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A Reliable, Highly Optimized, Lead-Acid Battery (RHOLAB) for Affordable HEVs – A Foresight Vehicle Project

Allan Cooper
European Advanced Lead-Acid Battery Consortium

Andrew Loyns
Hawker Batteries Group

Mike Kellaway
Provector Ltd

David Stone
University of Sheffield

Robert Ball
University of Warwick

ABSTRACT

The objective of the Project is to develop an optimized lead-acid battery solution for HEVs based on a novel, individual, spirally wound valve-regulated lead-acid 2V cell optimized for HEV use and low variability. This cell will be 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 will be thoroughly evaluated by substituting it for the NiMH pack in a Honda Insight.

The paper covers the first half of the 3-year project and will describe work carried out in the following areas:

- Development of cell and battery testing facilities and identification of mechanisms causing cell lifetime scatter.
- The design and development of the prototype double-ended cell.
- The development of the battery pack specification and pack design.
- The development of the battery management system.

The paper will also give details of the test results obtained on the demonstration vehicle with its original NiMH battery. Arising from these tests, there will be discussion of the merits of bench testing with a cycle derived from 'real vehicle' data as compared with the PNGV or Eucar power assist life cycle tests.

INTRODUCTION

BACKGROUND AND PROJECT OBJECTIVES - Uniquely among the battery systems claiming to be candidates for powering electric and hybrid vehicles, the lead acid battery is both cheap and is produced by well-established manufacturing organizations around the world. It also has a good infrastructure for recycling. While the traditional flooded lead acid battery is often presented as an ancient technology with limited scope for improvement, the sealed, or valve regulated (VRLA), designs adopted for the recent development work on batteries for EV applications, have a history scarcely longer than those of the newer battery chemistries. However, unlike these newer technologies, they are already available at reasonable cost.

At the beginning of the 1990's, the valve regulated lead acid battery available for consideration in electric vehicles had a very poor cycle life coupled with a modest specific energy and required a long time for recharge. Since that time, a worldwide programme of research has been carried out by the Advanced Lead Acid Battery Consortium and the performance of this type of battery has been improved dramatically. For example, specific energy has almost doubled in certain designs to around 45 Wh/kg, cycle life has increased by a factor of 10 to better than 750 cycles and, instead of an 8 hour recharge being the norm, 50% of charge can be returned in 3 minutes, 80% in 10 minutes with a complete recharge taking only 30 minutes. The key factors to this improved performance have been shown to be the need to compress and constrain the positive active material during the life of the battery, proper design of the separator to avoid acid stratification and the use of improved alloys with better corrosion resistance and creep strength. The correct management of charge and discharge of the battery is also a critical factor.

Much of the research has been done at the cell or module level (6 x 2V cells). What is needed now is work to reduce cell-to-cell variability and on the optimum way to assemble cells into a complete battery system. This complete system would include means of measuring data on cell condition and a central management system. Existing prismatic modules are not ideal for construction of a complete vehicle battery system as they have inherently different thermal conditions for different cells in each module. Because of this variation, and any performance scatter in the cells themselves as manufactured, there is generally a problem with shortened battery pack lifetimes caused by individual cell lifetime scatter. A single cell failure renders the battery inoperable. The modules are also not designed as a 'system' component that facilitates complete pack assembly, thermal and battery management and maintenance.

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 sulphation. 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 VRLA 2V cell as a building block and to develop a complete battery pack design that is optimized for a hybrid vehicle. The design concept must be scalable to allow it to be used in a range of vehicle applications from small, 36V power-assist hybrid cars to large 300V hybrid buses. 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 to install and maintain and must be equipped with thermal management which allows the fundamental performance to be optimised for different ambient temperatures, allowing the pack to operate effectively over an external ambient temperature range of at least –20C to +40C. 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.

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

PROJECT PLAN – The project plan as specified consists of the nine different activities outlined below:

<u>Activity A; Identification of Mechanisms Causing Cell Lifetime Scatter</u>. A programme of research will be carried out to identify and quantify the mechanisms that cause cell lifetime scatter. A flexible, PC-controlled test facility will be constructed which will also be used for the bench-testing programme in Activity H.

<u>Activity B: Design and Development of the Prototype Double-ended Cell.</u> In this activity, Hawker Batteries will build on their previous research with CSIRO in Australia which has demonstrated benefits from using double-ended prismatic cells, in order to design and construct a double ended, spirally wound cell. The approach offers potential improved thermal performance and reduces the effects of acid stratification.

<u>Activity C: Evaluation and Development of Cell State-of-Charge Models.</u> Various SOC models exist for lead-acid batteries. These range from simple electrical models to complex models which attempt to simulate the electro-chemical processes within a cell. The simple models enable the SOC to be evaluated quickly, but have a relatively low accuracy. The more complex models are computationally intensive making them slow or expensive to use. The utility of the various models in the difficult hybrid application will be evaluated and developed as appropriate for HEV applications, incorporating the lessons from Activity A.

<u>Activity D: Battery Pack Specification.</u> To focus the project a detailed specification will be drawn up for the complete battery pack, based on the 'user' requirements of the test vehicle. The specification will include requirements on cost, crashworthiness, recyclability, drive cycle, weight, fitting and refitting, instrumentation etc. Future vehicle trends will be incorporated. Where possible, relevant automotive standards will be called up and utilized.

<u>Activity E: Battery Pack Design and Development.</u> The whole system design must take account of a wide variety of factors including the cell-retaining structure material

and method of manufacture, thermal management, safety systems, power and signal interconnect, EMC, and any other factors identified from Activity A. As part of this activity, ways of cell conditioning and by-passing failed cells to give the pack a measure of fault tolerance will be examined.

Activity F: Battery Management System Development. A key part of the project will be the battery management system. The approach to be taken is to use individual cell controllers and to use a novel means of communication to link these to the central control system, which will also act as the interface to the rest of the vehicle and control the safety systems and thermal management. The prototype BMS hardware and software will be used for the test modules for both bench and vehicle trials.

Activity G: Prototype Battery Pack Engineering. Based on the results of Activity E, a 36V module can be prototyped using the best materials for the application. This will allow visualisation of the design, fluid flow measurements to be made, and a route through to tooling manufacture to be produced. After any redesign as a result of this work, the prototype pack will be detailed and manufactured Once the components are available the prototype modules and battery pack will be assembled ready for bench and vehicle tests.

Activity H: Bench Testing. The performance of the new pack will be evaluated on the test rig developed in Activity A. Analysis of the data collected from both the pack BMS and additional sensors will be used to assess the pack performance.

Activity I: Vehicle Testing. The two obvious choices for a test vehicle were the Toyota Prius and the Honda Insight, both of which were due to be on sale in the UK during 2000. Of these the Honda Insight was preferred as this has a lower voltage battery (144V) and is potentially easier for fitting of the prototype pack. It is planned to carry out an instrumented benchmark test of the test vehicle, as supplied, in order to evaluate the vehicle performance over an extended period and to investigate any deterioration of the standard pack (Ni/MH), particularly evidence of cell performance scatter. Once the prototype lead-acid pack is available this will be tested in the same way. It will be necessary to reproduce the test vehicle battery management dialogue from the prototype BMS to allow the vehicle to operate as normal.

PROJECT PROGRESS

The Project officially started on 1 September 2000, but unfortunately, due to some difficulties with notification to the Universities, some start up delays to the work have occurred, particularly at Sheffield. This means that work there is some three months behind plan. However, the rest of the Project is progressing well and progress in the various activities is reported below.

ACTIVITY A: Identification of Mechanisms Causing Lifetime Scatter. The work at Sheffield has concentrated on the design and construction of the cell conditioning and cycle testing rigs. An example is shown in Figure 1. This rig will simultaneously condition or measure the capacity of up to 16 cells, in a controlled temperature environment. The voltage, current and temperature of each cell are continuously monitored.

A temperature-controlled enclosure has been constructed from Perspex, the cells being supported between two sheets of Perspex which have a matrix of holes for ventilation. A rack-mounted heater/ventilation unit has been constructed to provide a stable and repeatable temperature environment in which to make accurate cell capacity measurements.

The cell driving cycle rig will subject two cells simultaneously, but independently, to the power/current demands of a user-specified driving cycle, in a controlled temperature environment.

The module driving cycle rig will subject a complete battery module of series-connected cells to the power/current demands associated with user defined driving cycles, in a temperature controlled environment. The cells will be selected after characterisation in the cell conditioning/capacity measurement rig.

Hawker Batteries initially supplied 160 standard Cyclon cells for these initial investigations and have subsequently supplied a number of the dual tab design. In view of the previously mentioned initial delay and some further problems in commissioning the rigs, it has been decided to concentrate the work on the new cell design.

ACTIVITY B: Design and Development of a Prototype Double-ended Cell. 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. 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 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 use a double terminal arrangement for the cell with a current take-off for both the positive and negative plates at each end of the cell, as illustrated in Figure 2. This improves active material utilization, reduces internal thermal gradients and increases cycle life. The concept has been demonstrated by Hawker Energy Products, in collaboration with CSIRO Energy Technology, Australia, (patent applied for) for flat-plate cells and this activity is developing this concept for cylindrical cells. In addition, the cell design is being optimised through the use of improved separation techniques and active materials to improve performance. The cell case will use an ABS/polycarbonate alloy rather than the steel jacket normally used. This is to give the cell enhanced high temperature and safety characteristics.

The design of the new cell was completed and all tooling and capital equipment for conversion of the cell assembly line was delivered on schedule. The first batch of cells was delivered in October 2001. A group of 18 of these cells is seen being readied for test in Figure 3.

In Figure 4, the comparison is plotted between the performance of the dual tab cell when it is connected at only one end and at both ends when subjected to a 250A (31C) constant current discharge. In this condition there is a clear difference between the configurations; the cells connected at one end have discharge times ranging from 8.1 to 18.6 seconds but the double-ended cells are more consistent with times from 26.5 to 28.2 seconds. This gives a clear indication that the dual tab design should have improved high rate discharge and recharge properties.

ACTIVITY C: Evaluation and Development of Cell State-of-Charge Models. HEVs generally use a battery as a short-term energy store that allows the heat engine to be operated in an optimum way. The battery is required to source and sink large and rapidly changing currents. Batteries for HEVs are generally operated in a partial SOC where they are most able to supply and accept large currents. Operation close to this point also helps to extend the service lifetime of the batteries. However, achieving this requires several problems to be overcome. The cells must remain in balance across the battery; have the same thermal environment and hence operating parameters; the estimate of SOC must remain accurate over long periods; and the BMS must correctly deal with rapidly changing conditions.

Cell balance is necessary so that all cells in a string operate similarly. It is important to ensure that each cell's voltage is accurately controlled during periods when it is accepting current. If the cells become imbalanced, the impressed voltage across the string is not equally divided between the cells, consequently they react differently. In all operating conditions, the thermodynamics of the cells are influenced by the voltages across them and imbalances cause internal heating differences which can only partially be dealt with by external thermal management. The capacity of each cell also varies as the battery becomes imbalanced, which reduces the usable capacity of the whole battery and results in lower capacity cells being worked harder and accelerating their deterioration. Once cells become imbalanced, the situation tends to worsen and a remedial charging regime is required. To avoid this, the cells must be kept in similar thermal environments, as temperature has a major influence on cell operation. It is likely however, that some kind of routine 'maintenance' charge cycle will be required from time to time to maintain the energy capacity of the cells.

The actual SOC of each cell must therefore be determined with some accuracy if the control system is to keep the cell at the correct operating point. This is difficult in the dynamic conditions found in hybrid operation but, if not done well, results in the cells' SOC drifting towards the high or low charge regions where their performance and lifetime are reduced. Most existing systems estimate the charge flow in and out of the cell from string current measurement and adjust this to take account of the cell's ability to store and deliver this charge, which itself is a function of temperature and cell state of charge. Most systems can remove drift in this estimate when the cell is fully charged. This is determined by observing the cell reaching a specific voltage, which must be corrected for cell temperature. A hybrid vehicle may never reach such a point and other means must be devised to provide the same function. Cell temperature is particularly difficult to measure with any confidence using a single sensor applied to one point on the cell after the cell has been manufactured. The most advanced battery management systems also detect failing cells from their voltage and temperature characteristics in operation. Some have the ability to add or remove a small amount of charge to assist in cell balancing.

Work to date has concentrated on providing means to determine accurately the string current flows and make spectroscopic impedance measurements. The module design will also allow individual cells to be brought to top state of charge if necessary to correct estimator drift.

ACTIVITY D: Battery Pack Specification. This has been completed and the document can be summarized in the following general description.

Product Perspective - The RHOLAB pack is designed to offer the hybrid car manufacturer an attractive battery pack option based on lead-acid cells. The key benefits of lead-acid are its low cost and established recycling infrastructure in comparison with Nickel and Lithium-based batteries.

The product will be designed to maximize the reliability of the complete pack with an overall objective of requiring no replacement of any cell in the normal life of the car. The pack will also incorporate many features to simplify the design, instillation and operation of the vehicles using the pack. This will include integration of components to reduce cost, weight and size; carefully designed thermal management of the system; integration of other system components (such as contactors and safety circuits) within the pack; and elimination of inter-wiring where possible.

Product Functions - The prototype pack will provide a nominal 144V 8Ah supply. The cells used will be thermally managed to equalize and optimize their temperature such that their performance and reliability is maximized. An intelligent battery management system will monitor all of the cells and provide equalization where required. This system interfaces to the overall vehicle management system, which can control some of the functions within the pack, such as the contactors, and obtain status information when required.

The battery management system also controls bypass elements which it can switch across failing cells to prevent them overheating. This allows the pack to continue to be used safely without requiring service with only a very small performance penalty. The bypass system can therefore greatly improve the reliability of the whole pack.

The prototype pack will incorporate safety circuits to detect potentially hazardous conditions and provide means of disconnecting the cells from the output terminals under remote command or manual intervention. Ventilation is also required to prevent the build up of hydrogen although this is not generated during normal operation.

User Characteristics - The final users of the pack will be automotive design and development engineers with considerable electrical system engineering and interfacing expertise. They will, however, be very demanding and require excellent documentation, thorough testing and a high-level of support.

The prototype pack is only required to be used by the project team but should demonstrate that the needs of final users have been taken into account. The prototype pack is to be tested in a Honda Insight.

General Constraints - The final pack must meet appropriate legislation and standards. These have been identified wherever possible but there are likely to be changes and extensions as with any new type of vehicle. Where possible, flexibility should be designed in to facilitate changes if required.

Recycling of the 2V cells is of particular importance and a process for initial dismantling must be identified.

ACTIVITY E: Battery Pack Design and Development. The current state of the art has produced single lead-acid cells that can give reasonable lifetime if operated at favourable temperatures and away from low or high SOC points. However, in typical vehicles up to 150 cells or more are operated in a series string. Manufacturing and operational differences of the cells in the string often result in considerable scatter in the cell service lifetimes and early failing cells create substantial imbalances within the string, further worsening the conditions. The construction and location of the batteries tends to make replacement of a single failing cell uneconomic, particularly as this needs to be done promptly to avoid safety problems. It is not a simple matter to operate a mixture of partially used and new cells in a string and may not be possible in many cases. There are generally no fault tolerant elements built-in to a lead-acid battery although these have been used in other types of battery to overcome high cell failure rates within sealed systems.

Typical lead-acid batteries are constructed from modules, which are usually made up of 3 or 6 x 2V cells. These modules require power interconnect and various other systems such as safety circuits and thermal and battery management systems to be integrated together to form the complete battery pack. In many cases, this ends in a solution that is expensive to install and maintain, particularly where battery management system requirements result in a considerable number of signal conductors within the battery pack. There are also difficulties with making meaningful temperature measurements where the sensors have to be added to standard cells after manufacture, which is generally the case. There has been little work done to design the whole battery as an integrated system generally by the vehicle manufacturer.

This project starts from the basis of using the 2V double-ended Cyclon cell as the building block for the individual 36V 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 proposed design of the Rholab battery by mounting the individual cells between two printed circuit boards as illustrated in Figure 5. It has been demonstrated that there is adequate current-carrying capacity for the battery when a 3 ounce copper foil is used on the 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 wires 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. Subsequent work within the ALABC has indicated that a potential problem of operating lead-acid batteries continuously in partial state of charge is sulphation 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. 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 36V 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.

Warwick Manufacturing Group have revisited 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 x 24 inches)
- 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
- BCM/MCM relocation
- IMA case and frame modifications
- Electrical interconnection of modules
- Access to spare wheel in the Insight vehicle.

The conclusion was that a '9 x 2 plus 1' cell configuration was preferable to a previous '6 x 3' proposal. This is illustrated in Figure 6. A simple space model was built and tried in the empty Insight battery bay to confirm this decision.

The change to the module shape has allowed an alternative construction method to be considered. This is for an extruded 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 allows easy production of other voltage variants of the module (12V, 24V, etc.). This is illustrated in Figure 7. Work continues into options for securing the cells to the PCB.

The end plates now incorporate most of the module functionality in their design (lifting handle, fan mounting, 2 power terminals, data terminal, air inlet, mounting brackets). It is intended that the same design of end plate would be used for both ends, variations in function being accomplished by the use of appropriate blanking plates.

In order to improve the cooling airflow, a two-piece, low-density, flame-retardant polypropylene foam moulding is proposed to loosely enclose cells within the module casing, leaving a 10mm gap around the periphery of each cell. Airflow can thus be directed to the surface of the cells to avoid stagnating in corners, whilst also providing thermal insulation and reducing the lost volume of air to be heated/cooled.

ACTIVITY F: Development of the Battery Management System. As it is desired to manage the battery at the cell level it is necessary to develop a BMS for the Rholab pack. Therefore BMS system design has been looked at in some detail. The key objectives are:

- Achieving the desired functionality
- Low production cost
- Potential for integration into custom silicon parts
- Ease of development
- 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.
- To minimise the energy lost during the conditioning process.

A number of alternative designs were looked at. MOSFET-based solutions were dropped because of their relatively high cost, drive requirement and energy lost through heating. The final design adopted uses a bypass relay which is configured to isolate one end of the cell when in the bypassed position. A second, smaller relay is used to connect both ends of 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 will be 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 0.1V resolution with the option of feed forward adaptive current-control. The sinking supply will probably use a current sink flyback converter, though further work is required here. Both source and sink supplies are in principle capable of rapid changes of voltage and current if required. The rated current still has to be fixed, but will be in the region of 5A.

Although single ended conditioning is probably sufficient for a production solution, the prototype will be fitted with the capability to condition from either end or both together. The control of the bypass and conditioning process will be carried out by the module processor.

ACTIVITY G: <u>Prototype Battery Pack Engineering.</u> With the design of the module almost complete, work continues at Warwick Manufacturing Group on the various components for the modules in readiness for the delivery of the new Cyclon cells.

ACTIVITY H: <u>Bench Testing.</u> This activity awaits some input from Activity A and the production of the prototype modules from Activity H. However, thought has been given to the test schedules to be used in this Activity. Examples of standard PNGV and Eucar Hybrid Electric Vehicle test schedules are given in Figures 8 and 9.

Initial testing of the Honda Insight with its NiMH batteries has been carried out and had the objective of investigating the vehicle's response to a set of standard test conditions available at the Millbrook Proving Grounds. 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:

- 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 SOC around
- Confirmation of OBD II connector functionality
- Developing understanding of Insight operation
- Developing planned instrumentation fit for main vehicle test.

Some examples of data accumulated are shown in Figures 10 to 14. This initial vehicle testing has produced some interesting and useful results. It has been possible to characterise the current and voltage signals and shown the range of values under various operating conditions. These have been shown to be:

- Maximum regenerative current 95A pulse, 50A continuous.
- Maximum drive current 70A pulses, 50A continuous
- Voltage recorded 120 to 190V.

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 tests.

The proposed 'real data' test cycle for the bench testing which is likely to be used alongside one of the standard test cycles is shown in Figure 15. Figures 16 and 17 compare the performance of a 18 cell pack of the original Cyclon Cells as compared with the newly developed twin tab variety when subjected to this test profile. The old cells voltage drops to 5V after 1000 seconds whereas the new twin tab cells complete the test without problem – confirming the benefits of this configuration.

ACTIVITY I: <u>Vehicle Testing.</u> As indicated previously, the Project has acquired a Honda Insight (see Figure 16) as a test vehicle for the RHOLAB battery. As stated above, the test specification is now agreed and the initial detailed driving cycles defined. Once the vehicle is fully instrumented, testing can proceed quickly. The special voltage-tapping isolation requirement and need to interface to serial, pulse-width modulated as well as digital signals has meant that some custom interface boards needed to be designed for the logging system. The work is under way, and the opportunity to create a cell controller prototype that can also be used as part of this logger interface will bring forward work on the cell controller hardware.

The logging system will be 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 GPS, OBD II and thermocouple information. The logger is controlled by a dedicated control unit which will be 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 CAN link to the logger.

Current intentions are to run on the NiMH batteries for 5,000 miles with the agreed driving cycle to benchmark vehicle performance. Once the Rholab pack is fitted, a 50,000 miles test with the same driving cycle is planned.

CONCLUSIONS

The RHOLAB Project has got off to a good start with most Activities running to plan. The new double-ended Cyclon cells have been delivered on time and the development work on the prototype battery pack and BMS design are progressing well. The test facilities are complete so that the work on the causes of lifetime scatter in cell performance and general cell performance testing are both underway.

The work on the vehicle has resulted in good understanding of the modus operandi of the Honda Insight and the work on instrumenting the vehicle for its' testing at the Millbrook Proving Ground is progressing well.

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CONTACT

For further information please contact: Allan Cooper of the European Advanced Lead Acid Battery Consortium, email: ACatCorfe@aol.com

DEFINITIONS

ALABC: Advanced Lead Acid Battery Consortium
BCM: Battery Condition Monitor
BMS: Battery Management System
CAN: Controller Area Network
EMC: Electro-Magnetic Compatibility
GPS: Global Positioning System
HEV: Hybrid Electric Vehicle
IMA: Integrated Motor Assist
MCM: Motor Control Module
NiMH: Nickel/Metal Hydride
OBD: On-Board Diagnostics
PCB: Printed Circuit Board
RHOLAB: Reliable, Highly Optimized Lead-Acid Battery
SOC: State of Charge
VRLA: Valve Regulated Lead Acid
WMG: Warwick Manufacturing Group

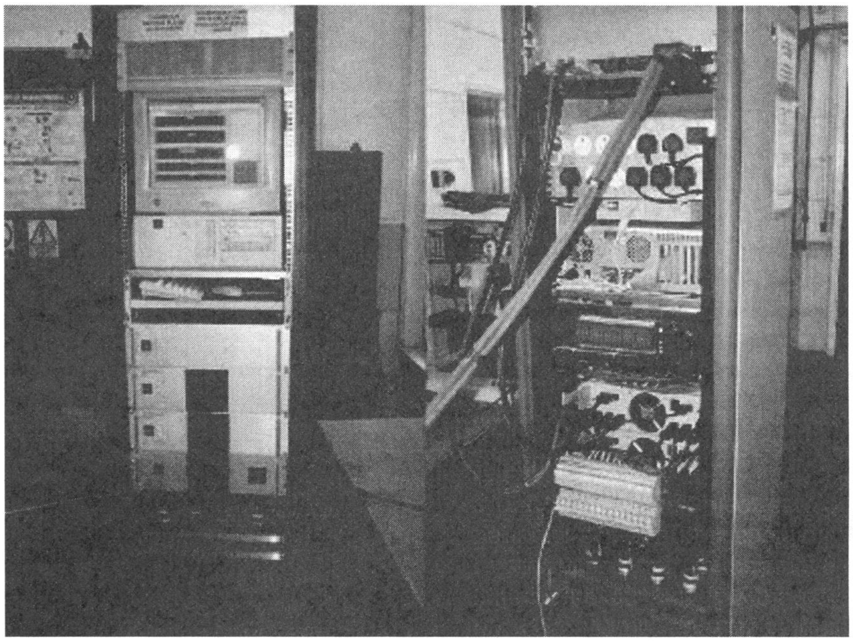

Figure 1: Cell Conditioning and Cycling Rig

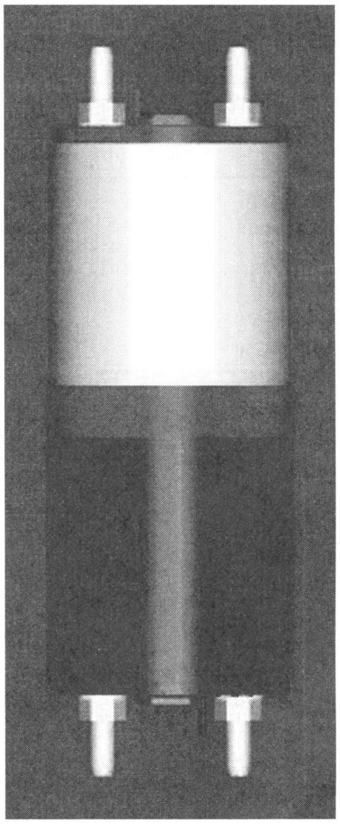

Figure 2: Double-ended Cyclon Cell

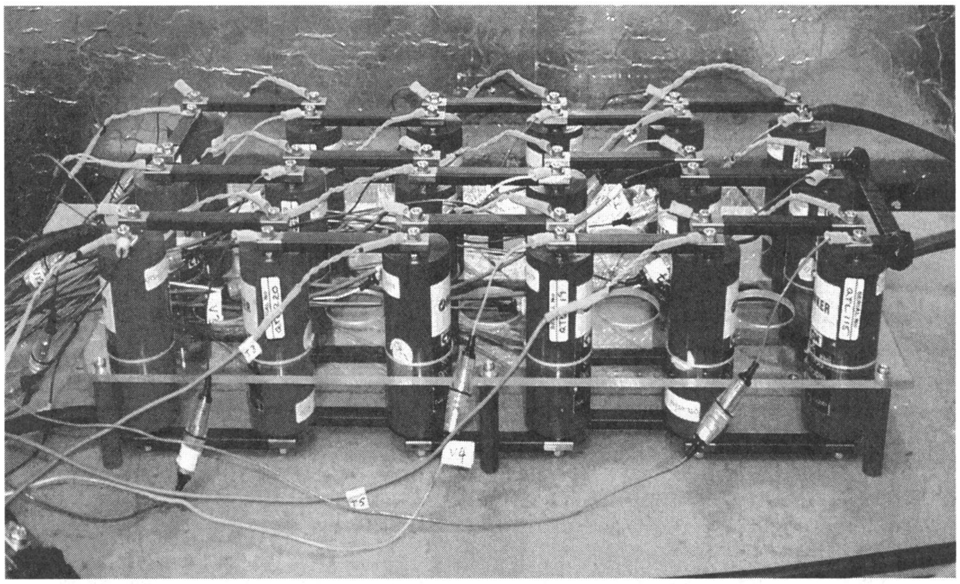

Figure 3: Double-ended Cells on Test in Sheffield Rig

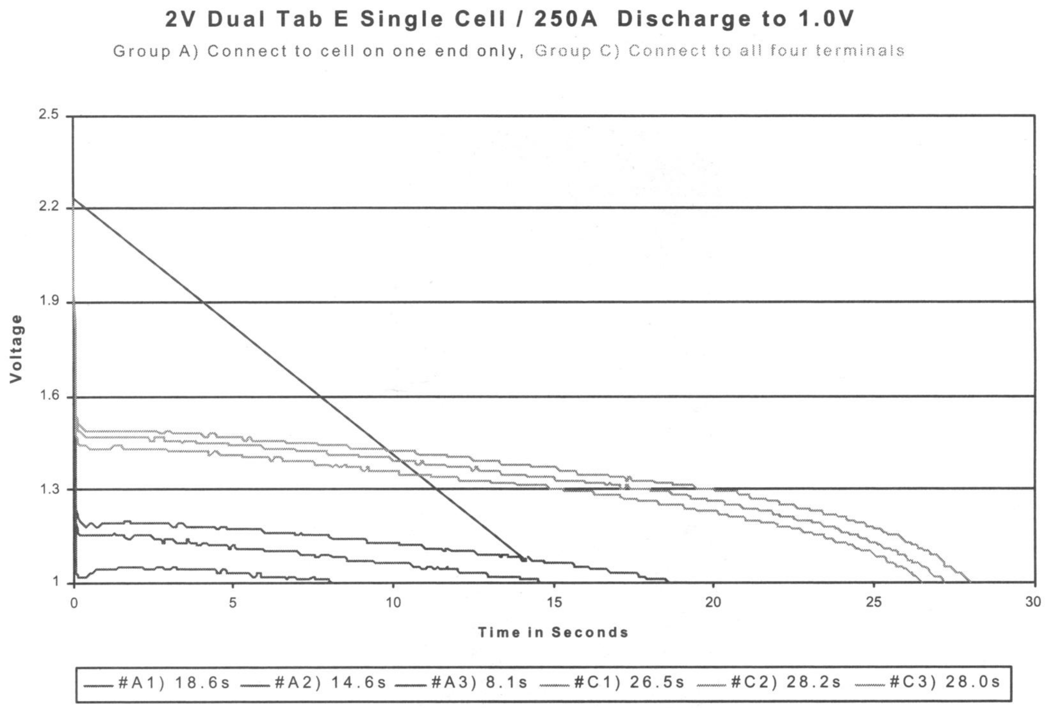

Figure 4: Comparison of Constant Current 250A Discharge with Connections to One End only and Both Ends of the Cell

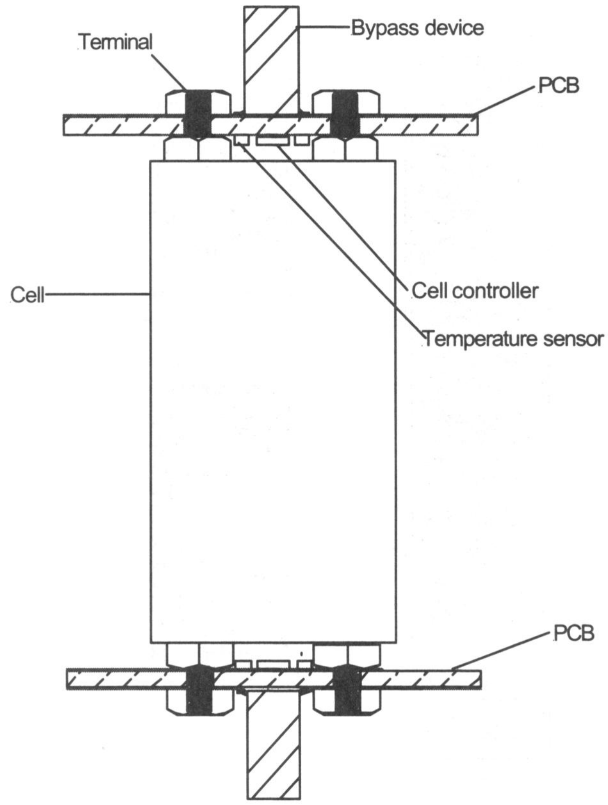

Figure 5: Diagrammatic View of Cell Mounting on PCB's

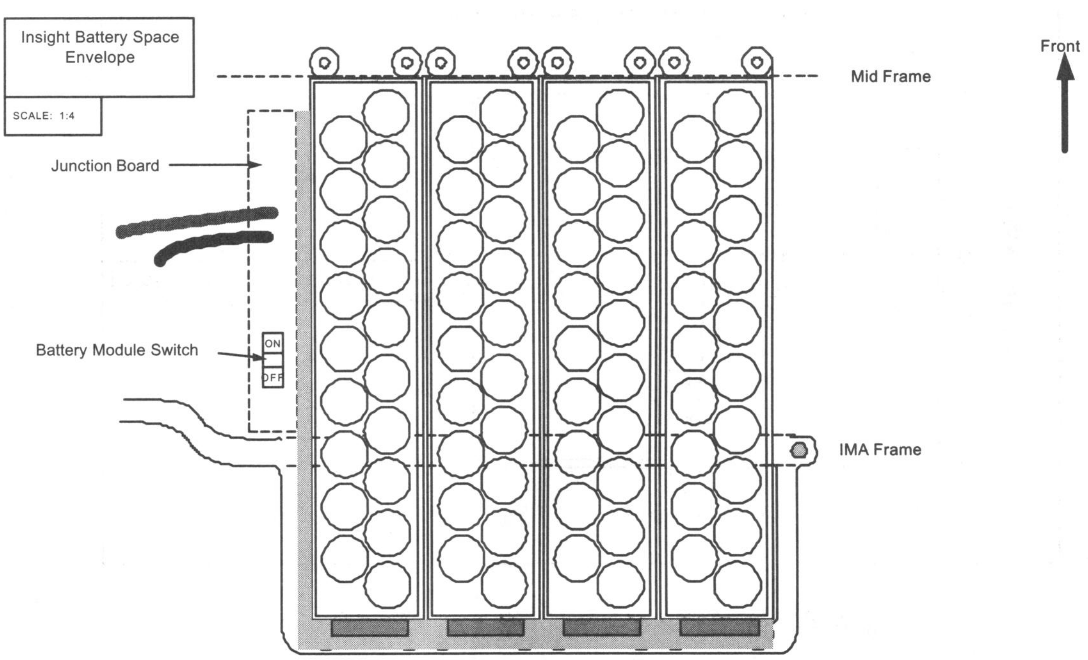

Figure 6: Layout of Proposed Four Module Pack Layout for the Honda Insight

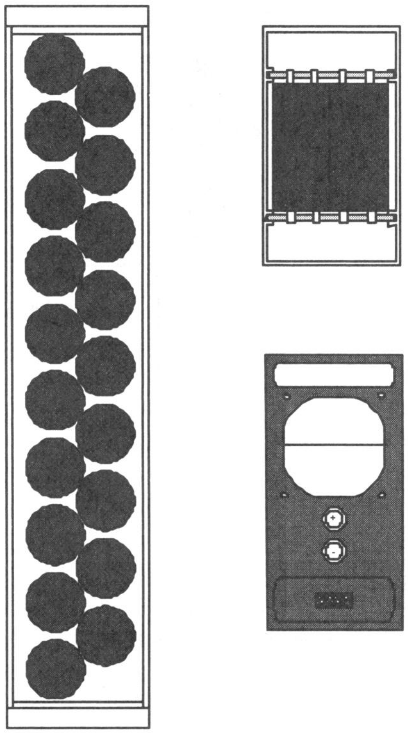

Figure 7: Module Layout and End Plate Design

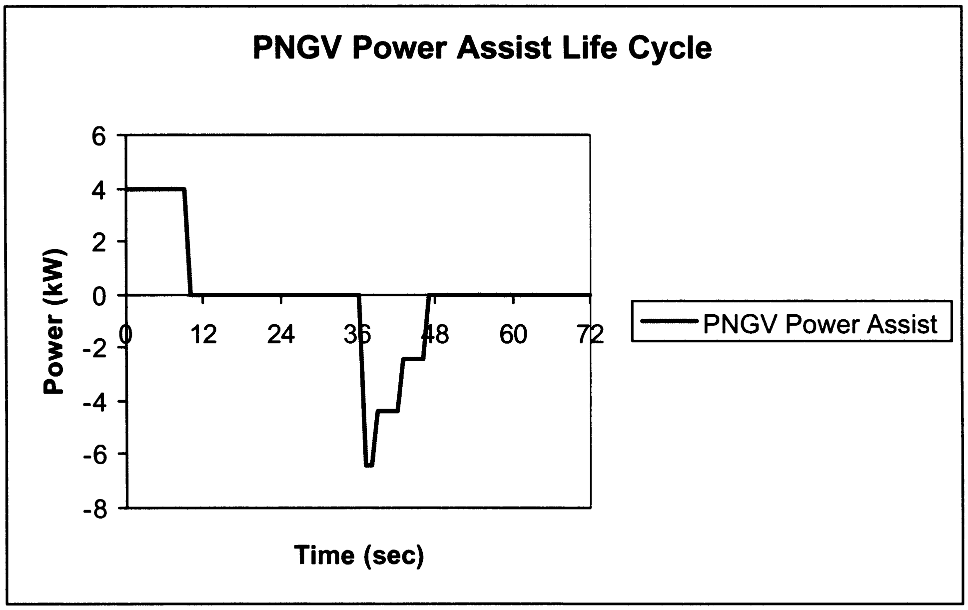

Figure 8: PNGV Power Assist Life Cycle Test Profile

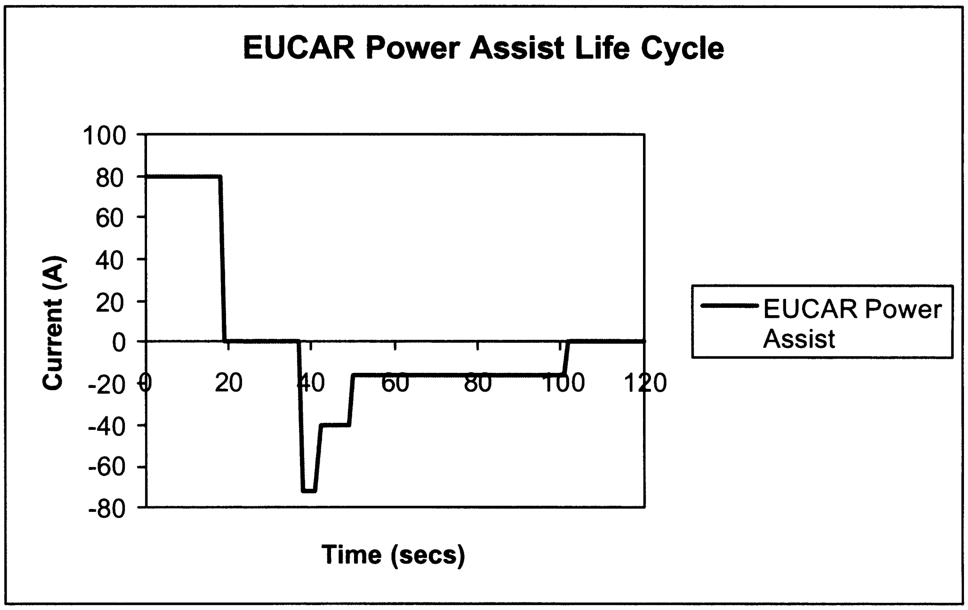

Figure 9: Eucar Power Assist Life Cycle Test Profile

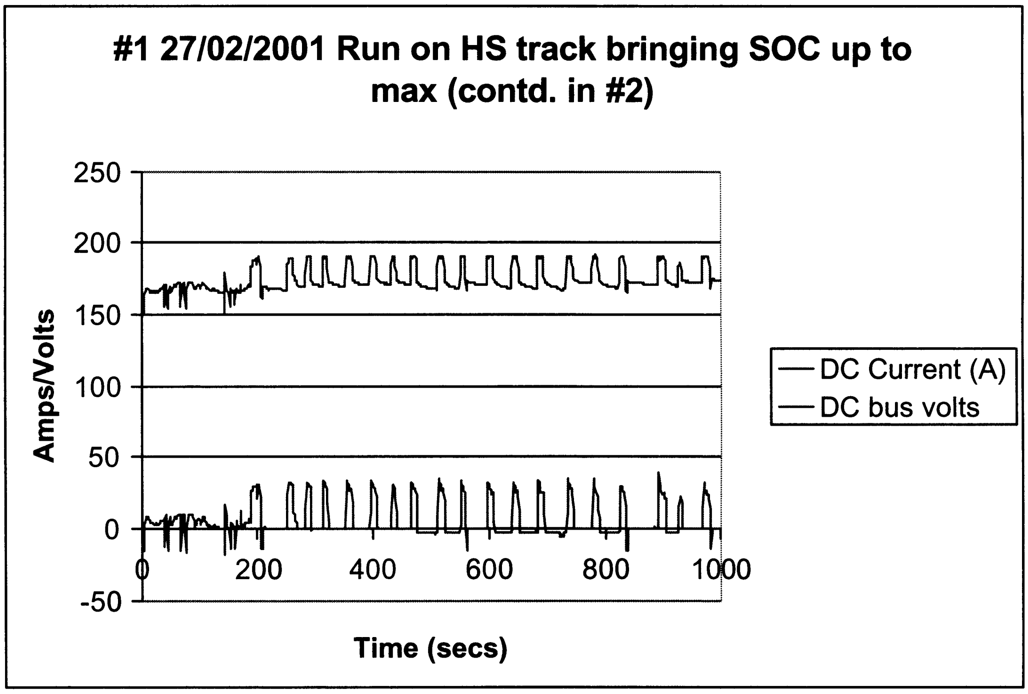

Figure 10: Current and Voltage Variation – High Speed circuit (Part I)

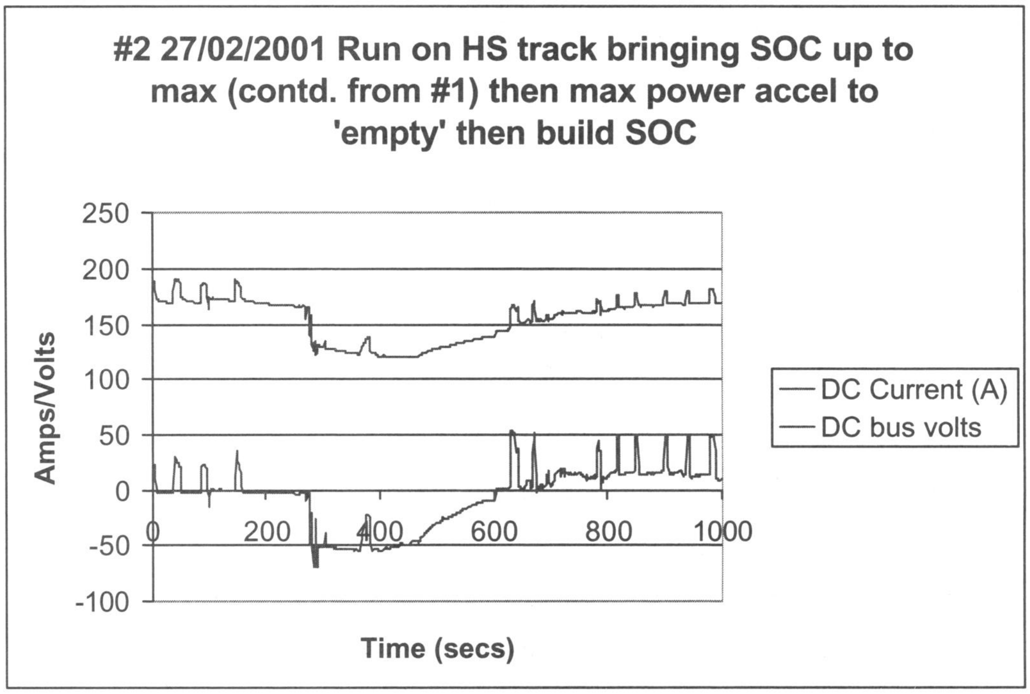

Figure 11: Current and Voltage Variation – High Speed Circuit (Part II)

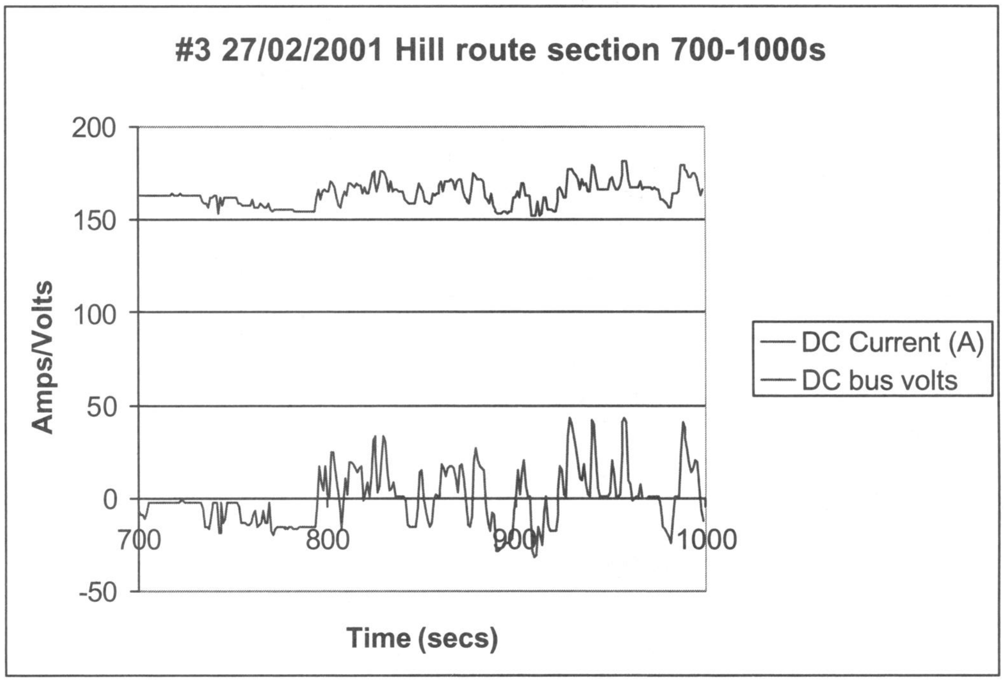

Figure 12: Current and Voltage Variation – Hill Route

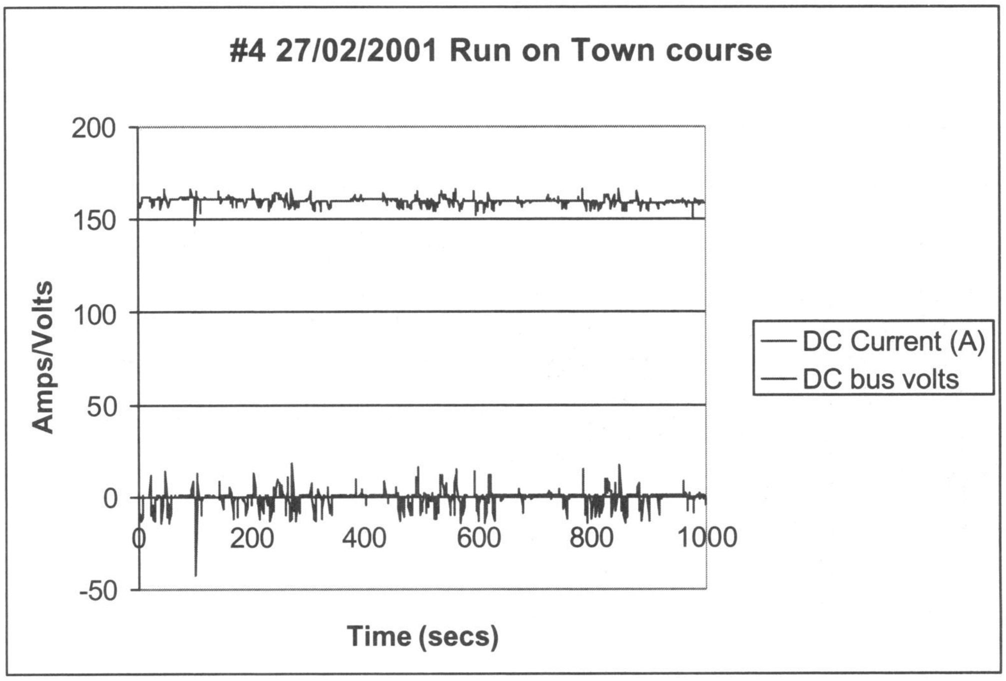

Figure 13: Current and Voltage Variation – Town Course

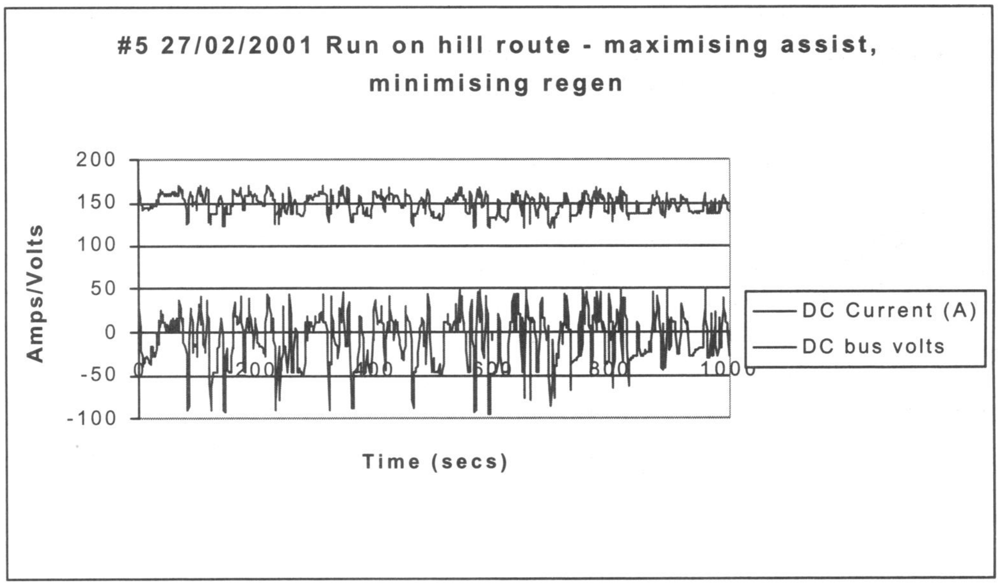

Figure 14: Current and Voltage Variation - Aggressive Driving on Hill Course

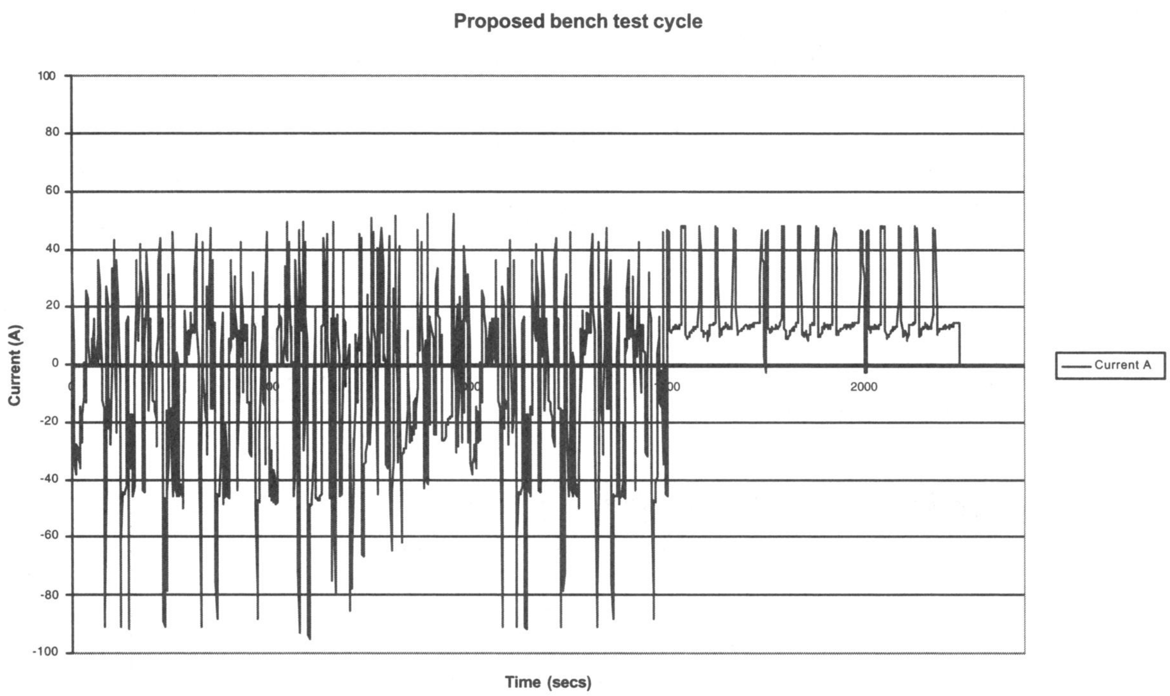

Figure 15: Proposed 'Real Data' Bench Test Cycle

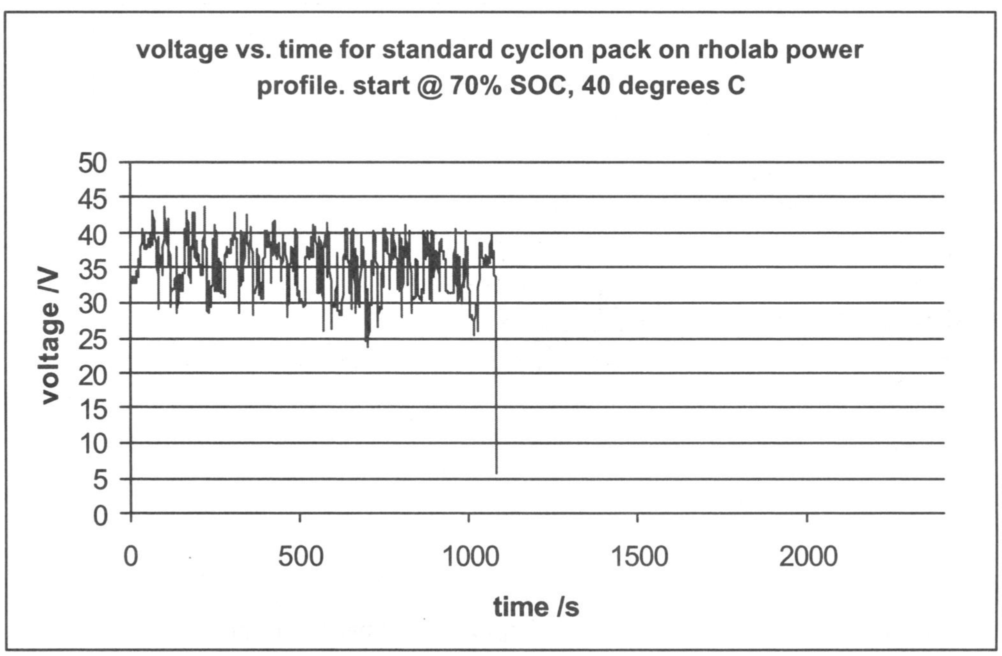

Figure 16: Voltage of Standard Cyclon Cell Pack when Subjected to the Rholab Test Profile

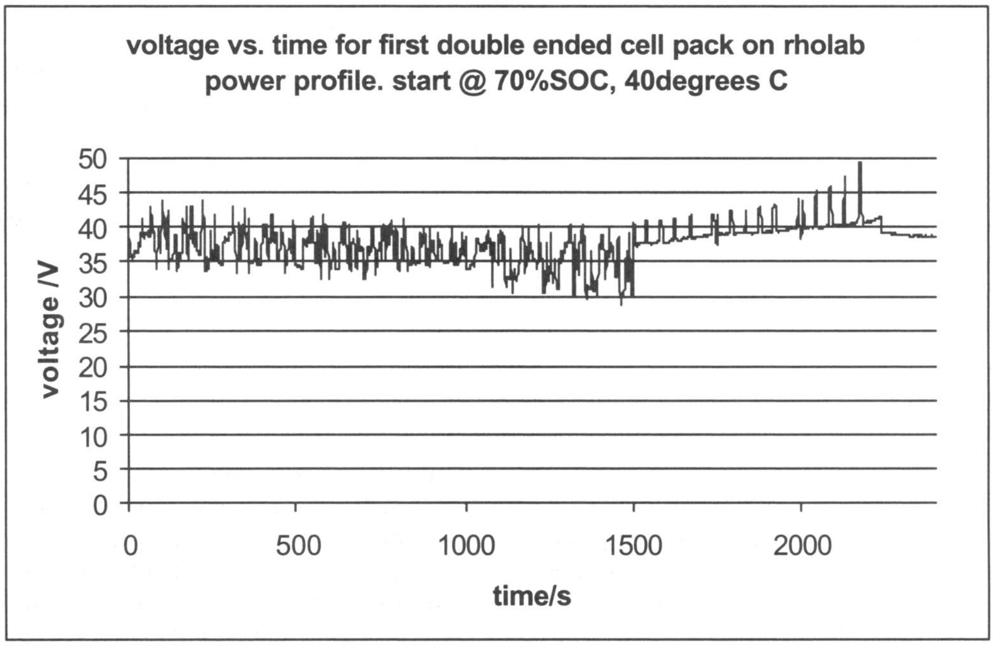

Figure 17: Voltage of the Cyclon Dual Tab Pack when Subjected to the Rholab Test Profile

Figure 18: The RHOLAB Honda Insight Test Vehicle