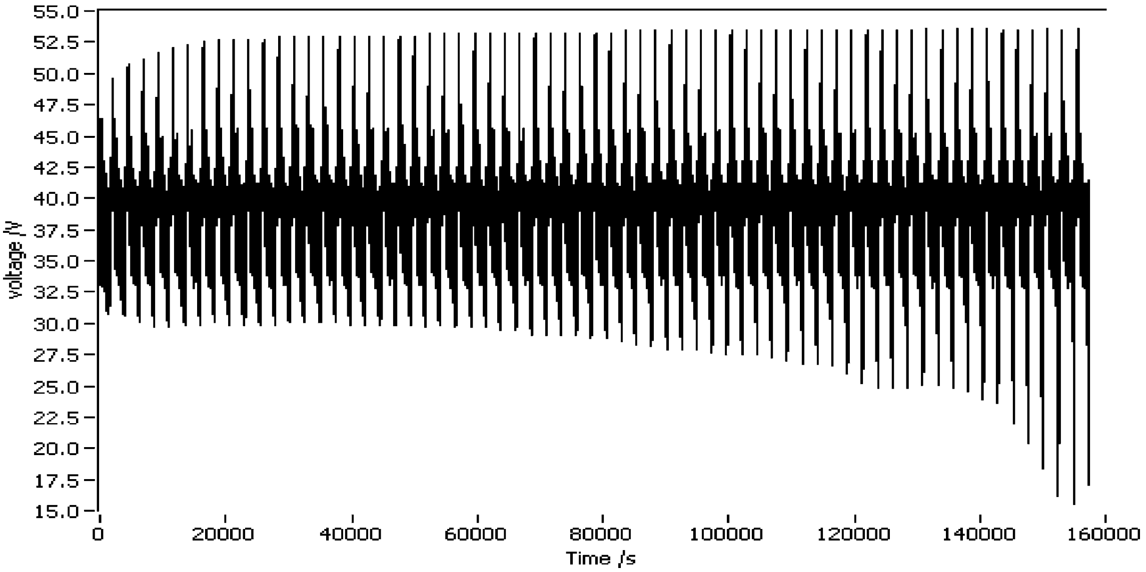

Fig. 13. Voltage vs. time for 65 cycles of modified RHOLAB power profile.

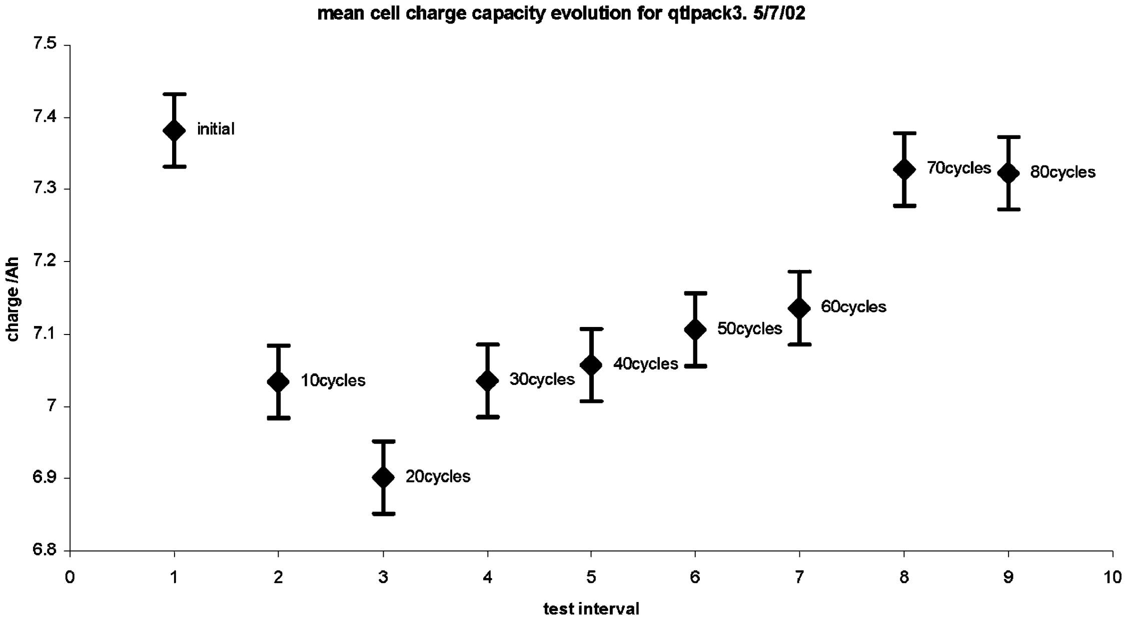

Fig. 14. Mean cell capacity of 18-cell test pack.

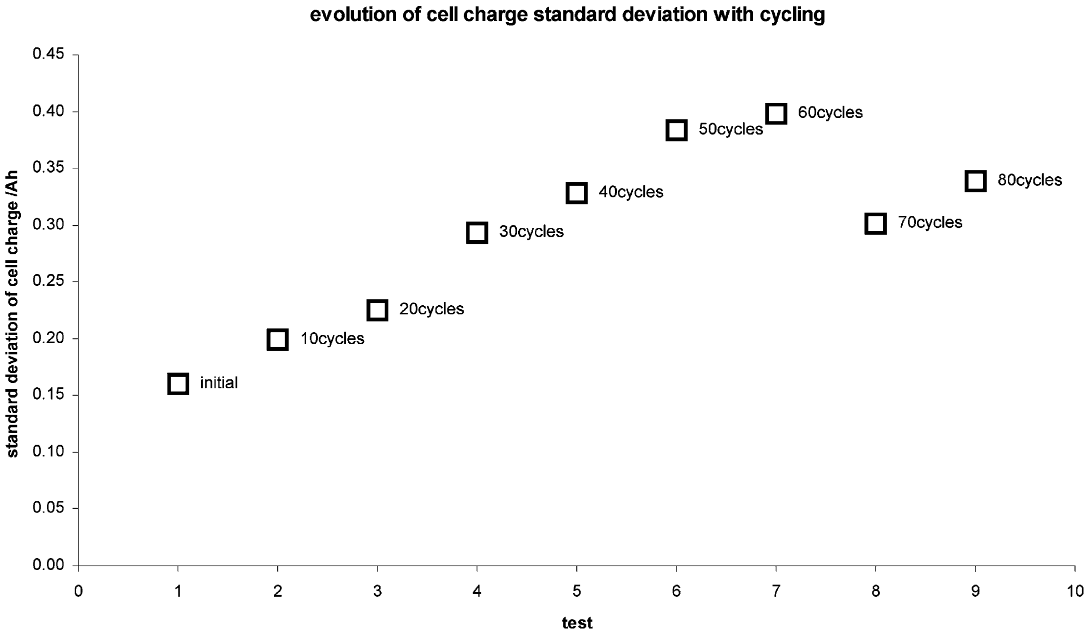

Fig. 15. Standard deviation in cell capacity across 18-cell pack.

cell (double tabs but standard Cyclon chemistry). It can be seen that the standard cell cannot complete one test cycle, whereas the new cell handles this well.

Fig. 13 shows the performance over 65 cycles, which is clearly a considerable improvement over the standard cell. It was decided at this point to add in a full pack conditioning cycle after every 10 cycles and the results are shown in Figs. 14 and 15.

The cells continued to perform well for over 80 cycles and after an initial dip recovered close to their original capacity. It can be seen from Fig. 15, however, that there is a significant increase in the standard deviation of the individual cell capacities, which might be improved by individual cell conditioning.

Once this test is complete the Generation 2 RHOLAB cells (double tabs with optimised chemistry) will be subject to the same tests. These have already shown promising performance in the Sheffield single cell test rig.

8. Vehicle testing

Because of the demanding requirement for a clean installation in the test vehicle and because it was thought important to fully characterise the performance of the NiMH pack the test vehicle has been fitted with comprehensive instrumentation and will shortly undergo 5000 miles of varied track and rolling road testing at Millbrook Proving Ground. The key objectives are to monitor the vehicle in a wide range of operational conditions but to a repetitive pattern which allows changes to be observed. The same instrumentation will be used to monitor the vehicle when it is fitted with the RHOLAB pack, in this case supplemented by a large amount of data directly from the RHOLAB BMS. To handle the large volume of data to be analysed parts of the process have been automated.

9. Project status

The RHOLAB cells are developed and two generations manufactured. Generation 1 keep the standard Cyclon chemistry and allow the effects of double tabs to be investigated directly. Generation 2 has a revised chemistry optimised for HEV applications principally directed at reducing cell impedance and delaying the onset of negative plate sulphation. This has been done in conjunction with CSIRO, who have advised on this aspect of the development.

The RHOLAB modules and BMS hardware are at an advanced stage of detailed design, with some components already manufactured. These should be completed within a few weeks, allowing time to test the system in isolation before being fitted to the test vehicle. The modules will be fitted with Generation 2 cells.

Acknowledgements

The project team wish to thank Dr. Pat Moseley and Dr. David Prengeman of the ALABC for their support and advice during the project, Dr. David Rand, Dr. Russell Newnham, Dr. Tony Hollenkamp and other members of the team at CSIRO for their advice and Fergal McGrath of Honda UK for many helpful discussions.

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