# DL OPEN REVOLUTION REBREATHER FAMILY OF PRODUCTS

# VERIFICATION OF VALENCE SAPHION IFR18650E CELLS AND THEIR CAPACITY PREDICTION ALGORITHMS FOR SAFETY CRITICAL DIVING APPLICATIONS


| | |
|---|---|
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## Revision History

| Revision | Date | Description |
|---|---|---|
| A | 27th Feb 2008 | Initial document from test plan by adding test results, and analysis |
| A1 | 15th Apr 2008 | Reviewed and released |

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## Special Note on Thumbnail Graphs:

Important graphs are shown on a large enough scale to read the axis labels easily.

This report uses thumbnail graphs to show general trends, to avoid cluttering the report with unimportant details.

If it is required to read the scale on a thumbnail graph, use the Zoom facility on the electronic version of this document or refer to the source data stored on Deep Life's SVN Source Control System. Generally, efforts are made to ensure the scale and axis of a thumbnail graph is the same as the detailed graphs dealing with the same material.

# 1 PURPOSE

Valence Saphion secondary cells use Lithium Phosphate chemistry: this is promoted by the manufacturers as the only safe high density power cell technology, incapable of explosion. Explosion is a distinct and real risk for other lithium power cells.

The purpose of this report is to determine whether the Saphion IFR18650e cells are suitable for use in pressurised life support systems as part of a redundant power scheme, in particular, in Deep Life's Open Revolution family of rebreather products.

# 2 SCOPE

This is a design verification report in accord with Deep Life Quality Procedure QP-20, for safety critical systems.

The scope of this study is:

1. Verification that the Saphion IFR18650e cells perform as described by the manufacturer's datasheet, including charge and discharge characteristics, across the full range of ambient temperatures.
2. Characterisation of the charge and discharge characteristics under the worst case load conditions presented by the equipment, across the full range of ambient temperatures the equipment can be expected to be exposed to.
3. Verification of the battery capacity prediction algorithm used by Deep Life as function of the charge level as seen from the terminal voltage, load current and temperature, and the charging parameters.
4. Verification that the cells do not explode under pressure or due to helium ingress.
5. Verification that the cells are not especially prone to sudden failure due to the worst case mechanical shocks that can plausibly occur in diving applications.
6. Verification of the discharge characteristics under conditions of the maximal thermal shock that can reasonably occur in the application. Note EN14143:2003 certification requires tests of storage and operating temperatures to -35C, as part of the overall equipment characterisation – those refrigeration tests are reported in the compliance documentation and are not duplicated here.

The scope does not extend to verifying there are no catastrophic failure modes other than due to mechanical shock, thermal shock, gas pressure or helium, as the manufacturer has provided an independent test report by Dr. Noah Budiansky, Dr. Quinn Horn, Xiaoyun Hu, Dr. Kevin White, , *"BN64159, Comparison of Selected Lithium-Ion Battery Chemistries, Testing Report"*, Exponent Inc[1], 11 July 2007 that verifies adequately that the chemistry used in the Valence Saphion cells does not carry any explosion or significant exothermic risk, unlike more common lithium power cell technologies.

Credible reliability information is available from Valence Technology Inc, so the present study does not try to establish MTBF data for the cells, or lifetime data. Items 4, 5 and 6 above consider whether there are any other failure modes in the Saphion cells specific to diving applications. A total of 60 cells were procured for this study, from two batches.

The datasheet for the IFR18650 is summarised in Appendix A.

[1] Available from Valence Technology Inc, or Exponent Inc, 21 Strathmore Road, Natick, MA 01760. USA

# 3 GLOSSARY

The word "Battery" refers to two Saphion cells connected in series. The word "cell" is used to refer to a single Saphion IFR18650e cell.

# 4 SAFETY INTEGRITY LEVEL ASSESSMENT

Safety Integrity is assessed in accord with EN61508:2004, by the application of Quality Procedure QP-22.

Deep Life's rebreather products have been assessed as SIL 4, requiring at least two power sources under all normal operating conditions. Loss of power is a safety critical event that is mitigated by the use of a variable orifice valve to maintain oxygen to the diver even when no power is present. The situation where a total power loss occurs underwater, and the diver continues to breathe from the rebreather then ascend has been tested in both unmanned and manned underwater tests, and has been verified to be relatively safe for normal ascent rates.

Deep Life's rebreathers have full power management features, including continuous power monitoring, power self test, brown-out circuits, power drop out detection, dual redundancy of all power systems and fail safety in the event of a total power loss. As a result of these safety features, the Safety Integrity Rating for an individual battery during a dive is not more than SIL 1: that is two independent SIL 1 systems are used in parallel for the SIL 4 application with a foundation layer that maintains safety with a total loss of power.

Despite this, loss of power seriously compromises the operation and safety of the equipment, so this study demands a detailed assessment of these cells. In the final analysis, use or rejection of these cells in Deep Life products is accepted as being the sole responsibility of Deep Life Ltd.

Separate Design Verification reports are available for the power supply and monitoring schemes used in Deep Life's rebreathers and for every major functional system which has a power source. This present report covers just the Saphion power cells, and their suitability for use in these systems.

# 5 TEST PLAN

The external variable parameters during cell discharge are the initial battery charge, load, and temperature, and similarly for the charging cycle.

The discharge currents for which the manufacturer's datasheet contains curves are 280 mA (standard), 0.5A and 1.5A. A maximum continuous current drain of 2.8A will also be verified in this report.

The maximum normal rebreather load is 0.3A, where injectors are active and shut off valves are activated. This is sufficiently close to the conditions under which the manufacturer's data sheet measured curves with a 280 mA load current as not to warrant separate testing.

Rebreathers operate for long periods with very low loads (less than 100uA). In preparing this test plan, the problem of the extremely long test period this presents, was considered: the tests would take more than 10,000 hours! An assessment was carrying out by charging a group of 6 cells, then waiting for 4 months with no load, then comparing the discharge curves of those cells with that for freshly charged cells. The results of this test are included herein. It was concluded that the high load conditions should be assessed, and it would be reasonable to simply scale these for the case where the load is less than the lowest load state considered here (280mA).

The datasheet will be verified with ambient temperatures of 4C, room temperature and 60C, as that is the widest operating range for the batteries in the equipment. Note the 4C case occurs when the water temperature the rebreather is immersed in, is -4C due to various heating effects within the rebreather. The highest temperature occurs when equipment is left out in the sun: the battery holder is external to the rebreather, in a one atmosphere housing, shaded by the rebreather outer case.

Special conditions exist in the application, namely risk of exposure to high gas pressures, helium, risk of mechanical shock and thermal shock. The deepest manned dive has been to 701msw during Comex trials, so pressures equivalent to double this depth will be tested, with compression and decompression rates of the worst case possible that could possibly occur in a saturation diving environment using a medical chamber transfer lock. Note in Deep Life applications, cells are maintained at one atmosphere pressure, but fault conditions are plausible where a seal leaks and the cells become subject to the ambient pressure.

| TEST PLAN | | |
|---|---|---|
| No. | Name/Note | Description |
| 1 | Pressure and helium shock | Fully charge a cell. Pressurise the cells to 140 bar in less than one second, without load, maintain at 140 bar for one week, and depressurise in one second. Repeat three times. Verify that the cell is not destroyed by verifying it can maintain a normal load. |
| 2 | Datasheet verification:<br><br>Discharge performance under room temperature Discharge current is 0.28, 0.5, 1.5, and 2.8 A.<br><br>Charge the battery after each test | Connect a 14.6 Ohm load (to dissipate 3,7W) to two charged cells connected in series. Measure the total battery voltage until it drops to 5 volts (2.5*2). The time of the test is approx 3 hours.<br><br>Repeat the test for 26Ohm/2W (0.28 A, ~5 hour), ~5Ohm/11W (1.5 A, ~1 hour) and ~2.6Ohm/11W (2.8 A, ~0.5 hour) |
| 3 | Discharge under extreme operating temperatures. | Repeat the above test for 4C and 60 C environment. 4C is the coldest water temperature around the equipment: it corresponds to a water temperature of around -4C due to thermal losses from counterlungs and due the insulating effect of the battery housing. 60C is based on diving in 40C, after solar heating on the surface. |
| 6 | Charge performance.<br><br>Repeat after each discharge. | Charge the battery using constant current. Log the battery voltage until it gets 7.5 volts (3.65*2). |
| 7 | Thermal shock to simulate cold dive after solar exposure | Place a cell into its normal housing. Heat in air at 100C to for 30 minutes, then drop into water at 4C. Measure discharge characteristics under normal rebreather load conditions. |
| 8 | Mechanical shock | Drop two fully charged cells from 1.5m onto a hard surface (Test 2a), and from 3m onto a hard surface (Test 3a), and verify the cells still operate.<br><br>Note only two cells are used: this is a verification report not a manufacturer's product characterisation. The purpose here is to verify the absence of systemic problems, not to obtain a statistical characterisation of a production process. |
| 9 | Discharge repeatability | Repeat the first test for 14.6 Ohm/3,7W |

# 6 EQUIPMENT

The following equipment was used for the tests. All equipment was checked before use to ensure it has current labels showing it has been maintained and logged in Deep Life's calibration log maintain by the QA Department.

## 6.1 Supply unit

Type: Laboratory DC power supply GPR - 1850

Constant voltage operation

| | |
|---|---|
| • Regulation Line regulation | < 0.01% + 3mV |
| • Load regulation | < 0.01% + 3mV (rating current < 3A)<br>< 0.02% + 5mV (rating current > 3A) |
| • Ripple & Noise | < 0.5mVrms 5Hz ~ 1MHz (rating current < 3A)<br>< 1mVrms 5Hz ~ 1MHz (rating current > 3A) |
| • Recovery Time | < 100μS (50% Load change, Minimum load 0.5A) |
| • Temp. Coefficient | < 300ppm/°C |
| • Output Range | 0 to rating voltage continuously adjustable |

Constant current operation

| | |
|---|---|
| • Line regulation | < 0.2% + 3mA |
| • Load regulation | < 0.2% + 3mA |
| • Ripple Current | < 3mArms |
| • Output Range | 0 to rating amperes continuously adjustable<br>(Hi / Lo range switch able) |

Meter

- Analog V-meter and I-meter each one 2.5 class Dimension 50 x 50 mm

## 6.2 Precision multimeter

Type: Time Electronics 5075 Ultra high precision 8 digit computing multimeter

| | |
|---|---|
| • Digit resolution | |
| • AC voltages: | from 3mV (resolution: 100nV to 3kV) |
| • DC voltages: | from 3mV (resolution: 10nV to 10kV) |
| • AC and DC currents: | from 3uA to 30A |
| • Resistance: | 30mOhm (resolution: 10nOhm to 1GOhm) |
| • Capacitance: | 30nF to 300uF |
| • Frequency: | 1Hz to 100kHz |
| • PT100: | -200°C to 600°C |

## 6.3 National Instruments Computer Data Acquisition System.

Type: PCI-6014

Analogue Input

| | |
|---|---|
| • Number of channels: | 16 single-ended or 8 differential |
| • Max sampling rate: | 200 kS/s guaranteed |
| • Input signal gain: | 0.5; 1; 10 ;100 |
| • Nominal range: | +/- 10; 5; 0.5; 0.05 V |
| • Absolute Accuracy at Full Scale: | 10 mV |

- Relative accuracy: ±1.5 LSB typ, ±3.0 LSB max
- Scaling error: ±2.0 μV max
- Gain error: ±74 ppm of FSD
- Input impedance: Normal powered on 100 GΩ in parallel with 100 pF
- CMRR (DC to 60 Hz), Gain 0.5, 1.0: 85 dB
- Bandwidth (-3 dB): 425 kHz
- Settling time for full-scale step: ±2 LSB: 5 μs max
- Stability:
  - Recommended warm-up time: 15 min
  - Scaling temperature coefficient: ±20 μV/°C
  - Gain temperature coefficient: ±32 ppm/°C

Analogue Output

- Number of channels: 2
- Range: 10V
- Resolution: 16 bits, 1 in 65,536
- Relative accuracy (INL): ±3 LSB, typ
- DNL: ±2 LSB, typ
- Monotonicity: 15 bits
- Scaling error: ±250 mV max
- Gain error: ±22,700 ppm
- Output impedance: 0.1 Ω max
- Current drive: ±5 mA max
- Protection: Short-circuit to ground
- Settling time for full-scale step: 8 μs to ±1 LSB accuracy
- Slew rate: 4 V/μs
- Noise: 360 $\mu V_{rms}$, DC to 400 kHz
- Scaling temperature coefficient: ±128 μV/°C
- Gain temperature coefficient: ±26.8 ppm/°C

Digital I/O

- Number of channels: 8 input/output
- Compatibility: TTL/CMOS

Timing I/O

- Number of channels: 2
- Resolution: 24 bits
- Compatibility: 5 V TTL/CMOS

I/O connector

68-pin male SCSI-II type

## 6.4 Test Chamber

All pressure tests were carried out using certified gases, using pressure chamber DL-03. This is a bronze 200 bar micro chamber designed for high pressure oxygen bomb testing, with facilities for very rapid compression and decompression.

## 6.5 Saphion Cells

IFR 18650e cells used for these tests were procured in two batches, in April 2007 and September 2007, directly from Valence Technology Inc, USA.

# 7 TEST RESULTS

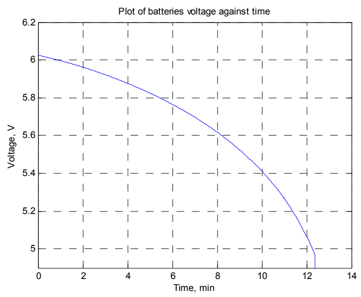
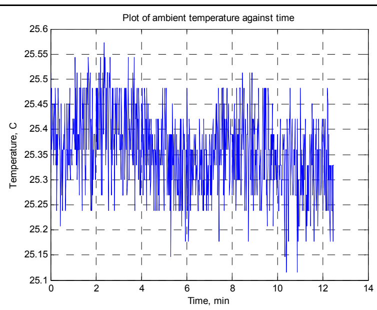
## 7.1 Pressure and helium

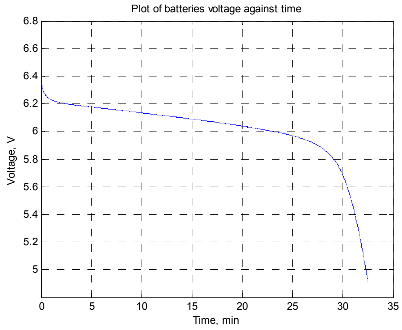
| No. | Name/Note | Description |
|---|---|---|
| 1 | Pressure and helium | Fully charge a cell. Pressurise the cells to 140 bar in less than one second, without load, maintain at 140 bar for one week, and depressurise in one second. Repeat three times. Verify that the cell is not destroyed by verifying it can maintain a normal load. |

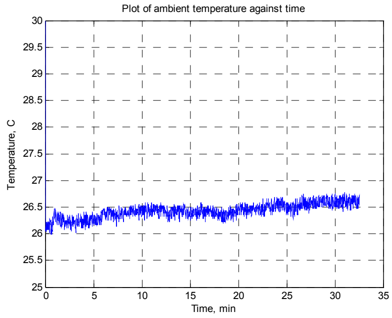
The cells passed the above test. There was no sign of any damage other than a slight crinkling of the wrapping around the cell.

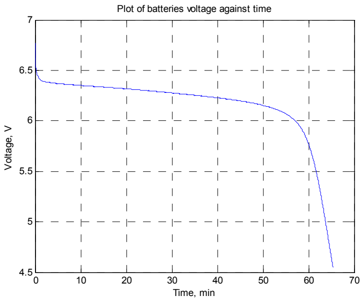
## 7.2 Discharge performance under room temperature

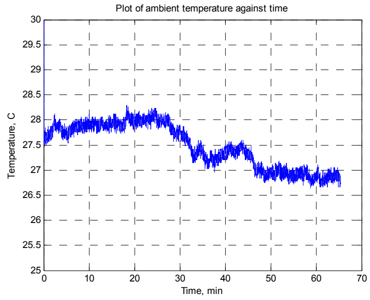
| No. | Name/Note | Description |
|---|---|---|
| 2 | Datasheet verification:<br><br>Discharge performance under room temperature Discharge current is 0.28, 0.5, 1.5, and 2.8 A.<br><br>Charge the battery after each test | Connect a 14.6 Ohm/3,7W resistor to two charged cells connected in series. Measure the total battery voltage until it drops to 5 volts (2.5*2). The time of the test is approx 3 hours.<br><br>Repeat the test for<br><br>~26Ohm/2W (0.28 A, ~5 hour),<br><br>~5Ohm/11W (1.5 A, ~1 hour)<br><br>~2.6Ohm/11W (2.8 A, ~0.5 hour) |

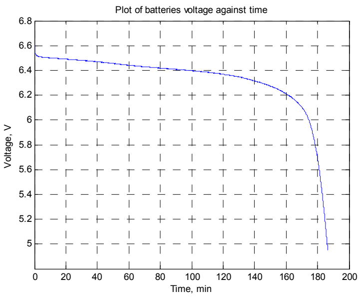
| N | Batteries voltage | Ambient temperature | Load resistance, Ohms | Description |
|---|---|---|---|---|
| 1 |   Discharge time (drop to 5V) is 12min |   Test data: Battery_test_1_current_0_5_A.mat | 14.7 | Cell shown was charged, stored for 4 months, then tested. Cells had never been discharged before. |

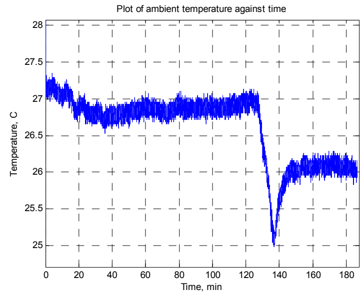
<table>
<tr>
<td>2</td>
<td>

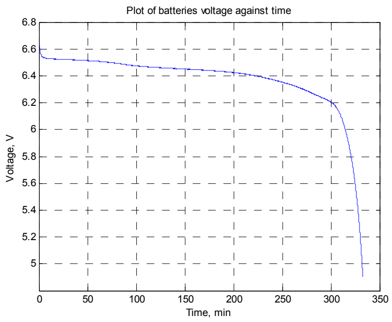
Discharge time (drop to 5V) is 32min</td>
<td>

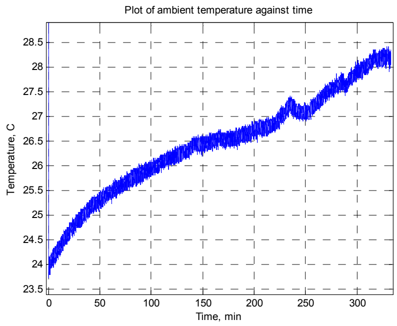
Test data: Battery_test_1_current_2_8_A.mat</td>
<td>2.6</td>
<td>Discharge test after the 3rd charge – discharge cycle.</td>
</tr>
<tr>
<td>3</td>
<td>

Discharge time (drop to 5V) is 64min</td>
<td>

Test data: Battery_test_1_current_1_37_A.mat</td>
<td>5.1</td>
<td>Discharge test after the 2rd charge – discharge cycle.</td>
</tr>
<tr>
<td>4</td>
<td>

Discharge time (drop to 5V) is 186min</td>
<td>

Test data: Battery_test_2_current_0_5_A.mat</td>
<td>14.7</td>
<td>Discharge test after the 1st charge – discharge cycle, Compare with first result above.</td>
</tr>
<tr>
<td>5</td>
<td>

Discharge time (drop to 5V) is 332min</td>
<td>

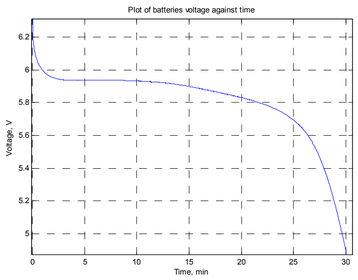
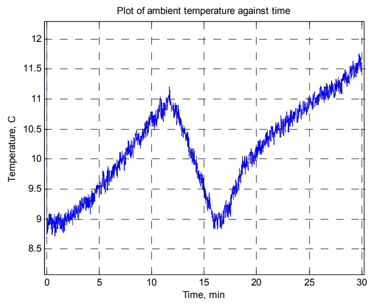
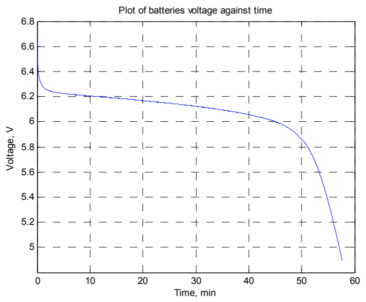
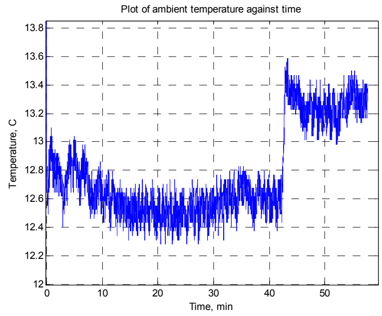
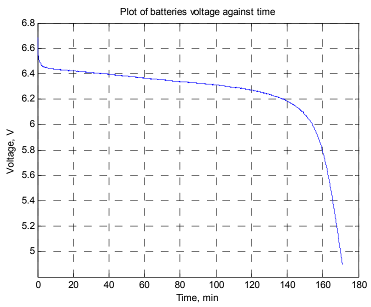
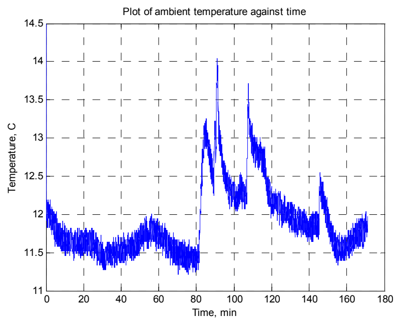
Test data: Battery_test_2_current_0_28_A.mat</td>
<td>25.5</td>
<td>Discharge test after the 5th charge – discharge cycle.</td>
</tr>
</table>

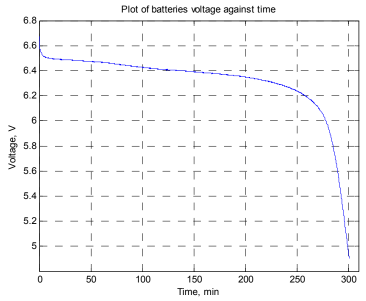
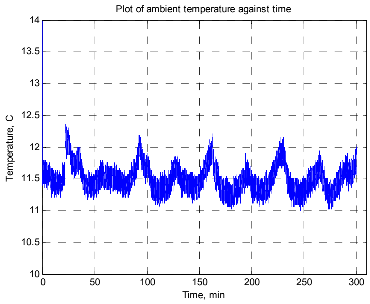
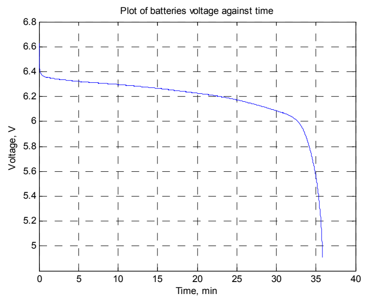
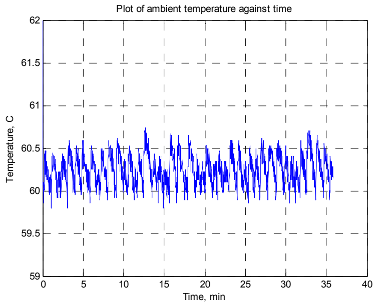
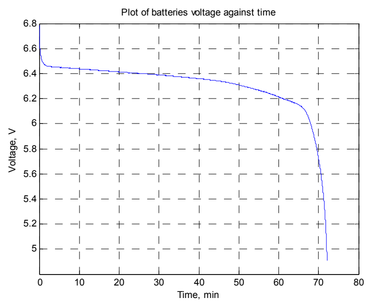
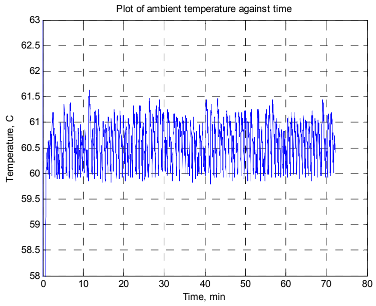
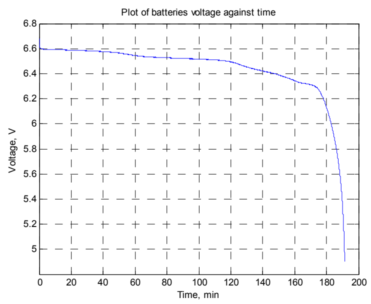
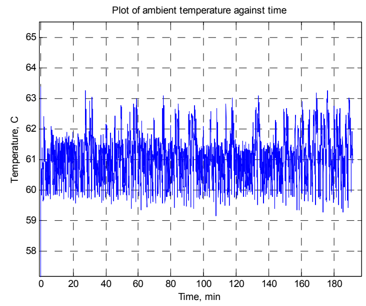
**Figure 7-1.** Typical battery voltage and ambient temperature against time, for different load currents and charge cycles.

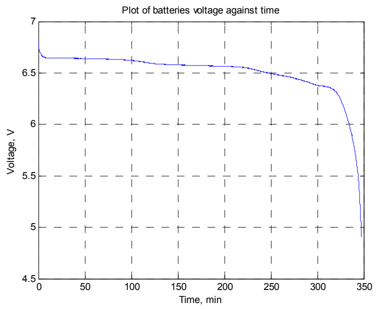
## 7.3 Discharge under extreme operating temperatures.

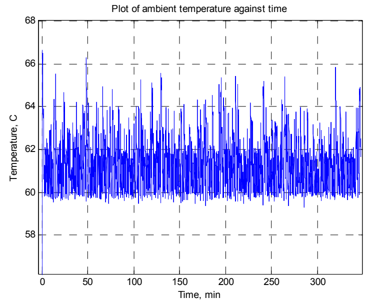
| No. | Name/Note | Description |
|---|---|---|
| 3 | Discharge under extreme operating temperatures. | Repeat the above test for 4C and 60 C environment. 4C is the coldest water temperature around the equipment: it corresponds to a water temperature of around -4C due to thermal losses from counterlungs and due the insulating effect of the battery housing. 60C is based on diving in 40C, after solar heating on the surface. |

**Note:** According to the manufacturer's specification the operating temperature range of these cells is: -10°C to 50°C so this test pushes the cells beyond their rated limits. Cells were tested without any cover.

| N | Battery voltage | Ambient temperature | Load resistance, Ohm | Description |
|---|---|---|---|---|
| 6 |  Discharge time (drop to 5V) is 29min |  Test data: battery_test_1_current_2_8_A_8C.mat | 2.6 | Discharge test after the 6 charge – discharge cycle. |
| 7 |  Discharge time (drop to 5V) is 57min |  Test data: battery_test_1_current_1_37_A_8C.ma t | 5.1 | Discharge test after the 7 charge - discharge cycle. |
| 8 |  Discharge time (drop to 5V) is |  Test data: | 14,7 | Discharge test after the 9 charge – discharge cycle. |

| | | | | |
|---|---|---|---|---|
| | 170 min | battery_test_1_current_0_5_A_8C.mat | | |
| 9 | <br><br>Discharge time (drop to 5V) is 300 min | <br><br>Test data: battery_test_1_current_0_28_A_8C.mat | 25.5 | Discharge test after the 10 charge - discharge cycle. |
| 10 | <br><br>Discharge time (drop to 5V) is 35 min | <br><br>Test data: battery_test_1_current_2_8_A_60C.mat | 2.5 | Discharge test after the 11 charge - discharge cycle. |
| 11 | <br><br>Discharge time (drop to 5V) is 72 min | <br><br>Test data: battery_test_1_current_1_37_A_60C.mat | 5.1 | Discharge test after the 12 charge - discharge cycle. |
| 12 | <br><br>Discharge time (drop to 5V) is 191 min | <br><br>Test data: battery_test_3_current_0_5_A_60C.mat | 14.7 | Discharge test after the 13 charge - discharge cycle. |

<table>
<tr>
<td>13</td>
<td>

Discharge time (drop to 5V) is 347 min</td>
<td>

Test data: battery_test_1_current_0_28_A_60C.mat</td>
<td>25.5</td>
<td>Discharge test after the 14 charge - discharge cycle.</td>
</tr>
</table>

**Figure 7-2.** Battery voltage against time under extreme operating temperatures.

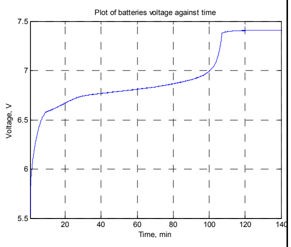
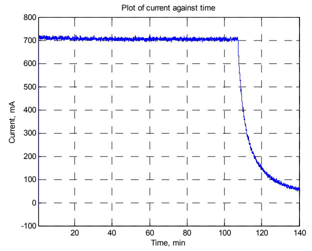
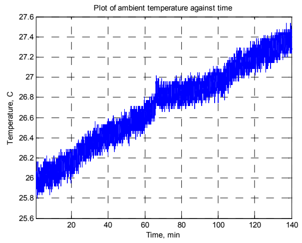
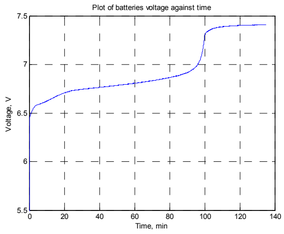
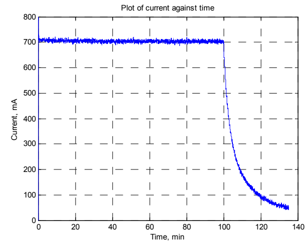
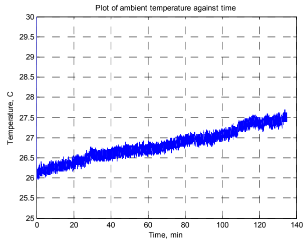
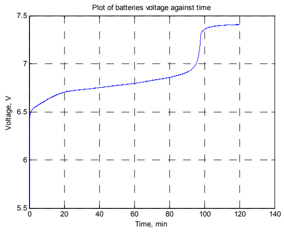
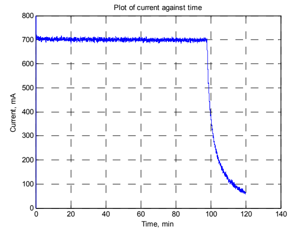
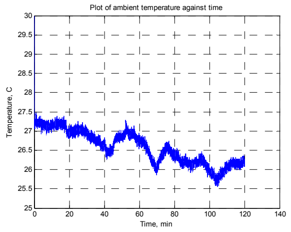
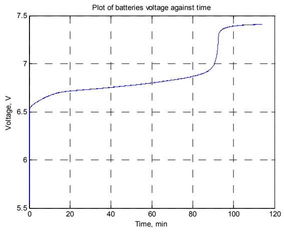
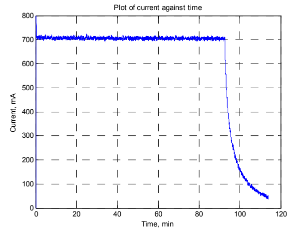
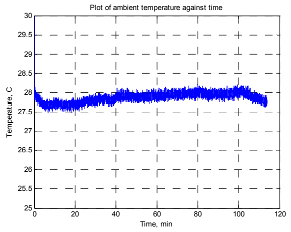
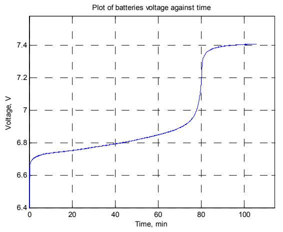
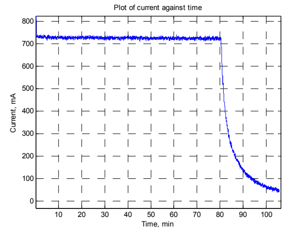
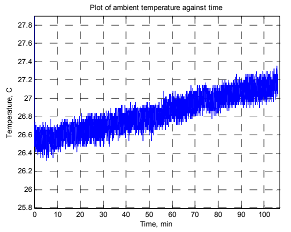
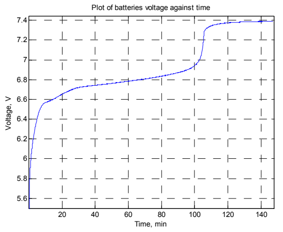
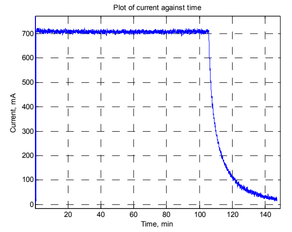
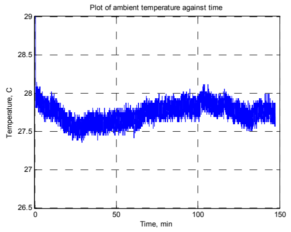
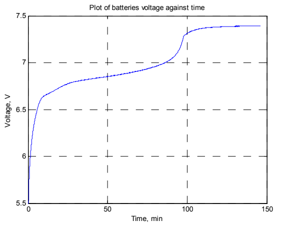
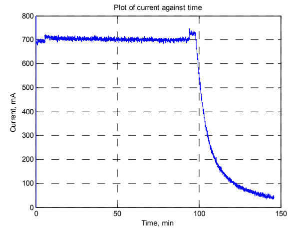
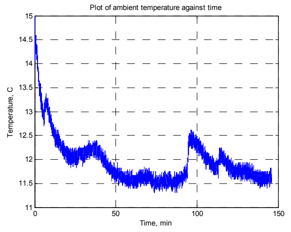
## 7.4 Charge performance

| No. | Name/Note | Description |
|---|---|---|
| 6 | Charge performance.<br>Repeat after each discharge. | Charge the battery. Measure the battery voltage until it gets 7.5 volts (3.65*2). |

A voltage supply unit with voltage and current indicators was used for battery charging. The output voltage of the unit records by MatLAB during the charge - discharge cycle.

The batteries are charged in according with the following steps.

1. Ensure that the external supply unit has no load connected
2. Switch on the power supply unit
3. Set the voltage to 7.5V (3.65V*2)
4. Switch off the power supply unit
5. Limit the possible output current to the minimum level on the power supply (200mA)
6. Connect the battery to be charged. Note all cells were charged as a battery of two cells connected in series.
7. Switch on the power supply unit
8. Set the current limit on 700mA
9. Keep charging until the current drops to 70 mA.
10. Disconnect the battery.

| Test N | Battery voltage | Charging current | Ambient temperature | Description |
|---|---|---|---|---|
| 1 |   |   |   | Test data: bt_charge_1.mat |
| 2 |   |   |   | Test data: bt_charge_2.mat |
| 3 |   |   |   | Test data: bt_charge_3.mat |
| 4 |   |   |   | Test data: bt_charge_4.mat |
| 5 |   |   |   | Test data: bt_charge_5.mat |
| 6 |   |   |   | Test data: bt_charge_6.mat |
| 9 |   |   |   | Test data: bt_charge_9_8C.mat |

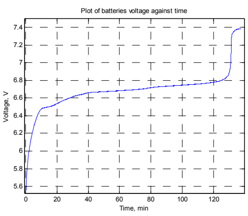
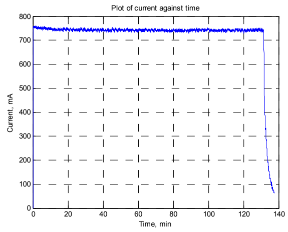
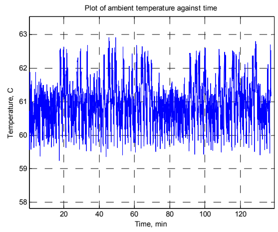
| | | | | |
|---|---|---|---|---|
| 15 |  |  |  | Test data: bt_charge_15.mat |

**Figure 7-3.** Battery charge characteristics under different temperatures.

## 7.5 Thermal shock to simulate cold dive after solar exposure

| No. | Name/Note | Description |
|---|---|---|
| 7 | Thermal shock to simulate cold dive after solar exposure | Place a cell into its normal housing. Heat in air at 100C to for 30 minutes, then drop into water at 4C. Measure discharge characteristics under normal rebreather load conditions. |

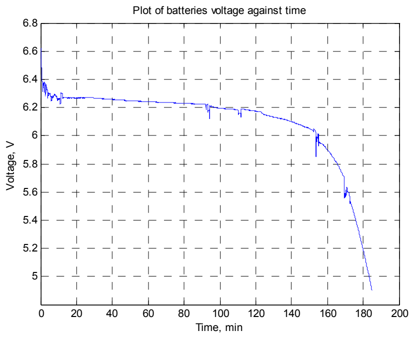
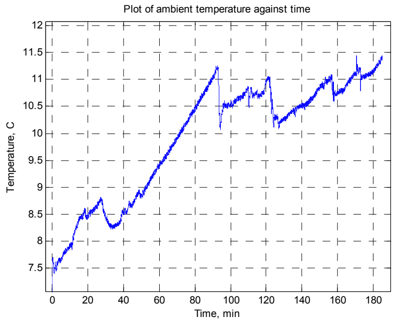
| Voltage, V | Ambient temperature, C | Description |
|---|---|---|
| <br>Discharge time (drop to 5V) is 183 min |  | Discharge current 0.5 A.<br>Test data: thermal_shock.mat |

**Figure 7-4.** Battery voltage and ambient temperature against time.

**Note**: Two cells were fully charged at room temperature, and the cells were then fitted inside their normal stainless steel housing. The housing was placed in an environmental chamber that was heated from 25 deg C to 90 deg C in10 min and then from 90 deg C to 105 deg C in 30 min. The housing with the cells was then dropped immediately into iced water and discharged via 14.7 Ohm load with a 0.5A current. The water temperature increased to room temperature as the cells warmed up the water: no attempt was made to refrigerate the water after the cells were placed in it, other than topping up with ice periodically, as can be seen from the ambient temperature plot.

**Result:** The cells behaved well under these test conditions.

## 7.6 Mechanical shock

| No. | Name/Note | Description |
|---|---|---|
| 8 | Mechanical shock | Drop two fully charged cells from 1.5m onto a hard surface (Test 2a), and from 3m onto a hard surface (Test 3a), and verify the cells still operate.<br>Note only two cells are used: this is a verification report not a manufacturer's product characterisation. The purpose here is to verify the absence of systemic problems, not to obtain a statistical characterisation of a production process. |

Two sets of tests were carried out:

- A: Two fully charged cells were dropped on a hard (wood) surface from a height of 1.5m. Cells without any cover are dropped one after another, for ten drops.

- B: Two fully charged cells were dropped on a hard (wood) surface from a height of 3m. Cells without any cover are dropped one after another, for ten drops.

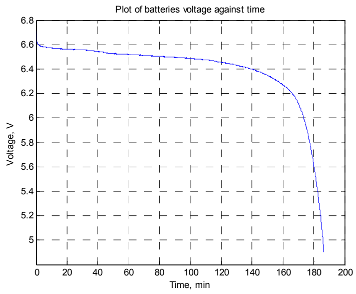
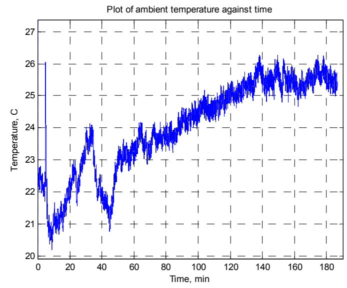
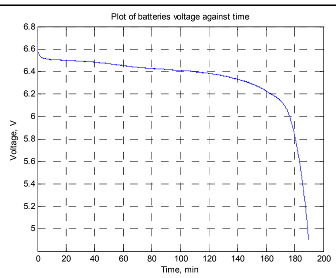
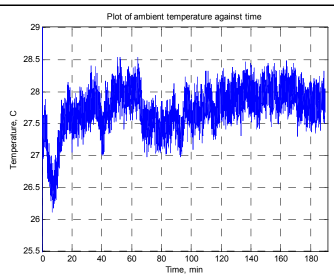
| Height, m | Voltage, V | Ambient temperature, C | Description |
|---|---|---|---|
| 1.5 | <br>Discharge time (drop to 5V) is 186 min |  | Discharge current 0.5A.<br>Test data: disch_aft_1_5m_gd.mat |
| 3 | <br>Discharge time (drop to 5V) is 189 min |  | Discharge current 0.5A.<br>Test data:disch_aft_3m.mat |

**Figure 7-5.** Battery voltage and ambient temperature against time after drops.

**Result**: After the drops there was no visible damage to the naked eye, other than slight compression of the outer plastic wrap. There was no effect on the cells discharge characteristics.

## 7.7 Discharge repeatability

| No. | Name/Note | Description |
|---|---|---|
| 9 | Discharge repeatability | Repeat the first test for 14.6 Ohm/3,7W |

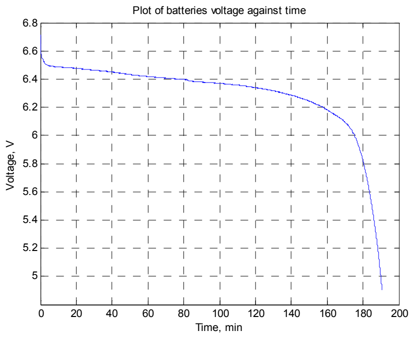
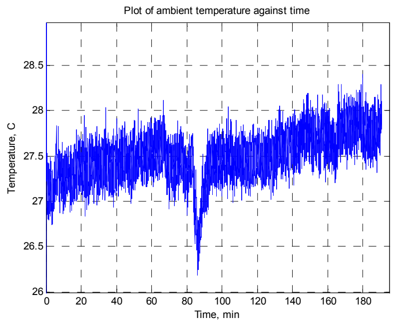
| Voltage, V | Ambient temperature, C | Description |
|---|---|---|
|   Discharge time (drop to 5V) is 189 min |   | Test data: discharge_repeat_after_all.mat |

**Figure 7-6.** Battery voltage and ambient temperature against time.

**Result:** Discharge characteristics under the same load done after several charge - discharge does not change significantly.

# 8 MTBF DATA APPLICABILITY

Temperature is the primary driver of MTBF data: reliability reduces at least as a positive quadratic function of temperature. Normally, MTBF tests are carried out at 60C. The application uses the Saphion cells at much lower temperatures: between 4C and 30C under normal conditions.

There are no indicators from any of the tests that have been carried out, that there is any deleterious effect from risk from any other factor involved in the design: pressure, helium, shock. Given the small size of the sample (60 cells), the Design Authority has isolated the cells from pressure, from helium, from thermal shock and to a reasonable degree, to mechanical damage.

Review of this data concludes the MTBF data from the manufacturer is applicable but will be conservative in this application.

Four sets of MTBF data shall be taken to provide 90% confidence limits.

# 9 ANALYSIS OF THE TEST DATA

## 9.1 Algorithm verification: Deep Life's remaining power prediction function based on Voltage, Load and Temperature

The existing algorithm developed by Deep Life to predict battery life of the Lithium Phosphate cells is compared with the test data under different voltages, loads and temperatures.

The algorithm calculates the remaining power available of two IFR18650e batteries connected in serial as a function of the battery voltage, load current and ambient temperature.

**Initial data**

- The array of 200 cells (**Array_V**) that contains the test data of the battery discharge by 0.5A under room temperature.

**Input data**

- Battery voltage in V: **V_battery**
- Battery load current in A: **I_load**
- Battery temperature in deg. C: **T_battery**

**Output data**

- Remaining power available in %: **TL**

**ALGORITHM**

1. Measure the Load current:
2. Measure the Battery voltage
3. Measure the ambient temperature
4. If V_battery > 6.55V the remaining power available is 100%

   else If V_battery < 5.13V the remaining power available is 0%

   else:
5. Calculate the data **Rotation**

$$Rotation = -0.07225 + 0.15331 \times I\_Load - 0.014922 \times I\_Load^2$$

6. Calculate the temperature scaling: **Scaling_T**

   If T_battery >=26:

$$Offset\_T = (0.12902 - 0.056199 \times I\_Load + 0.024897 \times I\_Load^2)\frac{T\_battery - 26}{34}$$

   If T_battery <26:

$$Offset\_T = (-0.023094 - 0.11045 \times I\_Load + 0.019818 \times I\_Load^2)\frac{26 - T\_battery}{14}$$

7. Determine the voltage scaling

$$V\_offset = V\_battery - Offset\_T + Rotation(2 - \frac{V\_battery - 5.13 - Offset\_T}{1.42})$$

8. Find the cell (**Cell_number**) in the Array_V containing the data closest to the V_scaling.
9. Calculate the remaining power available in % against the battery load, battery voltage and temperature

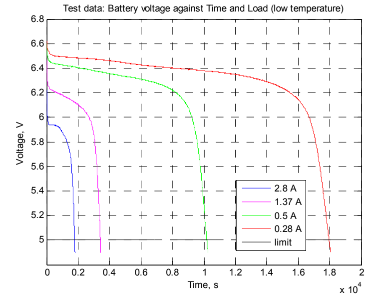
$$TL = \frac{201 - Cell\_number}{2}$$

10. Pass the TL throw the low pass filter.

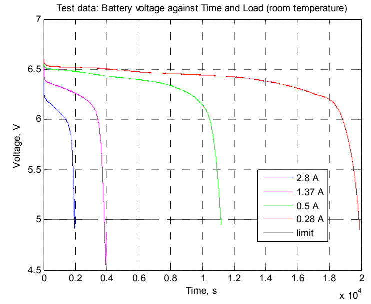
11. Show TL on a display.
12. End of the algorithm.

## 9.2 Empirical data

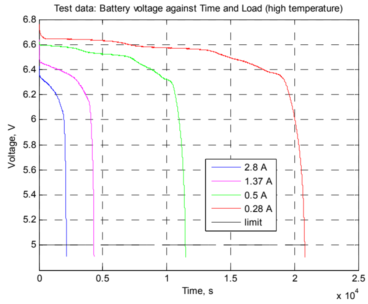
Tests were carried out capture data on the actual battery discharge characteristic as function of the battery voltage, battery load and temperature.




Low temperature is ~10..13C

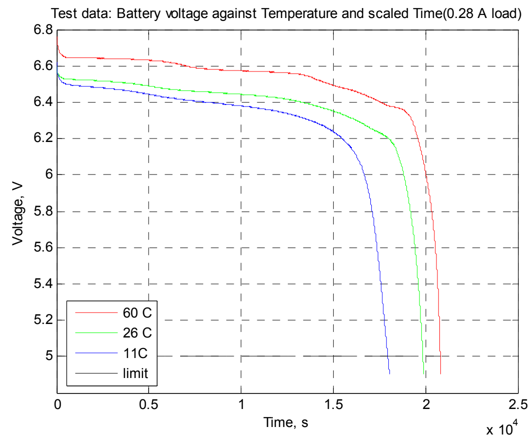



Room temperature is ~26..27C

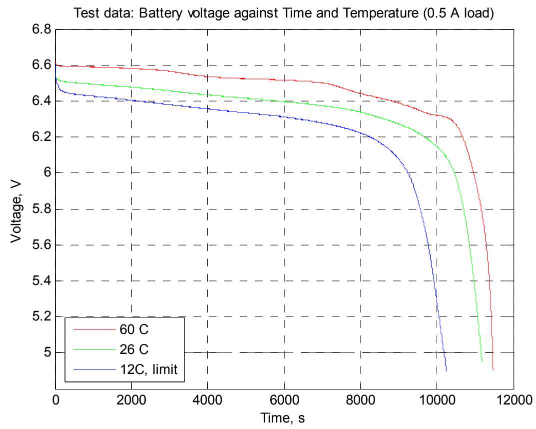



High temperature is ~60..61C

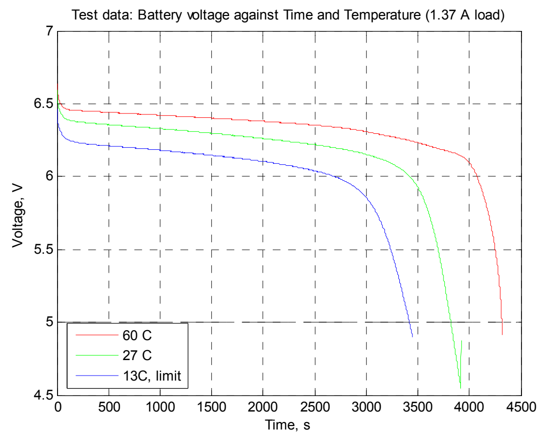
**Figure 9-1.** Battery voltage against load under constant temperature.



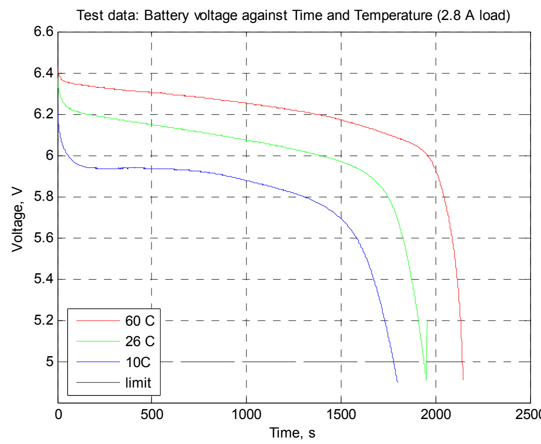

0.28 A load




0.5 A load




1.37 A load




2.8 A load

**Figure 9-2.** Battery voltage against temperature under constant load, empirical data.

## 9.3 Error of linear part of DL's remaining capacity prediction function

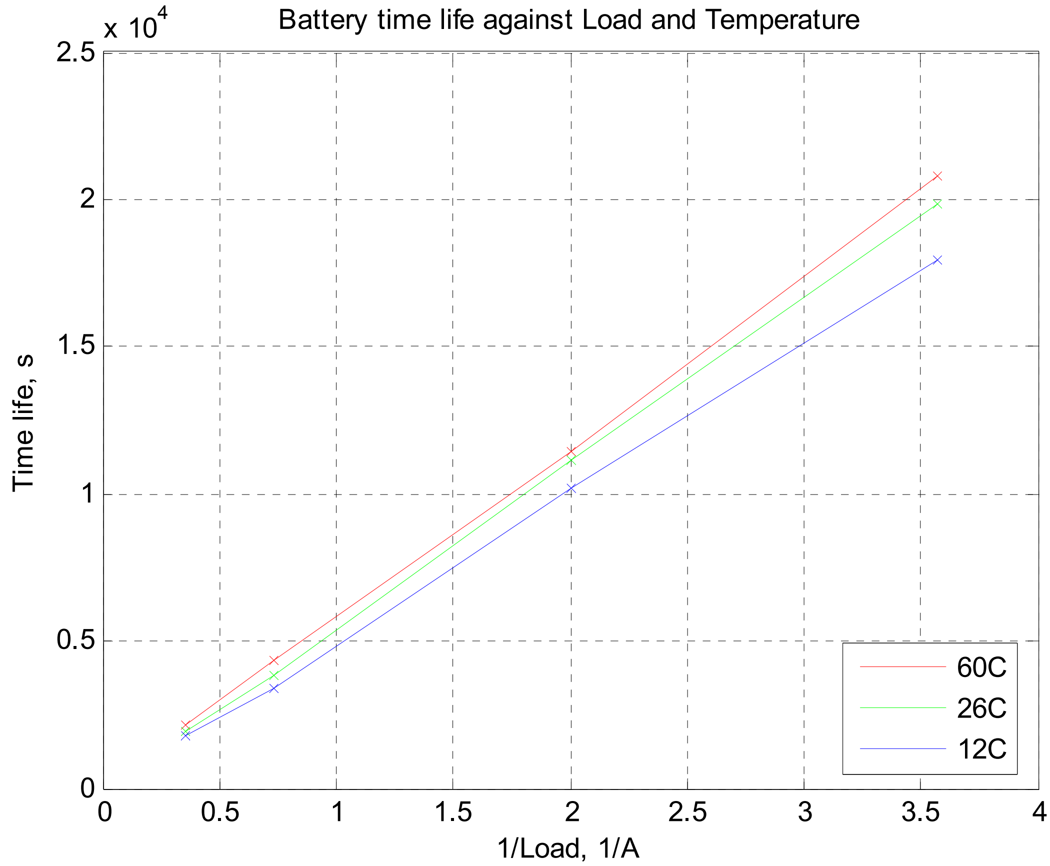



**Figure 9-3.** Remaining power available against temperature and 1/load. This function is the linear function against 1/load and non-linear function against temperature.

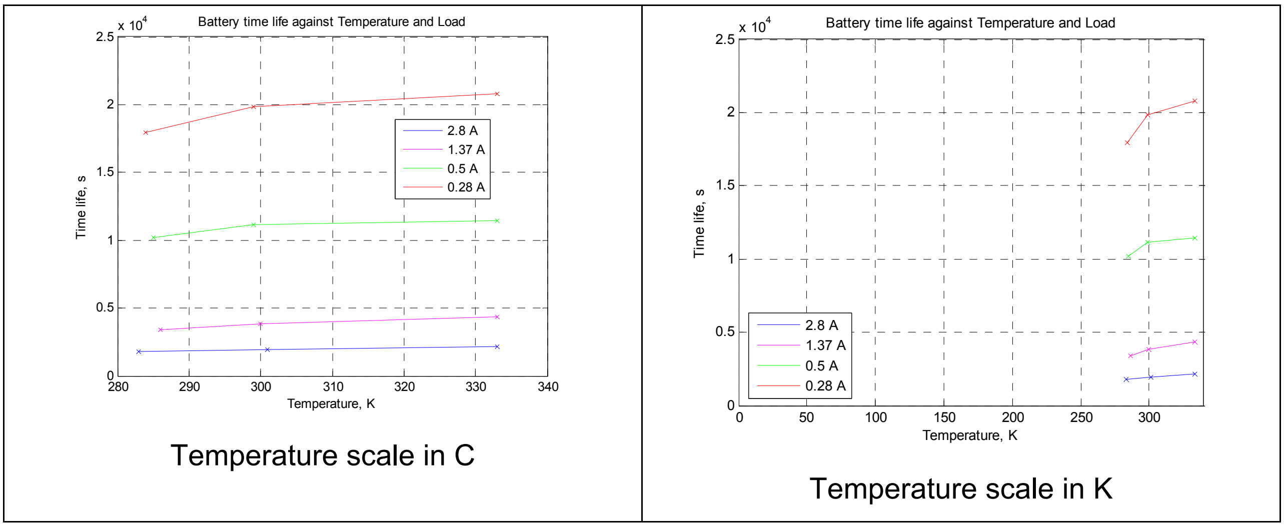



**Figure 9-4.** Effect of temperature. Lower temperatures decrease the remaining power available. Extrapolated zero power available is in the range 230..250K.

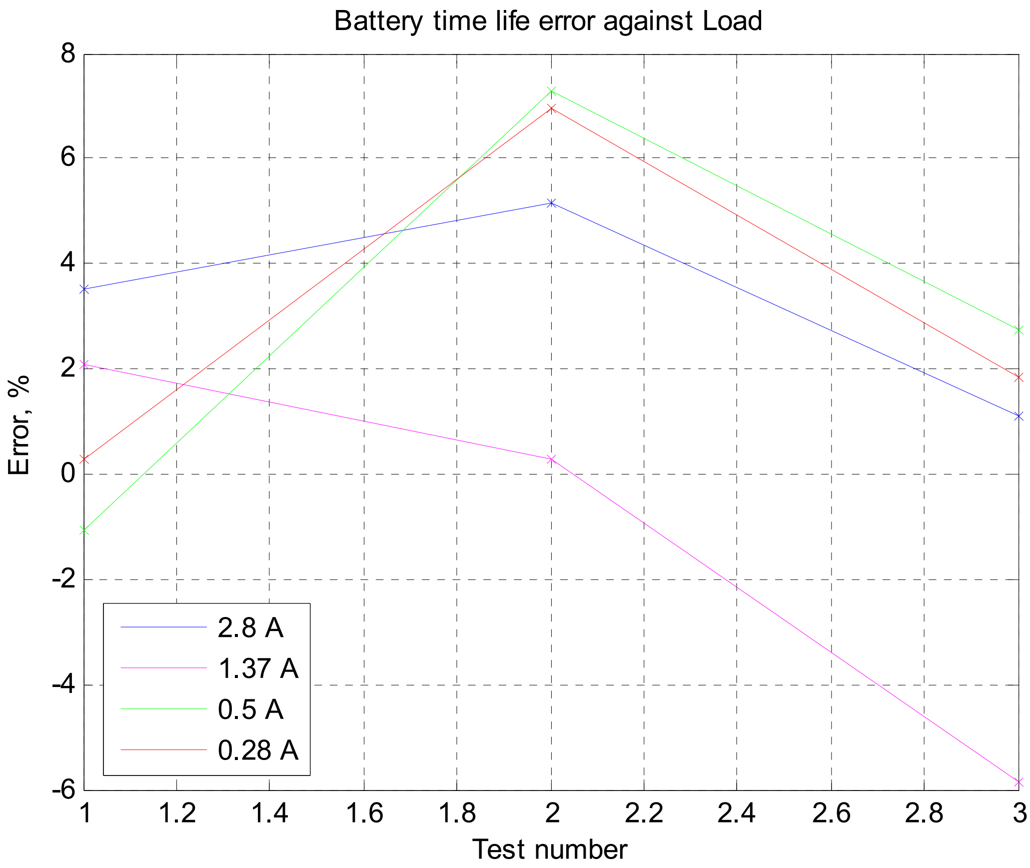
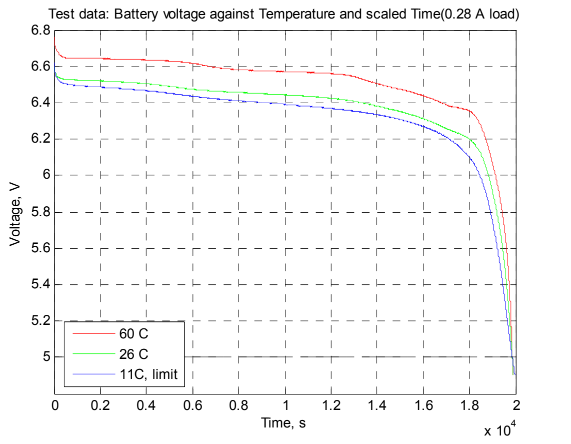
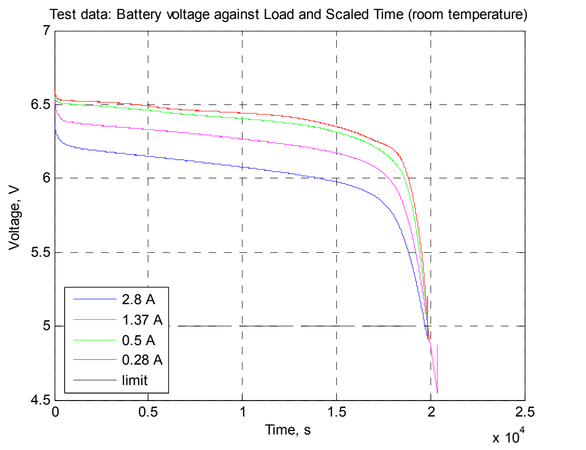



**Figure 9-5.** Error of the linear part of the algorithm predicting the power available: this is a plot of the error as a percentage of the actual remaining power available compared with that predicted by the linear function of the battery load and temperature. The maximum error is ~7%, but for the critical near exhausted condition the error under worst case rebreather load is less than 2%




Normalised function of temperature. The load is 0.28A. The temperature scalings the battery amplitude and changes the shape of the plots.




Normalised function of load. Room temperature. Increasing loads reduce the battery terminal voltage, as would be expected from their internal resistance.

**Figure 9-6.** Battery test voltage normalised to the same test time.

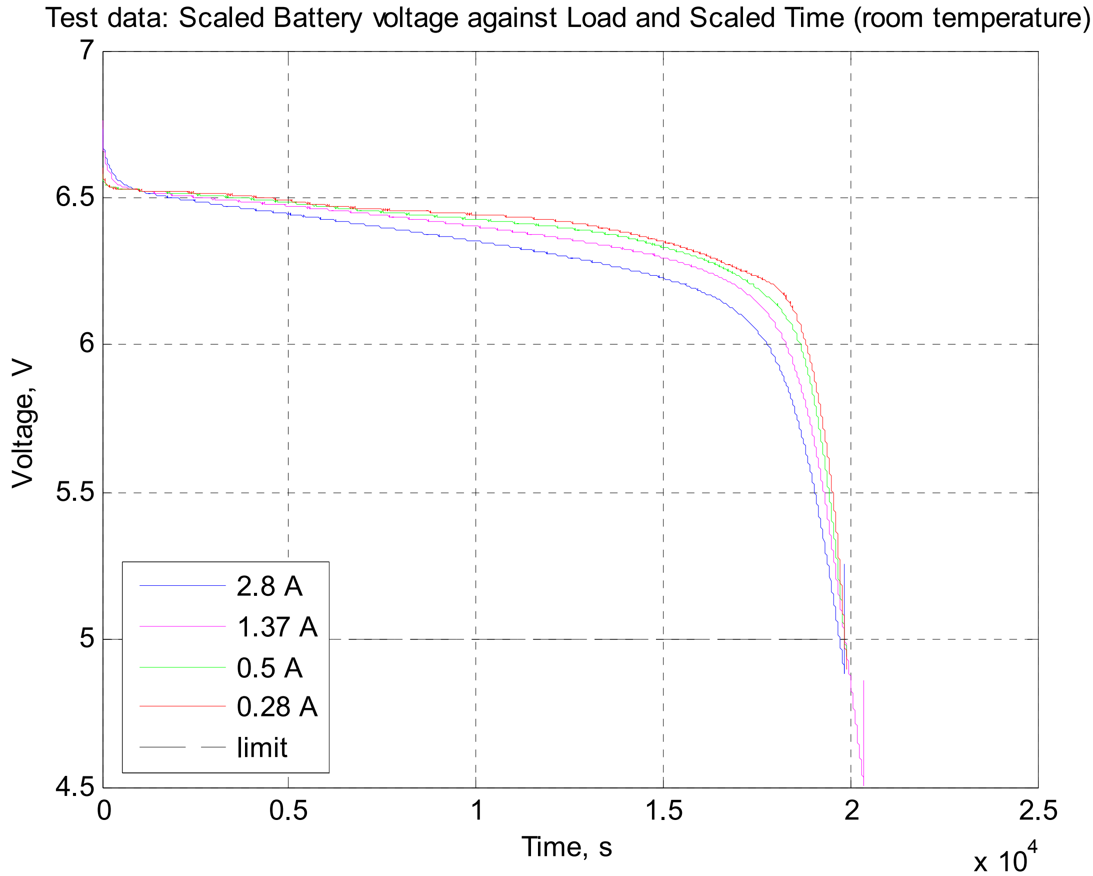



**Figure 9-7.** Battery test voltage normalised relative to the test time and terminal voltage. The load rotates the normalised data.

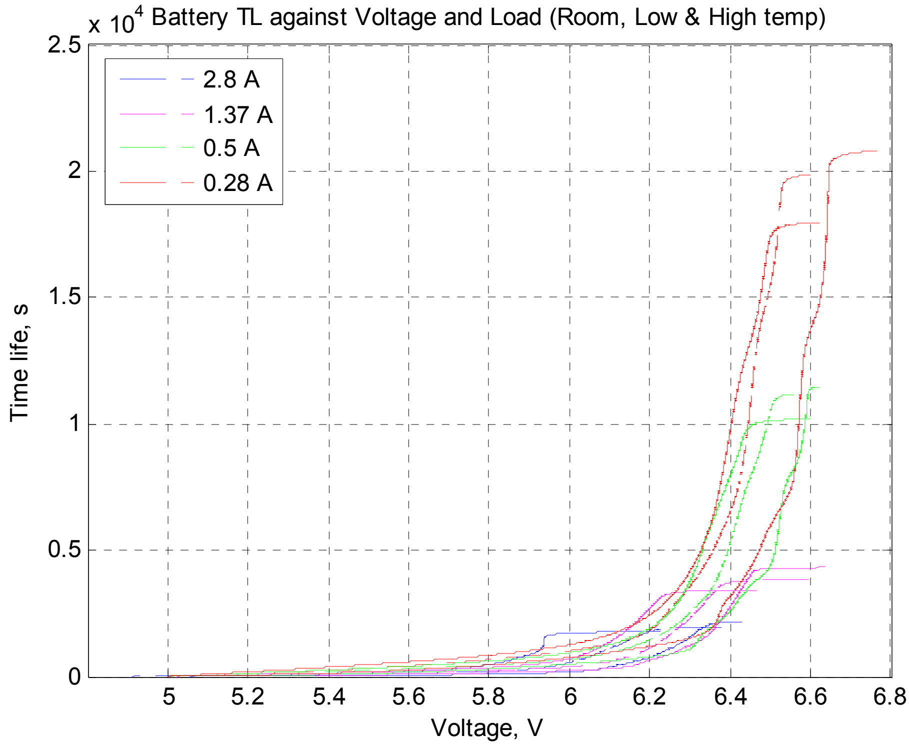



**Figure 9-8.** Remaining power available against battery voltage and temperature. The left plot of the same colour shows the remaining power available at the lowest test temperature. The right plot of the same colour shows the remaining power available at highest test temperature.

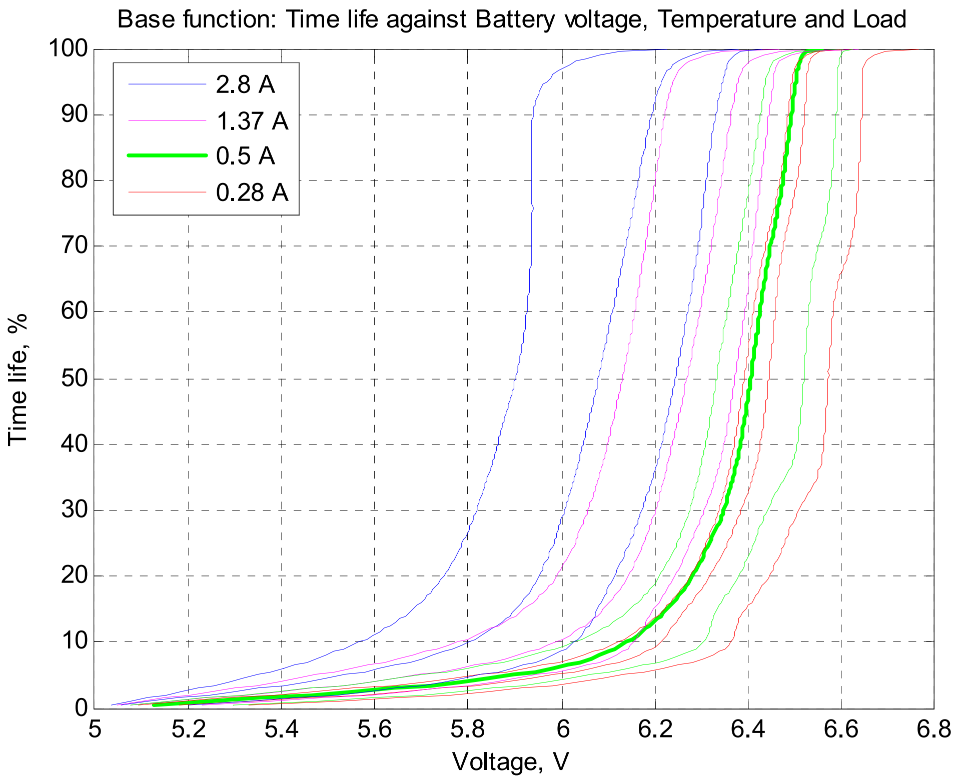



**Figure 9-9.** Normalised actual remaining power available against battery voltage and temperature. The left plot of the same colour shows the remaining power available at the lowest test temperature. The right plot of the same colour shows the remaining power available at highest test temperature.

# 9.4 Verifying the scaling and rotate capacity prediction function: Remaining power available against battery voltage and load

## 9.4.1 Accuracy of the battery function without data rotation

Battery discharge curves under a 0.5A load current at a room temperature of 26C was normalised and compared with the curves predicted using linear, exponential, simple polynomial and multi-polynomial approximations of the same curves.

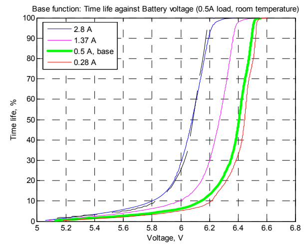
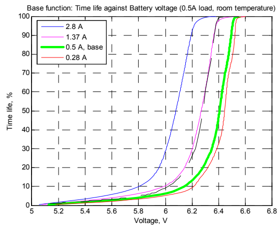
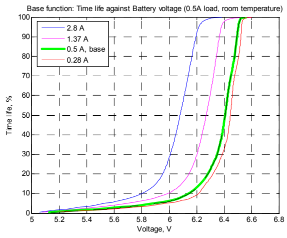
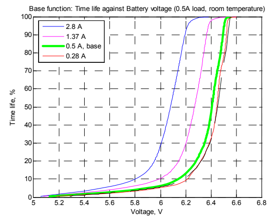
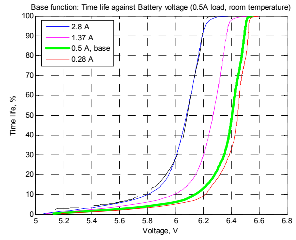
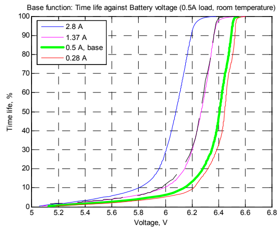
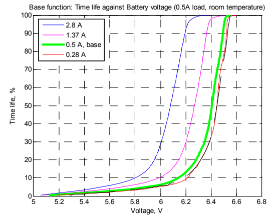
| | | | |
|---|---|---|---|
|  <br>V_scaling=0.3 |  <br>V_scaling=0.125 |   |  <br>V_scaling=0.05 |
|  <br>angle=0.27;<br>V_scaling=0.23 |  <br>angle=0.2;<br>V_scaling=0.1 | angle=0;<br>V_scaling=0 |  <br>angle=-0.01;<br>V_scaling=-0.04 |

**Figure 9-10.** Normalised remaining power available against battery voltage and load at room temperature. The black dot-dash line is the calculated remaining power available function. The function scalings the 0.5A/26C test data along the voltage axes and rotates them in the plot plane. Functions in the 2nd row of the above table (combining scaling and rotation) have less error relative to the actual data than the functions that use scaling only (shown in the first row).

## 9.4.2 Accuracy of the function with data rotation

Scaling and rotation of the base function are calculated using the test data:

angle = [0.24 0.11 0 -0.03];

scaling = [0.24 0.11 0 -0.03];

current = [2.8 1.37 0.5 0.28];

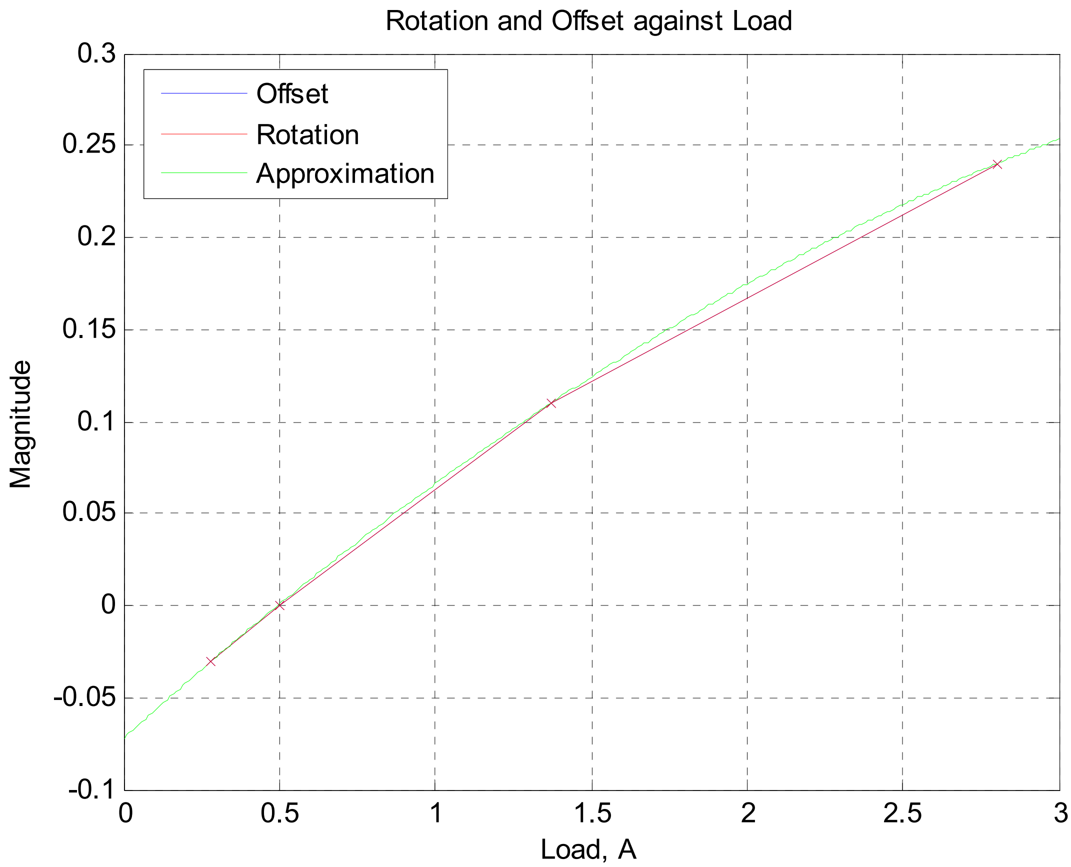



**Figure 9-11.** Discharge prediction function using scale and rotation, plotted against load. Rotation and scaling are zero for the 0.5 A load. The approximation equals the actual test data at the 0.5 A point where the scaling and rotation is zero.

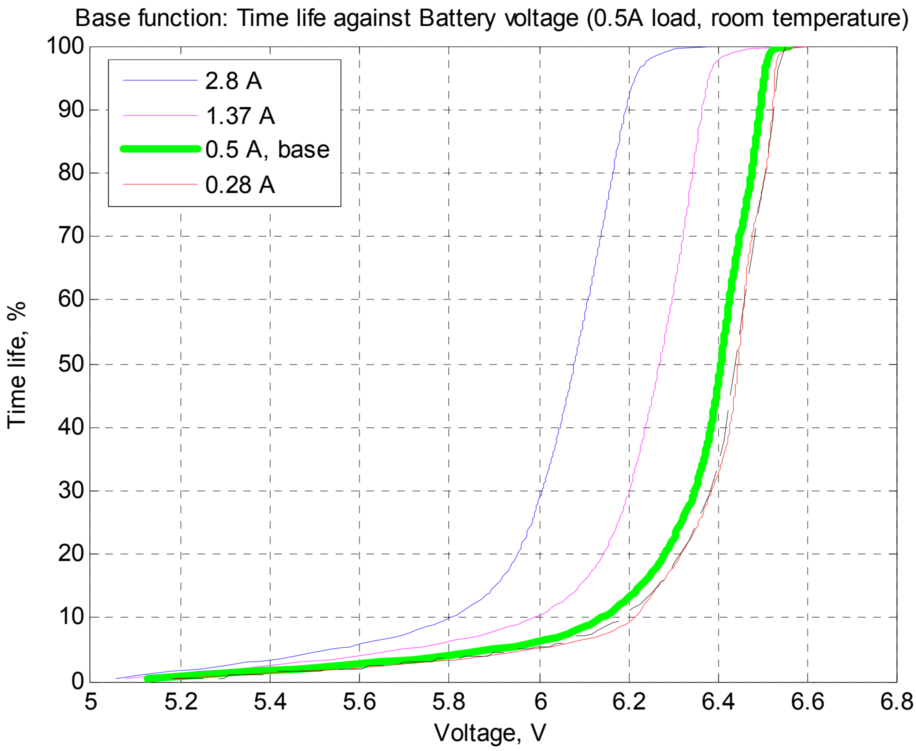
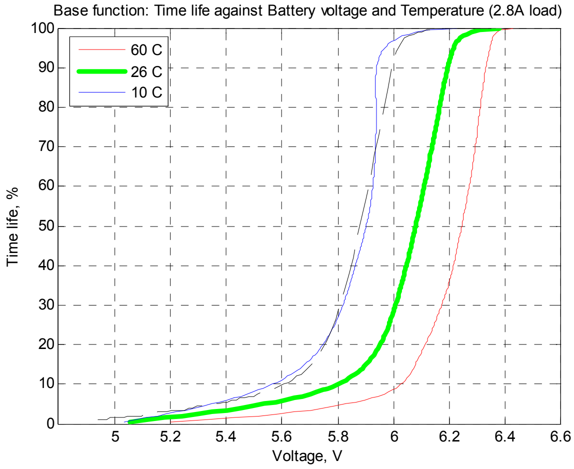
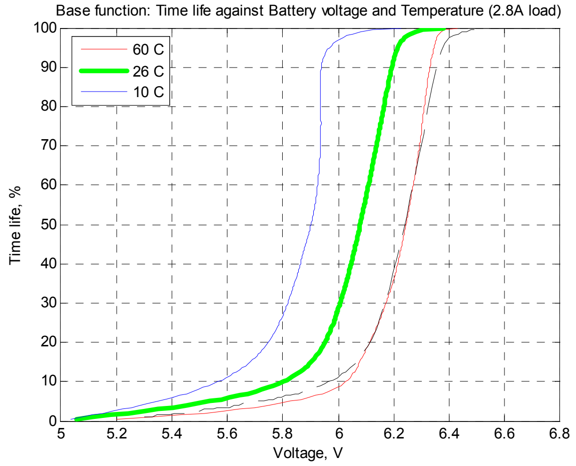


**Figure 9-12.** Accuracy of the base line scaling and rotation function relative to the 0.28A red curve. Load = 0.28A, Scaling & Rotation Angle =-0.03

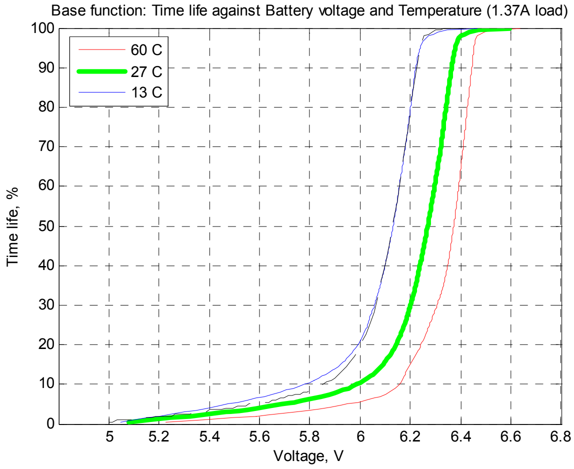
## 9.5 Scaling Function: Remaining power prediction function against battery voltage, load and temperature



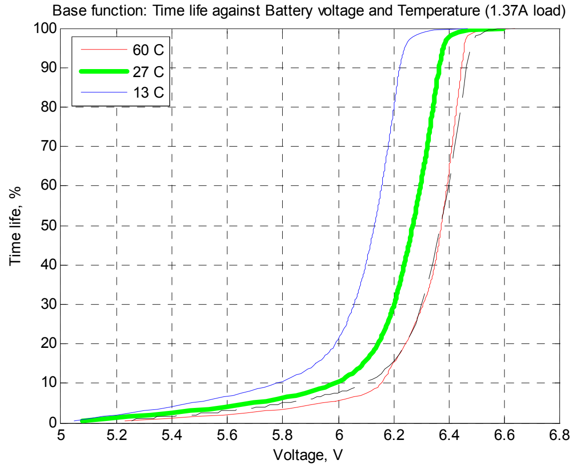

I = 2.8A, T = 10C, Scaling = -0.2V



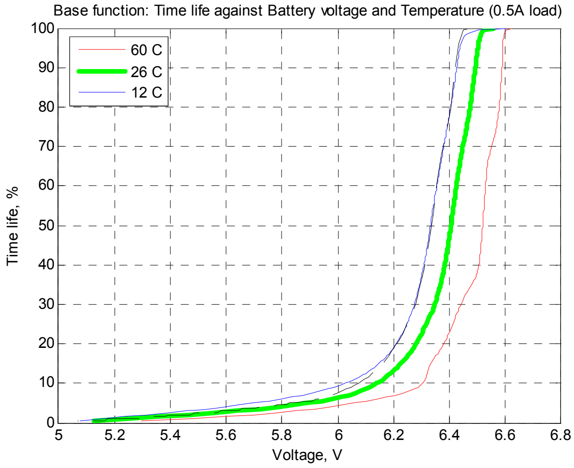

I= 2.8A, T = 60C, Scaling = 0.16V



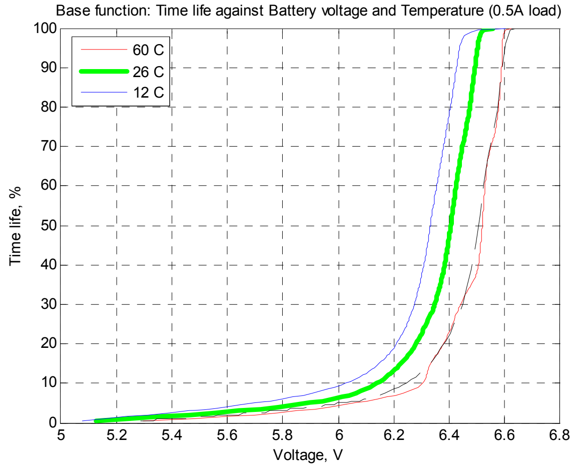

I= 1.37A, T = 13C, Scaling = -0.14V




I= 1.37A, T = 60C, Scaling = 0.1V




I = 0.5A, T = 12C, Scaling = -0.07V




I = 0.5, T = 60C, Scaling = 0.1V

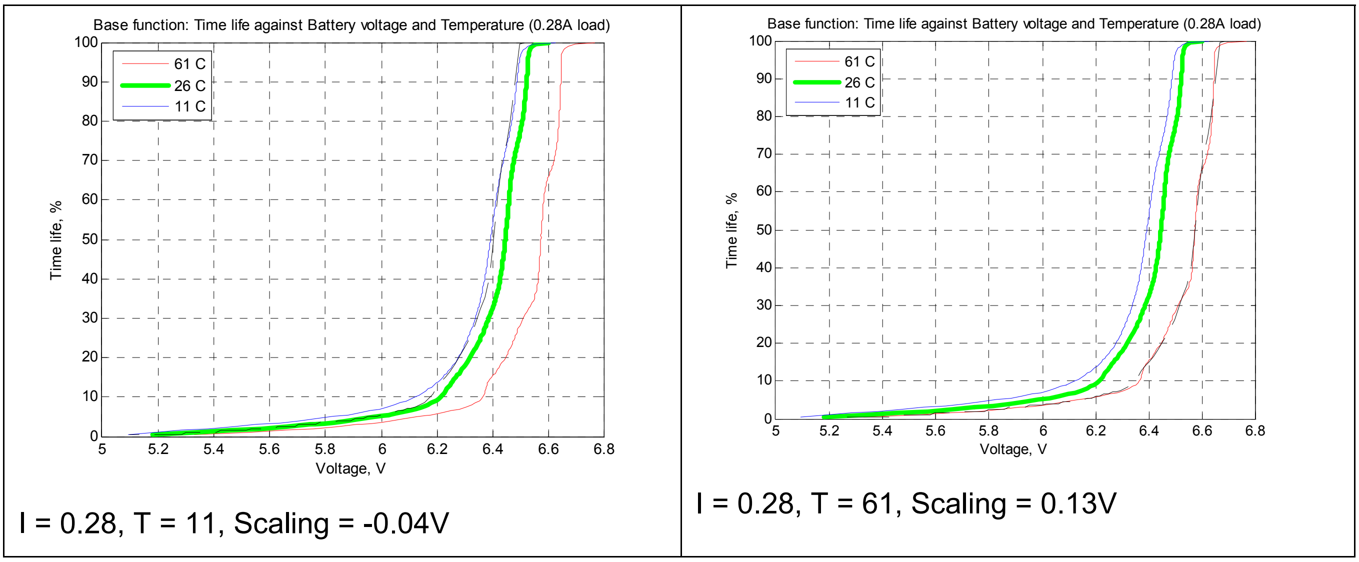



**Figure 9-13**. Calculation of the voltage scaling as a function of the ambient temperature. The scaling is the voltage difference between the green and blue or red line (marked by the approximated dot-dash line) at the point where 50% the remaining power is available.

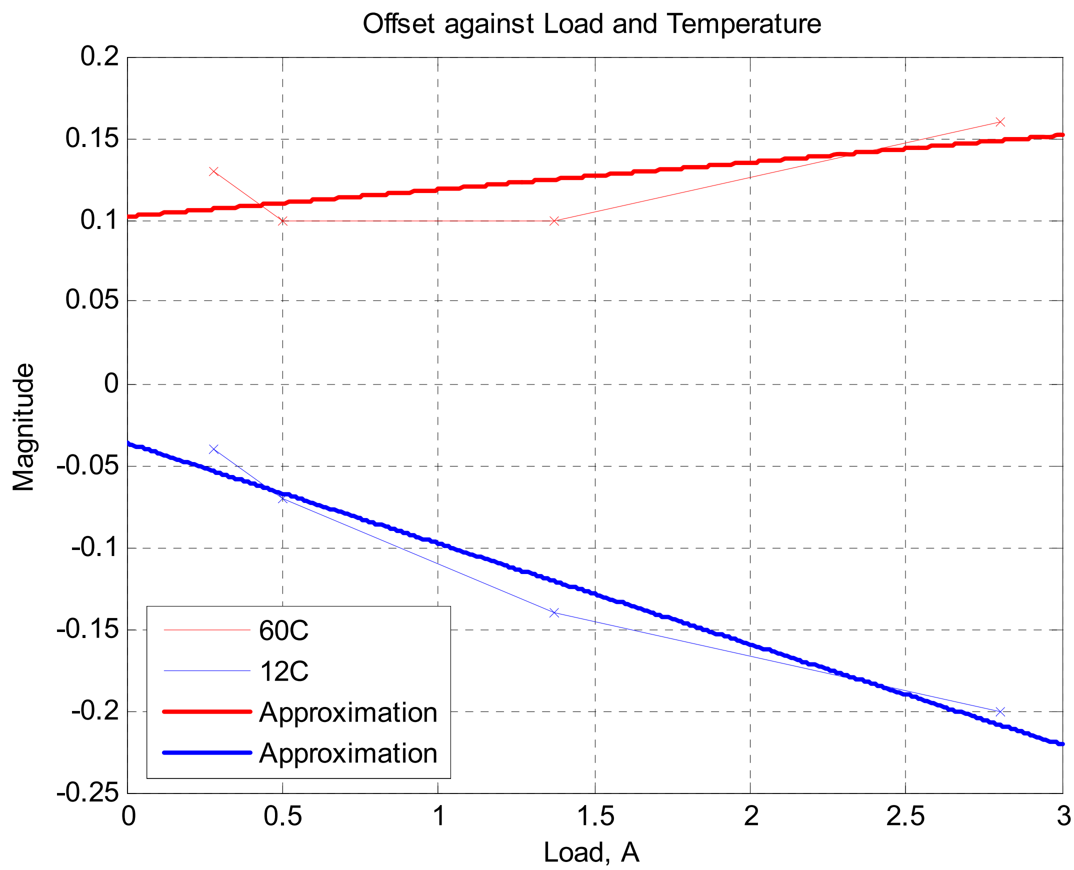
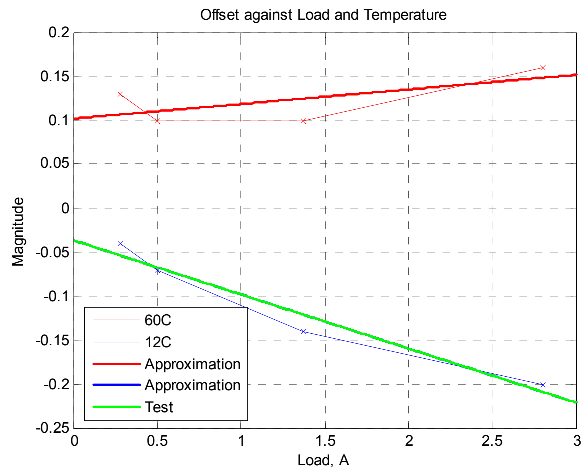
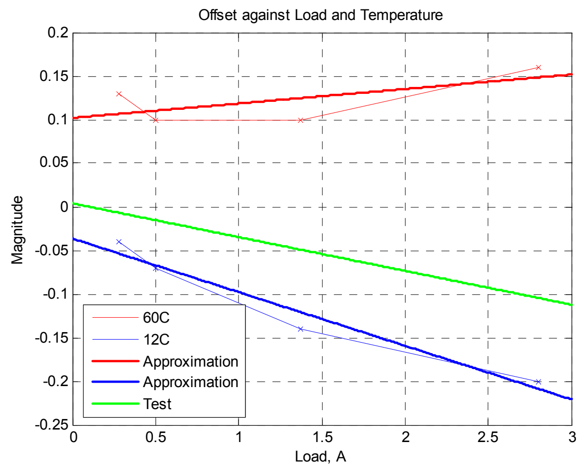


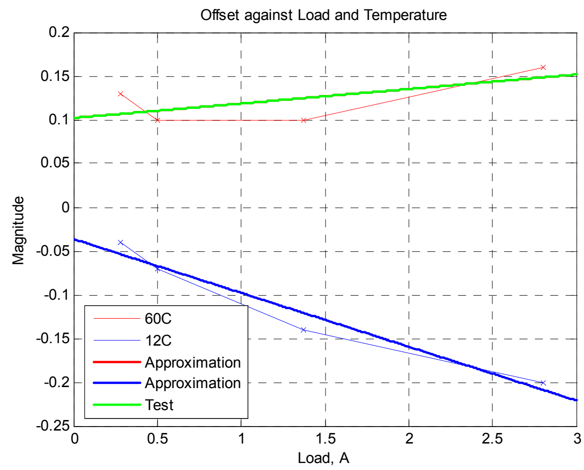

**Figure 9-14.** The scaling battery capacity prediction curves, and actual curves, against load under low and high ambient temperatures.



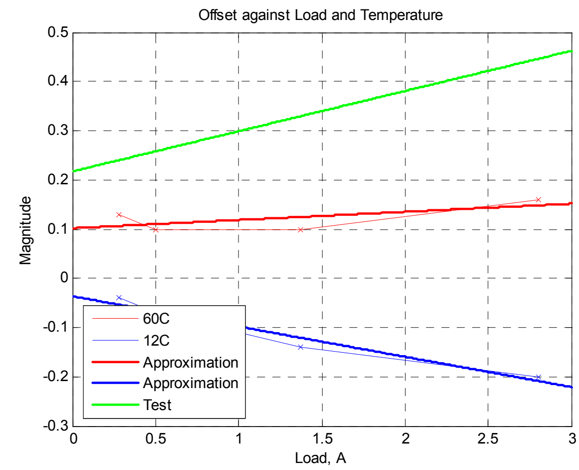

T = 12C




T = 26C



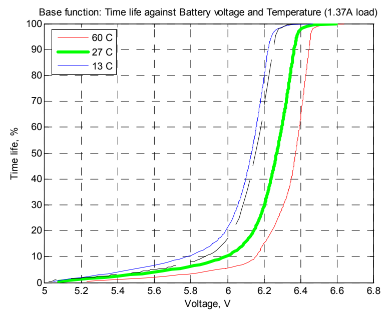
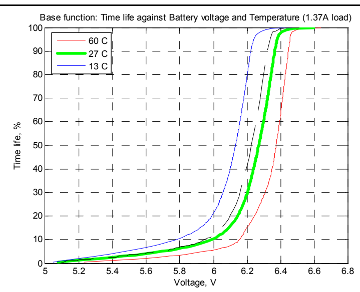
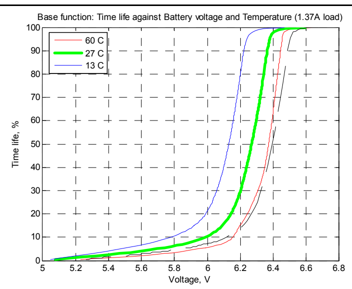

T = 60C

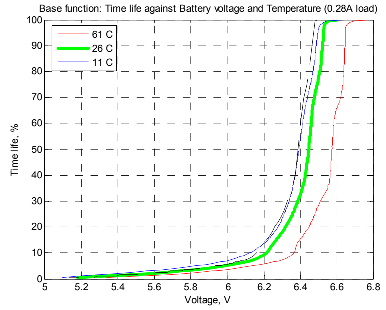



T = 100C

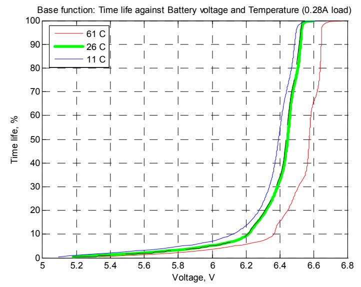
**Figure 9-15.** Error of the linear approximation function predicting battery life, as a percentage, plotted against load: The error is proportional to the load.

### 9.5.1 Accuracy of the linear scaling approximation

| | | |
|---|---|---|
| I = 2.8A, T = 10C, Scaling = -0.2V | | I=2.8A,T=60C,Scaling= 0.16V |
|  I= 1.37A, T = 13C, Scaling = -0.115V |  I= 1.37A, T = 27C, Scaling = -4.3979e-002V |  I= 1.37A, T = 60C, Scaling = 1.2470e-001V |
| I = 0.5A, T = 12C, Scaling = -0.07V | Base function with zero scaling | I = 0.5A, T = 60C, Scaling = 0.1V |




I = 0.28A, T = 11C, Scaling = -0.056936V




I = 0.28A, T = 26C, Scaling = -0.0068V

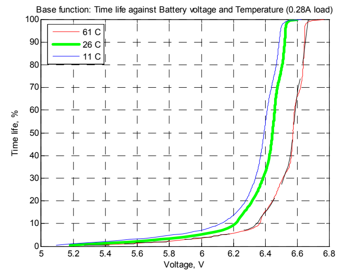
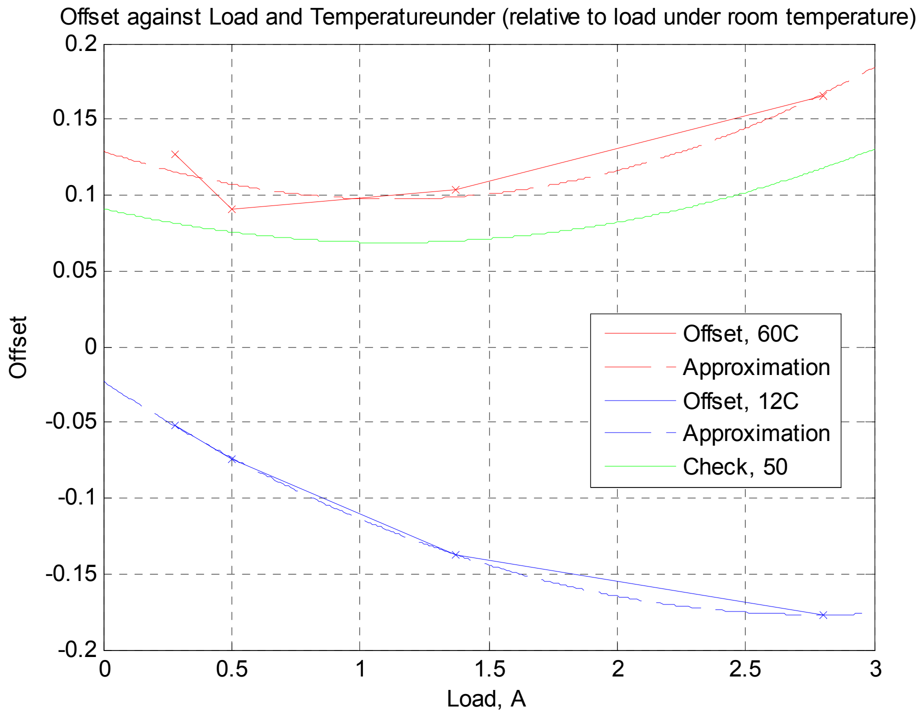
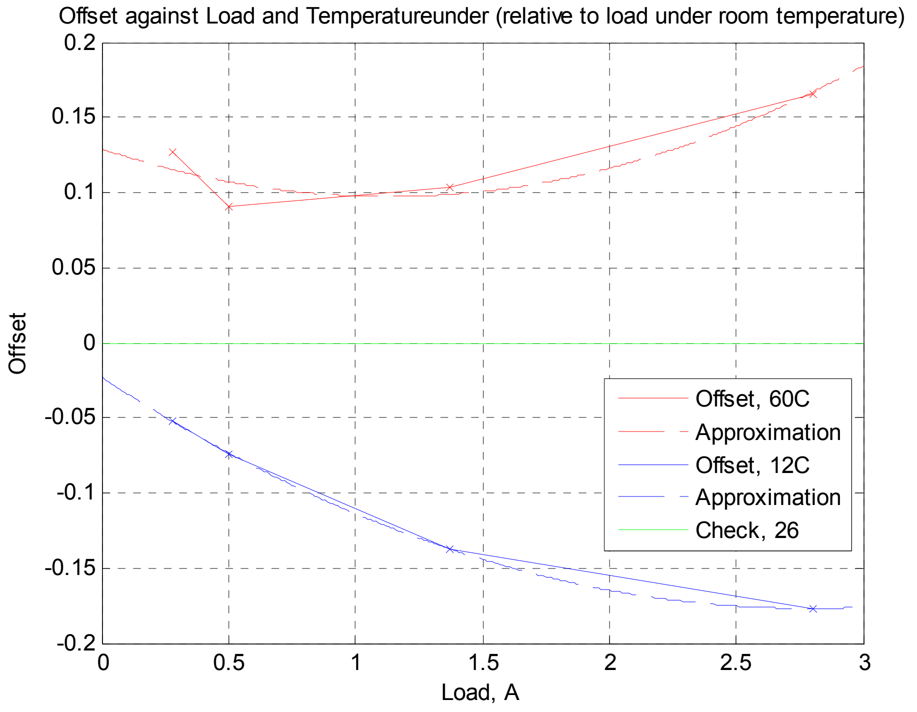



**Figure 9-16.** Error of the linear approximation function as function of temperature.

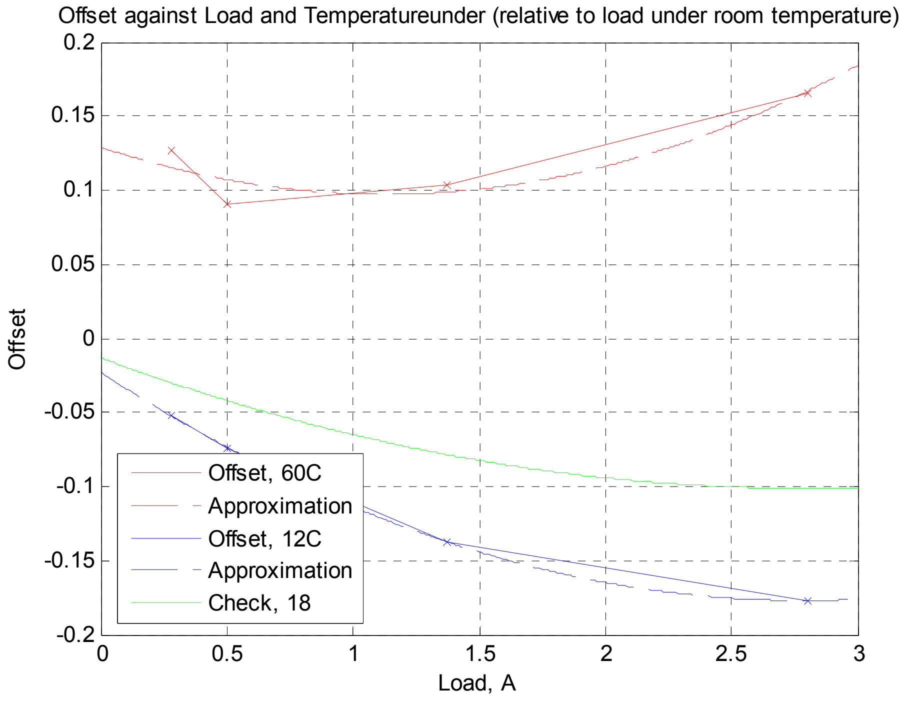
### 9.5.2 Quadratic polynomial scaling function for predicting remaining capacity




Green line is scaling against the load under 12C



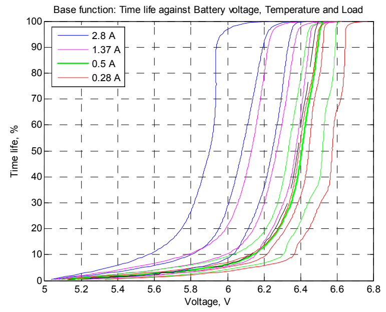

Green line is scaling against the load under 26C. It is zero



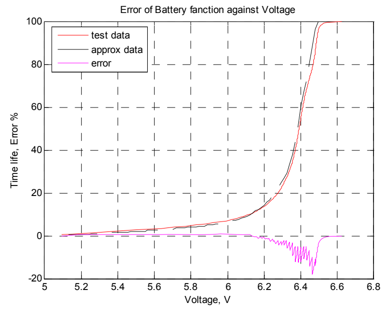

Green line is scaling against the load under 18C

**Figure 9-17.** Quadratic Polynomial approximation of the scaling. The scaling is zero.

### 9.5.3 Accuracy of the quadratic battery capacity prediction function against voltage, current and temperature

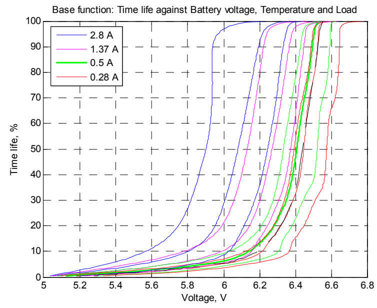



I = 0.28, T = 11C

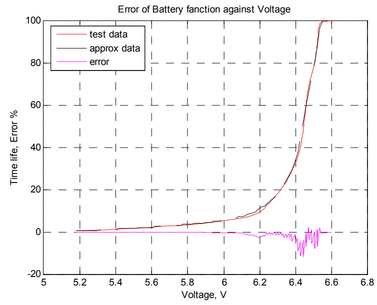



max error = 0.9%

min error = -17.5%

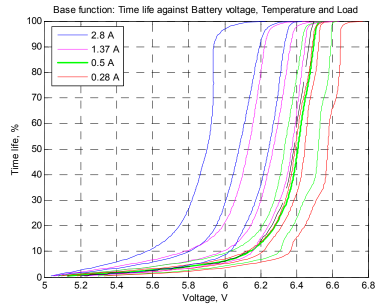



I = 0.28, T = 26C

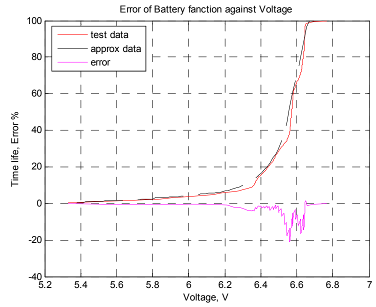



max error = 2%

min error = -11.6%

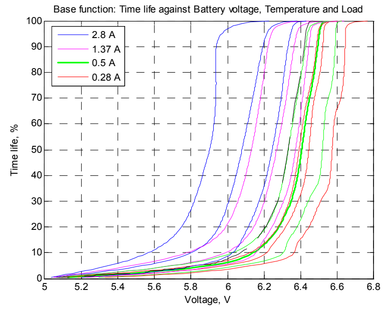



I = 0.28, T = 61C

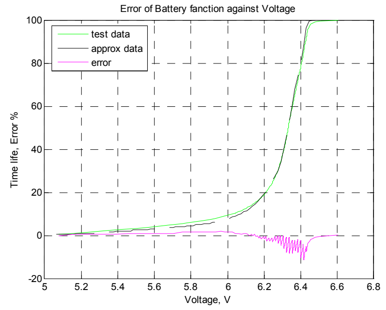



max error = 1.5%

min error = -21.1%

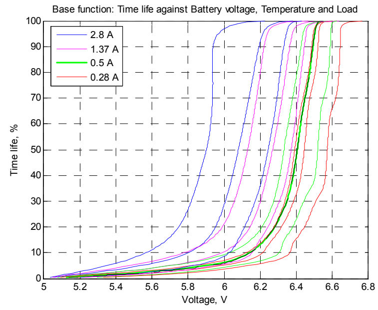



I = 0.5, T = 12C

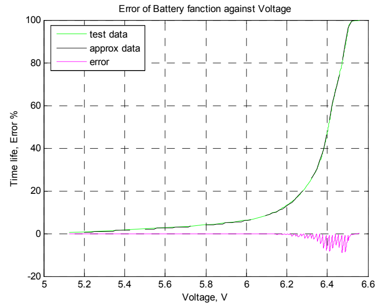



max error = 1.9%

min error = -11.5%

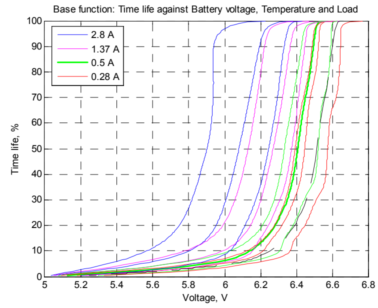



I = 0.5, T = 26C

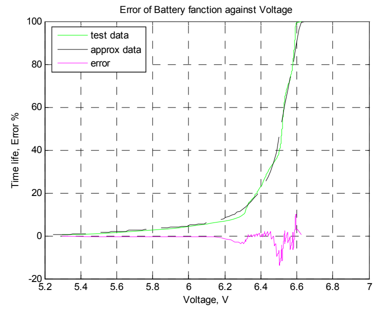



max error = 0%

min error = -8.9%

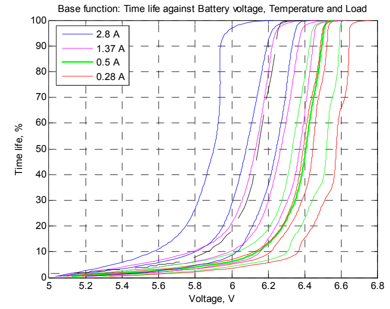



I = 0.5, T = 60C

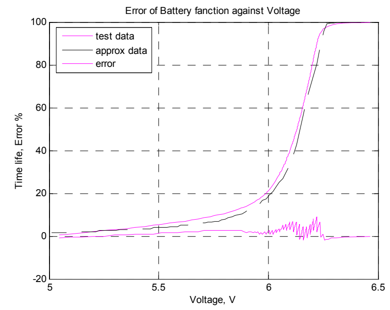



max error = 10%

min error = -13.8%

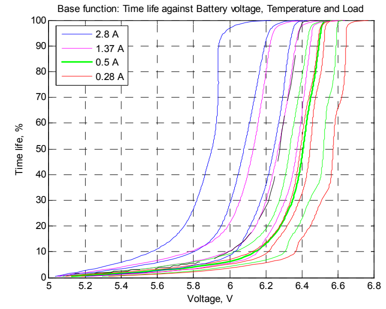



I = 1.37, T = 13C

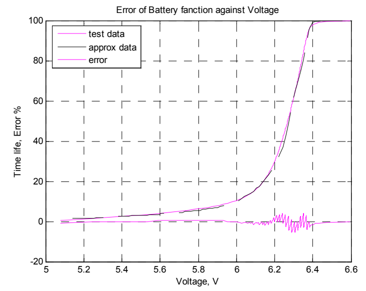



max error = 9%

min error = -2%

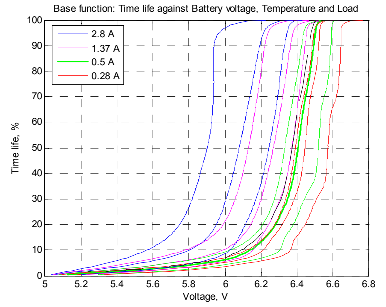



I = 1.37, T = 27C

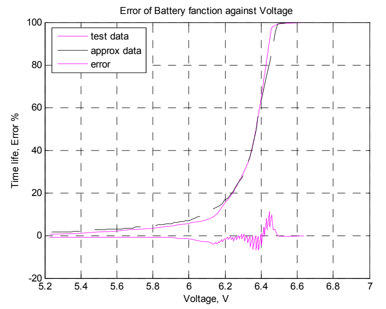



max error = 4%

min error = -5.5%

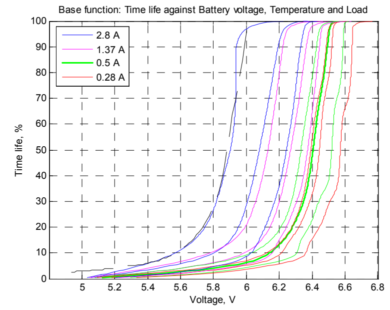



I = 1.37, T = 60C

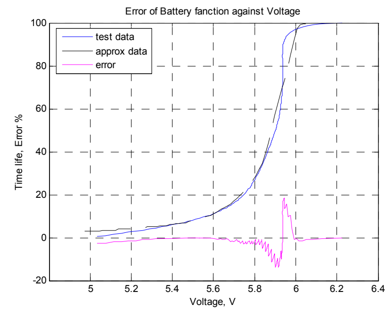



max error = 11%

min error = -7%

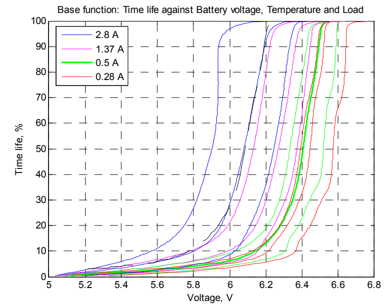



I = 2.8, T = 10C

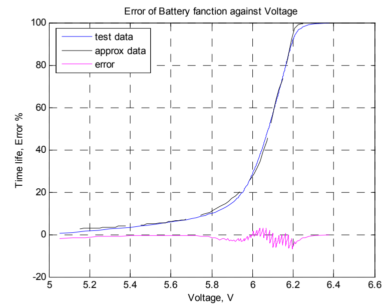



max error = 18.5%

min error = -14%

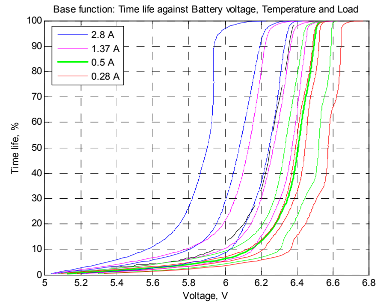



I = 2.8, T = 26C

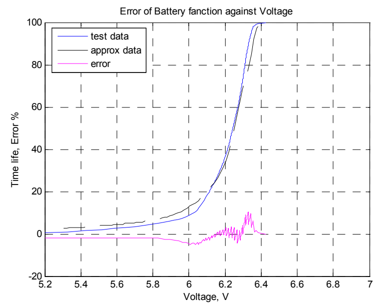



max error = 3%

min error = -7%



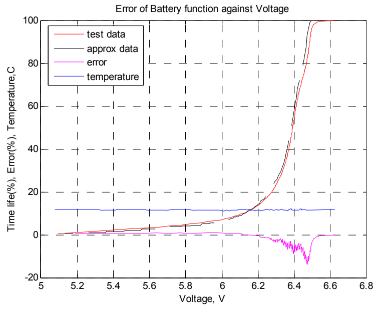

I = 2.8, T = 60C




max error = 10.5%

min error = -5%

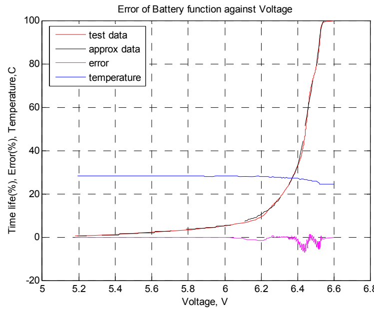
**Figure 9-18.** Error of the remaining power available against battery voltage, load current and temperature. The temperature is the average value. Array is 100 cells.




I = 0.28, T = 11C

max error = 0.9%

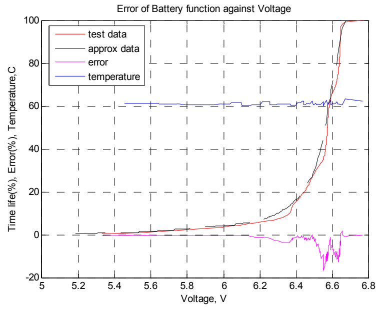
min error = -13.9%




I = 0.28, T = 26C

max error = 1.4%

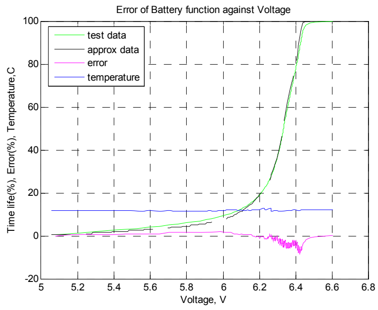
min error = -7%




I = 0.28, T = 61C

max error = 1.5%

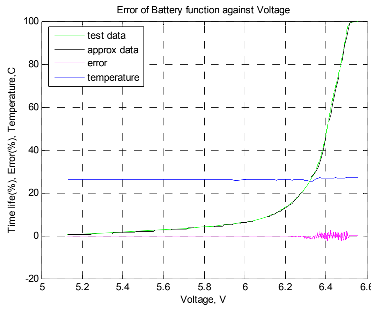
min error = -16.5%




I = 0.5, T = 12C

max error = 1.9%

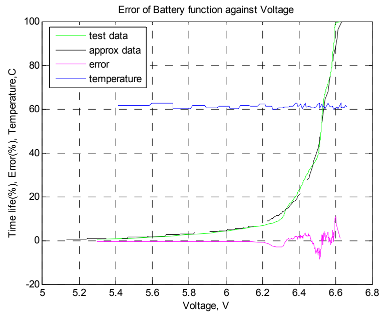
min error = -8.4%




I = 0.5, T = 26C

max error = 2.7%

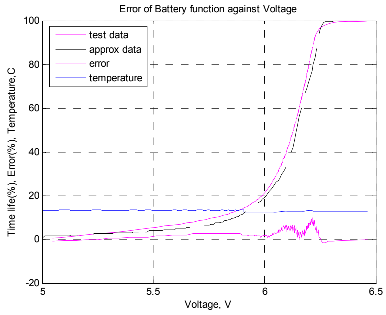
min error = -2.4%




I = 0.5, T = 60C

max error = 10.6%

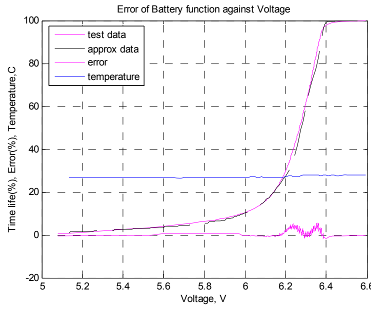
min error = -8.7%




I = 1.37, T = 13C

max error = 9.5%

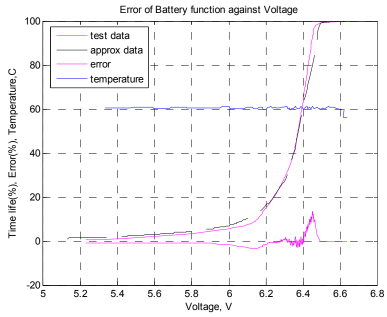
min error = -1.5%




I = 1.37, T = 27C

max error = 5.5%

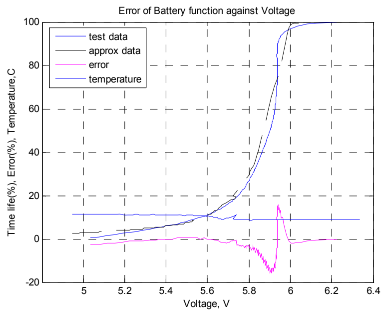
min error = -1.5%



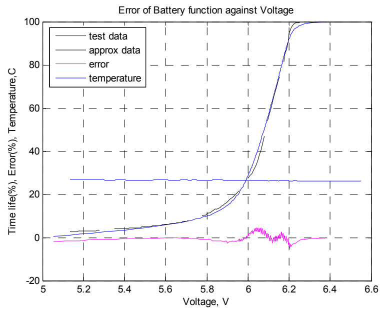

I = 1.37, T = 60C

max error = 13.7%

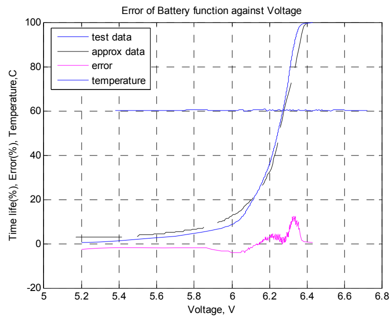
min error = -3.5%




I = 2.8, T = 10C




I = 2.8, T = 26C




I = 2.8, T = 60C

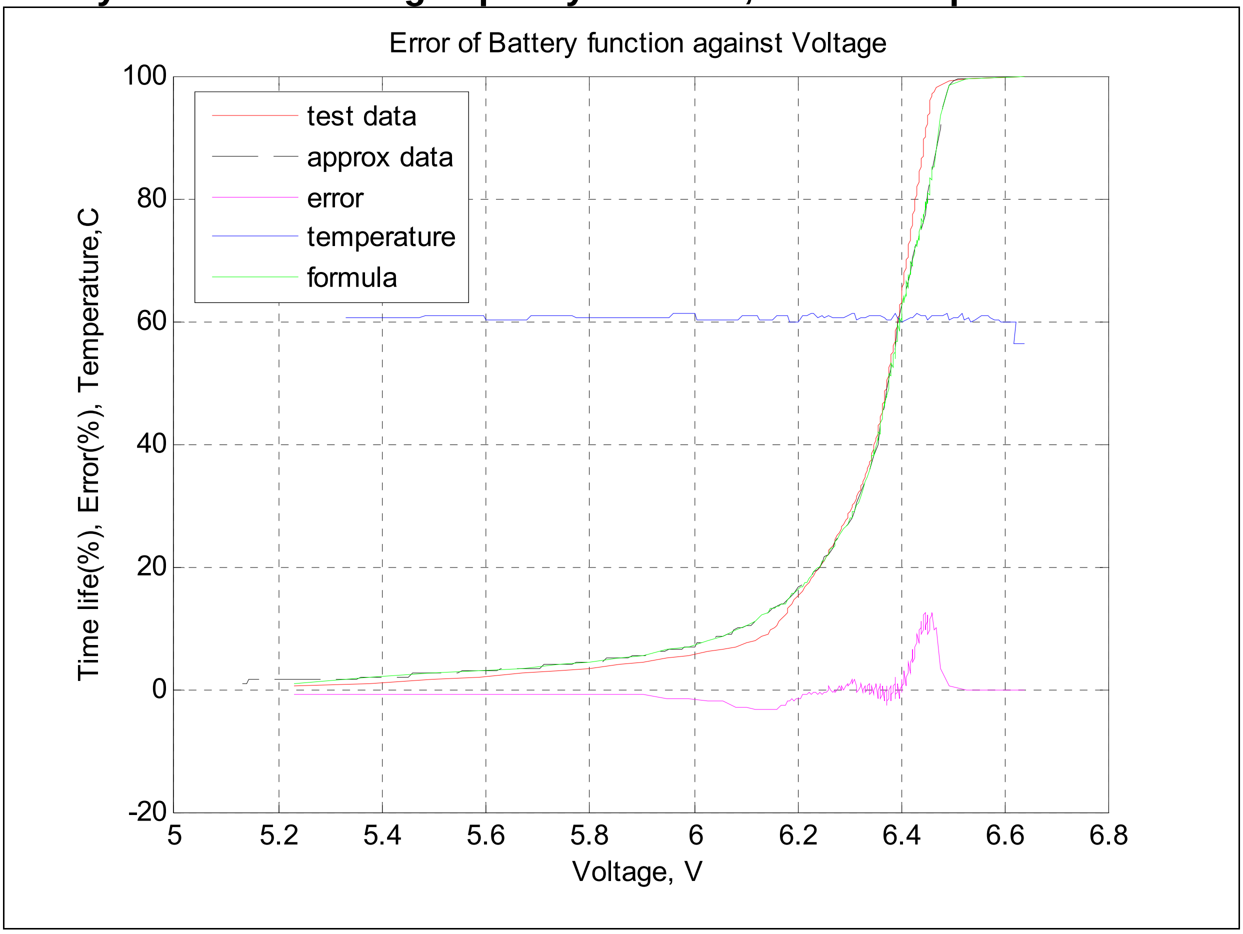
| | | |
|---|---|---|
| max error = 15.5% | max error = 4.5% | max error = 12.5% |
| min error = -15.5% | min error = -5% | min error = -4% |

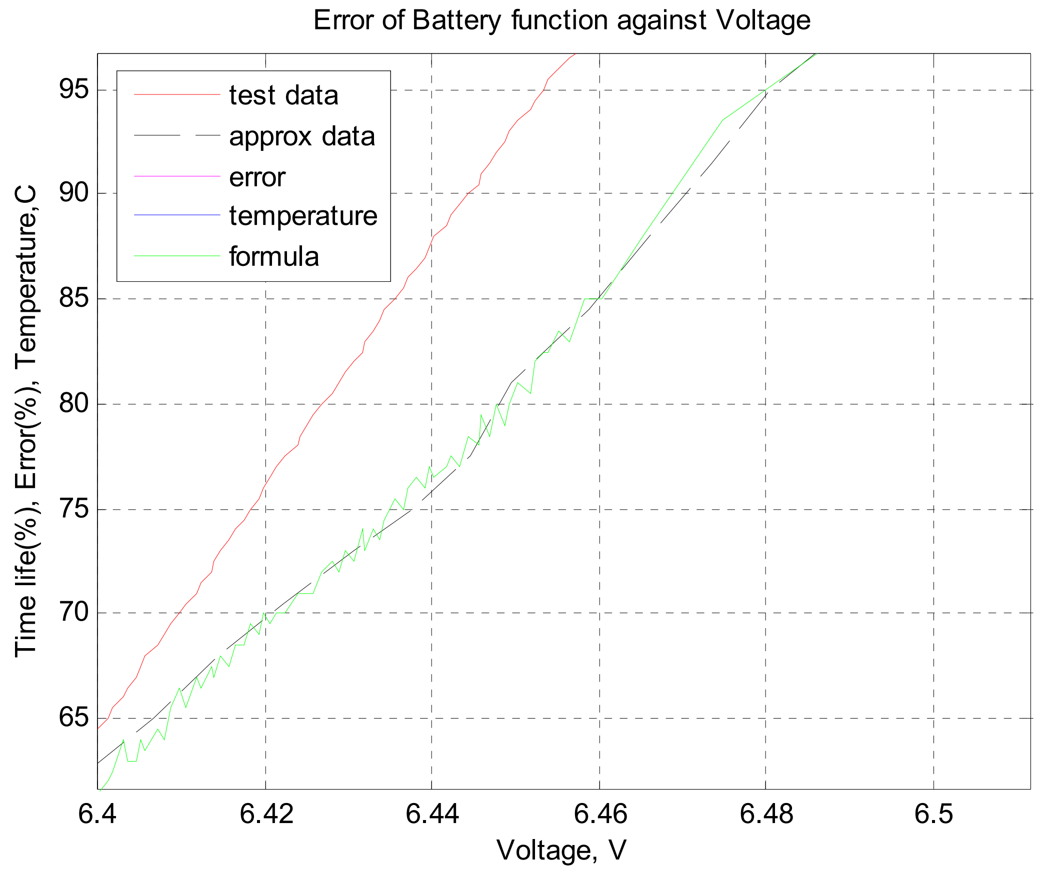
**Figure 9-19.** Error of the remaining power available against battery voltage, load current and temperature. Array in this case is 200 cells.

**Table 1. The maximum error of the quadratic remaining power function, in percent (%)**

| Temperature, C | Load | | | |
|---|---|---|---|---|
| | 0.28 A | 0.5 A | 1.37 A | 2.8 A |
| ~12C | 0.9%/-13.9% | 1.9%/-8.4% | 9.9%/-1.5% | 15.5%/-15.5% |
| ~26C | 1.4%/-7% | 2.7%/-2.4% | 5.5%/-1.5% | 4.5%/-5% |
| ~60C | 1.5%/-16.5% | 10.6%/-8.7% | 13.7%/-3.5% | 12.5%/-4% |

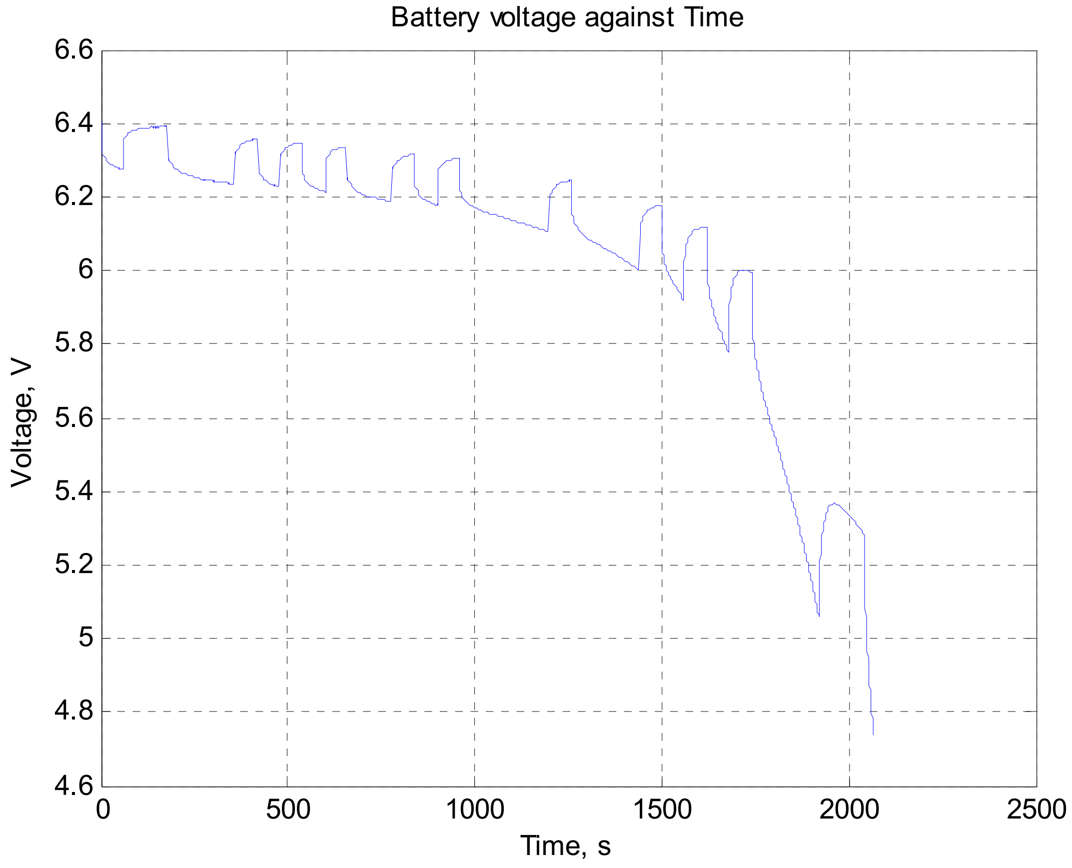
## 9.6 Polynomial remaining capacity function, versus empirical data



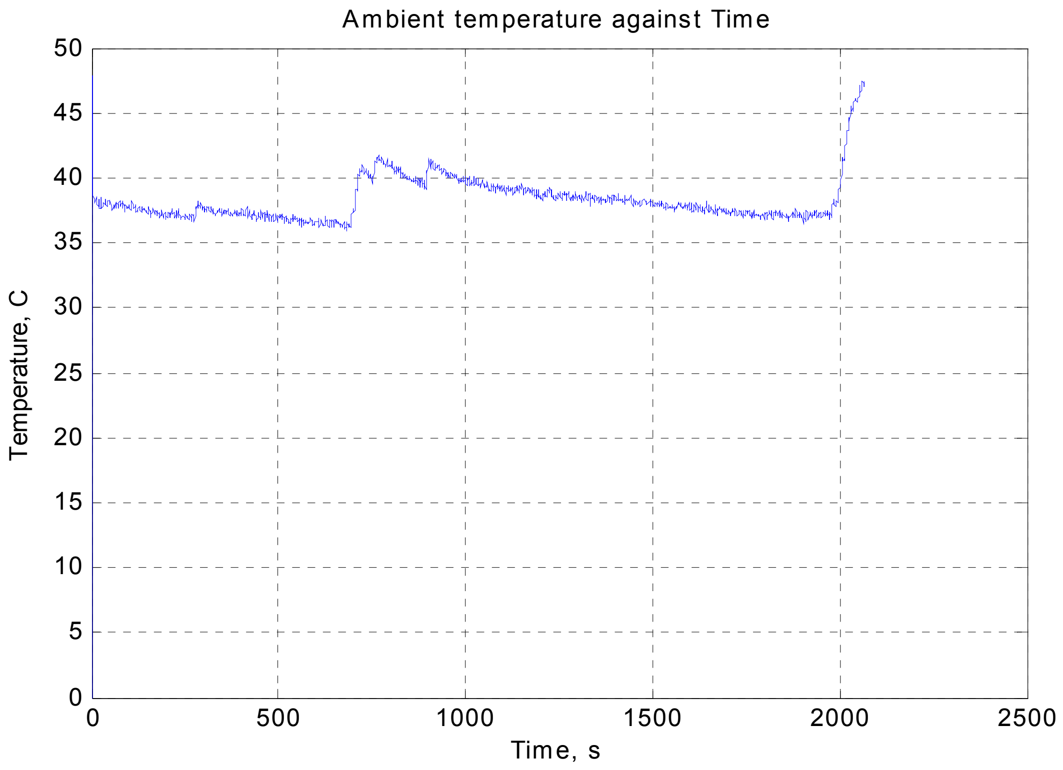


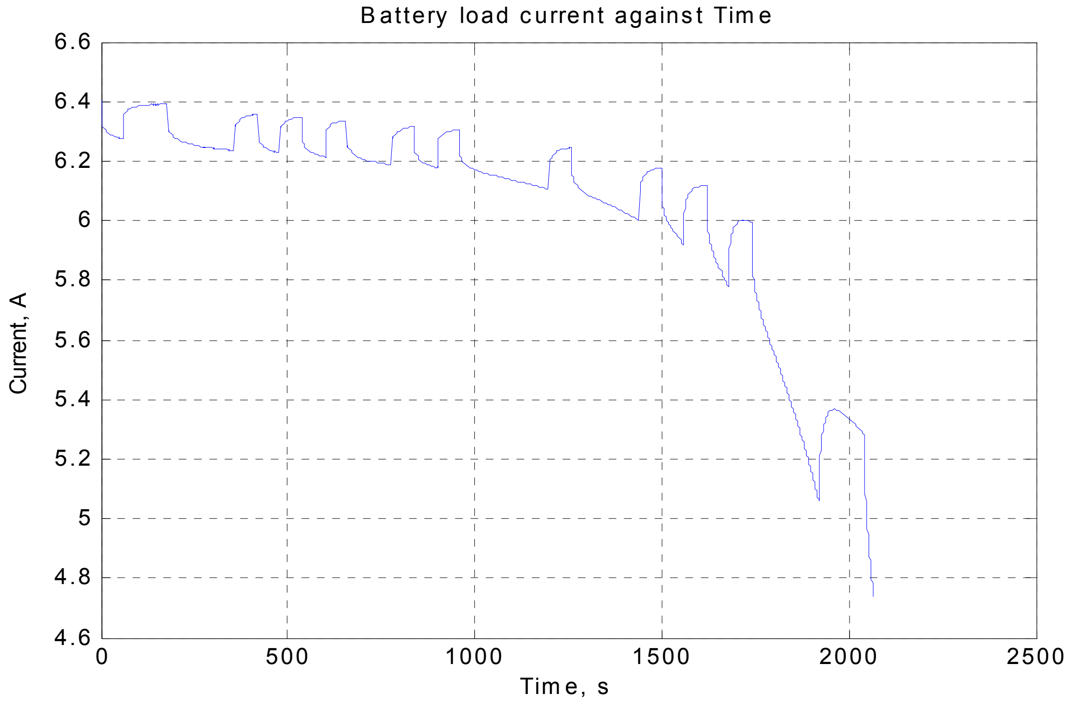

Detail of the above plot

**Figure 9-20.** Test results of the polynomial prediction algorithm. The battery test voltage, temperature and 1.37A load are used as input parameters to check the scalar algorithm (green line). The black plot is the MatLAB vector battery function.




Jumps of the battery voltage






Step changes in the load current

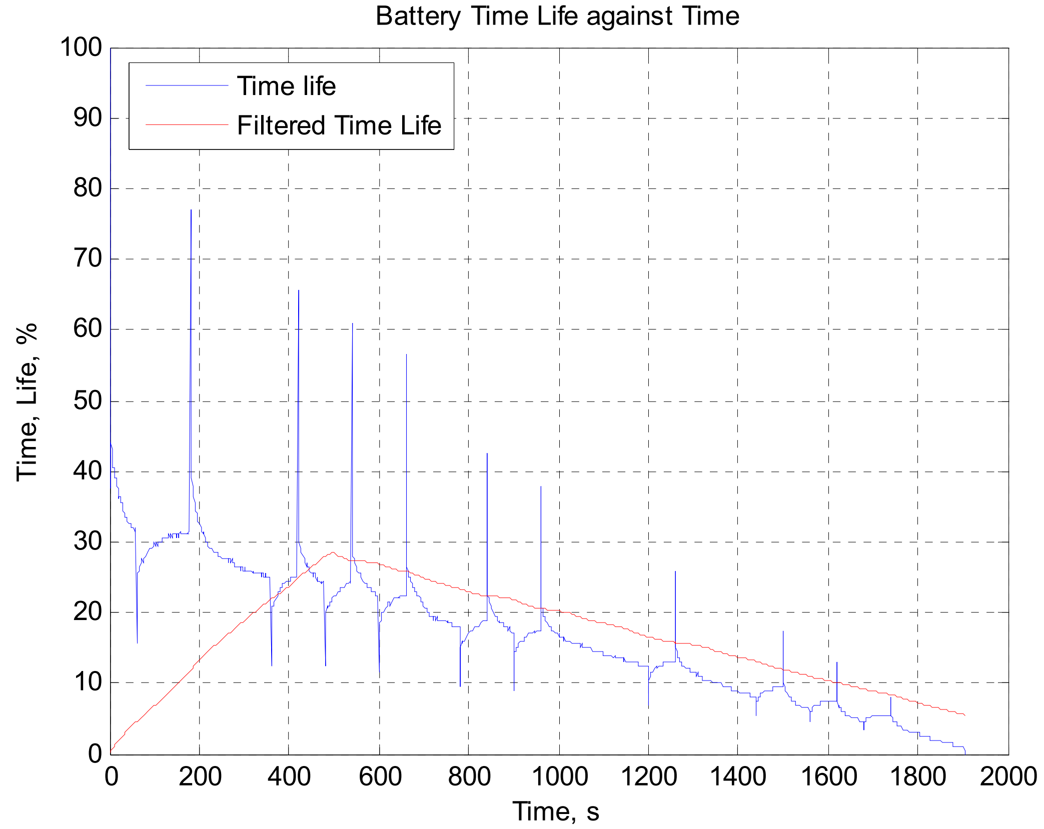



**Figure 9-21.** Test of the function using variable temperature and random current load passed via 5.1 and 13 Ohm. The remaining power available plot contains positive jumps or steps proportional to the jumps or steps in the load current. It needs low pass filtering to provide calculation of the TL without these positive jumps. The red curve shows the output of an averaging low pass filter.

# 10 CONCLUSION

1. Datasheets issued by Valence Technology Inc are reasonably accurate descriptions of their products and characteristics.
2. Valence Technology Inc has provided safety data from independent sources, that reflects professional and thorough testing of their products.
3. The Valence Technology Inc Saphion IFR18650e cells tested pass all verification tests reported herein and are suitable for use in safety critical systems. The cells are very reproducible with little variance between samples.
4. The risks of pressure, helium, mechanical shock and thermal shocks unique to dive applications are not likely to cause catastrophic failure of the Saphion cells
5. Deep Life's battery capacity prediction algorithm is generally very accurate, and even under the worst conditions can be expected to be accurate to within +/-10%, and for the important near exhaustion conditions, the error is less than +/-2%. This means that if the remaining battery life is 1000 minutes, the prediction function will be in the range 900 minutes to 1100 minutes, but when the battery has just 10 minutes left, then the error will be just +/-12 seconds.
6. Capacity of the Saphion cells depends on the charge temperature: charging at a higher ambient temperature increases their capacity as shown in the table below. The battery capacity remaining algorithm used by Deep Life is accurate except for this factor: the algorithm should be updated to reflect charge temperature.

| Charge temperature | Discharge temperature | Discharge current | | | |
|---|---|---|---|---|---|
| | | 2.8A | 1.37A | 0.5A | 0.28A |
| 11C | 25C | - | - | 186 min | - |
| 25C | 25C | 32 min | 64 min | 186 min | 332 min |
| 60C | 25C | - | - | 200 min | - |

7. Increases in ambient temperature increases the remaining power available
8. The battery life algorithm needs low pass filtering of the input data or filtering of the calculated remaining power available to remove increases in the remaining power available, which might mislead the user into believing the battery life is greater than their average use.
9. All the algorithm improvements that result from this work have been made and verified.
10. The terminal voltage of the Lithium Phosphate cells is higher than that for other Li-Ion technologies. This can be used to check automatically that the correct cells are installed, and the user has not replaced the cells: cells would not be user replaceable, but it is prudent to check the user has not taken on himself to do so, or to substitute another cell type that may not comply with these safety requirements.

# 11 WARNING AND CAVEATS

Power systems are the Achilles heel of electronics, hence the degree of resource committed by Deep Life to the four Design Verification studies dealing with power issues with its Open Revolution family of products.

Designers of safety critical systems should not take this report in isolation.

The following hazards and notes are worthy of particular mention:

1. It is known that common primary cells off-gas toxic substances. Placing primary cells within breathing loops is an obvious safety hazard. It is not unreasonable to expect that secondary cells, such as the Saphion cells tested here, to also off-gas toxic substances under some conditions. Given the long term health hazards posed by toxic gases, it was considered inappropriate to assess that risk using small sample batches with a view of determining whether the Saphion cells could be placed within breathing loops. Deep Life keep power cells outside any breathing loops, with at least two physical barriers between the loop and the cells; namely, a bronze plate separating the breathing loop from a chamber filled with silicone oil containing the electronics, and a pressure resistant gland separating the chamber from the battery holder – the batteries are kept at one atmosphere pressure outside the rebreather.
2. The cell manufacturer carries no responsibility for the application their cells are used in. The cells are a standard product, and the manufacturer has no control and often no knowledge how their customers use their products. It is the sole and exclusive responsibility of a designer of a safety critical product to ensure the power systems are safe under all plausible conditions, including those conditions where cells fail. The designer is responsible for verifying all data used in that assessment, and for performing that assessment with the necessary degree of diligence.
3. It is patently unsafe, and contrary to basic safety guidelines and regulations, for a safety critical system to depend on any single power source.
4. It is common practice for dive systems to use multiple redundancy at a system level, such as multiple independent monitors each of which have a low SIL level or no SIL. This may be suitable for pure monitors, but is not suitable for high SIL applications where a controller regulates oxygen levels or other parameters needed to sustain life. The requirement in these high SIL applications is that systems always work when required. This report is compiled on the basis that at least dual redundancy of the Saphion cells is used to power any one high SIL controller.
5. The life cycle of the Saphion cells in a safety application, is 300 charge – discharge cycles. The system using these cells should monitor the number of cycles and ensure the cells are replaced during annual servicing if there is a risk of this limit being exceeded.
6. All power systems used to supply any state machine or computer, must include adequate circuitry to detect and respond safely to power drop outs, brown outs or power swings. This is covered in FMECA Volume 5, for the Open Revolution Rebreather rebreather products. Other manufacturers or designers using this data would need to carry out their own assessment of these aspects of their system design.
7. Samples from each procurement batch should be assessed to ensure the batch is typical of the product tested here.
8. This report will be published with open distribution. No responsibility is assumed or taken by Deep Life Ltd for any use of any cells, other than use in products designed by Deep Life Ltd when fitted by the manufacturer in accord with ISO 9001 controlled procedures issued by the Design Authority.

# APPENDIX A. BATTERY MANUFACTURER'S DATASHEET SPECIFICATION

Valence Technology Inc provide a full data sheet of their cells. For reasons of copyright, it cannot be reproduced here but is available from their web site.

To reduce the need for cross referencing between documents, an outline specification of the t Saphion cells that were tested, is listed below

- Type: IFR18650e
- Charge Voltage: 3.65V standard (3.4V float, 4.2V max)
- Nominal Operating Voltage: 3.2V @ C/5
- Nominal Rated Capacity: 1400 mAh @ C/5
- Discharge Method .Standard: 280 mA (C/5)
- Max Continuous Discharge: 2.8 A (2C)
- Max Pulse Discharge (30sec): 5.6 A (4C)
- Discharge Cut-off Voltage: 2.5V
- Charging Time: Standard Charge = 2.5 hours
- Charging Method: Constant C/2 current to 3.65 V limit, then constant voltage (3.65V) with floating current taper to C/20
- Cycling Life Characteristics: > 1000 cycles* to 90% capacity*80% DOD
- Operating Temperature: Charge : 0°C ~ 45°C<br>Discharge : -10°C ~ 50°C
- Storage Temperature: -40°C ~ 50°C
- Humidity: 5-95% relative humidity
- Cell Weight: 38g ±2g
- Cell Dimensions: Length: 65.0 ±0.3 mm (without tabs)<br>Diameter: 18.0 ±0.3 mm