ISSN : 0974 - 7443 Volume 9 Issue 4
CHEMICAL TECHNOLOGY
An Indian Journal
Full Paper
CTAIJ 9(4) 2014 [121-127]

Studies on charge and discharge characteristics of lithium ion polymer batteries

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ABSTRACT

Conventionally, magnesium sea water activated batteries are employed as main power source to torpedoes and other under water vehicles. With the advent of lithium-ion battery technology, efforts are being concentrated to develop a suitable battery unit for these under water applications. In this regard, investigations have been carried out experimentally to study the charge and discharge characteristics of lithium ion polymer (Li-Po) batteries. A single cell module has been used to study the discharge voltage under constant current mode using 1C, 2C, 3C and 4C discharge rates. Variation in temperature of anode and cathode were also measured. The rise in temperature of anode and cathode were correlated in terms of time and C-rate by regression analysis. Charging characteristics of the single cell were also investigated at 1C rate. The discharge voltage characteristics of all individual cells of a 9-cell pack were also obtained at 1C rate and compared. It was found that all the cells in the 9-cell pack exhibited almost uniform discharge voltage.

KEYWORDS

Battery;
Discharge;
Lithium-ion;
Underwater vehicle;
Power source.

INTRODUCTION

Torpedoes are the underwater missiles that can be launched from ships and submarines. A torpedo needs extensive control and navigation systems with all inclusive power sources. So far, sea water activated batteries such as Mg/AgCl and Mg/CuCl batteries are being used to meet the power requirements of these activities. Now-a-days it is known that Li-ion and Li-ion polymer (Li-Po) batteries have captured much of the market share in many commercial applications. Therefore, the present work has been undertaken to evaluate the possibility of using the Li-ion polymer batteries for under water applications.

Lithium batteries are available as primary batteries and secondary batteries. The secondary batteries are also available as Li-ion batteries and Li-ion polymer batteries. The lithium batteries have the characteristic nature of light weight, high voltage, high electrochemical equivalence, good conductivity and can be shaped in various geometries with very high aspect ratios. The advantages include sealed cells, no maintenance, long cycle life, long shelf life, low self-discharge rate, rapid charge capability, high rate and high power discharge capability, high energy efficiency, high specific energy and energy density and no memory effect. The disadvantages include thermal runaway, sensitive to over charge and over discharge, degradation at high temperature, need for protective circuitry etc. The range of applications of these batteries vary from very small button cells used in watches to very large batteries used in military uses. Therefore, these batteries are employed as power sources in consumer electronics, cell phones, laptop computers, personal data assistants, military electronics, military radios, mine detectors, aircrafts, space crafts, satellites, electric and hybrid electric vehicles[1].

Several reviews appeared in the literature relevant to the present study. The development of batteries in various aspects in the last 50 years has been thoroughly reviewed by Dell[2]. The advantages and limitations of VRLA batteries and the recent advances taken place in its technology have been presented in detail by Berndt[3]. The factors of concern in Asian battery market have been enumerated by Eckfeld et al[4], and the changes likely to be expected in the coming decade were also focused. A detailed review on lithium batteries, their present status, prospects and future has been covered thoroughly by Scrosati and Garche[5]. Ritchie and Howard[6] presented a review on recent development and the likely advances achieved in lithium-ion batteries. The conduction phenomena in Li-ion batteries has been comprehensively reviewed by Park et al[7]. The status of Lithium ion batteries and the lithium ion polymer secondary batteries has been reviewed by Blomgren[8].

Hikmet[9] presented a new lithium-ion polymer battery concept for increased capacity. Appetecchi et al[10] prepared a novel composite gel type polymer electrolyte by dispersing selected ceramic powders into a matrix formed by a lithium salt solution contained in a poly acrylonitrile network that has high ionic conductivity. Lee et al[11] investigated the battery dimensional changes occurring during charge/discharge cycles of thin rectangular lithium ion and polymer cells. Croce et al[12] reported the usability of two electrolytes to be employed in advanced lithium polymer batteries. Lithium ion polymer batteries using microporous polyvinylidenefluoride filled by the liquid electrolyte as polymer electrolyte have been investigated by Saunier et al[13]. New designs for safe lithium-ion gel polymer battery were proposed by Sato et al[14]. Overcharge performance of lithium-ion polymer batteries have been studied by monitoring their temperature variation and heat generated by Zeng et al[15]. Several solutions against thermal runaway have been proposed.

Satyavani et al[16] carried out experimental investigation to study the charge and discharge characteristiscs of a Li-ion Polymer battery. Three numbers of 40 Ah Li-Po cells were connected in series as a pack and such packs were used for carrying out their investigation. These packs were subjected to normal cycling and quick cycling and the corresponding charge – discharge curves were obtained. The discharge profiles of such a pack at 0.5C, 1C, 2C, 3C, 4C and 5C rates were also obtained. The variation of temperatures of cathode and anode for these packs at C rates of 1 to 5 was also obtained. However, there is a need for investigating charge and discharge characteristics of a single cell and a pack of more number of cells. The literature survey thus revealed that there is a need for identifying a suitable Li-Po battery to use as the main power source for torpedoes that necessitated the present investigation.

TABLE 1 : Specifications of lithium-ion polymer battery (cell & single cell module)

S.No.	Parameter	Description
1	Length of cell	220 ± 2 mm
2	Weight	840 ± 30 g
3	Capacity of each cell	40 AH at 1C rate
4	Open Circuit Voltage (OCV)	4.2 V
5	Nominal Cell Voltage	3.7 V
6	Discharge current	40 A
7	Discharge cutoff voltage	2.7 (At 1C rate)
8	Discharge time period	Not less than 54 min at 40 A
9	Peak Current	120 A for one second
10	Cycle life	Not less than 200 cycles at 90% discharge on duty (DOD) at 1C rate
11	Shelf life	More than 5 years at a storage temperature of 25-40^{o}C
12	Operating temperature	15 to 65^{o}C

In the present experiments discharging and charging studies of a LiPo battery have been carried out using suitable circuits. The Lithium Ion Polymer (LiPo) batteries chosen for the present experiment are (i) a single cell module, and (ii) a 9-cell pack in which all cells are connected in series. These cells were obtained from trade. The specifications of the single cell module and the 9-cell pack used in the present study are compiled in TABLES 1 and 2 respectively. The ranges of variables covered are provided in TABLE 3.

EXPERIMENTAL

TABLE 2 : Specifications of lithium-ion polymer battery (9-cell pack)

S.No.	Parameter	Description
1	OCV	37.8 V
2	Normal cell voltage	33.3 V
3	Discharge current continuous	40 A
4	Discharge cutoff voltage	24.3 V (at 1C rate, upto 90%)
5	Cell connection	Series
6	Protective circuits	Provided

TABLE 3 : Experimental conditions used in the present experiment

Parameters studied		Values/Range of parameters
Charging rate		9 A/h
Discharging rate		40, 80, 120 & 160 A/h
C-rate	Current	Duration
1C	40 A	60 min
2C	80 A	30 min
3C	120 A	20 min
4C	160 A	15 min

Li-ion polymer (Li-Po) cells of 40 Ah capacity were used in the present experiments to study the charge, discharge and thermal characteristics at different C rates. The apparatus and equipment employed to carry out the discharge studies of the single cell module and a 9-cell pack in the present study essentially consisted of an electronic load bank, and thermocouple based temperature sensors TC303 & TC324 of Selec make, individual cell voltage monitoring unit and alarming unit with individual channel alarm setting, connected in a circuit as shown in Figure 1. The electronic load bank is used to choose and implement the mode of operation.

The apparatus and equipment employed to carry out the charge studies of the Li-Po battery unit employed in the present study essentially consisted of the charging unit, an mcb switch, the cell to be charged and a voltmeter to measure the voltage across the battery terminals. The electrical circuit is shown in Figure 2.

A pouch type single cell module for charge and discharge studies and a 9-cell pack kept along with elec-

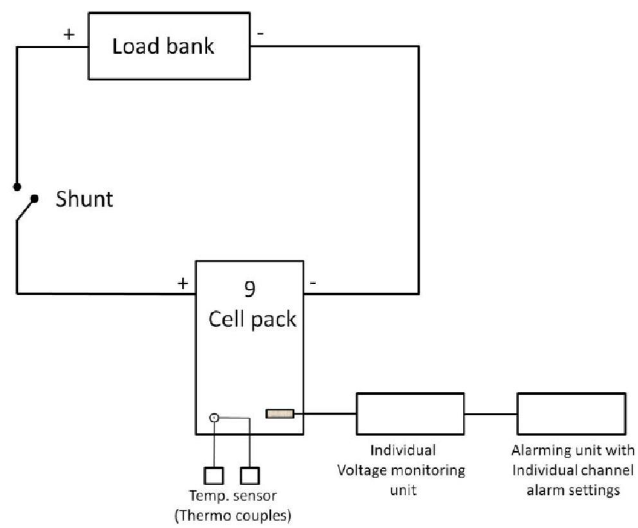

Figure 1 : Electric circuit for carrying out discharge studies

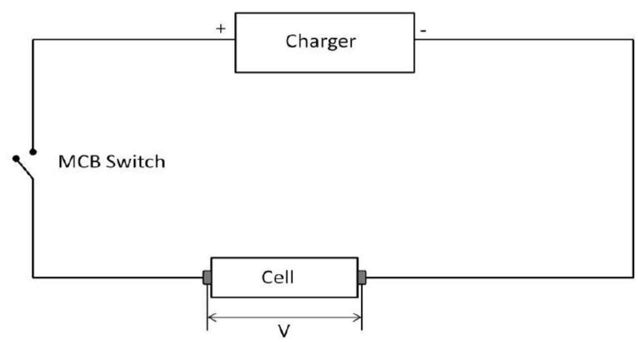

Figure 2 : Electric circuit for charging battery

tronic protection circuit for discharge studies are employed. Battery can be discharged in various modes. One such mode is the Constant Current (CC) mode. Other modes are constant voltage, constant resistance and constant power. To perform the capability test, the Electronic Load Bank employs Constant Current (CC) mode of operation.

The charging is done by connecting the battery as per the charging circuit shown in Figure 2 and the current is kept constant at 9 A for a period of approximately 270 minutes. The battery is then disconnected from the circuit, then kept for 2 to 3 hours for stabilization and then again connected in the same circuit, by keeping the current constant at 0.5 A for a period of approximately 180 minutes. Then the battery is given 5 to 6 hours rest period for stabilization.

RESULTS AND DISCUSSION

The discussion in this section has been presented in the following four subsections. The discharging characteristics of single cell module, the discharging characteristics of the 9-cell pack have been presented in subsections 3.1 and 3.2 respectively. The temperature variations at select points were also provided at appropriate places in the text in these subsections. The charging characteristics of a single cell module has been shown in subsection 3.3. The development of correlations for temperature rise of anode and cathode has been presented in subsection 3.4.

Discharge characteristics of single cell Li-Po battery

Discharge voltage characteristics have been examined by obtaining discharge voltage data versus time for the constant current mode operation. The discharge voltage obtained by keeping current constant at 40 A were plotted against time and shown as plot A in Figure 3 for the single cell module. The requirement is that during mission time of 8 minutes, the minimum voltage should not be less than 90% of specified voltage of 4.0 V. To indicate whether the voltage obtained is within the required limit or not, a line was drawn, denoted as 'aa' (corresponding to 3.6 V, i.e., 90%). A close inspection of the plot of the data reveals that upto 27 minutes of discharge time of the battery at 1C rate, the battery voltage was above 3.6 V. Therefore, the discharge voltage requirements during the mission time would be fulfilled if the discharge is maintained at 1C rate. An attempt is also made to study the discharge voltage characteristics of the single module Li-Po battery under constant current mode at 2C rate, i.e., at a rate of 80 A. The discharge voltage plotted against time has been shown as plot B in Figure 3. It is observed that the battery voltage was above 3.6 V for a discharge duration of 12 minutes. Even at 2C rate the discharge voltage was meeting the specifications by considering the mission time of 8 minutes. In order to find out the suitability of the Li-Po battery for the defence applications, it is studied to know its ability to meet the specified requirements at 3C rate also. The discharge voltage data obtained were shown as plot C. The current was kept constant at the rate of 120 A. Analysis of the graph revealed that the discharge voltage was above 3.6 V for a duration of 7.5 min. Rather, it is almost near 3.6 V or above this value for the anticipated mission time of 8 minutes specified by the client. The suitability of the Li-Po battery at a discharge rate of 4C was also examined. This means the current was kept at 160 A under constant current mode of operation. In order to ensure safety of the personnel and equipment, the battery was covered with grills and sand bags in open area with a mesh around. The discharge voltage curve is shown as plot D. Upto a duration of 5.5 minutes, the voltage was above 3.6 V, and upto a duration of 8 min, the voltage was above 3.5 V, as observed from Figure 3. Therefore, within tolerance, for the mission duration of 8 minutes the specified voltage could be maintained. It is now understood that during the mission time of 8 minutes, even with 4C rate i.e. at a rate 160 A, the discharge voltage was meeting the specified value.

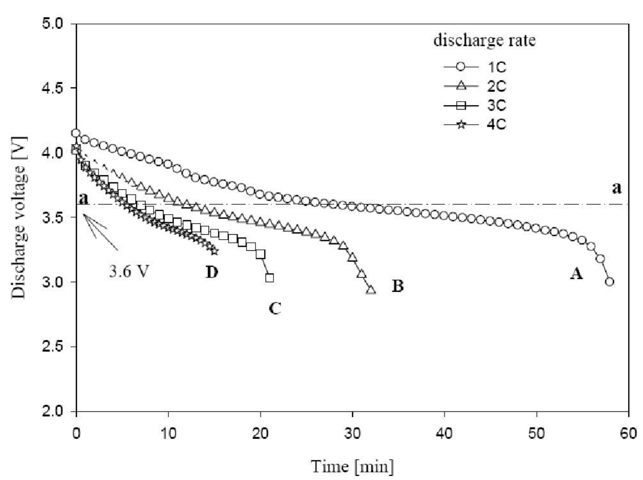

Figure 3 : Discharge voltage versus time at different C-rates

Therefore, if other requirements are fulfilled, the Li-Po battery at a high discharge rate of even 4C can be used for under water applications. The temperature of the battery should be always between -20°C and 65°C for optimum operation. If the temperature were less than -20°C, the discharge rate may not be sufficient because of the slow mobility of the ions at lower temperatures. If the temperature is more than 65°C, the battery may get damaged leading to thermal runaway and causing destruction of the cell and other equipment. Therefore, the temperature measurement is essential in studying the suitability of these batteries for respective applications. In this regard, the temperature rise was measured at anode and cathode terminals during discharge at different C-rates. The data on temperature rise thus obtained at anode terminal were plotted and shown in Figure 4. Since the room temperature was 30°C, an examination of the plots of the figure reveals that the temperature was well below the specified value of 65°C during the entire discharge duration considered under the present experiment for all C-rates. Two cross-plots were drawn to elucidate the temperature rise with C-rate at two different time values. Figure 4a corresponds to t = 5 minutes, and Figure 4b corresponds to t = 15 minutes. It can be observed from the plots of these two insets that the temperature rise is strongly influenced by the C-rate of discharge.

Similarly, the variation in temperature rise measured at the cathode terminals, when the battery is discharged at different C-rates has also been plotted and shown in Figure 5. In this case also, it can be found from the plots of the figure that the temperature of the cathode remained less than the specified maximum limit of 65°C.

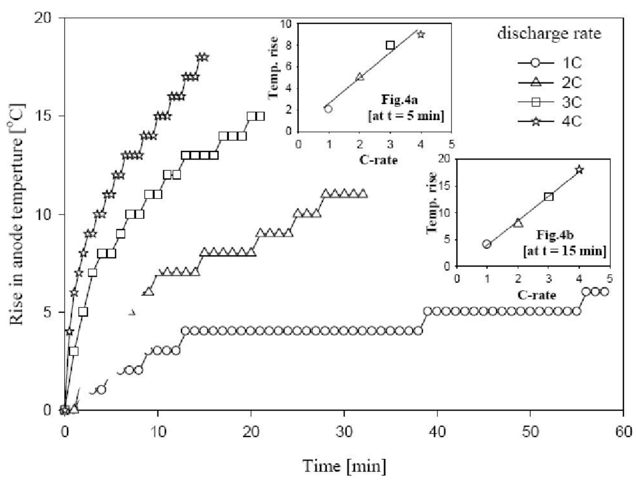

Figure 4 : Variation of rise in anode temperature versus time at different C-rates

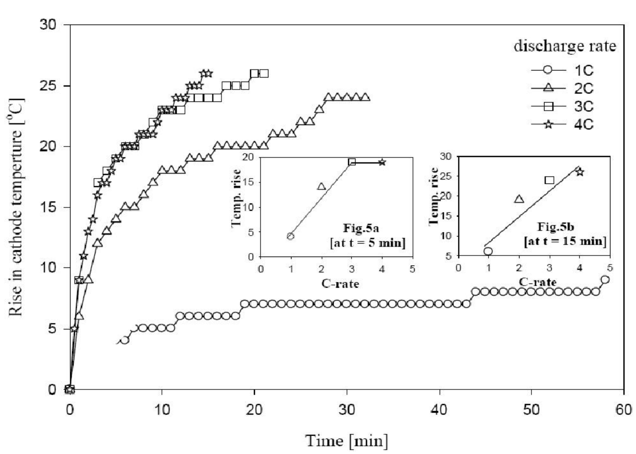

Figure 5 : Variation of rise in cathode temperature versus time at different C-rates

Inset graphs were drawn for this case also and are shown as Figures.5a and 5b corresponding to time values of 5 min and 15 min respectively. It is observed that the temperature rise of cathode was also strongly influenced by the C-rate.

Discharge characteristics of a 9-cell pack of Li-Po battery

The discharge voltage data were also obtained for each cell in the 9-cell pack in constant current mode at 1C rate by keeping current at 40 A. These data were plotted in Figure 6. A look at the plots of the figure revealed that all the discharge voltage plots are clustered together, indicating that the discharge voltage was almost same for all the 9 cells employed in the pack.

Temperature has also been measured at two select points by keeping temperature sensors. These two points were chosen in such a way that the temperature in the interior portions of the battery would be known. One sensor was placed in between third and fourth cells and another sensor was placed between sixth and seventh cells. The temperature thus measured has been plotted

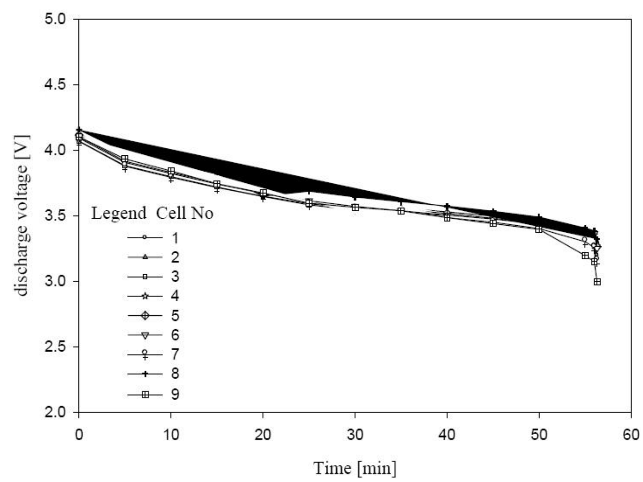

Figure 6 : Discharge voltage of all nine cells in a 9-cell pack at 1C rate

and shown in Figure 7. It is to be understood that the rise in temperature is insignificant, when the battery was discharged at 1C rate.

Charge characteristics of a single cell pack Li-Po battery

It is also important to know the charge characteristics of a Li-Po battery. In the present experiment charging was done at a constant rate of 9 A. To charge the battery fully, about 4½ hours were required. Then the

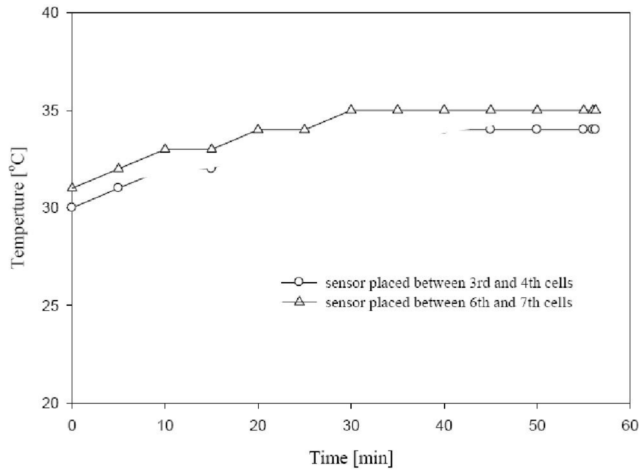

Figure 7 : Variation of temperature of 9-cell pack at select points versus time when discharging at 1C rate

battery was disconnected from the charging circuit, kept in rest for 2 hours for stabilization and again charged at a constant rate of 0.5 A for a period of 3 hours. After 6 hours of stabilization, the battery can be subjected to discharge. The variation of voltage during charge against time was plotted and shown in Figure 8 for the single cell module. During charging at 9 A, as observed from the plot of Figure 8, the voltage increased from 3.5 V to 4.2 V during a time period of 270 minutes. For three consecutive charging operations, the voltage data were obtained and shown plotted in Figure 9. An examination of the plots of this graph revealed that the voltage remained same during all consecutive charge cycles with respect to time.

Development of correlations

One of the essential parameters that plays vital role in regard to the Li-Po batteries discharge characteristics is the temperature rise of electrodes which can lead to thermal runaway of the battery system resulting in structural damage to the battery and sometimes an explosion. Therefore, an effort is made to correlate the data obtained on temperature rise of anode and cathode with its pertinent variables such as C-rate of discharge and time.

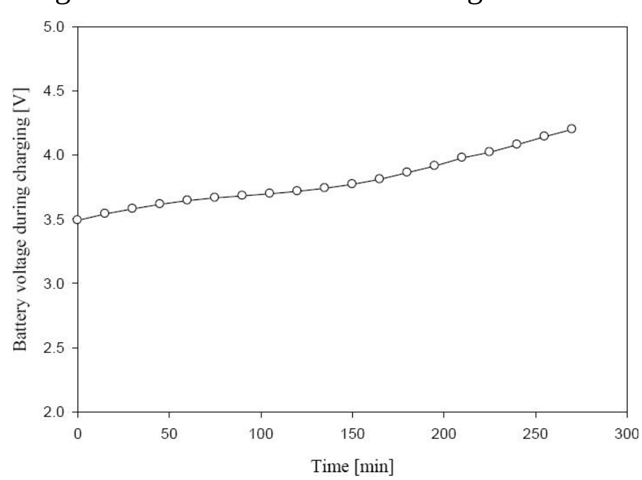

Figure 8 : Battery voltage during charging versus time when chrged at a rate of 9 A

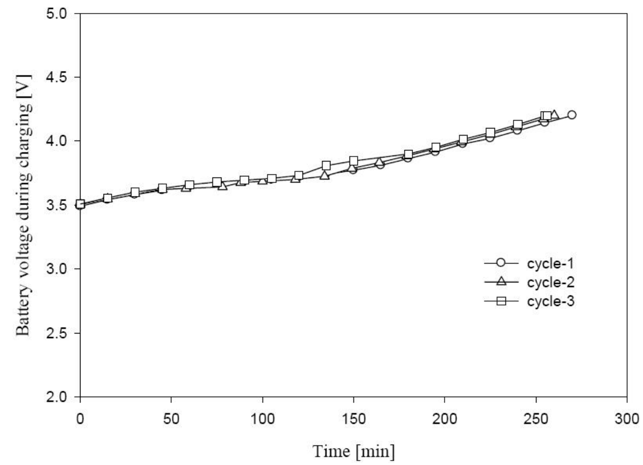

Figure 9 : Comparison of charging voltage during three different cycles all at a same rate of 9 A

The following correlation was obtained for temperature rise of anode by regression analysis.

$$T_{Ra} = 0.861 t^{0.418} C^{1.311} \quad \textbf{(1)}$$

Average deviation = 4.39%; Standard deviation = 5.77%

The correlation plot thus obtained based on eqn.(1) is shown in Figure 10. $T_{Ra} C^{-1.311}$ was taken on Y-axis and time was taken on X-axis.

Similarly the rise in temperature of the cathode was also correlated and the following equation was obtained.

$$T_{Rc} = 2.377 t^{0.346} C^{1.206} \quad \textbf{(2)}$$

Average deviation = 8.03%; Standard deviation = 9.26%

The correlation plot thus obtained based on eqn.(2) is shown in Figure 11. $T_{Rc} C^{-1.206}$ was taken on Y-axis and time was taken on X-axis.

CONCLUSIONS

The present investigation was carried out to study the discharge characteristics of a lithium polymer battery single cell module and a 9-pack unit. Temperatures of anode and cathode during charging of the single

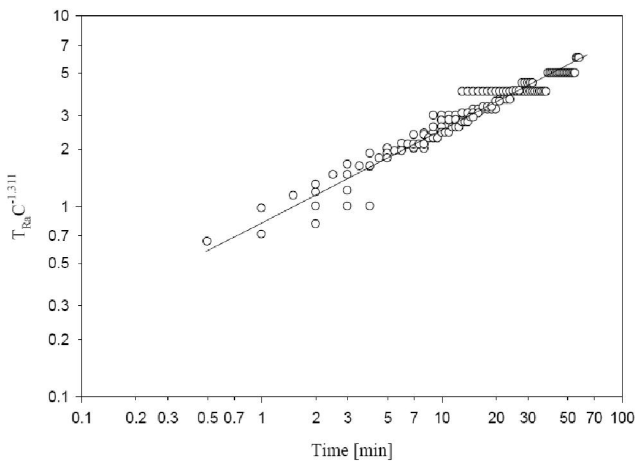

Figure 10 : Correlation plot for anode temperature rise according to eqn.1.

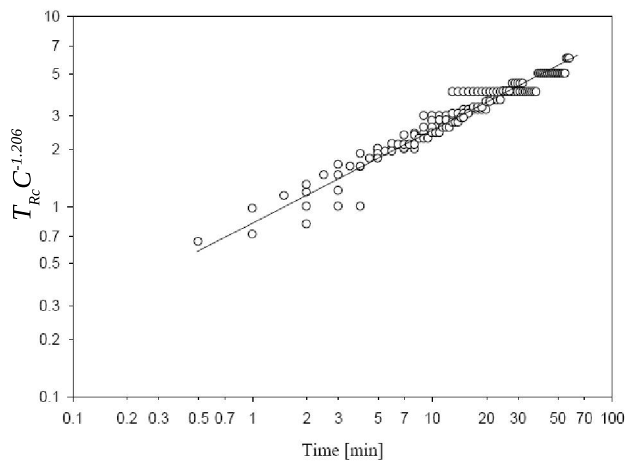

Figure 11 : Correlation plot for anode temperature rise according to eqn.2.

module have also been measured. Based on the analysis of these data, the following conclusions were drawn:

1 Upto 4C rate of discharge, the discharge voltage remained above the specified minimum value when the current is maintained constant during the mission time. This is the major requirement for the torpedoes to be launched from underwater stations.

2 The temperature rise of anode and cathode were also measured and found that upto 4C rate of discharge, the temperature of the battery is less than 65°C, a limit essentially to be maintained to avoid any thermal damage, runaway and explosion.

3 The rise in temperature of the single cell module electrodes have been well correlated in terms of C-rate of discharge and time using least-squares regression analysis.

4 The discharge study taken up for a 9-cell pack, obtained at 1C rate revealed that all individual cells exhibited almost same voltage during the discharge period under constant current mode.

5 Temperatures measured at two points within the 9-cell pack were found that they are much less than the prescribed limit when the discharge was carried out at 1C rate.

6 Charging of a single cell module has also been done at 1C rate. The voltage of the battery during charging exhibited a linear increase with time.

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