ZEBRA (ZERO EMISSION BATTERY RESEARCH ACTIVITY) BATTERY
THE SOLUTION TO SUBMARINE ENERGY STORAGE

BY

LIEUTENANT COMMANDER N. BENSTEAD BENG(HONS), CENG, MIMAREST RN
(*MLSIPT – MoD Abbey Wood*)
D. WILLIAMSON BENG(HONS)
(*Rolls-Royce plc*)

This is an edited version of the paper that was presented at the RINA Warship 2005 Conference *held on 22 June 2005.*

ABSTRACT

For over a hundred years, the lead acid battery has met the need for electrical energy storage in ships and submarines. For most of that time, this was the only viable option and even the advent of nuclear submarines did not remove the need for batteries, due to the requirement to ensure safe operation.

In recent years alternative technologies have become available, particularly closed cycle diesel engines and batteries based on alternative chemistries. The ZEBRA battery represents one of the most advanced and safe alternatives to lead acid and can meet the power demands of a submarine. The technology is fully developed for the automotive market and is close to being available for naval marine applications. It will be able to support practically any energy storage requirement for naval applications, from a standby source for instrumentation systems through to full propulsion system support, and is ideally suited for submarine installations.

The article will explore and discuss the benefits of ZEBRA over lead acid, which have prompted investment from the UK MoD. Higher energy density and the prospect of significantly reduced through life costs have resulted in a programme of development work funded by the UK's Submarine Marine Engineering Development Programme.

This work presents the work being done to make ZEBRA available for naval applications and concludes with a view of energy storage for future submarines.

Introduction

Since the very first submarines a suitable battery has been fundamental to the overall safety and operation of the platform. The main battery in a submarine has been specified as a Lead Acid Battery (LAB) for over a century now – the design has improved but the principles remain the same. Whilst these batteries have performed admirably it is generally acknowledged that operators have come to accept their shortfalls, since the technology and maintenance regimes are well understood. We are now nearing the time that we can remove the need for such time consuming and costly maintenance requirements, removing the potential hazards that arise through the use of LABs and therefore reduce the likely through life costs of a submarine main battery.

As submarines developed, the main battery's role evolved from being the main source of power for the propulsion when dived, as in conventional submarines, to being an immediate back-up for essential support functions for the propulsion and instrumentation in a nuclear submarine. LABs were used in this role as they were able to float on charge and provide the instant back up required for this role. They did have a number of recognized shortfalls and it was these that tended to dictate the operating profile of the submarine.

Background to ZEBRA

The need to re-assess the use of LABs in submarines came about because technology has continued to develop and is now in a position to replace them in submarines. The technology used today in submarines is, in the most part, similar to that used when LABs first went to sea. Technologies available now that will in future provide the required amounts of energy include fuel cells, flywheel technologies, and flow cells, amongst others.[1,2] In those papers the author described LAB experience, other established technologies and outlined the ZEBRA battery and its characteristics. The intention in this article is therefore not to dwell further on other technologies.

In general there is a reluctance to move away from LABs in submarines. This is for a number of reasons, which can be judged to represent the opinion that other technologies are unreliable, or not yet ready, or simply that LABs have got us this far so why replace them? There are also the counter arguments that ask whether lead acid would be selected now as the best system to use as a main battery. The fact is that LABs can be unreliable and known failure modes and short circuits can lead to the battery self discharging, sudden 'death', or cells requiring replacement, and that single cell failure can degrade the overall performance of the battery. The battery is only 'lifed' for a set number of years and so submarine refits are tied to this periodicity to provide a reliable and robust back up for reactor safety. The main battery in most submarines is a very large item of equipment, and so can only sensibly be replaced during upkeep and maintenance periods. In the meantime, between upkeep periods, the battery is required to undergo periodic capacity tests, is subject to agitation of the electrolyte and is vented continuously so as to remove hydrogen gas that is given off. It is also normally sited in a lined compartment to prevent corrosion from any spilt acid, and requires the maintainer to go through more and more safety procedures, such as donning IPE for personal safety.

ZEBRA is a system that allows the battery to be charged and retains 100% charge regardless of whether the battery is maintained at temperature or is left to cool down. There is a small load (50W) to provide the required heating to maintain the battery temperature. The system gives off no emissions, resists over charging and if it does fail, it fails in a benign manner that has no significant effect on the battery overall. The voltage remains the same and there is only a minor drop in capacity, unlike the LAB which loses capacity and voltage.

Work previously presented on ZEBRA

Much work has previously been presented on ZEBRA batteries, highlighting a proven track record in the automotive industry – indeed they have already been used in cars, buses and light goods vehicles since 1984. Their use in the marine industry is evolving and much work is underway to investigate their use and installation as a submarine main battery. A major advance in the marine use of the ZEBRA battery is in its selection for use in the NATO Submarine Rescue System (NSRS) a joint venture between the UK, French and Norwegian governments. Whilst this represents a major advance in the use of ZEBRA batteries at sea, it was not required to pass all submarine related safety criteria as the batteries are housed in sealed pods and not in manned compartments. The batteries in this role make use of their suitability for traction, but also instrumentation and life support for this versatile submersible. It is envisaged that the batteries fitted will exceed the performance criteria that were initially required of the batteries in this role and initial performance tests are demonstrating that this is the case.

Fuel Cells/AIP and Diesels

The use and development of a replacement battery for submarines cannot be considered without looking at the other alternatives that are available. These include systems such as fuel cells and Air Independent Propulsion (AIP) diesels. These types of system do have their own advantages and disadvantages, not least because they are able to provide the propulsive power required for a dived submarine. Where they do not work so well is as a standby system, ready to react in the event of an unplanned reactor shutdown or system blackout, so that a battery of some form remains essential for system support.

The ZEBRA system

FIG.1 – TYPICAL ZEBRA BATTERY

The ZEBRA battery (FIG.1), is a high performance, zero emission, loss-free Sodium/Nickel Chloride battery system. The technology has been adopted by Rolls-Royce as an ideal candidate for energy storage in submarine and surface ship applications.

The battery module is compact, being about 40% of the weight of an equivalent LAB, and is constructed from a series of cells that are secured within a double skinned steel chamber, with a layer of evacuated mineral insulation between the two skins.

The battery system comprises assemblies of modules, with various ancillary features whose configuration depends on the application requirements; the modules are assemblies of cells. The battery system combines a Battery Assembly, the Battery Installation, which is designed to suit the application, and a Battery Management System (BMS).

The fundamental unit of the battery system is the ZEBRA cell. This is a sealed container that holds all the active components with no emissions during normal battery operation.

The nickel/sodium chloride and the sodium aluminium chloride granules that form the positive electrode are inserted into the cell, which is then completely sealed. This means that the cell is completely inert upon manufacture. Once the entire module has been manufactured, the cells are heated, and it is at this stage that the secondary electrolyte melts to allow the battery to be charged. As the battery reaches full charge the only requirement is to heat the battery (at low power) to ensure the battery is maintained in an optimum condition. Should this power be removed the electrolyte solidifies and the battery can be considered to be ready for storage. If the battery is needed again, it must first be heated for 24 hours to ensure that it is ready for use. In a standby role the battery will be heated continuously meaning that the battery is ready for immediate standby use. The battery is a 'hot' battery – that is, the temperature inside is around 270-350˚C but owing to the insulation materials and thermal jacket the external temperature of the battery module is only approximately 5˚C above ambient temperature. It is for this reason that the battery operates independently of the outside atmosphere, and cooling requirements vary according to the role.

Each ZEBRA Cell has a nominal Open Circuit Voltage (OCV) of 2.58V. The cells are connected together in series strings to provide full system voltage. Each string has a capacity defined by the Amp-Hour capacity of the cell type used and for marine applications this is expected to be 38Ah for an ML3 Cell. This capacity applies for any length of string of cells. Coupled with the voltage for a particular string, the energy rating of the string is then defined as kWh =Ah*V. The physical size of each cell type is fixed, so to provide a battery of greater capacity than that given by a single string, the strings are connected together in parallel.

Depending on the topology of the system and module thermal efficiency calculations a single module may contain more than one string of cells. The standard electric vehicle battery comprises 216 cells in two variants; a single cell string at 557V or two parallel strings at 278V. The single string module has a capacity of 38Ah/21kWh while the twin string module has a capacity of 76Ah/21kWh. Note that the kWh capacity is defined by the number of cells in the module, regardless of topology. If more capacity is required than is available from one module, modules are connected in parallel. The module dimensions can be customized to the application. As mentioned previously, the modules operate at an internal temperature of approximately 270-350˚C in order to maintain the optimum performance of the system.

The major failure mode of cells results in a 'short circuit' that is chemically inert but maintains approximately the resistance of a normal cell. Failure of a single cell simply results in the loss of one cell's worth of voltage, coupled with an equivalent loss in power delivery. Consideration of a single string of cells within a system shows that at least 10% of cells can be lost before the applied system voltage causes over-charge damage and total failure of that string. Practical considerations included the ability of a 'weak' string to contribute to the system, resulting in the present assessment that a module should be removed from service when 5% of cells in a string have failed.

At system level, modules are connected in parallel to deliver the total capacity required for the system, and a submarine main battery will contain in the order of one or two hundred modules. When a module eventually contains sufficient failures to be removed from service, simply operating an isolation switch will clear the fault at a cost of between one half and one percent of total installed capacity.

Benefits of ZEBRA

As outlined above there are many benefits to be gained from using the ZEBRA battery system in a submarine main battery. These can be broadly broken down into the maintenance benefits, operational advantages, and also benefits that can be realized through improvements in safety and final disposal.

Maintenance Benefits

In the marine environment LABs require constant maintenance to give the operator maximum confidence that the battery will be available on demand. LABs use a number of corrosive and flammable materials in their construction and give off a flammable and explosive gas during normal operation. Although ZEBRA does contain liquid sodium this is contained by a sealed and protective environment and has the advantage of giving off no corrosive, flammable or explosive by-products, either in normal operation or in all but the most extreme cases of abnormal operation. Without the hazardous environment, control of access and entry for routine maintenance are much simplified; only standard precautions associated with access to any electrical compartment are required. Without fumes and chemicals being given off there is no requirement for a lining to be in place inside the battery compartment, and hence a hull inspection can be carried out with the battery still in place. It is envisaged that ZEBRA batteries will be mounted on a rack system, which in itself can be shock mounted if necessary. Another maintenance advantage of the ZEBRA system is that the maintainer can identify the exact module where there may be a failure and is able to interrogate each module to identify its state of charge and temperature. The maintainer would have access to the monitored parameters for each module and can therefore plot cell failure rates or stand a module down once a predetermined number of cells has failed. There are many different possibilities and the exact operational advantages and disadvantages would be considered before deciding on any standard policy.

ZEBRA modules can be replaced individually without isolating the remainder of the battery and therefore without loss of battery availablity. The main battery therefore no longer governs maintenance routines for the submarine. Given the success of trials to date it is envisaged that a ZEBRA battery will be lifed for the lifetime of the platform.

Operational advantages

There are also advantages to be made on the operational side of the battery system. The ZEBRA battery is able to accept charge very quickly for the first 80% of its charge cycle and has a high endurance, whilst also having a degree of flexibility built in. In its role as a standby power source all that is required is to maintain heater power, which is not a significant drain on the submarine’s power system. Given that each module of the ZEBRA battery is fitted with its own operator interface it is therefore possible for the maintainer to interrogate each module in order to check performance and maintenance routines.

The maintainer can be confident that with this continual monitoring of the system defects are notified and can be rectified before they become significant. Also the State of Charge indication provides an accurate indication of the energy remaining in the battery, as a percentage and a true capacity reading, removing the need for reference to time to run curves etc. Another advantage of the ZEBRA battery is that although the battery is ‘hot’, it is enclosed within an insulated, evacuated steel container so that the battery is unaffected by ambient conditions. The battery is also able to operate at angles of up to 75° from the horizontal, greater than any system requirement for submarine operations. The life of the module is reduced if it is operated at any greater inclination, but trials have demonstrated that a module will operate upside down, for at least several days.

Safety benefits

As mentioned previously the ZEBRA battery module will not give off any gaseous by-products and will withstand a lot of abuse, including prolonged overcharge. Without the explosive gas environment, there is no requirement for either a dedicated ventilation system or an installation that is intrinsically safe for the associated hazards (explosion, fire etc.). Normal ventilation will provide the environmental control required. Tests for the automotive industry have shown that the system will withstand a prolonged intense petrol fire and impact testing.

Final disposal

In recent years, lead has become a major environmental issue and its disposal is now subject to legislation in many industrial sectors. Naval applications are presently not included in such legislation but, even if this does not occur in the near future, it is likely to be politically expedient to address the problem of disposal of the large amounts of lead used in LABs and for ballast.

The ZEBRA battery contains no pollutants or materials of environmental concern. The module can be completely disposed of by recycling as feedstock for a blast furnace, from which the metals can be recovered and the remaining materials come off as benign salts in the slag.

Proving of technologies

As previously explained, ZEBRA is a COTS technology that has been developed for application in electric vehicles. It has been used in either single module applications (electric cars) or small parallel arrays (electric buses). Parallel applications have largely been integrated into hybrid systems and have not included parallel charging. These applications have incorporated protection, by contactors, at module level and include a control and monitoring system using software that is of unknown pedigree (SOUP), which has been developed through several different organizations by many different engineers. A preliminary safety assessment has shown that such protection, particularly considering common mode failures, cannot be used in submarine main battery applications.

Developing the technology for naval marine applications requires demonstration of both performance and environmental compliance. Rolls-Royce has been testing the performance of the technology for several years. As part of its ongoing assessment through the Technology Readiness Level (TRL) system the MoD has determined that the technology has developed sufficiently for its support to be added to the project. The strategy for testing is broken down into several key areas:

- Parallel Discharge

  It must be demonstrated that many ZEBRA modules will share a large load through the full range of operation (i.e. from fully charged to fully discharged), that this sharing will continue for modules containing weak strings and that this will be achieved without automated individual module protection.

- Parallel Charge

  It must be demonstrated that a high power charging supply through a single point of connection will be distributed sufficiently evenly that an acceptable overall charge time without degrading the modules can be achieved.

- Charge Time

  The charging regime applied so far has been developed for the known market, assuming ideal conditions and a vehicle being parked up overnight to allow the charge. Trials are required to investigate alternative charging regimes to reduce charge times, particularly in an environment where partial charging is likely to be the norm.

- Short Circuit

  ZEBRA delivers a significantly higher fault current at system level than LABs. Although an individual module only delivers in the order of 350A per string into a short circuit, this equates to roughly double the value for an equivalent LAB for a conventional submarine battery tank. In addition, an uninterrupted short circuit will eventually result in destruction of the module, due to cell failure, resulting in a vapour emission. This vapour can react with any moisture in air to give a mildly acidic atmosphere. Theoretical assessment suggests that at worst this vapour will cause a minor irritation and no lasting effects. However, a trial is planned to determine both the electrical transient response to short circuit and the quantitative effects of allowing the short circuit to heat the module to destruction.

- Shock Testing

  Trials are planned to determine the level of shock protection, if any, required to mount ZEBRA in a naval application.

- EMC Testing

  Testing against naval EMC standards rather than the normal IEC standards are planned to take place over the next twelve months.

- Testing of alternative software

  A new control and monitoring system is being developed. In particular, some of the present monitoring algorithms require isolation of the module from the system for a short period of time by opening the contactors. As this option will not be available in a submarine main battery application, alternative algorithms have been developed and these will be validated by additional trials.

To continue the development of the technology, Rolls-Royce and the MoD are undertaking a series of work packages to assess the performance of the technology, including a joint project to run a trial with a ZEBRA battery in a 24V Transformer Rectifier Unit (TRU). This work will culminate in proving that the ZEBRA technology will work in a submarine operational environment to demonstrate that the technology is suitable for marine applications. A subsequent piece of work will investigate integration issues relating to the application of ZEBRA in submarine systems, and will include:

- Parallel array testing.
- Short circuit testing.
- Shock analysis.
- EMC confidence testing and preliminary safety assessments.

- Through life cost modelling.

Summary of Trials Results

Rolls-Royce's partner in the development of this technology is Beta Research and Development in Derby, UK. Their facility includes a test bay that allows individual cells to be monitored for modules of up to 10 cells, which has been invaluable in early development testing to establish alternative charging regimes.

ZEBRA cells are presently charged using a constant voltage charging regime, at 2.67V per cell, with a current limit of 10A, with full charge taking approximately 7 to 8 hours. Initial trials have been carried out to establish requirements for operation in a float arrangement and to determine alternative charging regimes that could reduce charge times.

Small Module Float Charge Testing

Trials have been implemented to float a ten cell module at 27V, 27.5V and 28V. The higher value has been used as the limiting voltage for current MoD applications. The modules are put through approximately 100 cycles of operation to be representative of full platform life for this type of application. The criterion of note for the trial is the resistance of the module, which increases through life, and the ability of the module to deliver an acceptable power level at end of life. Note that the Ah capacity of the module does not change and is still available at end of life, although at a reduced maximum power because of increased cell resistance. Additionally, after each discharge cycle, the modules were allowed to charge, at the float voltage, without limit on charge current, to determine the effect on charge time. To date, the first two trials have been completed and the third is approximately half way through. For the 27.5V trial, typical results profiles are as shown in (FIGs 2 and 3).

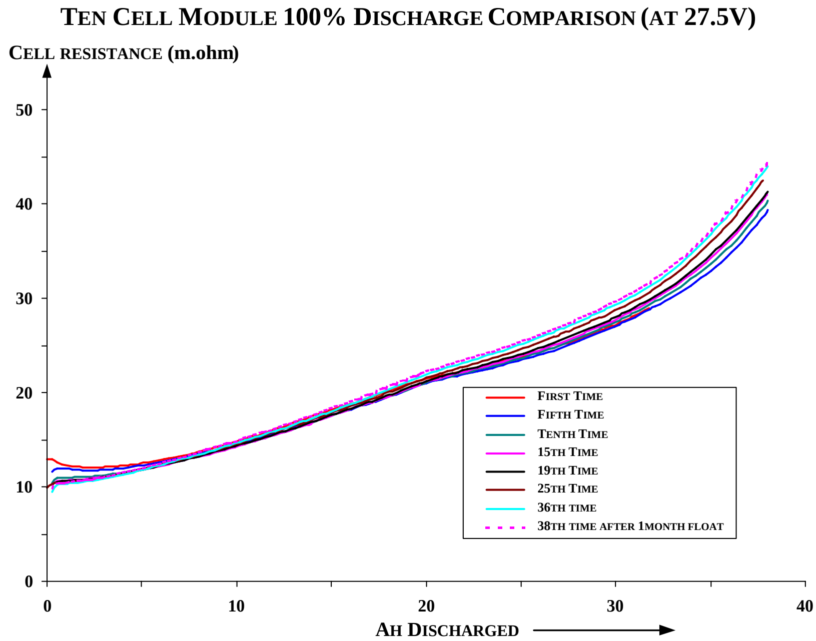

FIG.2 – FLOAT CHARGE AT 2.75V/CELL

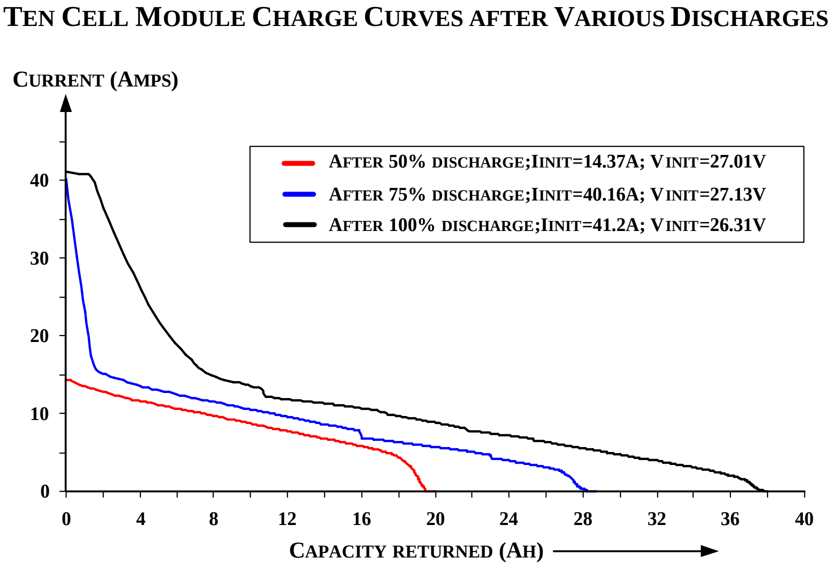

FIG.3 – FLOAT CHARGE WITHOUT CURRENT LIMIT

FIG.2 demonstrates that there is no significant effect over the life of the module from the operating regime, and FIG.3 demonstrates that a high percentage of the charge can be replaced quickly. (Note that the charge current from 100% Depth of Discharge (DOD) was limited by the capability of the charger used but can be extrapolated to approximately 50A).

As a result of such high charging currents, the nickel granules in the cathode become 'polarised', with increasing resistance during the latter stages of the charge. The overall result is that the total charging time is not significantly reduced, however, the trial clearly demonstrates that a large proportion of the total energy can be returned very quickly. ZEBRA modules do not require maintenance charging to completion, so that not completing a charge has no overall detrimental effect. As the monitoring system uses measured values to calculate state of charge, there will always be some error in the calculated State of Charge resulting in a drift from the true value over time. It is recommended that a full charge is carried out occasionally as this gives the major set point against which calculated values can be calibrated. As this is not required for battery health, such charges can be scheduled as convenient when the battery is not required or when operational conditions permit.

MoD Rationalized Internal Communications (RICE) TRU Minor Trial

As part of its increasing support to the ZEBRA project the MoD is facilitating the installation of a ZEBRA module in a UK Submarine to carry out operational trials. The chosen application is as a replacement for the LAB currently in service as back up to the 1kW RICE TRU. The battery in this application is required to deliver 1kW of power for 1 hour. The existing battery, while meeting the requirement when new, quickly degrades, even with ideal maintenance and has to be replaced regularly as a result.

A RICE TRU has been supplied to Rolls-Royce for installation in the ZEBRA Module Array Test Facility (MATF) at the Raynesway site in Derby. This TRU is being used to integrate a ZEBRA module into the system, both electrically and mechanically, as well as allowing implementation of interfaces to operators and to identify all training requirements for operators and maintainers. Rolls-Royce has procured a 24V ZEBRA module, containing 4 strings of 10 cells to give a total installed capacity of 150Ah/3.8kWh nominal. It should be noted that this module uses the main standard production cells (the ML3G) which are too large for the available space envelope. The final trial module will therefore use an alternative cell, possibly the ML4G, giving a final installed capacity of 125Ah/3.25kWh nominal, and will occupy a similar space envelope to the current lead acid module.

LEAD ACID VERSUS ZEBRA BATTERY DISCHARGE COMPARISON

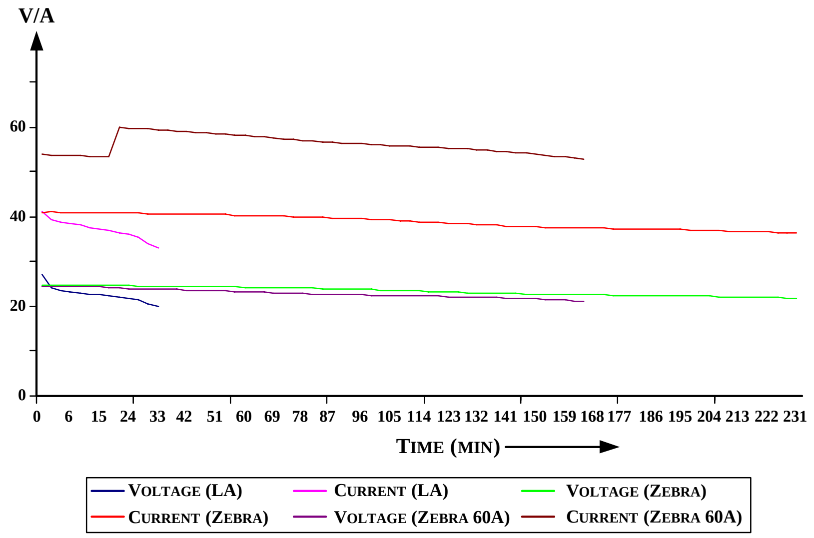

FIG.4 – LEAD ACID AND ZEBRA BATTERY DISCHARGE COMPARISON

Initial discharge comparison trials have been carried out between the ZEBRA and LAB modules with results as shown in (FIG.4). The figure shows that the discharge voltage and current curves for ZEBRA are significantly flatter and that ZEBRA provides the required system power for a significantly longer period. The system specification is for support for 1 hour with an initial discharge rate of 42A and the test battery lasted for just under 4 hours at this rate. The 60A discharge trial was carried out to use the trial battery to represent fitting of a battery of lower capacity running at the required 42A discharge. The LAB used (supplied by the MoD with the TRU) managed only half an hour, although it is known to meet the system requirement when new. Allowing for the smaller cells that may be used in the submarine trial, the ZEBRA module will clearly last about 3 times longer than the LAB, with a significantly flatter voltage profile (even with a 50% higher discharge rate). This is also without maintenance requirements and with full operator visibility (through the Battery Management System) of the module status at all times.

Integration of the module into the TRU is presently considering module floating and charging. The ten cell module trial described above suggests that the module can be permanently floated and charged at 27.5V. It is expected that by the time of the trial itself a 28V regime will have been approved, to give the maximum terminal voltage to allow for volt drop at the load. The TRU itself is being analysed to determine the optimal DC output of the rectifier for the transformer tappings available.

High Voltage Module Parallel Operation

The MATF is primarily used to test modules for submarine main battery applications. An initial fit of six batteries, to be expanded to ten in August 2005, is being tested to meet the previously mentioned issues of discharging and charging of large arrays, particularly with regard to the removal of individual module protection. The set comprises three healthy modules, one with one failed cell and two with two failed cells to allow some through life assessment with degraded modules.

Each of the batteries has been subject to a series of individual baseline trials to provide data against which parallel trials can be assessed. (FIG.5) shows the voltage change for all six batteries, at various rates of discharge, when discharged individually. Note that the legend has been omitted for clarity.

COMBINED GRADE CURVES FOR INDIVIDUAL DISCHARGES

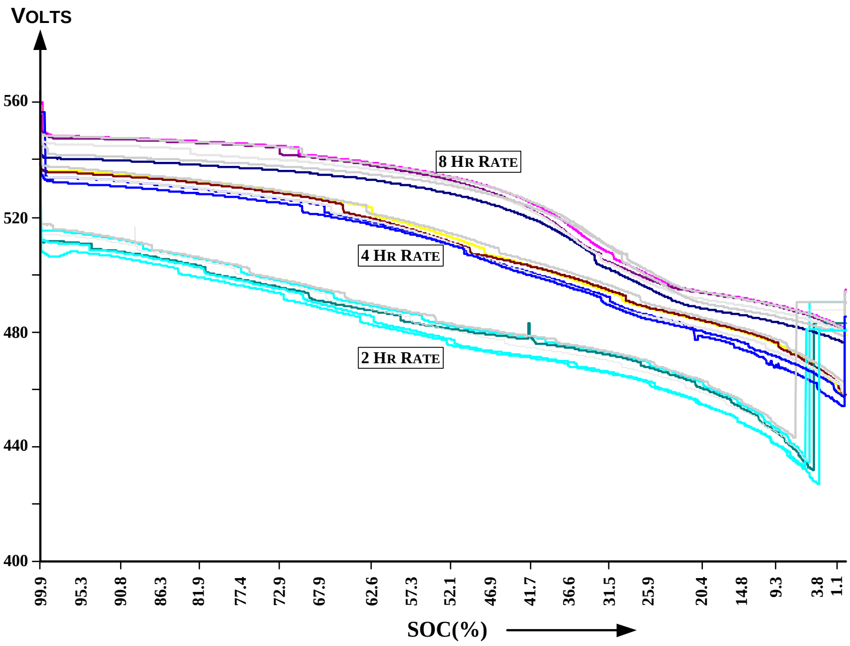

FIG.5 – INDIVIDUAL BATTERY GRADE CURVES

The main points to note from FIG.5 are that:

- The voltage gradient for ZEBRA modules is significantly flatter than that for a LAB, which could be expected to fall well below 400V for a similar battery.
- At the 2 hour rate the module reaches maximum operating temperature before reaching 100% DoD. A ZEBRA battery system maximum power calculation would be based on the total power demand at approximately this rate.

Following the baseline measurements, the next stage was to carry out parallel discharge trials. These trials are progressing at the moment, but an 8 hour trial has been carried out with all 6 batteries in parallel. The trials are demonstrating that the modules took an acceptably equal share of the load (all modules were completely discharged over a 25 minute period at the end of the 8 hour discharge with the three fully healthy modules being discharged within a 5 minute period). The grade curves for this discharge are shown in (FIG.6).

PARALLEL GRADE CURVES FOR AN 8 HOUR DISCHARGE

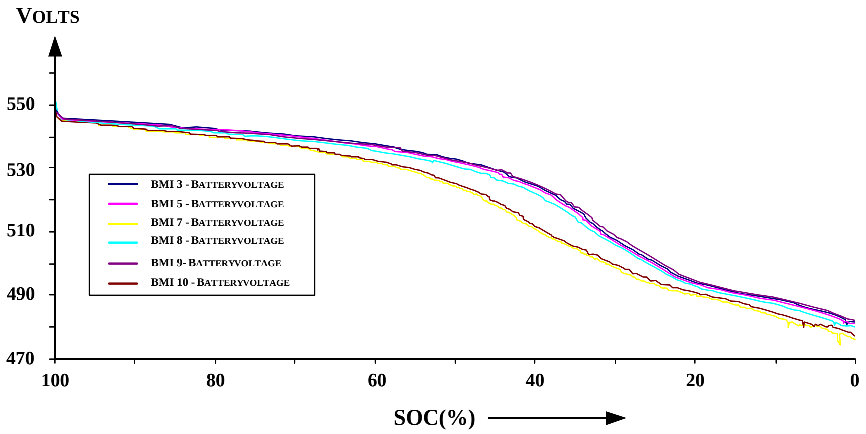

Fig.6 – PARALLEL GRADE CURVES FOR AN 8 HOUR DISCHARGE

LOAD SHARING FOR AN 8 HOUR PARALLEL DISCHARGE

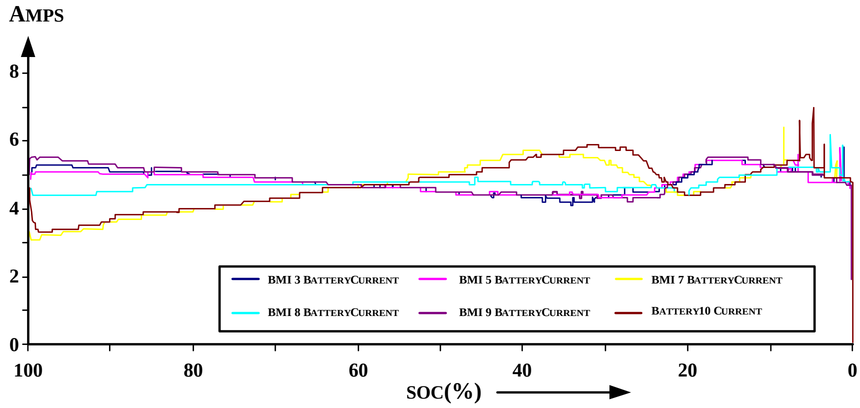

FIG.7 – LOAD SHARING FOR AN 8 HOUR PARALLEL DISCHARGE

The ability of the modules to share load is demonstrated in (FIG.7). The important points to note from FIGs 6 and 7 are as follows:

- The voltage for modules with failed cells is, as expected, lower than that for healthy modules.
- Initially, the modules with failed cells supply less current than healthy modules.
- As the healthy modules are first to begin the transition between the nickel chloride and iron chloride operating regions, the modules with failed cells take more of the load until they reach their transition point and fall away.
- The worst case degraded module completed its discharge with approximately 8% of charge remaining in the healthy modules.

Proposed Work

More work will clearly be needed before a submarine main battery can be commissioned and ZEBRA is specified as the main battery type. This work will need to prove that the battery can spend much of its time in the standby mode (on float) and when required can immediately and reliably switch over to provide power at a suitable level to ensure the safe controlled shutdown, and subsequent restarting of the propulsion system.

A high voltage, high current charger has recently been installed in the MATF and will be used to demonstrate the ability of ZEBRA modules to evenly distribute charging current and to further investigate alternative charging regimes. The facility will then be used to carry out verification and validation activities for a new BMS that will be developed to Safety Integrity Level 2 based on initial safety assessments for a submarine main battery.

As part of its support to Rolls-Royce for the development of the technology, the MoD intends to fund a series of work packages aimed at demonstrating the technology. The work packages are:

- Continued Parallel Array Testing.
- Short Circuit and Material Analysis.
- EMC Confidence Testing.
- Development Planning for UK submarine applications.
- Preliminary Safety Assessment for UK submarine applications.
- High Level Through Life Cost Analysis.

In addition to this work, Rolls-Royce will begin testing against all remaining environmental issues in late 2005 and continuing through 2006.

Conclusions

This article has considered the history of LABs in submarines and problems inherent with their use. The discussion has then shown how the ZEBRA system will eliminate these issues and subsequently remove the need for extensive support systems to deal with the associated hazards.

Ongoing performance testing has demonstrated to the MoD that the technology is sufficiently advanced to justify its involvement in the project. The benefits that have been described have been recognized to be applicable to the current classes of UK submarine. The MoD has partnered with Rolls-Royce to assist in the development of the system, to bring it to a state that will enable the technology to be tested at sea in an operational submarine.

The article has shown the strategy that must be followed to bring the technology to full readiness for use in naval marine applications and has shown where the MoD is currently involved.

Results from the most recent performance tests have been described, and show that:

- The ZEBRA system can operate through a platform lifetime of cycles in a stand-by application.
- The system can recharge rapidly and suffers no degradation as a result of repeated partial cycles.
- As a low voltage battery ZEBRA has demonstrated that its endurance will be approximately three to six times longer than an equivalent LAB in similar conditions.

- ZEBRA batteries connected in parallel have clearly demonstrated the necessary ability to share load equally throughout a full discharge, even in a degraded state representative of through life conditions.

For the MoD the ZEBRA system offers many advantages and removes the difficulties associated with LABs. In order to justify investing in such a project the MoD recognizes that this is a significant project and that there are clear benefits to be realized in its use onboard submarines, and also spin-off benefits for use in surface ships.

References

1. DONALDSON A.J. 'Energy Storage – New Technologies and New Roles.' *INEC 2002 Conference Proceedings, 2002*.
2. DONALDSON A.J. 'AIP and Advanced Batteries.' *SMI Conference Proceedings, April 2002*.