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Development of a lead-acid battery for a hybrid electric vehicle

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Abstract

In September 2000, a project reliable, highly optimized lead-acid battery (RHOLAB) started under the UK Foresight Vehicle Programme with the objective of developing an optimized lead-acid battery solution for hybrid electric vehicles. The work is based on a novel, individual, spirally-wound valve-regulated lead-acid 2 V cell optimized for HEV use and low variability. This cell is being used as a building block for the development of a complete battery pack that is managed at the cell level. Following bench testing, this battery pack is to be thoroughly evaluated by substituting it for the Ni−MH pack in a Honda *Insight*.

The RHOLAB cell is based on the 8 Ah Hawker Cyclon cell which has been modified to have current take-off at both ends—the dual-tab design. In addition, a variant has been produced with modified cell chemistry to help deal with problems that can occur when these valve-regulated lead-acid battery (VRLA) cells operate in a partial-state-of-charge condition. The cells have been cycled to a specially formulated test cycle based on real vehicle data derived from testing the Honda *Insight* on the various test tracks at the Millbrook Proving Grounds in the UK. These cycling tests have shown that the lead-acid pack can be successfully cycled when subjected to the high current demands from the vehicle, which have been measured at up to 15 C on discharge and 8 C during regenerative recharging, and cycle life is looking very promising under this arduous test regime.

Concurrent with this work, battery development has been taking place. It was decided early on to develop the 144 V battery as four 36 V modules. Data collection and control has been built-in and special steps taken to minimize the problems of interconnect in this complex system. Development of the battery modules is now at an advanced stage. The project plan then allows for extensive testing of the vehicle with its lead-acid battery at Millbrook so it can be compared with the benchmark tests which have already been carried out on the vehicle with its Ni−MH batteries.

Keywords: Lead-acid battery; Valve-regulated; Spiral-wound; Dual-tab; HEV

1. Introduction

In the short to medium term, hybrid electric vehicles are generally regarded as having the greatest potential for improving air quality, since they offer significantly improved emissions performance without operational restrictions. However, to be successful they must be affordable. Lead-acid batteries are the only feasible way of achieving this, but their performance must be improved to meet HEV requirements. A battery serving as the auxiliary power source in an HEV is placed in a very unusual environment from the standpoint of a battery duty cycle. It must operate continuously in a partial-state-of-charge configuration, having the capability of furnishing and absorbing relatively high current pulses in an irregular programme over a long calendar life. There are indications that under these conditions, early capacity decline can occur because of negative plate sulfation. In addition, the vehicle control system must be able to ascertain the battery state-of-charge and keep it in a fairly narrow operating range, preventing it from being heavily overcharged or discharged.

The objective of this project is to take an individual, advanced, spirally wound valve-regulated lead-acid battery (VRLA) 2 V cell as a building block and to develop a complete battery pack design that is optimized for a hybrid vehicle. It must reduce the performance scatter of individual cells so that the battery as a whole can realize the potential lifetime performance of a single cell. The pack must be easy

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Abbreviations: ALABC, Advanced Lead-Acid Battery Consortium; BCM, battery condition monitor; BMS, battery management system; CAN, controller area network; GPS, global positioning system; HEV, hybrid electric vehicle; IMA, integrated motor assist; MCM, motor control module; Ni−MH, nickel−metal-hydride; OBD, on-board diagnostics; PCB, printed circuit board; PNGV, partnership for new-generation vehicles; RHOLAB, reliable, highly optimized lead-acid battery; SoC, state-of-charge; VRLA, valve-regulated lead-acid battery; WMG, Warwick Manufacturing Group

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to install and maintain and must be equipped with thermal management which allows the fundamental performance to be optimized for different ambient temperatures, allowing the pack to operate effectively over an external ambient temperature range of at least −20 °C to +40 °C. The pack must offer a standard electronic interface to the rest of the vehicle, which can indicate the status of the pack, including state-of-charge, and allow the battery to be electrically isolated from the vehicle. The design concept must meet applicable safety and other standards and be cheap to produce in quantity.

1.1. Project partners

The project is coordinated by the European Advanced Lead-Acid Battery Consortium (ALABC) and the research partners consist of the Hawker Batteries Group, Provector Ltd., the University of Sheffield (Electrical Machines and Drives Group, Department of Electronic and Electrical Engineering) and the University of Warwick (Warwick Manufacturing Group).

1.2. Project plan

The project plan as originally specified consisted of the activities outlined as follows:

(a) The development of a dual-tab, spirally-wound 2-V cell to act as a building block for the battery.
(b) Bench testing of the 2 V cells.
(c) Battery pack specification, design and development.
(d) Battery management system (BMS) development.
(e) Bench testing of a prototype battery module.
(f) Bench marking of the vehicle with the existing Ni−MH battery pack.
(g) Vehicle testing with the reliable, highly optimized lead-acid battery (RHOLAB) pack.

2. Project progress

The project officially started on 1 September 2000 and was scheduled to last 3 years. Coincidentally, the Honda *Insight* was launched in the UK on that day and the vehicle was acquired at the start of the project. This enabled some early work to be done on the vehicle which proved useful in terms of developing test procedures.

2.1. Development of cycle test procedures

Early discussion in the project had revolved around the use of either the partnership for new-generation vehicles (PNGV) or Eucar cycles as illustrated in Figs. 1 and 2. However, initial testing of the Honda *Insight* with its Ni−MH batteries was carried out and this led to a change of view. The initial testing had the objective of investigating the vehicle's response to a set of standard test conditions available at the Millbrook Proving Grounds during runs on the high speed circuit, the hill circuit and the urban circuit. Only simple instrumentation was fitted to avoid modifications to the vehicle, determining the main battery voltage and current and a number of temperatures. The objectives of this initial work were:

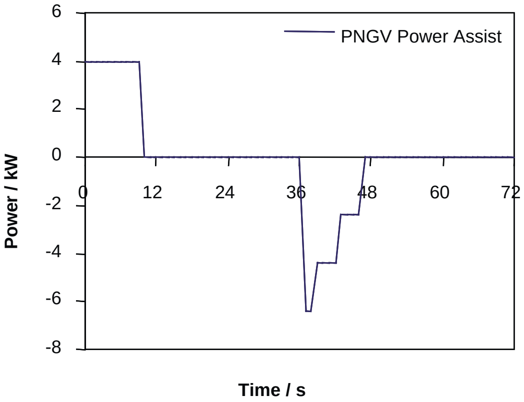

Fig. 1. PNGV test profile.

- exploratory testing to look at pack current and voltage in a range of test situations (high speed, hill and town routes);
- development of techniques to move battery state-of-charge (SoC) around;
- confirmation of on-board diagnostics (OBD) II connector functionality;
- developing understanding of the *Insight* operation; and
- developing planned instrumentation fit for the main vehicle test.

This initial vehicle testing produced some interesting and useful results. It was possible to characterize the current and voltage signals and show the range of values under various operating conditions. Examples of traces obtained on the urban, high speed and hill circuits are shown in Figs. 3–5. A particularly aggressive test on the hill circuit where maximum use was made of the power assist and attempts were made to minimize regenerative charging, is illustrated in Fig. 5. It can be seen that regular power demands of 100 A were experienced with regenerative current around 50 A.

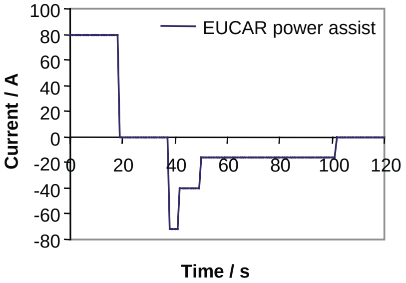

Fig. 2. Eucar test profile.

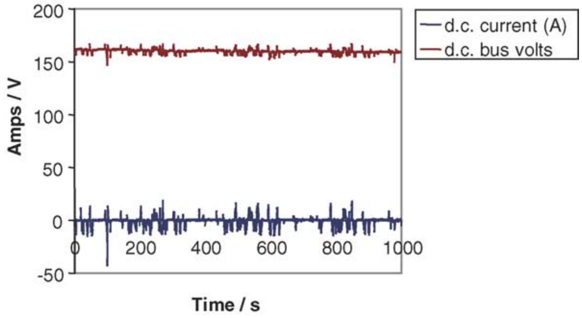

Fig. 3. Voltage and current variation—urban circuit.

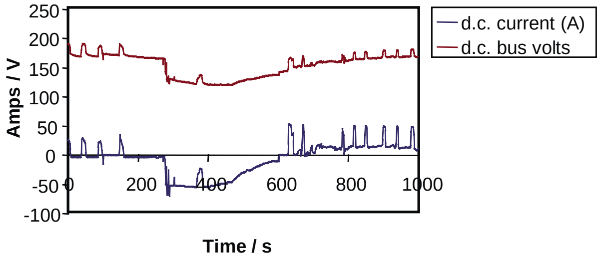

Fig. 4. Voltage and current variation—high speed circuit.

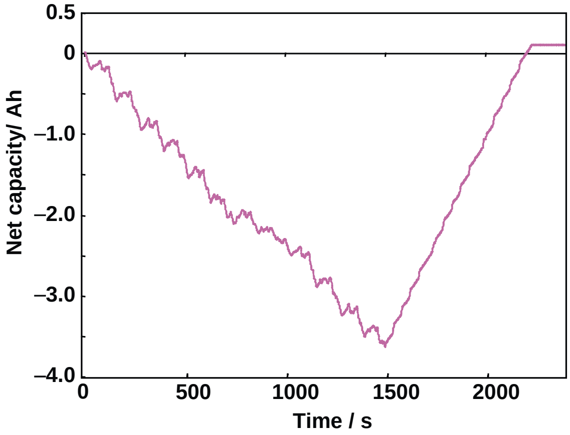

Fig. 7. Pack SoC change during RHOLAB cycle test.

It was decided to adopt a test cycle for bench testing based on real vehicle data in preference to the PNGV or Eucar cycles and this cycle is shown in Fig. 6. This has been derived from data recorded during an aggressive driving run on the hill circuit combined with high-speed circuit data serving to bring back the state-of-charge. The state-of-charge at the start of the test procedure was 80% and the way the state-of-charge varies with time during the 2200 s test cycle is shown in Fig. 7.

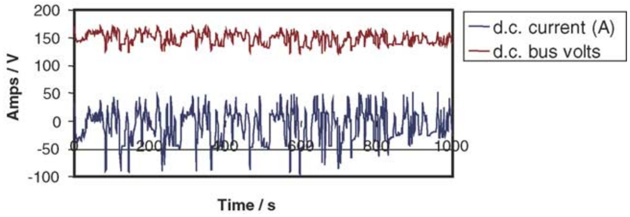

Fig. 5. Hill circuit—maximizing assist and minimizing regen.

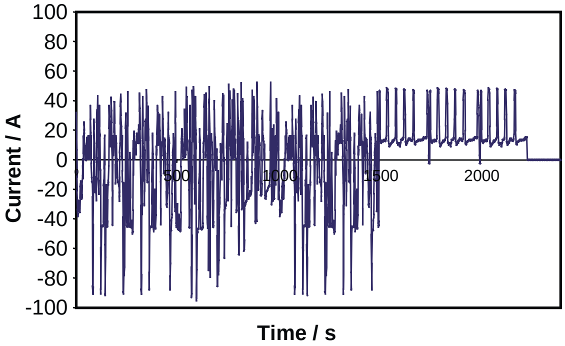

Fig. 6. RHOLAB 'real data' test regime.

The OBD II port has been shown to supply information and the battery state-of-charge seems to be easily controllable. In general, a greater degree of familiarity with the vehicle operation was obtained. This gave a basis for setting the main vehicle test cycle and the overall test programme has been revised accordingly with the initial detailed driving cycles defined—in terms of a combination of the high-speed, town and hill circuits.

2.2. *Cell development*

Research work done within the ALABC programme has shown the need to maintain compression on the positive active electrode in order to improve cycle life [1]. The geometry of the spirally wound cell makes it easier to maintain this compression than in the conventional flat plate battery. In addition, the round cell is an ideal shape to allow assembly into a larger battery unit while allowing space between cells for adequate thermal management. The basic building block for the proposed HEV battery is a new spirally-wound VRLA cell which incorporates a number of novel features to adapt its performance to this type of duty cycle. The basic concept is to develop the original Hawker Cyclon cell to use a double terminal arrangement with a current take-off for both the positive and negative plates at each end of the cell, as illustrated in Fig. 8. This improves active material utilization, reduces internal thermal gradients and increases cycle life. The concept had been demonstrated by Hawker Energy Products, in collaboration with CSIRO Energy Technology, Australia, for flat-plate cells and this activity has developed this concept for cylindrical cells. In addition, the cell design is being optimized through the use of improved separation techniques and active materials to enhance performance. The cell case uses an ABS/polycarbonate alloy rather than the steel jacket normally used.

The design of the new cell was completed and all tooling and capital equipment for conversion of the cell assembly

Fig. 8. Prototype dual-tab cell.

line was delivered to Hawker on schedule. The first batch of cells was delivered in October 2001.

A comparison of the performance of the dual-tab cell when it is connected at only one end and at both ends is given in Fig. 9 400 A (50 C) constant-current discharge was applied. In this condition, there is a clear difference between the configurations; the cells connected at one end die virtually immediately but the double-ended cells give current for between 6–9 s. This gave a clear indication that the dual-tab design should have improved high rate discharge and recharge properties.

2.3. Cell bench testing

The cell testing work is being carried out at the University of Sheffield. A group of 18 of the dual-tab cells is seen being readied for test in Fig. 10. The performance of an 18-cell pack of the original single-tab Cyclon cells as compared with the newly developed dual-tab variety when subjected to the real data test profile is shown in Fig. 10. For the old cells, voltage drops to 5 V after 1000 s whereas the new dual-tab cells complete the test without problem—confirming the benefits of this configuration Figs. 11 and 12.

Fig. 10. A pack of 18 dual-tab cells under cycle test.

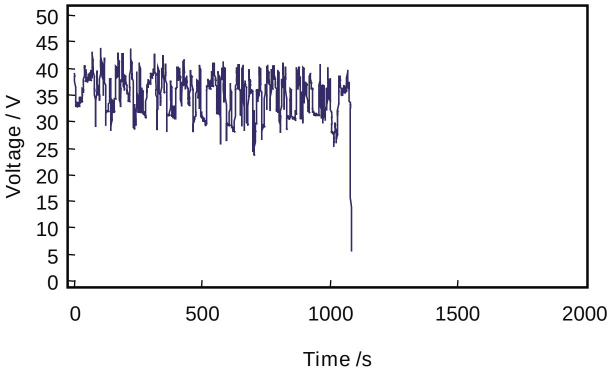

Fig. 11. Voltage vs. time on testing normal Cyclon pack.

The result of continuously cycling the dual-tab cells under the RHOLAB test profile is shown in Fig. 13. It should be noted that during the course of the 65 cycles, the pack voltage declines quite rapidly towards the end. It is thought that this is due to a progressive sulfation of the negative plate which can occur when a lead-acid battery is operated in a partial-state-of-charge condition.

Work in other ALABC programmes has shown two possible ways in which this problem can be avoided. One way

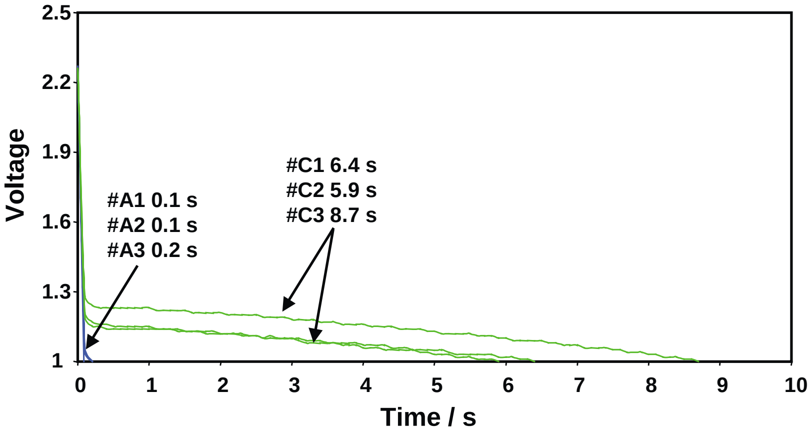

Fig. 9. Comparative discharge times for cells connected one end only and both ends.

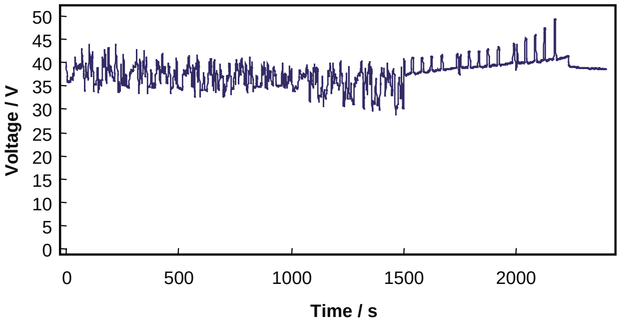

Fig. 12. Voltage vs. time for dual-tab Cyclon pack.

is alterations to cell chemistry and to this end some additional cells have been produced with added carbon in the negative active material, but have yet to be tested as a pack [2]. An alternative approach is to regularly condition the cells—which in effect means bringing each cell routinely up to full state-of-charge [3]. This approach has been tried at Sheffield where the cells are conditioned after every 10 RHOLAB cycles. There is an initial drop in the mean capacity of the cells over the first 20 cycles (Fig. 14), but on further cycling and conditioning, the capacity recovers to a level above the initial capacity of the cells. In addition, the standard deviation of the capacity of the individual cells also declines with the cycling and conditioning routine (Fig. 15).

The above test was terminated at 291 RHOLAB cycles which is equivalent to over 12,000 miles of very hard driving. This is encouraging when compared with the performance of the pack of single-tab Cyclon cells which failed to complete a single cycle and more than four times the life where no conditioning is done. This is especially so when it is considered that these tests are being carried out without the benefit of a battery management system to control the maximum and minimum state-of-charge of the cells accurately. The fact that a pack of 18 of the single tab cells was able to perform the PNGV test adequately, in an ALABC programme carried out at Southern California Edison [4], is some justification for the use of real vehicle data to bench test these cells. It is a demanding test designed to stress the

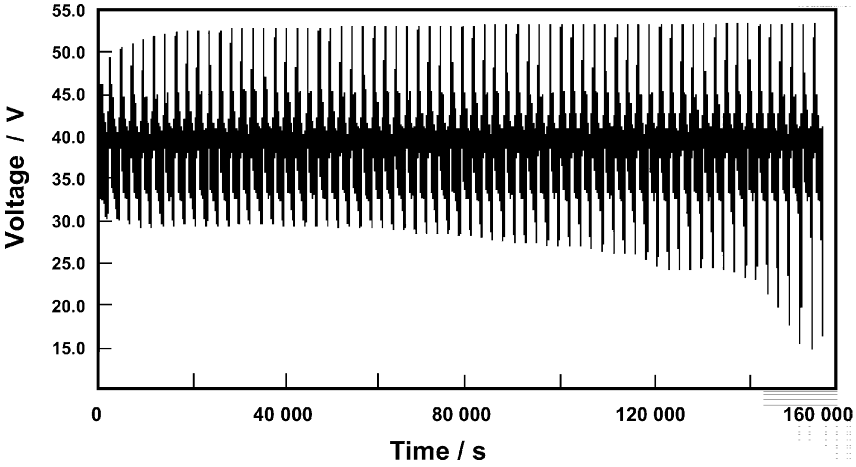

Fig. 13. Drift of voltage with cycling a pack of dual-tab cells.

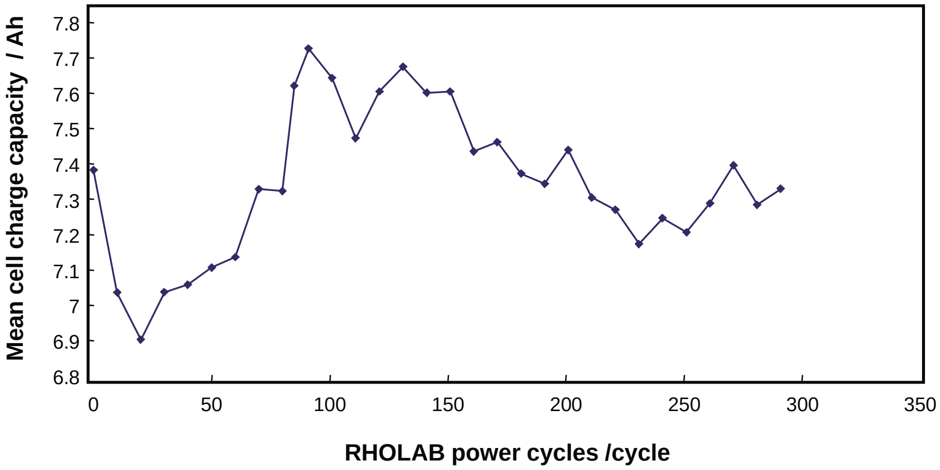

Fig. 14. Effect of conditioning on the evolution of cell capacity.

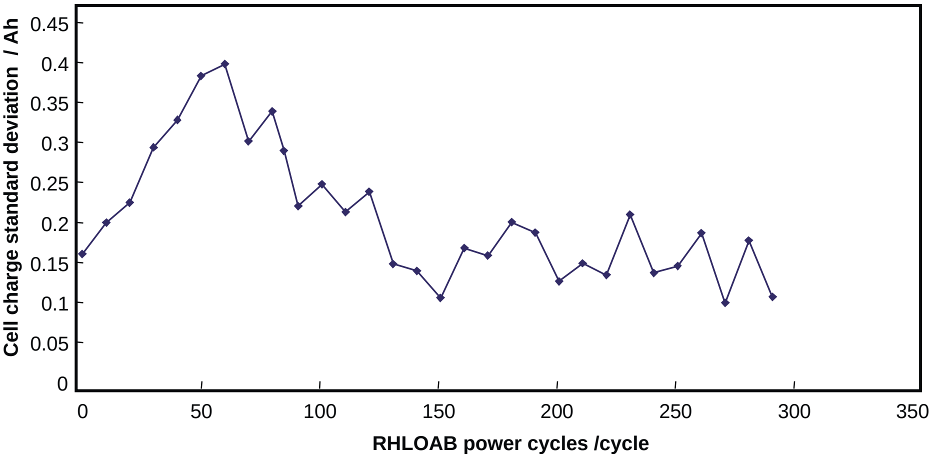

Fig. 15. Effect of conditioning on the evolution of the standard deviation in cell capacity.

battery pack and some tear-down analysis is to be carried out on this pack to assess the levels of negative plate sulfation. The fact that the amount of charge required during conditioning was increasing during the test is indicative that the ultimate failure mode may be dry-out but this has yet to be verified.

2.4. Battery pack design and development

This project starts from the basis of using the 2 V double-ended Cyclon cell as the building block for an individual 36 V module. This gives the possibility for ensuring that each cell can operate in an identical thermal environment and the opportunity for managing the battery at cell level. In this situation, a major problem to be overcome is how best to cope with the problems of sensing the various parameters needed to manage the battery and then getting this information to the battery management system while minimizing the problems of interconnect. This has been resolved in the design of the RHOLAB battery by mounting the individual cells between two printed circuit boards as illustrated in Fig. 16. It has been demonstrated that there is adequate current-carrying capacity for the battery when a 3 ounce copper foil is used on the printed circuit board (PCB). Other interconnect between the various sensors, the cell micro-controller and the module controller is provided by tracks on the PCB, completely eliminating conventional wiring within the pack.

The initial proposal for the project suggested giving the individual modules a degree of fault tolerance by incorporating a bypass device which would allow a faulty cell to be removed from service—resulting in only a mild reduction in battery performance. As mentioned earlier, other work within the ALABC has indicated that a potential problem of operating lead-acid batteries continuously in partial-state-of-charge is sulphating of the negative plate, which will result in gradual loss of capacity. It is felt that this can be resolved by periodically bringing cells up to full state-of-charge as demonstrated at Sheffield. This could be done on a module-by-module basis when the vehicle is at rest, utilizing the current in the other three modules to bring the fourth module to full state-of-charge and then re-distributing the current to equalize all four modules. This is not entirely satisfactory as it could result in the vehicle being driven before the process was complete and potentially resulting in damage if one module was at a high state-of-charge. It is proposed to carry this process out on the RHOLAB pack in a dynamic fashion, by continually isolating individual cells for a conditioning charge. This has resulted in the proposal to utilize 19 cells in each 36 V module, where one cell is routinely withdrawn from service for conditioning. If required, the permanent removal of a failed cell could still be carried out.

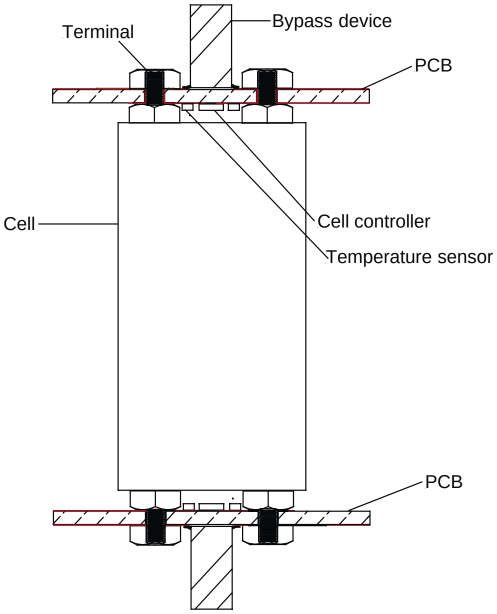

Fig. 16. Diagrammatic view of cell mounting on PCBs.

Warwick Manufacturing Group (WMG) examined the *Insight* vehicle installation in the light of the above decision to incorporate a 19th cell in each module. Other factors that were considered were:

- PCB manufacturing capability (normal maximum UK PCB panel size is 18 in. × 24 in.);
- target vehicle fit;
- module attachment to the vehicle structure;
- airflow within modules;
- interfacing of vehicle airflow supply;
- potential interference with airflow to power inverter module;
- battery condition monitor/motor control module (BCM/MCM) relocation;
- IMA case and frame modifications in the *Insight*;
- electrical interconnection of modules; and
- access to the spare wheel in the *Insight* vehicle.

The conclusion was that a '9 × 2 plus 1' cell configuration was preferable to a previous '6 × 3' proposal. This is illustrated in Fig. 17. A simple space model was built and tried in the empty *Insight* battery bay to confirm this decision. The proposed layout in the battery bay is shown in Fig. 18 which necessitates a modification to the IMA frame.

The change to the module shape has allowed an alternative construction method to be considered. This is for a sintered module case body, supporting the PCBs and incorporating the upper and lower air plenums, with two module end plates providing all interconnection functions. This method of construction greatly reduces the size and cost of tooling and would allow easy production of other voltage variants of the module (12, 24 V, etc.). Fig. 19 shows the prototype module casing. The cells have threaded terminals so that they can be secured on the PCBs with nuts—although other options may be examined for a speedier assembly process in large-scale production.

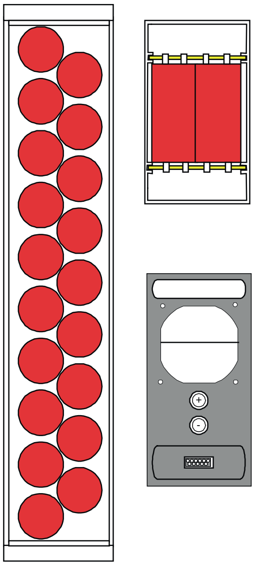

Fig. 17. Module layout and end plate design.

The end mouldings now incorporate most of the module physical functionality in their design (lifting handle, fan mounting, two power terminals, signal connector, air inlet, mounting brackets). It is intended that the same design of moulding would be used for both ends, variations in function being accomplished by the use of appropriate blanking plates.

2.5. *Development of the battery management system*

Provector and WMG have cooperated closely on the design of the battery and battery management systems as well as the software requirements. As it is desired to manage the battery at the cell level it is necessary to develop a BMS specifically for the RHOLAB pack. Therefore, BMS system

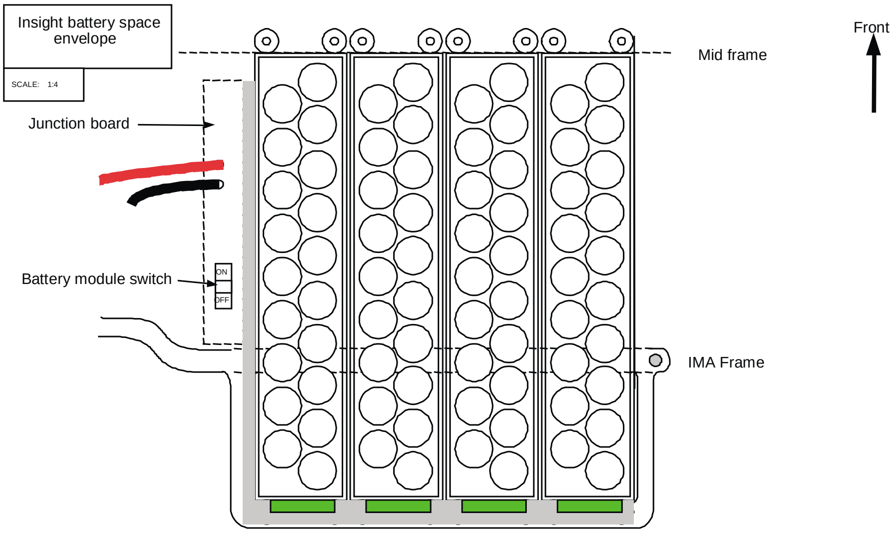

Fig. 18. Layout of proposed four module battery pack layout for the Honda *Insight*.

Fig. 19. Prototype module casing with cooling fan.

design has been looked at in some detail. The key objectives were:

- achieving the desired functionality;
- low production cost;
- potential for integration into custom silicon parts;
- ease of development; and
- reliability.

In this activity, alternatives for many of the sub-systems were looked at to determine the best overall approach. The key area is the location and approach to isolation. A good solution has been found which has considerable potential for integration leading to a low production cost.

The first main option considered is to isolate the cell processors from the module processor, which leads to a relatively large number of isolation barriers and limited opportunities for integration. The second main option is to isolate the module from the central controller, but to work within the module voltage range without isolation through the use of differential amplifiers and attenuated signals. This requires precision resistors or some calibration in the circuits which are removing the common-mode signals and is an inherently more complex analogue design. However, there is excellent potential for integrating many of the components into a single part on a production system and the approach is cleaner on the prototype. The power flows are also more easily managed with this approach.

The bypass and cell equalization (conditioning) strategy has also been considered carefully. In summary, the requirements are:

- to be able to bypass one or more cells in a module so that the module can continue to be used even when it has faulty cells that would otherwise prevent safe or satisfactory operation;
- to be able to condition one cell at a time, which requires energy to be passed in and out of the cell;
- to be able to carry out conditioning on a single cell even when the module is in use; and
- to minimize the energy lost during the conditioning process.

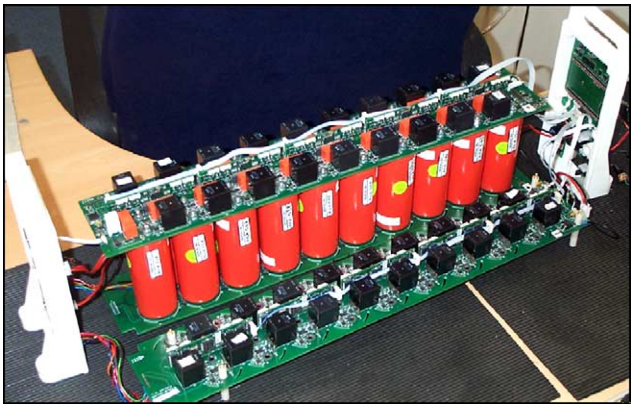

Fig. 20. RHOLAB battery module during construction and test.

A number of alternative designs were looked at and the final design adopted uses bypass relays which are configured to isolate the cell when in the bypassed position. A smaller relay is used to connect the cell to be conditioned to a conditioning bus which runs throughout the module. This bus is connected to two power supplies, the first of which supplies energy to the cell, the second removes energy from the cell. These power supplies are both connected to the module string voltage and source and sink energy from/to the module, respectively. The production implementation will be a custom isolated power electronic design. In the prototypes, modular, isolated supplies are used to create intermediate rails which will be connected to controllable elements that perform the detailed conditioning cycle. The current design uses a digitally controllable voltage source with 6 mV resolution with the option of feed forward adaptive current-control. The sinking supply will probably use a current sink flyback converter in production versions, although a simpler load bank is used in the prototype. Both source and sink supplies are in principle capable of rapid changes of voltage and current if required. The control of the bypass and conditioning process will be carried out

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Fig. 21. Data logger in the *Insight*.

by the module processor, which also controls the fan and heater elements in the thermal management of each module. Fig. 20 shows a module under construction and test.

2.6. Bench testing of a prototype battery module

The battery modules for the bench testing and for installation into the vehicle are in the final stages of construction. One module will be subjected to bench testing at Sheffield to the RHOLAB test profile as already described. However, the conditioning routine and state-of-charge of the module will be under the control of the BMS which has been developed. This work should start in October.

2.7. Bench marking of the vehicle with its Ni–MH battery pack

As indicated previously, the project has acquired a Honda *Insight* as a test vehicle for the RHOLAB battery. The specification for the testing of the vehicle at Millbrook was agreed and the initial detailed driving cycles defined.

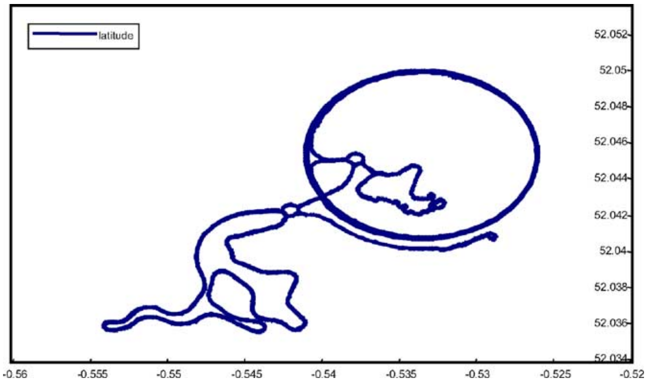

Fig. 22. GPS plot showing vehicle location during testing.

The logging system is based around an existing Provector PC104 stack repackaged in a box mounted on the top of the Honda IMA box lid. In addition to the interface to the Honda signals spliced out of the loom, the logger will record global positioning system (GPS), OBD II and thermocouple information. The logger is controlled by a dedi-

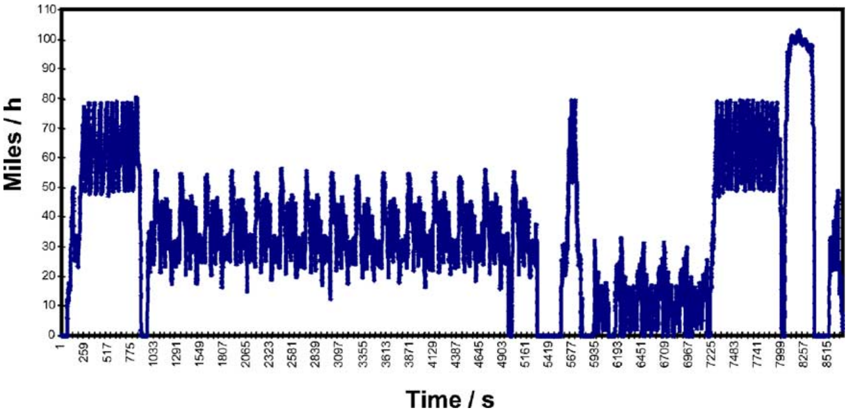

Fig. 23. Speed plot during the test sequence (acceleration run on the right of the graph).

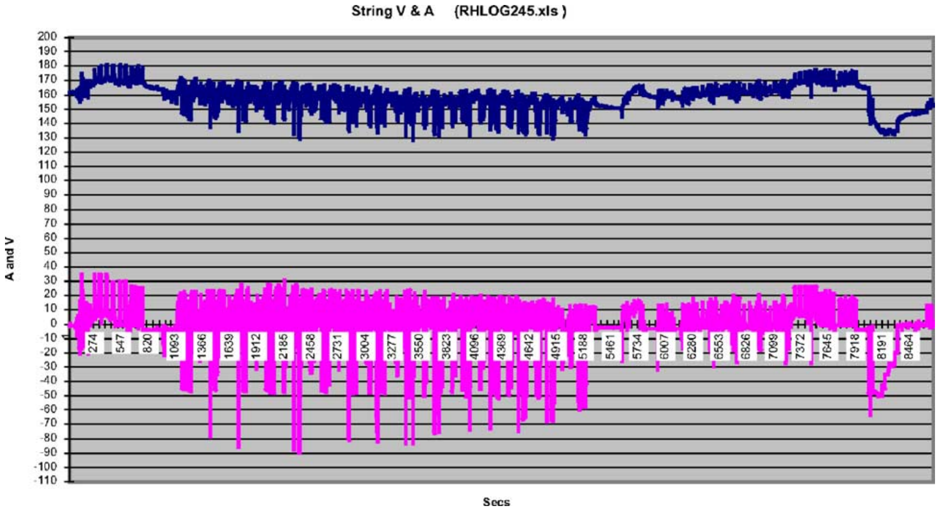

Fig. 24. Voltage and current traces during run.

cated control unit which is fixed to the dashboard and has a VGA display to output data and status messages. The logger design makes provision to take the RHOLAB system data, of which there will be a larger amount than with the standard battery, across a controller area network (CAN) link to the logger. The logger in position in the car is illustrated in Fig. 21.

The vehicle benchmark testing at the Millbrook Proving Grounds with the Ni–MH battery has been completed and the extensive data collected on the test has all been processed and bulk analyzed. Some further analysis is yet to be carried out to look at specific areas and to address questions raised by the testing. The Millbrook Report indicated that there were frequent driver reports of failure of the Ni–MH battery to recharge—particularly after the acceleration run and this has been attributed to the battery overheating. The fuel consumption in these tests is also significantly higher than that previously obtained—suggesting fairly rigorous testing. Some typical graphs from these results are shown below in Figs. 22–24. These show the GPS traces of the vehicle location during testing, the speed plot during a given test sequence, the equivalent string voltage and current from various sensors on the battery pack.

Once the RHOLAB pack is fitted to the vehicle, a 50,000 miles test with a similar driving cycle is planned. The battery should be available for fitting into the *Insight* during October 2003 and following some initial shakedown testing, the full testing at Millbrook will commence.

3. Conclusions

During the initial phase of the project, the design of the dual-tab cell was completed and the cells built and delivered. Subsequent testing of these cells under 'real vehicle' cycling regimes have shown that the cells will be capable of meeting the high input and output currents as demanded by the application.

Complex design work on the battery modules and the BMS has been completed and construction of these items is well advanced. Bench testing of a module with its BMS should start in the last quarter of 2003.

The benchmark testing of the *Insight* with its Ni–MH batteries has been completed and the vehicle should be fitted with the RHOLAB battery in the last quarter of 2003. It will then undergo testing at Millbrook of up to 50,000 miles under the agreed programme.

Acknowledgements

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