The Experience and Limitations of using Manganese Alkaline Primary Cells in a Large Operational AUV

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1. INTRODUCTION

The AUV Autosub, funded by the UK Natural Environment Research Council and hosted by Southampton University, was first tested in June 1996 in the dockside alongside the Southampton Oceanography Centre (SOC) where we managed a run of approximately 1/4km before being in the danger of colliding with the dockside wall. The vehicle was then powered by seven 12V 80Ah gel lead acid cells that served the purpose to prove the vehicle would dive, navigate and return [1]. Being 0.9m diameter and nearly 7m long, with a form displacement of 3.5T, there was considerable scope for increasing the battery payload to enable the vehicle to carry out lengthy science missions and in 1999 a two year programme of six science campaigns began. At this time, the energy payload was changed from the lead acid cells to primary manganese alkaline. The choice of battery was pragmatic, to limit the development time and cost and to keep the momentum of the programme. In this form, the vehicle began to be used for scientific missions, with missions up to 253km [2,3].

The vehicle was upgraded in the year 2000 to accommodate larger, stronger pressure vessels with a working depth of 1600m to accommodate up to 700kg of batteries to enable even longer missions. With this set-up, Autosub completed further science campaigns such as hydrography surveys in the Strait of Sicily [4] and investigations into krill populations under the Antarctic sea ice [5]. Between 1999 and 2001 Autosub was mobilised on six different ships and covered 2500km (550 hours mission endurance), 1800km of which was unescorted.

II. THE RATIONALE FOR USING PRIMARY MANGANESE ALKALINE CELLS

The choice of energy source for an AUV programme is a compromise of performance and economy (which in itself might be expressed in a number of ways). Factors such as development effort, cost, reliability and infrastructure needed to support maintenance all come into play.

At the time of re-equipping Autosub with a new energy source, the principal battery options considered were:

Secondary cells

- Nickel Cadmium
- Nickel Metal Hydride
- Silver Zinc
- Lithium Ion

Primary cells

- Manganese Alkaline

The approximate performance of these cells is listed in Table I.

Nickel Cadmium cells have an energy density only slightly better than lead acid cells and require a greater level of care and maintenance to avoid damage through charging from a semi discharged state. At the time of re-equipping Autosub with a new energy source, nickel metal hydride cells would have been a credible choice since large packs were being developed for use in hybrid motor cars, partly in response to Californian zero emission laws which were due to come into force. But such developments were being carried out under considerable secrecy and obtaining data proved difficult and no doubt purchasing the packs might have proved equally problematic. In recent years the progress of these cells seems to have trailed off, possibly due in part to the rapid developments in lithium ion cells that give a significantly better specific energy.

Silver Zinc cells were one option that was considered, they have a good specific energy, are available in large packs and have track record of use in submersibles. They suffer from a limited cycle life compared with other secondary cells and we noted applications tended to be in regions where strict quality control measures could be enforced, e.g. naval vessels, to limit the degradation that occurs as a function of their cycle life. With limited resources allocated to civil science, we considered it unrealistic to achieve the data sheet cycle life.

All secondary options other than lead acid cells were going to prove to be a costly investment and, on the scale of Autosub, were largely untried in terms of keeping large packs (>600kg) balanced during the charge and discharge cycle. The choice of manganese alkaline cells enabled the programme to maintain rapid progress from the trials phase to a vehicle suitable for substantial scientific missions and allowed greater investment to be made in areas of sensor payload and ship time.

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TABLE I COMPARATIVE BATTERY PERFORMANCE AS APPLIED TO AUTOSUB, BASED ON A 600KG PACK.

Battery Type	Specific energy/ mass (kJ/kg)	Specific energy/ volume (kJ/litre)	Approximate cost to equip Autosub with 600kg of cells (£k)	Approximate range/charge or /pack (km)	Approximate Cycle Life	Minimum No. cycles to break even with alkaline energy cost	Total possible distance covered through the life of the pack (km x 10^3)
Sealed lead acid	110	290	14	150	300	12	45
Nickel Cadmium	140	420	40	190	1500	24	280
Nickel metal hydride	330	1150	90	430	1500	26	640
Silver Zinc	580	1550	170	750	80	29	60
Lithium Ion	470	1140	170	610	800	34	490
Manganese Alkaline	460 at 21ºC & 0.1 W per cell	1320	5	640	1	1	0.64

The relatively low capital value of the manganese alkaline load served to reduce the value of the whole vehicle by some 30-35% compared to a lithium ion or silver zinc option, reducing insurance premiums and the outlay needed on the part of the programme sponsors, particularly for the Autosub Under Ice Shelves programme.

Table I shows an indication of how many cycles from a secondary pack are needed before the investment breaks even with the consumable cost of manganese alkaline cells, based on the relative energy density and cost. These comparisons are based on the endurance achieved from the primary cells after a number of overheads have been deducted such as the need for test missions and a reserve of energy at the end of a mission, these are discussed in further detail in section V. For secondary cell options that provided a long range per charge (>200km) the total break-even distance to be covered was in the range of 11,000 to 22,000km. Whilst it might not be unusual for a single vehicle to cover this distance through its life, it is very nevertheless high, and as operators we had to consider the likelihood of loss before realising the payback distance [6]. The same argument of total vehicle loss also applies to the total lifetime distance a rechargeable pack might achieve (final column in Table I) e.g. for considering a through life energy cost. These distances tend to be so large as to be of more interest to AUV operators in the offshore industry running their AUVs on a near continuous basis rather than the expeditionary nature of current use of AUVs by the scientific research community.

III. DESIGN OF THE PACK

The main volume of dry space and source of buoyancy in Autosub is provided by the seven carbon fibre reinforced composite (CFRP) centre tubes clad in syntactic foam, forming the centre section of the vehicle. Fig. 1 shows an end view of the open tubes assembled to form the overall cylindrical shape of the vehicle. The battery packs are designed to fill the bottom four tubes, the remaining three are free to accommodate other electronic systems, the vehicle being weight rather than volume limited.

A number of requirements need to be considered in the design of the whole battery load; the following nomenclature is used when describing these design features:

- A **cell** is an individual ‘D’ size1.5V electrochemical cell
- A **pack** is a number of cells connected and fitted out with protection devices as a sub assembly
- A **load** is the total number of packs carried by the AUV

Key issues include:

1. The battery load is changed by manual handling of individual packs; this dictates the upper weight limit of each pack.
2. The pack should be economic in the use of space to maximise dry space for other systems.
3. The battery load needs to be restrained to accommodate extreme pitch angles. Although in normal use the vehicle does not pitch more than 20º, in extreme unforeseen circumstances, the vehicle may be vertical. Any movement of the packs could result in a risk of shorting or breaking contacts, and would also have an effect on the trim of the vehicle.
4. Battery packs need to be reliable. Autosub operates on a voltage of 75 to 113V, requiring 75 cells connected in series. With a target pack failure rate of say no more than one in two loads, the failure rate of the cells must be less than 1 in 10^4. Cells from some manufacturers cannot meet this requirement (see section VI).
5. The battery load needs to have reliable insulation. The cells are only protected with a thin heat shrink cover, substantial additional insulation is needed, including peripheral connections, leads and the way packs are connected to each other.
6. Provision needs to be made to protect every pack in the parallel arrangement from being charged and the AUV protected against damage through short circuits and over heating.
7. The packs need to be economic to manufacture. Although economies of scale drive the cost of the cells

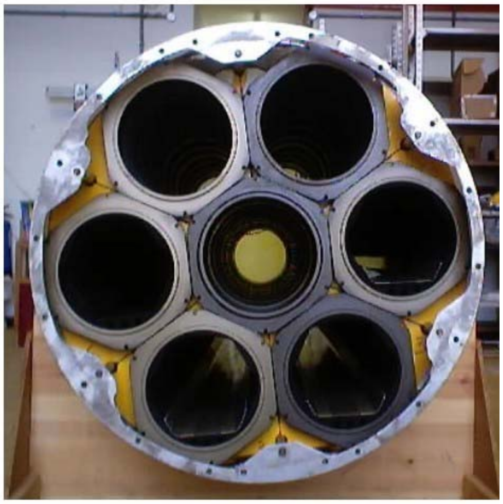

Fig. 1 Photograph showing the ends of the 7 main CFRP pressure vessels with the syntactic foam.

down, other hardware built into the packs that has to be considered consumable needs to be minimised.

Fig. 2 pictures a single pack as would fit in one of the main pressure vessels. Each pack, weighing 10.5kg, comprises of 75 cells connected in series to provide an operating voltage of at least 75V at the end of useful life. Pairs of packs fit in glass reinforced plastic (GRP) trays and are connected in parallel, with up to nine pairs fitted into each pressure vessel. Within the overall heat-shrink layer helping to bind the pack together is a slow-blow fuse, charge-protection diode and over-temperature switch. The fuse within the pack protects the vehicle against major shorts that could cause damage within the pressure vessel; the slow blow feature prevents accidental fusing due to momentary shorts. If the fuse does blow then either the AUV must run with that pack inactive or the pack has to be changed. This is a feature to prevent serious chemical breakdown of the cells which, if it occurred would damage the CFRP tubes. The AUV sub-systems are protected by an accessible main fuse located outside of the pressure vessels.

The conversion of chemical to electrical energy produces waste heat within the pack. This can be put to good use in raising the operating temperature of the packs (see section V) but since the upper bound of temperature is difficult to predict and dependant on ambient conditions, a high temperature cut out switch is necessary to prevent overheating, which again would cause a chemical breakdown of the cells. The overtemperature cutouts automatically switch back on after the temperature has dropped. Thus, although having packs switched out is undesirable, it is unlikely all packs would switch out simultaneously, causing a failure of mission e.g. packs near the end of the vessel have greater cooling, or the packs would cool when the AUV dives beneath the warm surface water.

The loading and unloading of packs is not trivial. The cells themselves are dense but are not structurally strong therefore they can be easily damaged in the process of moving large loads of packs in and out of the vehicle. Since the overall load is limited by weight rather than volume, there is space to provide protection but weight needs to be kept to a minimum and metal structures should be avoided because of the danger of electrical shorts. The use of the electrically insulating and light GRP trays provide a strong case to protect the packs. The trays slide along PTFE runners in the pressure vessels that are lined with closed cell foam for mechanical shock protection and additional electrical and thermal insulation. A cross section of a vessel fitted with packs is shown in Fig. 3. A webbing strap fitted around the entire string of packs is used to pull out discharged packs. Additional features, peripheral to the battery packs, are a leak sensor on each vessel and a temperature probe linked to the data logger. These run in channels along the bottom of the vessel formed in the foam insulation.

Fig. 2 Single battery pack in GFRP tray with a section of foam insulation around it

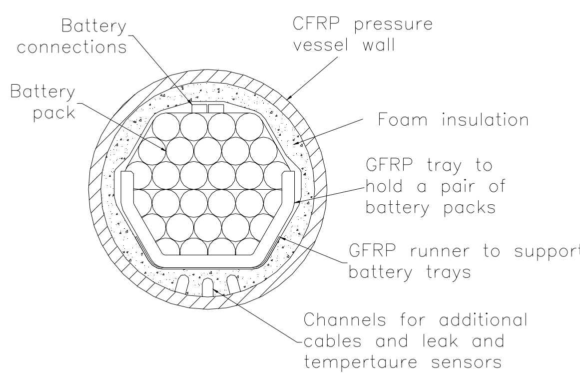

Figure 3 Cross section of pressure vessel fitted with batteries.

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IV. Characteristics of Manganese Alkaline Cells

Some performance characteristics of consumer and industrial manganese alkaline primary cells can be obtained readily from the manufacturer's data sheets, for example [7,8]. However, the information is usually available in the form of graphs, most commonly as terminal voltage against time when terminated with fixed resistors as loads at a set temperature or at a series of temperatures. Rarely is the AUV designer presented with the available energy in a cell during discharge as a function of load current and temperature. General texts on batteries, e.g. [9], while explaining the factors affecting cell capacity, do not provide the needed information on specific products. Research papers in the literature on the electrochemistry of manganese alkaline cells. e.g. [10,11], discuss and derive detailed models of cell behaviour based on tens of parameters, many of which prove to be inaccessible to an engineer designing an AUV power system. This paucity of quantitative information in accessible form has led to the AUV community using empirical functions to estimate the capacity of battery packs made up from manganese alkaline cells.

In [12] Bradley et al. describe, in graphical form, the results of measurements on individual 'D' and 'AA' manganese alkaline cells as a function of load power consumption and temperature. The authors concluded that while "alkaline cells continue to be one of the cheapest and easiest chemistries to work with … at low temperatures … with a high discharge rate … they will only deliver a fraction of their stored energy".

The performance of a battery load of 2160 Duracell manganese alkaline 'D' cells (30 packs in parallel of 72 cells in series) in the Autosub AUV was reported in [13]. The observed voltage decay over the service period was compared to laboratory measurements at a current drain equivalent to the 'cruise speed' of the vehicle at 27ºC and 45ºC, bracketing the temperature range during the mission. Based on a simple three-stage model of vehicle power consumption (hotel load only; hotel and low speed propulsion; hotel plus cruise propulsion) and the measured capacity at the two temperatures, the estimated energy consumed from the battery pack on a 253km mission was 94.38MJ or 43.7kJ per cell. The estimated energy remaining on completing the mission was between 11 and 24 MJ at a load equivalent to hotel plus cruise propulsion [13]. In this paper we describe a more detailed, yet practical, model of the performance of manganese alkaline cells and packs, based on simplified electrochemistry and an analysis in [14].

A. Predicting the voltage decay

The electrochemical basis for predicting the voltage decay of a cell as a function of time is (1)

$$V_t = V_h - \frac{\phi RT}{F}\ln\left(\frac{Q_t}{Q_r}\right) + \Delta\eta_c - \Delta\eta_a \qquad (1)$$

where V_h is the cell voltage at half the useful life of the cell, ϕ is a constant, Q_t is the useful energy (J) extracted from the cell to time t, Q_r is the total useful energy remaining (that is, $Q_T - Q_t$, where Q_T is the total electrical energy available from the cell) and $\Delta\eta_a$ and $\Delta\eta_c$ are the anodic and cathodic overpotentials respectively, R is the gas constant (8.3144 J kg^{-1} mol^{-1}), T is the absolute temperature (K), F is Faraday's constant (9.6485×10^4 C mol^{-1}). The overpotentials vary with temperature, current drain and with the stage of discharge and 'in most practical situations it is not possible to obtain analytical expressions' [6, p. 51]. Hence they are ignored in the simplified model below. V_h can be obtained [14] from measurements on cells under discharge followed by a least squares linear model based on temperature and current (current calculated from the power drain and the terminal voltage)

$$V_h = K_1 + K_2 T - K_3 I. \qquad (2)$$

For Rayovac cells (Table II) $K1$ = 0.507, K_2= 0.00266 and K_3 = 0.258 with coefficient of linear regression squared of 0.940.

Q_t can be measured on the AUV during discharge or can be simulated prior to running a mission. However, Q_r can only be estimated. A simple model for estimating Q_r is described in the next section.

B. Predicting the remaining capacity

Predicting the remaining capacity Q_r requires knowledge of the initial capacity of the cells Q_T as a function of temperature and load current. There is significant variation in capacity between cells from different manufacturers [15], and there is some evidence that capacity decreases with time on the shelf. Sample cells from batches to be used in Autosub were monitored at several constant power drains at three temperatures to determine the initial capacity as a function of temperature and load power. Initial capacity was then modelled [14] as

$$Q_T = C_1 + C_2 T - C_3 I + C_4(I*T) \qquad (3)$$

Fitting this model to the measured capacity data for Rayovac cells (Table III) gave

$$Q_T = -251406 + 1106T - 101482I + 820((I-0.1767)*(T-278)) \qquad (4)$$

with a coefficient of linear regression squared of 0.996. For a practical battery pack, (2) and (4) should take into account the series/parallel arrangement of cells to determine the current per cell.

TABLE II
V_h AS MEASURED FOR RAYOVAC 'D' CELLS AT SELECTED DISCHARGE POWERS AND TEMPERATURES

Power drain (W)	V_h (V)	V_h (V)	V_h (V)
	20°C	5 °C	-10°C
0.100	1.28	1.225	1.19
0.150	1.26	1.20	1.18
0.200	1.25	1.195	1.16
0.250	1.24	1.185	1.145
0.300	1.22	1.18	1.17

TABLE III
INITIAL CAPACITY AS MEASURED FOR RAYOVAC 'D' CELLS AT SELECTED DISCHARGE POWERS AND TEMPERATURES

Power drain (W)	Q_T (kJ)	Q_T (kJ)	Q_T (kJ)
	20°C	5°C	-10°C
0.100	64	57	33
0.150	58	48	25
0.200	55	40	21
0.250	52	34	16
0.300	48	29	12

C. Comparing model and measured battery load voltage

The modelled terminal voltage of a complete load can be obtained by substituting (2) into (1) and taking account of the series parallel arrangement of cells in the pack. Fig. 4 compares the model and actual data for a load of 4350 Rayovac 'D' cells (58 packs in parallel of 75 cells in series) over Autosub missions 250-253 beneath icebergs and sea ice in Antarctic waters in February 2001.

For the first 5 hours of use, the model predicted a lower terminal voltage than was found in practice, but after 8 hours, the situation was reversed, with the model predicting a higher voltage by 4-5 V. This may be due to the omission of the cathodic and anodic overpotentials.

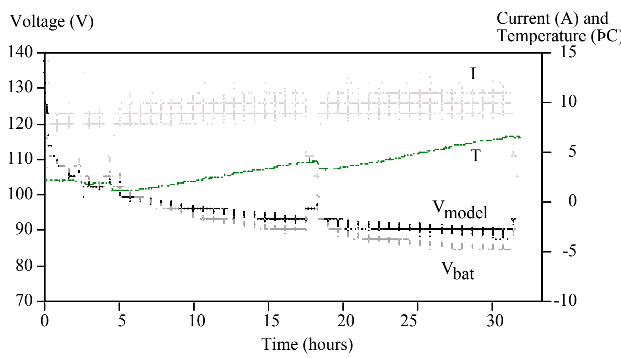

Fig. 4 Comparison of the actual terminal voltage of the Autosub battery pack as measured during missions 250-253 (V_{bat}) and the model results (V_{model}) using the measured current consumption (I) and the average temperature of the battery pack (T).

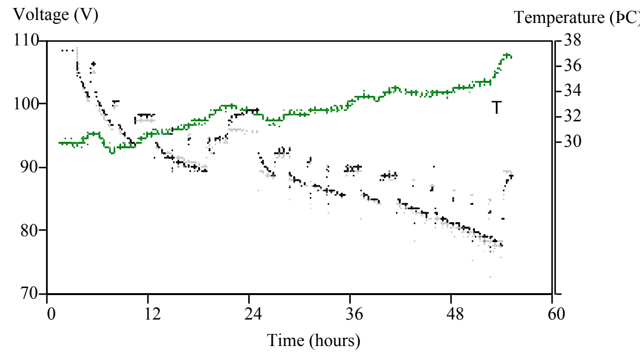

Fig. 5 Comparison of the actual terminal voltage of the Autosub battery pack as measured during mission 145 (dark points) and the model results (light points) using the measured current consumption and the average temperature of the battery pack (T).

Notwithstanding this error, the model provides a reasonable estimate of the behaviour of the battery load, reproducing the general decay in terminal voltage, the increase in terminal voltage at reduced current (the hotel load only periods) and the further decrease in terminal voltage during the brief periods when the vehicle accelerates on the surface prior to a dive. By altering the coefficients in (2) and (3) the voltage decay model can be applied to cells of different manufacturers.

In Fig. 5 the model voltage decay for the load of 2160 Duracell 'D' cells used on a mission off Bermuda [2,13] is compared to the measured voltage. Here there is very good agreement over a range of ~ 30V including several periods of lower current drain when under hotel load. There is a slight tendency for the model to predict a higher voltage at low loads. For the Duracell cells the coefficient K_I in (2) was reduced by 50 mV to 0.457V and the coefficient C_I in (3) was increased by 6% to 266.49kJ compared to the coefficients for the Rayovac cells.

D. Applying the Fuel Gauge algorithm

The encouraging comparison of model and actual voltage decay gives a degree of confidence in the ability of (3), hence (4), to predict the capacity of a manganese alkaline battery load under varying current drain and temperature. Fig. 6 shows the cumulative energy extracted per cell from the 4350 Rayovac cell load used on missions 250-259 in the Antarctic. The pack was exchanged after mission 259 as it was deemed to have reached the end of its useful life. Here, the validity of this decision can be examined by adding on a rerun of the 60km mission 253 after the completion of mission 259.

Initial inspection of Fig. 6 shows that there was sufficient energy remaining at the end of mission 259 (the black line) for some 6 hours of operation at cruise speed. However, closer examination shows that at 'A', at the start of the 'rerun' of mission 253, during the acceleration phase on the surface prior to diving, the increased current required reduced

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the effective capacity to near zero (the light grey points near the zero axis). As a consequence, the terminal voltage of the battery pack would have dropped and full power would not have been available for the pre-dive run-up. This could have led to a failure to dive, which could have serious consequences if the AUV was operating unescorted. Two conclusions can be drawn, first, the decision to exchange the battery pack at the end of mission 259 was correct, and second, where an AUV follows the same pre-dive procedure as Autosub, completing a mission with several hours energy in hand is not, of itself, a guarantee that there is sufficient energy remaining to dive at the start of a subsequent mission. With this margin of safety, the effective usable capacity of each cell during this set of missions in the Antarctic was only 29.8kJ. Compare this to the performance of the smaller battery pack off Bermuda (Fig. 7) where 45.0kJ was extracted per cell in the far warmer conditions (see temperature in Fig. 4 compared to Fig. 5) and a predicted energy remaining per cell of some 20kJ.

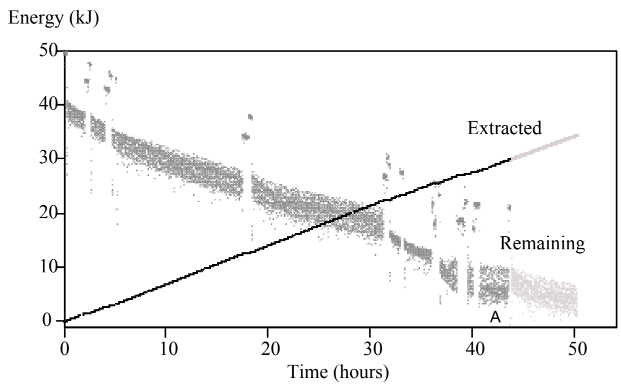

Fig. 6 Energy extracted per cell on Autosub missions 250-259 (thin black line) followed by a 'rerun' of mission 253 until depletion of the battery pack (thin grey line) and predicted energy remaining (medium grey band).

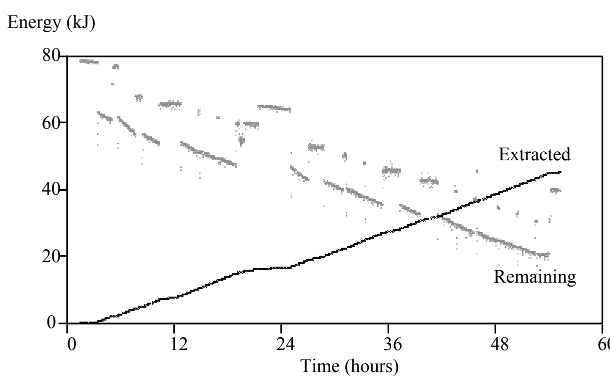

Fig. 7 Energy extracted per cell on Autosub mission 145 (thin black line) and predicted energy remaining (grey band).

V. THERMAL MANAGEMENT OF A BATTERY LOAD

Autosub has operated in the warm waters off Bermuda, Florida and Sicily to freezing waters off Antarctica; both have highlighted problems in the battery load operating too hot or too cold. The cells release heat during operation due to Joule heating caused by the internal electrical resistance of the cell, energy loss due to polarisation, and the heat generated by the chemical reactions. These three sources of heat increase with current drain [16]. Problems of over-heating occurred when a relatively small pack of 2160 cells were packed into a single pressure vessel without any internal heat sink when operating in waters where the surface temperature was above 30ºC. Since then, the load size has increased, resulting in lower current drain per cell, the load has been split between four pressure vessels and we now tend to operate in cooler waters. As a result, the problem has changed from inadequate heat sinking to the need for thermal insulation to make the most of this self-heating characteristic.

Table II has illustrated how temperature affects the total energy available from a cell and it is clear from Fig. 4 that the temperature of the battery load rises over a series of missions even though the vehicle was operating in waters at a temperature of ~-1.8ºC. During the first two short missions (under icebergs) at the left hand side of Fig. 4, the average battery pack temperature decreased from 2.23ºC to 2.03ºC, then from 1.90ºC to 1.79ºC but then increased steadily during a 60km under sea ice mission (from 1.17 to 4.05ºC). The load cooled down slightly overnight when the vehicle was in air on deck, and then increased again (from 3.5 to 6.7ºC) during another 60km under sea ice mission. The only thermal barrier present was the thickness of the CFRP and syntactic foam. No use was made of the space between the packs and inside of the vessel for additional insulation, over and above the air gap, Fig. 3.

Attempts have been made at modelling the thermal response of the battery load to assess what improvements to overall capacity could be made. The simple model begins by approximating the pressure vessel assembly as a number of concentric tubes comprising:

- the string of battery packs in a tube;
- air space between packs and inside diameter of the tube;
- CFRP tube;
- syntactic foam.

Although the geometry of the model is crude compared with actual shapes seen in Fig. 1, greater errors are likely to occur in:

- the difficulty in estimating the waste heat emitted from the packs;
- the convective heat transfer in the air space;
- the effect of the thermally conductive aluminium end domes.

The temperature response of the system is calculated from the sum of the first order response of the temperature decay (5) due to a “warm “ vehicle entering cold water and the temperature rise due to the heating effect of the batteries (6). Definitions of the variables are given in Table IV.

$$T_{decay} = (k_1, t) = T_0 + (T_{init} - T_0)e^{\frac{-t}{\tau k_1}} \quad (5)$$

$$T_{rise} = (k_1, t) = T_0 + (T_{init}(k_1, t) - T_0)(1 - e^{\frac{-t}{\tau k_1}}) \quad (6)$$

t= the time constant for the system given by:-

$$\tau(k_1) = \frac{mC\ln\left(\frac{r_4}{r_1}\right)}{2\pi k_{mean}(k_1)L} \quad (7)$$

k_{mean} is the effective overall thermal conductivity of the assembly, given by:-

$$k_{mean}(k_1) = \frac{\ln\left(\frac{r_4}{r_1}\right)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_1} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_2} + \frac{\ln\left(\frac{r_4}{r_3}\right)}{k_3}} \quad (8)$$

TABLE IV HEAT FLOW PARAMETERS

Parameter	Value and units	Known or estimated
Mass of packs in one tube (m)	189kg	known
Specific Heat of the cells (C)	1027 J $kg^{-1}K^{-1}$	Measured +/- 16%
Effective thermal conductivity air space (k_1)	0.2 W m^{-1} K^{-1}	estimated
Thermal conductivity insulating foam (k_1)	0.051 W m^{-1} K^{-1}	data sheet value
Thermal conductivity CFRP (k_2)	0.1 W m^{-1} K^{-1}	Transverse to fibres, known
Thermal conductivity syntactic foam (k_3)	0.122 W m^{-1} K^{-1}	known
Length of tube (L)	2.7 m	known
External water temperature (T_0)	-1.8^{o}C	known
Initial battery temperature (Tinit)	2.3^{o}C	known
Battery heat generation (Q(t) where t is in seconds)	17+1.22.10^{-4}t W	estimated from model and data
Radii - battery pack outer r_1	105 mm	known
- inner, CFRP tube r_2	127 mm	known
- outer, CFRP tube r_3	142 mm	known
- outer, foam r_4	170 mm	equivalent

The value k_1 takes the value for air or for the added insulating foam within the CFRP tube. Using a compromise of estimated data (Table IV) where no hard data exists and knowledge of the actual response, Fig. 8 shows the model calculation for the first 30 hours of a polar mission and an indication of the temperature increase resulting from the insulating foam. A sample of insulating foam is shown wrapped around the pack in Fig. 2. This foam fits the whole length of the vessel for additional insulation

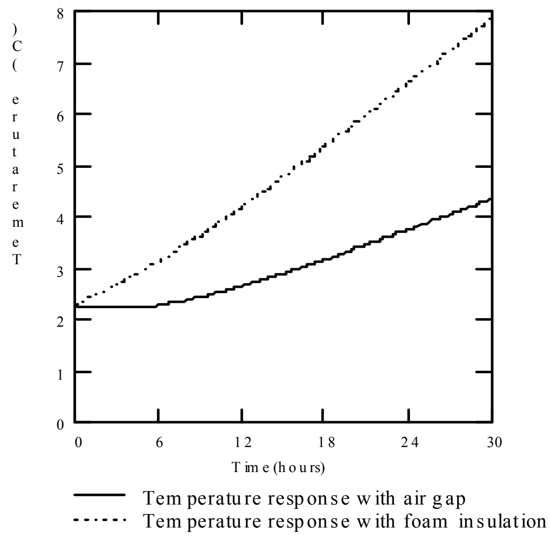

Fig. 8 Approximate modelled temperature response, the upper line shows an indication of the higher temperatures due to additional internal insulation.

From the data in Table II, the predicted increase in temperature of the battery load would yield an increase in energy capacity of some 10% over a 100 hour mission, more if the batteries were pre-heated before launch. For the Autosub Under Ice Shelves programme, the vehicle will be kept in a heated container hanger on the stern of the ship, this is essentially to provide easier working conditions for the engineers but will also have the benefit of pre-heating the batteries before the launch.

VI. RELIABILITY OF THE POWER SOURCE

Reliability of the power source is crucial to the successful operation of AUVs. During the time from 1998 when Autosub began using manganese alkaline cells it has been found that reliability can vary from brand to brand and also depends on the way the cell is used. Early packs had minimal testing carried out by the assembler and it was discovered later that packs displaying the expected open-circuit voltage could have a high internal resistance under load. This problem has been known to cell manufacturers, referred to as Low Voltage Instability (LVI), but has not been well publicised. The problem is usually solved by a sharp jolt to the pack to re-establish proper internal connections. The relevance to Autosub is not just the possibility of losing a pack but losing a number of packs, creating an increased load on the remaining packs, causing the fuses to blow in a domino fashion. This critical failure happened once when Autosub was launched but would not start the mission. Upon subsequent recovery it was found that 40% of the packs had blown fuses and the remainder either indicated open circuit under load or were functioning properly. An investigation with the cell manufacturers revealed the LVI problem and a search through their quality records showed the batches used were vulnerable to this fault. The design of the cell has since been improved, nevertheless we have changed the brand of cell used in Autosub.

The other main source of unreliability is the number of connections to be made. With a load of 58 packs there are 8700 welded connections on the cell ends. The welding process has been used for the connection of large packs for a considerable time and this has not been found to be a problem. The packs are then connected in pairs with in-line plug and socket leads terminating in a circuit board plug and socket mounted in the end dome. If each plug and socket is treated as having three connections (crimp to the plug\plug to socket\socket to crimp) there are some 400 connections, excluding final power lead connections from the pressure vessel. Whilst the fault rate has not been high it has been significant. Future packs are being made using push-in connectors designed for use with solid core wire; without the need for crimped ends, the number of connections reduces to 116. More important, the quality of the connection is now governed by production machinery making the connectors rather than by hand crimping operations.

VII. Conclusions

The use of manganese alkaline batteries for the Autosub science programme has enabled the project to progress swiftly from being a technological demonstrator to providing new ways of gathering environmental data not possible by other methods. Throughout the programme all areas of the battery system have undergone development, that is:

- specification, design and manufacture of the pack;
- inspection and testing;
- packaging, storage and physical handling;
- electrical and thermal insulation;
- estimates of remaining endurance;
- disposal of depleted packs;

If the project at a later stage were to change to secondary cells, the development successfully completed during the phase of using of primary cells will prove to be invaluable. For the immediate future, these cells are a practical choice for the new science planned for the Autosub Under Ice Shelves programme scheduled for 2003-2005.

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