DESIGN VERIFICATION OF THE ACCURACY OF PPO2 MONITORING AND PPO2 PROTECTIVE DEVICES IN THE DEEP LIFE OPEN REVOLUTION REBREATHERS

DOCUMENT NUMBER: [Filename]	DV_PPO2_Device_Accuracy_110105.doc
ORIGINATOR:	Oleg Zagreblenny, Dr. Bob Davidov, Mikhail Solovyev, Marat Yevtukov
DEPARTMENT:	Baltic Assessment Institute (Verification), Deep Life Ltd (Design Verification), Deep Life Ltd (Engineering Mangement), respectively. Report issued by Deep Life Ltd.
DATE ORIGINATED:	5th Jan 2011
REVISION:	A9

APPROVALS	
______/Dr. Alex Deas/_____________ Project Leader	____5th Jan 2011_______ Date
______/Dr. Vladimir Komarov/_______ Quality Officer	____5th Jan 2011___________ Date

Controlled Document Y ☐ ~~Classified Document DO NOT COPY~~.

Revision History

Revision	Date	Description
A	18th Dec 2006	Initial report
A1	15th May 2007	DL sensors. Temperature test result
A2	26th Oct 2007	Sensor output temperature correction review
A3	10th Dec 2009	MY: Temperature compensation reviewed. New coefficients added. IIR filter coefficients added.
A4	11th Dec 2009	MY: O2 sensors individual charts added.
A5	24th Feb 2010	MY: O2 sensors temperature re-verification charts added. ALVBOV failure modes added, including observation on an ALVBOV that developed a fault during testing.
A6	24th June 2010	Validation of eCCR alarm levels detailed in Section 10.2 added (even though code and circuitry is identical to that in the PPO2 pods). No other change except the addition of that Section.
A7	4th August 2010	Clarified that 1.5 atm high PPO2 warning levels are used.
A8	31st Dec 2010	Addition data added on linearity of Analytical Industries sensors to 5 bar and 8 bar of oxygen, and CO2
A9	5th Jan 2011	Proof read and approved for release

Acknowledgement is made to the Baltic Assessment Institute for the test and verification tasks reported herein.

Table of Contents

1 Purpose and Scope

The document describes an assessment carried out on the accuracy of the PPO2 monitoring and warning devices on the Deep Life Open Revolution Family of Rebreathes. Three models were considered:

1. OR_Apocalypse iCCR
2. OR_Incursion
3. OR_Umbilical

Exactly the same firmware and software is used on all models, but there are differences in electrical traces and number of sensors between the iCCR and eCCRs so all models are assessed. The PPO2 monitoring on the OR_Incursion (4 cells) and OR_Umbilical (8 cells) eCCRs is absolutely identical, so OR_Incursion sample Rev D, Sample 3 was used for the tests as even mixing of the gases across the face of the sensors was easier to achieve in the empirical testing of that model: the OR_Umbilical is effectively two Incursions running independently in parallel. Samples of the Apocalypse rebreather PPO2 Pods were also tested with the same rigour.

This report focuses on the primary factor affecting accuracy of the PPO2 monitors: the temperature compensation of the galvanic PPO2 sensors used in Deep Life rebreather apparatus, including the derivation of the formal model, validation of the model, and verification of the correct implementation of the specified compensation functions.

This report also covers the accuracy of the Active Warning Devices, and the display devices fitted to the rebreather.

The work affects critical safety functions, and is a verification report within Quality Procedure QP-20 and QP-24.

2 SIL Assignment

The SIL assignment of the system is SIL 3, reported in SA_SIL_Assessment_YYMMDD.pdf held on Deep Life's SVN, and that assignment hinges on the performance of the PPO2 monitoring, control and related active warning devices,

3 Requirements

The safety requirements for measurement of oxygen are listed on Mantis (Categories: Oxygen Insufficiency related, Oxygen Level Monitoring raletd, and PPO2 related), and measurement of the accuracy of the PPO2 monitoring is a requirement in EN 14143:2003. The requirements arising from prEN 14143:2010, NORSOK U101:1999 and NATO STANAG 1410:2006 are also considered.

3.1 Safety Requirements

The Deep Life Mantis system was checked for all safety requirements and the following requirements were identified relating to the accuracy of the PPO2 monitoring or PPO2 warning devices:

Mantis Item Number	***Category***	***Description***
0000961	PPO2 Related	Uncalibrated O2 cells should be indicated to the diver
0000960	PPO2 Related	O2 monitors should not report PPO2 at or below 0C

0000959	PPO2 Related	Refuse to calibrate oxygen sensors below 4C or above 40C
0000771	PPO2 Related	CCR controller shall track CNS and maintain within safe limit (FMECA V6 Risk 18.11)
0000707	Diver Physiology related	Decompression risk if PPO2 reading is erroneous (within Mantis item)
0000389	PPO2 Related	PPO2 level shall be limited to 0.2 < PPO2 < 2.0 always
0000384	PPO2 Related	*PPO2 level shall be reported to the diver or supervisor with an accuracy of 0.0243 ATA*

Reviewing these requirements in the context, there are seven main parameters that need to be characterised to quantify their influence on the accuracy of the PPO2 reading:

1. the temperature range that the sensor must operate over (0C to 40C)
2. the PPO2 range the sensor needs to operate over (0.2 to 2.0 normal range, 0 to >2.3 atm monotonicity).
3. The pressure range is the diveable range plus a 12% margin: this is 0 to 100m for normal diving, and up to 400m for Deep Life's eCCR models.
4. Alarm levels (in Mantis 384) are low alarm <= 0.3 atm, low warning <= 0.4, high warning >= 1.5 atm, high alarm >= 2.0 OR >= 1.6 for 60s. Once the high alarm has triggered, it stays triggered until the the PPO2 falls below 1.6 atm. The reality of these warnings and alarms must be verified by appropriate tests (reported herein).
5. For ambient pressures <= 1.089 bar and respiratory rate < 1 bpm, the PPO2 alarm is suppressed subject to the PPO2 being >= 0.20 * ambient pressure in atm and PPO2 >= 0.16 atm. This is necessary to prevent continuous alarm states when the rebreather is being set up for a dive, including for alpine diving. Warnings continue to be <= 0.4 atm. Again, this must be verified by the appropriate tests.
6. Tolerance to CO2: reported in the O2 Sensor characterisation study DV_O2_cell_study_RevXY_YYMMDD.pdf.
7. Tolerance to Helium: reported in the same O2 Sensor characterisation study.

There are three main hazards that result from a PPO2 reading being in error:

1. The PPO2 can be too low, causing hypoxia leading to loss of awareness, unconsciousness, and death. This occurs if the PPO2 is below 0.16 atm (Mantis Requirement 389).
2. The PPO2 can too high, causing CNS or Pulmonary oxygen toxicity, resulting in serious injury or death. The limits for this are generally a PPO2 of 1.6 atm for more than one minute, or over 2.0 atm at any time (Mantis Requirement 389). However increased retained CO2 levels can cause these limits to be reduced substantially (Mantis Requirement 711).
3. The diver's decompression can be incorrect, increasing the risk of DCS and serious injury or death. The magnitude of the permissible error is 10% because the decompression software should be instructed to use a PPO2 figure 10% worse than that read (Mantis Requirement 707). This 10% figure is reinforced by comparison of decompression times using PPO2 values that differ from actual by 10%: there is a significant increase in DCS risk to the diver on dives with long decompressions with this error magnitude.

The treatment of oxygen sensors is clearly a high SIL requirement that defines the overall SIL rating of the apparatus.

3.2 Functional Requirements

Galvanic PPO2 sensors are used. These have been the subject of extensive characterisation, reported in DV_O2_cell_study_RevXY_YYMMDD.pdf on the Deep Life web site and under SVN.

Galvanic PPO2 sensors (oxygen cells) have a long thermal response, and the output is a function of the temperature inside the cell: the output can vary +/-50% or more for any given PPO2, depending in thermal history of the sensor.

Most oxygen cells on the market have a temperature compensation circuit built in, but none of these passed Deep Life's functional safety verification tests for rebreather applications. There are several reasons for this:

1. the fault modes caused by failure of the temperature compensation are difficult to detect
2. the thermal compensation is a crude thermistor mounted on a circuit board behind the sensor, which has a fast thermal response. This results in over and under compensation when temperature changes occur, such as a rebreather on a hot dive boat, suddenly going to cold water.
3. the thermistor also has significant errors even in the static environment.

To compensate for the thermal response of the sensor, Deep Life use independent thermal sensors that have the same thermal environment as the oxygen sensor: they MUST NOT be touching the oxygen sensor (otherwise there is an uncontrolled heat transfer between O2 sensor and thermal sensor). The thermal sensors are free standing with similar thermal inputs and outputs as the O2 sensor.

There are four parameters affecting the temperature of the oxygen sensor:

1. Thermal transfers to and from the gas around the sensor
2. Thermal transfers to and from the gas around the sensor through the connectors to the PCB.
3. Thermal transfers to and from the gas around the sensor from the IR from the scrubber exothermic reaction: IR imaging has found this to be a major factor, so both sensors need a similar IR cross-section.
4. Thermal transfers to and from the frame holding the oxygen sensors in place. This can be modelled using transfer functions derived from the other sources above.

A particular hazard is the PCB heats up when the batteries are being charged, or when it is in use, due to the energy being stored in or lost from the batteries. If the thermal sensor is in PCB, then this transfer can affect the thermal sensor much more than the O2 sensors: it is essential that the oxygen sensors and thermal sensors be free-standing. This risk is particularly acute if the unit is charged (heating the battery to around 50C), then immediately calibrated, and then subsequently dived in cold conditions. Calibration shall require that the thermal environment be stable for at least 3 thermal time constants of the sensors.

3.3 Statutory Compliance Requirements

The application falls within EN 14143:2003.

The PPO2 requirements fall into the following sections:

5.7.1 requires the PPO2 be controlled within 0.2 to 2.0 bar, with no more than one minute above 1.6 bar. This is achieved on the OR Rebreathers using the ALVBOV. The primary test method is EN 14143:2003 Test 6.7. This is a PPO2 control test, not a PPO2 accuracy test.

5.7.2 requires the PPO2 be maintained with an accuracy of +/-0.1 bar. The control is outside the scope of this document, except that the controller depends on reading the PPO2 accurately.

5.7.3 Display for inspired partial pressure of oxygen. This has a limit deviation of +/0.03 bar for the interval 0.1 bar <= PPO2 <= 0.4 bar, and +/- 0.06 bar for the interval 0.4 bar < PPO2 <= 2.0 bar. This is the primary PPO2 accuracy test, and the primary test method is Test 6.10.2.

5.9.3 This refers to Test 6.7 as well as 6.10.2. The Test 6.7 in turn references Test Conditions 6.6.1 and 6.6.2. This unravels to become a large number of test conditions. However, the context of those tests is clearly for PPO2 control (that is the monitor is recordeding during the PPO2 control tests), rather than a second set of tests. The primary test of accuracy is Test 6.10.2.

5.9.4 Requirements for Active Warning Devices refers to Test 6.10.4, which is appropriate to perform using the test method of Test 6.10.2.

The test methods of visual inspection (Section 6.2) and manned dives (Section 6.15 of the standard) are fulfilled as a by-product of other tests.

The requirements arising from prEN 14143:2010, NORSOK U101:1999 and NATO STANAG 1410:2006 are a subset of those contained within the EN 14143:2003 standard: i.e. are looser.

EN 14143:2003 Section Ref	Condition	Observation
6.10.2 referenced by 5.7.3	Test the PPO2 in the range 0.1 bar to 2.0 bar in increments of 0.2 bar.	0.1 to 2.0 is not divisible by 0.2. The test that follows it covers the interval 0.2 to 2.0.
6.10.2 referenced by 5.7.3	The PPO2 monitor shall be pressurised to 1.1 times the maximum stated depth with suitable gages to maintain a constant partial pressure of 0.2 bar and 2.0 bar respectively.	"Respectively" does not refer to anything. It is assumed this means the device is exposed to a PPO2 of 0.2, then pressurised to 1.1 times the maximum depth at which point the PPO2 should be 2.0 bar. This is then a straightforward test to carry out, simply by pressurising a chamber with a suitable Nitrox or Heliox mixture.
6.10.2 referenced by 5.7.3	The PPO2 monitor shall be held at 1.1 times the maximum stated depth for a period of 1.5 times the maximum bottom time specified by the manufacturer.	This means the above test is held for a period of time. There is reference to decompression by specifying bottom time, which infers a surface dive. To ensure that the diver in standard configuration would have sufficient decompression endurance and bailout this is calculated as 20 minutes bottom time at 100m, for a surface dive. The iCCR was also tested at 100m depth for 3 hours with descent and ascent at 30m/min. For saturation and submarine transfer diving on the Umbilical and Incursion models, this is 400m depth for 6 hours, without ascent.
6.10.4.1 referenced by 5.9.4	Active warning device activates within +/-0.05 bar of the warning levels.	There is no specific test for this, so it can be tested by the same test as 6.10.2 above.

There appears to be two interpretations of the tests required from the compliance standpoint:

1. Pressurisation from 0.2 bar to 2.0 bar of oxygen by increasing the ambient pressure from atmospheric to 1.1 times the maximum depth of the equipment.
2. Monitoring the reading of the PPO2 at 1.1 times the maximum depth, sweeping the PPO2 from 0.1 to above 2.0 bar.

Both methods are used here: that is the PPO2 monitor and Active Warning Devices are tested with both methods.

The standard allows testing of subassemblies, and in the case of a PPO2 monitor, it is appropriate to test it as a subassembly as the dry gas that can be used in this situation avoids complex correction factors to obtain measurements referenced to STP 0C.

4 EQUIPMENT

Instrument	Serial Number	Next Calibration Date
National Instruments Computer Data Acquisition card PCI-6014	HA4375847	Calibration prior to each use
TTi1906 Reference Computing Multimeter	111474	December, 2010
Analytical Industries PSR 11-39-DL Oxygen Cells	As stated	One year from date of manufacture, except for ceiling tests, which were performed using 2 year old sensors.
Innovision AMIS 2000 Respiratory Mass Spectrometer	SN 0911243	Calibrated on certified span gases before each use
Keller LEK 1 pressure gauge, Reference accuracy +/-0.01 bar	002333	June 2012
LM35DZ	N/A, Single chip	Calibration prior to each use
HIH4003-300	N/A, Single chip	Calibration prior to each use
Deep Life 160mm Mini-chamber		Next hydrostatic 2014.
Deep Life 800 mm test chambers, ith environmental control, rotateable	CH03	Next hydrostatic Sept 2014

5 METHOD

The overall process is that set down in QP-20: this requires formal modelling, verification, exhaustive validation and empirical testing to be carried out on the PPO2 monitoring, control and related devices.

The performance of the sensors depends critically on the temperature compensation of the sensors. The method used is to measure the response of the sensors as a static function of temperature, and to measure the dynamic response. A formal model based in measured characteristics, is developed. A compensation function is derived from the formal model.

An independent group then took measurements of a different batch of sensors and compare the results. The compensation function is converted from a maths specification into a realisable filter and linear regression function.

The correct implementation of the filter and regression function, was then verified by the first group using the formal model and measurements in heated and cooled pressure chambers.

The filter and regression function was implemented, and both the first and second team (who are independent of the firmware and software teams), verify again both the static and dynamic compensation matches the model and meets the safety requirements. Following this, practical tests were performed with the sensors operating in PPO2 monitors and rebreathers on test dives under lab conditions and on manned dives.

6 DEVELOPMENT OF FORMAL COMPENSATION MODEL

6.1 Empirical Sensor data

Table 1. AII PSR-11-39-DL Sensor Samples

Sensor label	Serial number	Initial output (mV)	Date sensor package opened (DD/MM/YY)	ADC channel No
6	60741629	4.5	02/11/06	8
8	60741633	4.4	02/11/06	9
9	60741635	4.2	02/11/06	10
10	60741626	4.0	02/11/06	11
11	60741630	5.5	02/11/06	12
12	60741625	4.2	02/11/06	13

The 2006 sensors were used in the formal model development. Later in this study, the response of sensors from a November 2008 batch are given, using the same models: the close correlation indicates the Analytical Industries PSR-11-39-DL sensors are of particularly uniform characteristics.

6.2 PSR-11-39-DL sensors: temperature correction.

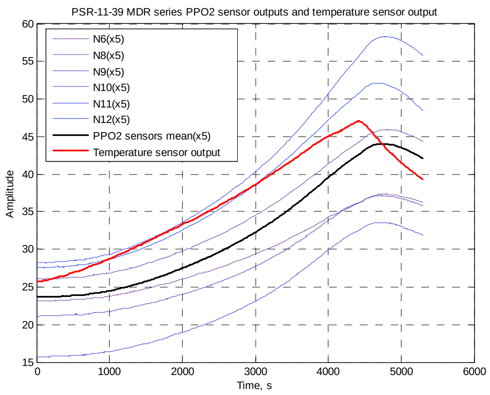
6.2.1 Low gradient heating and cooling tests

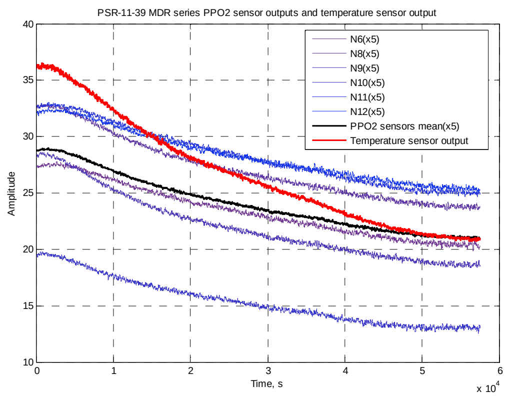
The purpose of this series of the test is to reveal the correction for static change of the temperature. The need of this correction is to improve accuracy of the PPO2 measurements with AII PSR-11-39 DL sensors.

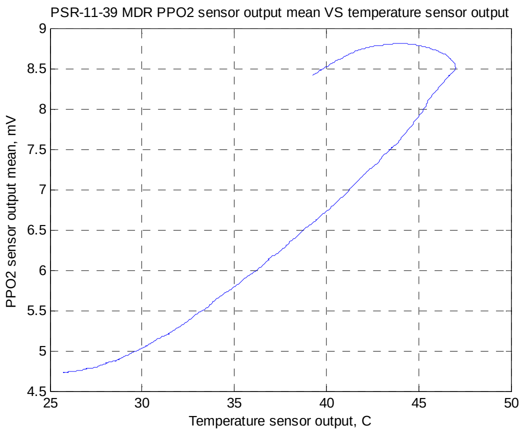
To get low gradient temperature change a special compartment was assembled. It consists of heat-insulation chamber, the controlled heater and the temperature sensors including the external one. The control and speed of heating (+0.3C/min) is set from Matlab. The cooling grade (about -0.18C/min) depends on heat-insulation. Ambient temperature is monitored via temperature sensor located among the PPO2 sensors.

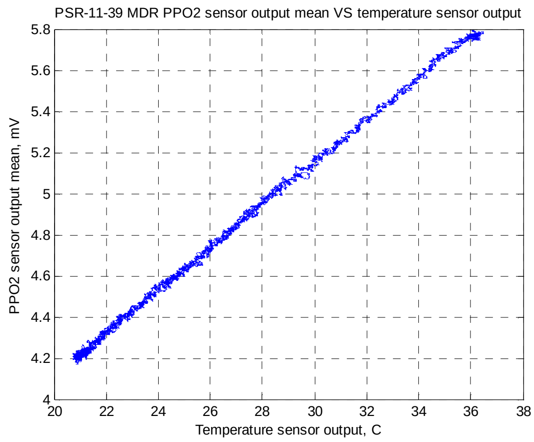
The PPO2 sensors output results are presented in the Table 2.

Table 2. Test data of low gradient heating and cooling.

<table>
<tr><th>Low gradient heating (+0.3C/min)</th><th>Low gradient cooling (about -0.18C/min)</th></tr>
<tr><td>


Test data: 2007426_16_20_4.mat
</td><td>


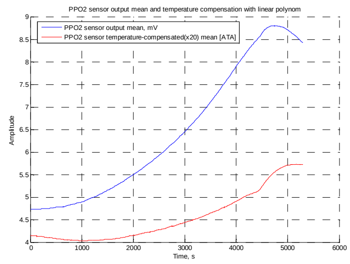
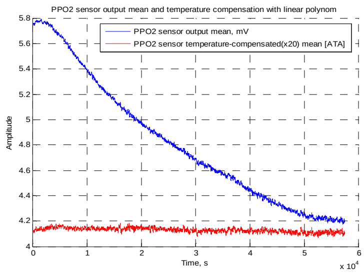
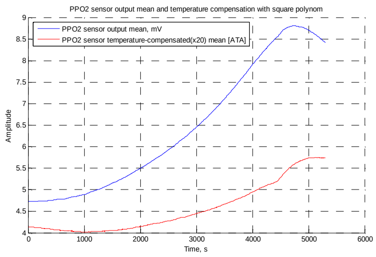
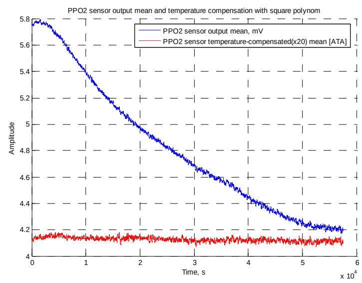
Test data: 2007428_22_0_53.mat
</td></tr>
<tr><td>


The 'hook' at the top of the curve means that there is a dynamic influence of the temperature.
</td><td>


The math presentation of this dependence is showed at Table 3.
</td></tr>
</table>

Table 3. Test result approximation parameters.

N		Linear approximation	Square approximation
1	Type	PPO2sens_out = PPO2_gasx(p2xT+p1)	PPO2sens_out = PPO2_gasx(p3xT^2+p2xT+p1)

2	Coefficients p1, p2, p3 [1] (with 95% confidence bounds)	p1 = 9.637 (9.627:9.642) p2 = 0.488 (0.4879:0.4884) p3 = 0.0	p1 = 9.472 (9.439:9.500) p2 = 0.5464 (0.5441:0.5488) p3 = -0.001036 (-0.001077:-0.000996)
3	Approximation parameters	Goodness of fit: SSE: 7.452 R-square: 0.9989 Adjusted R-square: 0.9989 RMSE: 0.0161	Goodness of fit: SSE: 6.617 R-square: 0.9991 Adjusted R-square: 0.9991 RMSE: 0.01517
4	Plot of the corrected PPO2 output [ATA]	Low gradient heating:  Low gradient cooling: 	Low gradient heating:  Low gradient cooling: 

Static temperature correction with linear and square polynoms gives almost equal accuracy (comparing approximation parameters at the Table 3 row N3) for range temperature of +20...+35C. Therefore the dependence of PSR-11-39-DL PPO2 sensors at the ambient range of +20...+35C for static mode (the temperature change grade not exceeding 0.18C/min, pressure = 1 ATA) can be presented as follows:

PPO2sens_out = PPO2_gas x(0.488xT+9.637).

The measured value of PPO2 in a gas is:

PPO2_gas = PPO2sens_out/(0.488xT+9.637),

Where PPO2sens_out is PPO2 sensor output and T is the ambient temperature.

Comparing the more quicker heating (0.3C/min) than the cooling (0.18C/min) reveals the need of the dynamic temperature compensation. Also it's necessary to correct PPO2 DL series sensors for temperature ranges wider than +20...+35C.

6.2.2 'Step action' heating and cooling tests with measuring PPO2 sensor case temperature

[1] It's assumed that during these tests PPO2_gas = 0.2121 [ATA] and $p_i = p_{i\_approx}$ / PPO2_gas = p_{approx} / 0.2121; i.e. p_{2_approx} = 0.1035, therefore p2 = 0.1035 / 0.2121 ≈ 0.488 .

The purpose of this series of the test is to define the correction for dynamic change of the temperature. The need of this correction is to improve accuracy of the PPO2 measurements with All PSR-11-39 DL sensors.

The model of dynamic correction (at 1ATA ambient) is based in assumption that PPO2 sensor can be replaced with the first order dynamic element. Its transfer function is:

$$PPO2sens\_out(T, PPO2, s) = PPO2\_gas(s) \times \left(p1 + p2 \times \frac{T(s)}{Tau \times s + 1} + p3 \times \left(\frac{T(s)}{Tau \times s + 1} \right)^2 \right),$$

where PPO2sens_out(T,PPO2,s) is PPO2 sensor output of the sensor / ambient temperature, PPO2 [mV], PPO2_gas(s) – ambient PPO2 [ATA], T(s) – sensor / ambient temperature [C], p2, p3 – transfer coefficient, Tau – PPO2 sensor 'temperature-to-output' constant, p1 – constant for static mode when T(t) = 0C.

The PPO2 sensor model representation is provided with the results of the previous tests.

The device under test is one from the batch of the sensors tested in the section 6.2.1. Its serial number is 60741635 (the Oxygen cell number is N9).

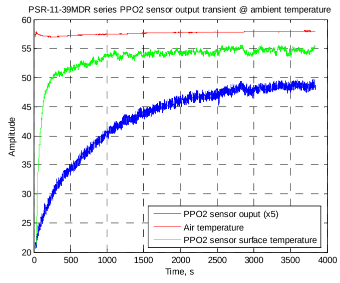
'Step action' series consist of three tests:

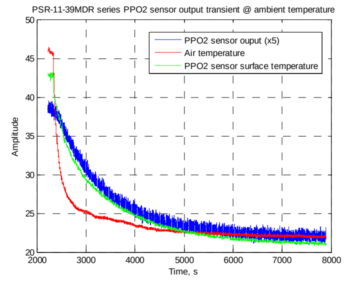
1. *Heating up from the room temperature (+20C) to +58C*. Initially a small plastic chamber open at its bottom was heated with hot air to +58C while the device under test was kept at stable room temperature for two hours. The chamber temperature sensor was located at the wall of the chamber. Note that air had low flow to decrease the influence in temperature constant of the sensor. Then the PPO2 sensor attached to its case temperature sensor was inserted to the chamber. This simulated 'step action' heating. But due to small size of the chamber the PPO2 sensor insertion influenced the internal temperature (**Figure 6-1**). Therefore the 'step action' correction is used for the results.
2. *Cooling in the ambient temperature from +44C to +22C*. The PPO2 sensor was kept in the small test chamber for two hours at temperature of +44C. Then the hot air flow was switched off. The PPO2 sensor was removed from the chamber and left for itself cooling.
3. *Heating up from -4C to the room ambient temperature*. The PPO2 sensor was kept in a refrigerator for one and half hour at the temperature of -4C. Then it was removed from the refrigerator and switched to the Matlab data acquisition system, also the DL case temperature sensor was installed. The PPO2 sensor was left for itself heating in the room.

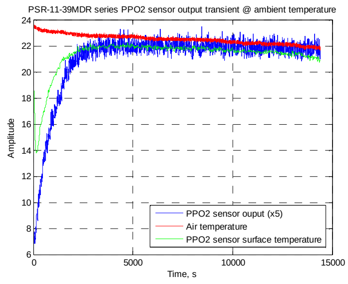
PPO2 sensor output with temperature sensor installed in case of the PPO2 is presented in the Table 4.

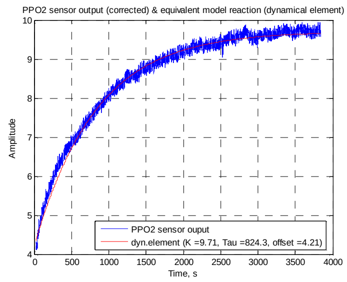
Table 4. Test data of the 'step action' heating and cooling.

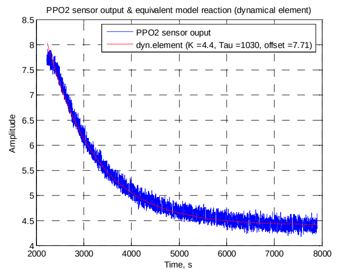
N	'Step' heating up from +20C to +58C in the small chamber	'Step' cooling in the ambient air from +44C to +22C	'Step' heating up from -4C to +22C in the room

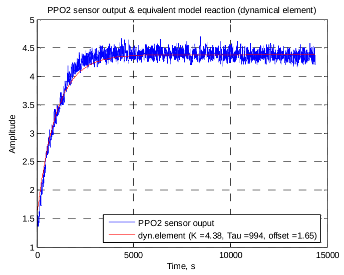
<table>
<tr>
<td>1</td>
<td>

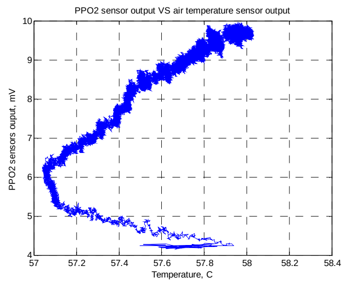
Test data:
O2sensor_temp58C_step_1.mat
Note: presented data is corrected for ambient temperature decreasing. Original data is presented at Figure 6-1</td>
<td>

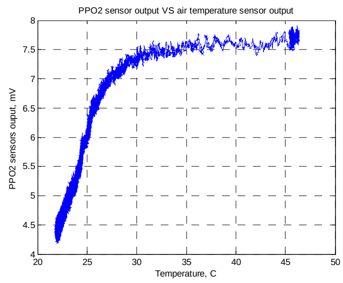
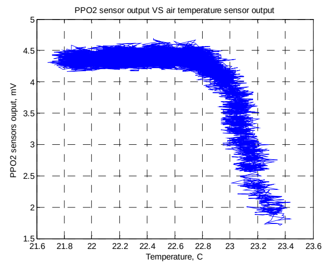
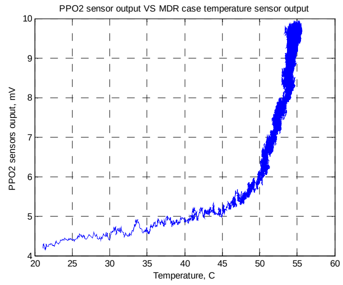
Test data:
O2sensor_temp58C_step_2.mat</td>
<td>

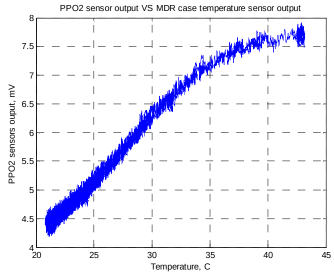
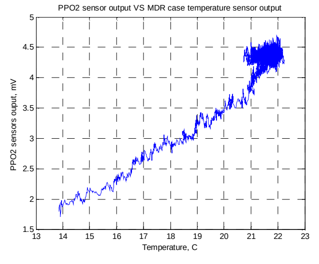
Test data:
O2sensor_temp-4C_step_1.mat</td>
</tr>
<tr>
<td>2</td>
<td>

Tau = 824s
Note: presented data is corrected for ambient temperature decreasing</td>
<td>

Tau = 1030s</td>
<td>

Tau = 994s</td>
</tr>
<tr>
<td>3</td>
<td>

Note: presented data is corrected for ambient temperature decreasing</td>
<td>
</td>
<td>
</td>
</tr>
<tr>
<td>4</td>
<td>

Note: presented data is corrected for ambient temperature decreasing</td>
<td>
</td>
<td>

Note: DL case temperature sensor output transients are removed.</td>
</tr>
</table>

Plots above can be zoomed, when viewed with a PDF viewer.

Comparing the plots of the dependence of PPO2 sensor output and air (ambient) temperature (Table 4 row 3) and DL case temperature (Table 4 row 4) it can be noticed that correlation between PPO2 sensor output and its case temperature is stronger than between the PPO2 sensor output and ambient temperature. Also taking into account dependence of the thermal constant on such parameters as distance between surfaces of the PPO2 sensor and the ambient temperature sensor, gas flow, gas density and so in PPO2 sensor output and its case temperature correlation is much stable than in case with ambient temperature. Therefore dynamic temperature compensation using PPO2 sensor body temperature has higher accuracy than using the ambient temperature information. That's why the dynamic algorithm is based in temperature of the PPO2 sensor, not ambient one.

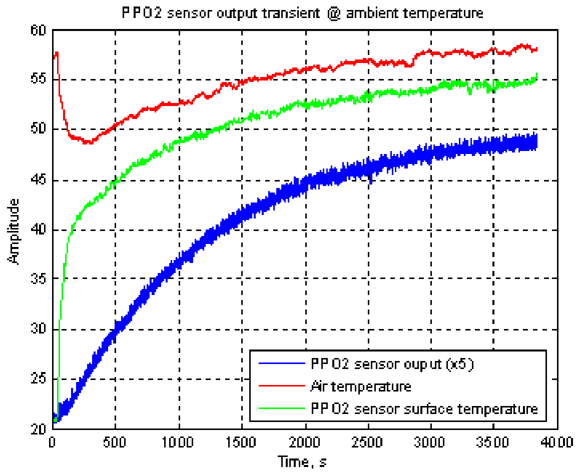


Figure 6-1. Sensors output as a function of temperature. Raw test data without 'step action' correction (O2sensor_temp58C_step_1.mat). X scale seconds, Y scale normalised amplitudes (Normalisation 0 to 40C temperature, mV PPO2 output x5).

6.3 Compensation algorithm development

The algorithm of defining the dynamic temperature correction of PPO2 sensor output is described below:

1. Find the static characteristic for the sensor using points with periods of more than 1.5 hours for stable sensor temperature. Note each sensor has its own parameters also they are not stable in the tests (see Figure 6-2). Therefore the temperature compensation should be carried out with batch mean coefficients (see low gradient cooling section 6.2.1).
2. Select the test with the most stable external parameters (ambient temperature and humidity, pressure, gas flows and other influences that can additionally disturb the PPO2 sensor output). Find the 'temperature-to-output' constant (Tau) for the case when there is a 'step action' change of the PPO2 sensor temperature.
3. Enter the found parameters to the sensor model. Calculate the model output for applying step temperature change of the PPO2 sensor.
4. Evaluate the difference (error) between the real (*PPO2_sens*) and model (*PPO2_model*) sensor outputs. Change the impact to the model in such way to minimize the real and model outputs error (the *PPO2_sens–PPO2_model* error).
5. Comparing the PPO2 sensor model impact and the PPO2 sensor case temperature to define the parameters of the reverse transfer function of the case temperature sensor to minimize the error between them.

6. Apply the DL case temperature sensor output to its reverse transfer function. Set the function output to the reverse PPO2 sensor model.
7. Replace the static parameters of the reverse PPO2 sensor model with batch mean ones. In this case the reverse PPO2 sensor model output is PPO2 of gas.

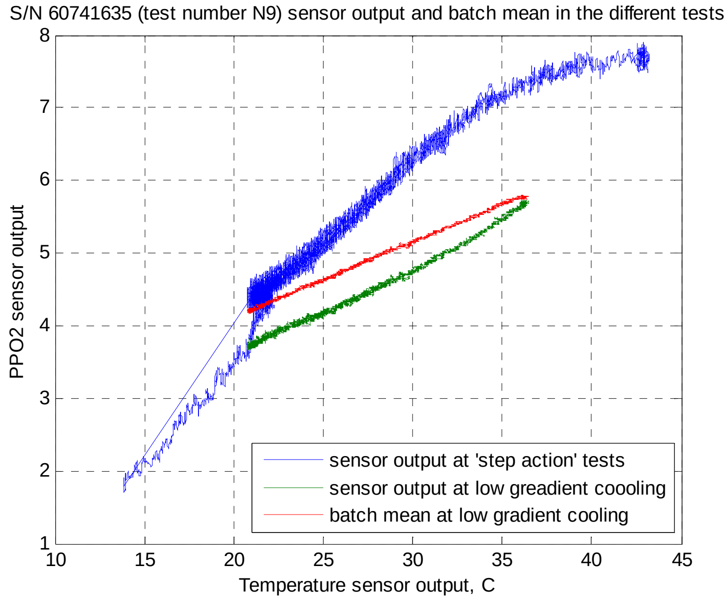


Figure 6-2. Comparing temperature dependence for the individual sensor from the batch and the batch mean (low gradient cooling section 6.2.1). Note the same sensor (S/N 60741635 or N9 in the tests) has different dependence in the tests.

The static temperature characteristic for the N9 PPO2 sensor is shown in Figure 6-3. The quality parameters of approximation are presented in the Table 5. The quadratic approximation is used as the static temperature characteristic for the N9 PPO2 sensor in the PPO2 sensor model as it gives more accuracy than linear one.

Table 5 Two types of static temperature approximation for the PPO2 sensor N9

	Linear approximation	Quadratic approximation
Type	PPO2sens_out = PPO2_gasx(p2xT+p1)	PPO2sens_out = PPO2_gasx(p3xT^2+p2xT+p1)
Coefficients p1, p2, p3 [2] (with 95% confidence bounds)	p3 = 0; p2 = 0.7115 (0.6407, 0.7822); p1 = 6.5582 (4.2277, 8.8873)	p3 = 0.00237 (0.00132, 0.00339); p2 = 0.58887 (0.5323, 0.64545); p1 = 7.07214 (6.47336, 7.6662)
Approximation parameters	Fit: SSE: 0.15329 R-square: 0.99707 Adjusted R-square: 0.9961 RMSE: 0.22605	Fit: SSE: 0.003142 R-square: 0.99994 Adjusted R-square: 0.9999 RMSE: 0.039636

[2] It's assumed that during these tests PPO2_gas = 0.2121 [ATA] and $p_i = p_{i\_approx}$ / PPO2_gas = p_{approx} / 0.2121; i.e. p_{2_approx} = 0.1509, therefore p2 = 0.1509 / 0.2121 ≈ 0.7115.

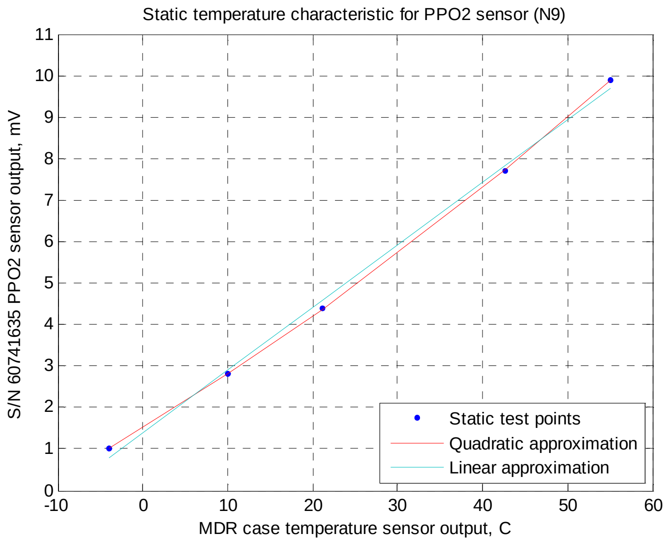


Figure 6-3. Two types of static temperature approximation for the PPO2 sensor (S/N 60741635 or N9 in the tests).

The *'step cooling' in the ambient air (from +44C to +22C)* test is assumed as for the base test for the algorithm listed above. The *'step' heating up from +20C to +58C in the small chamber* test doesn't suit for base one as there is hot air flow influence in DL case temperature sensor. This can be noticed comparing the results for heating and cooling in other tests (see Table 4 row 4) as a great growth of the case temperature and slow change of the PPO2 sensor output. The *'step' heating up from -4C to +22C in the room* test also doesn't fit the requirements of item 2 because of the DL case temperature sensor was installed in PPO2 sensor after its removing from the refrigerator, therefore there were complex transients of temperature sensor output. Actually the initial period of this test gives rough data about the DL case temperature.

The 'temperature-to-output' constant (Tau) for the *'step cooling' in the ambient air (from +44C to +22C)* test is 1030s (see Table 4 row 2).

PPO2 sensor model is shown in

Figure **6-4**.

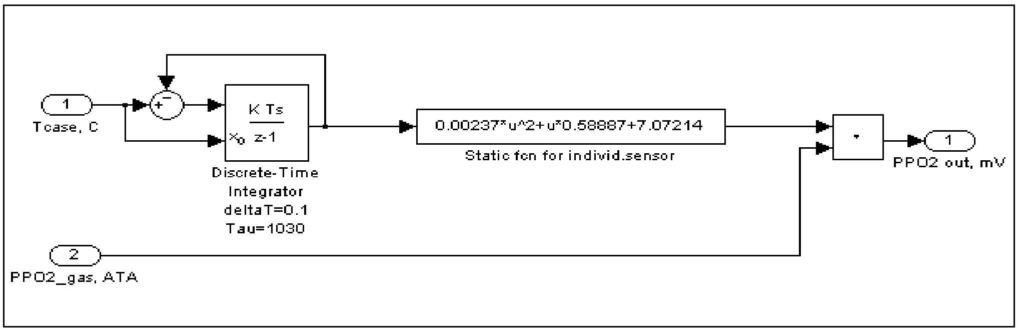
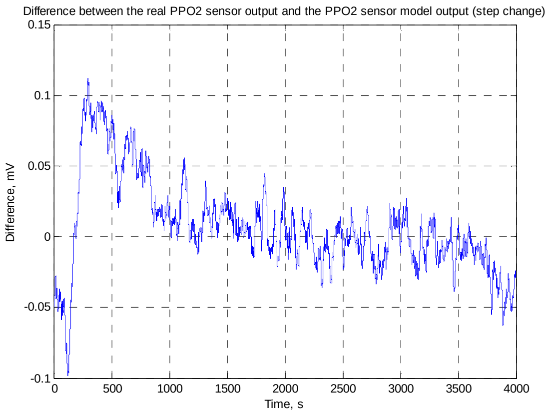
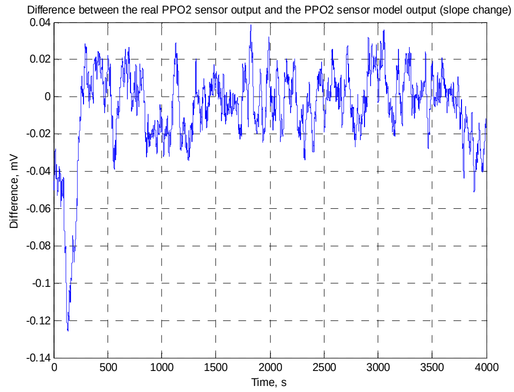


Figure 6-4. PPO2 sensor model (Static function presented for the sensor with S/N 60741635 or N9 in the tests).

The *PPO2_sens – PPO2_model* error PPO2 sensor model output for the step change of the PPO2 sensor temperature from +43C to +22C and for slope change are shown below:



Step change of the PPO2 sensor temperature at the 100s



Slope change of the PPO2 sensor temperature at the period of 100s…150s

Figure 6-5. PPO2 sensor model reaction in step and slope change of the PPO2 sensor temperature.

It's seen that there is initial offset of the PPO2 sensor output (Figure 6-5). It's combined with small offset of 0.1C in DL case temperature mean at the period of 0…100s. The peak at 120s…130s is alone noise impulse offset of 0.2mV in the PPO2 sensor output.

The reverse transfer function with its parameters of the case temperature sensor is shown below:

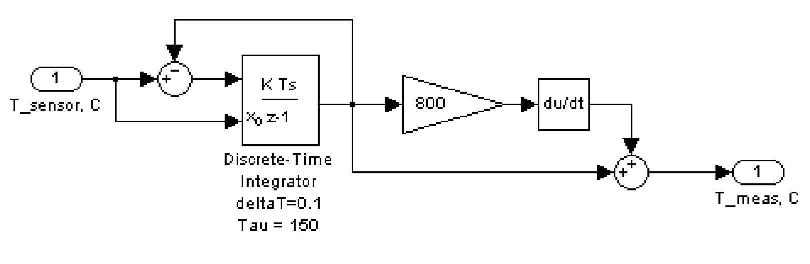


Figure 6-6. Reverse transfer function of the DL case temperature sensor.

The structure of the function is based on assuming the temperature sensor (LM35) is the first order dynamic element with Tau of 60…70s in still air (according to its datasheet). But the real signal (ideally it's a step) is slightly different than the artificial model impact (ideally it's a sharp slope) – see Figure 6-7. Therefore the applied reverse transfer function slightly differs from the original reverse transfer function of the DL case temperature sensor.

The output of the reverse transfer function and the difference between the model impact and output are presented in the Figure 6-8.

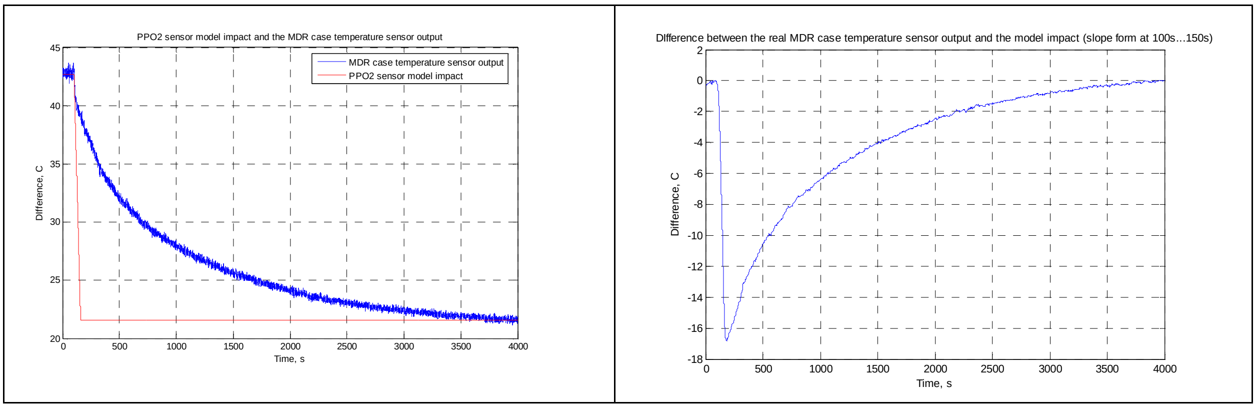


Figure 6-7. The model impact, the DL case temperature sensor output and their difference.

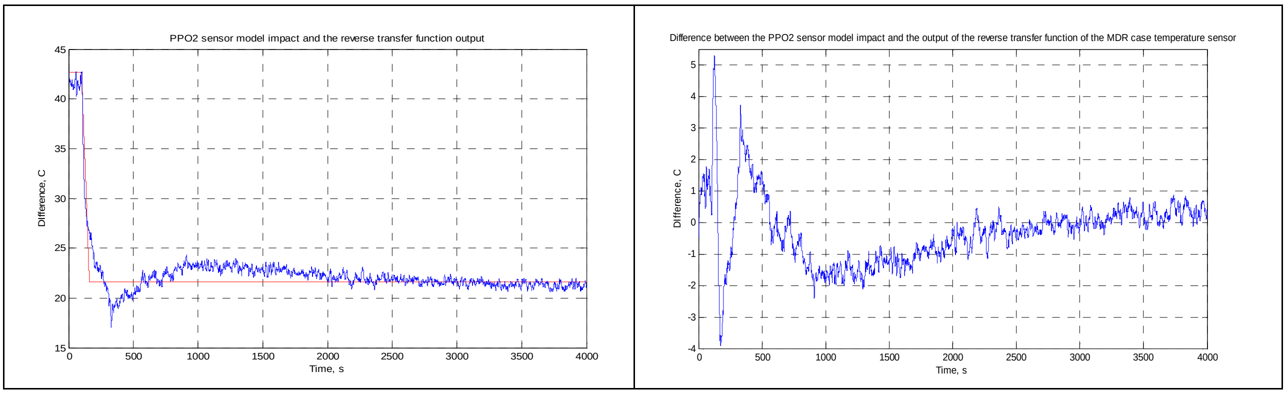


Figure 6-8. The model impact, reverse transfer function output of the DL case temperature sensor and their difference.

The reverse PPO2 sensor model is shown in the Figure **6-9** and its output is presented in the Figure 6-10 below.

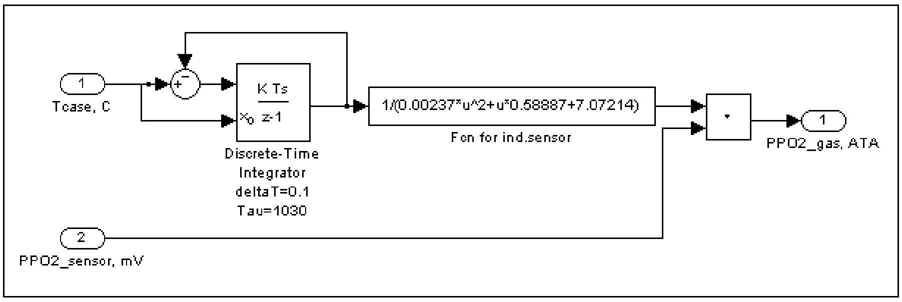


Figure 6-9. Reverse PPO2 sensor model.

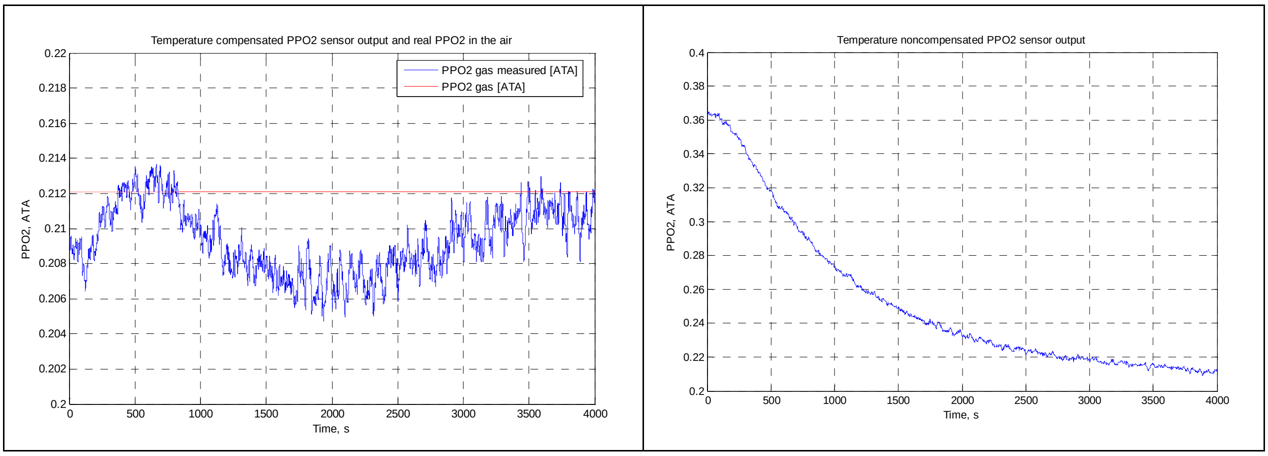


Figure 6-10. Reverse PPO2 sensor model output and noncompensated PPO2 sensor output [ATA].

Replace the static parameters of the reverse PPO2 sensor model with batch mean ones. In this case the reverse PPO2 sensor model output is PPO2 of gas.

6.3.1 Dynamic temperature compensation algorithm description

The dynamic temperature compensation needs using of the general variables and constants described in the Table 6. Note the key-note features of the parameters marked with **bold** and *italics*.

Table 6 General variables and constants used in the dynamic temperature compensation

N	Parameter name	Parameter designation	Description of the parameter
Variables			
1	DL case (PPO2 sensor) temperature	Tppo2	DL case temperature sensor output is computed to the degrees of Celsius with its ***static*** reverse transfer function.
2	PPO2 sensor group mean	PPO2_sens	PPO2_sens is the mean of the ***working*** group of the PPO2 sensors. This value is calculated at the ***one*** dTsys.
3	Integrated value of Tppo2	i_Tppo2	Discrete-time integration output using for calculating discrete-time derivative. ***Initial value*** of i_Tppo2 is equal the first sample of Tppo2.
4	Derivative value of i_Tppo2	d_Tppo2	Discrete-time derivative output. ***Initial value*** of d_Tppo2 is equal the first sample of Tppo2.
5	Integrated value of	s_Tppo2	Discrete-time integration output using for calculating static

	d_Tppo2		temperature compensation value. ***Initial value*** of s_Tppo2 is equal the first sample of Tppo2.
Constants			
1	Sampling period using for PPO2 and temperature sensors sampling	dTsys	***Constant*** time period between PPO2 and temperature sensors sampling.
2	Polynomial coefficients of PPO2 sensor output temperature dependence	p1=7.07214, p2=0.58887, p3=0.00237	Polynomial coefficients of the PPO2 sensor output static temperature dependence. These coefficients should be tuned for mean of the used group of the sensors.
3	Time constant of the reverse transfer function output of the DL case temperature sensor	Ki_ts = 150	Actually it's intergral proportional coefficient used in the discrete-time integration at the reverse transfer function. Should be ***tuned at the unit***.
4	Derivative constant of the reverse transfer function output of the DL case temperature sensor	Kd_ts = 800	It's differential proportional coefficient used in calculation of the discrete-time derivative at the reverse transfer function. Should be ***tuned at the unit***.
5	Temperature time constant of the PPO2 sensor	Ki_ppo2 = 1030	It's intergral proportional coefficient used in the discrete-time integration at the static temperature compensation transfer function output of the PPO2 sensor.

6.4 Formal Specification

The temperature compensation of the PPO2 sensor output can be described in terms of transfer functions (Laplace transformation) as follows:

1. Dynamic part:

   a. $T^*(s) = F_{Ts}^{-1}(Tppo2(s)) = \dfrac{Tppo2(s)\times\left(Kd\_ts\times s+1\right)}{Ki\_ts\times s+1}$ – reverse transfer function output of the DL case temperature sensor.

   b. $T^{**}(s) = F_{ppo2}(T^*(s)) = \dfrac{T^*(s)}{Ki\_ppo2\times s+1}$ – Temperature transfer function output of the PPO2 sensor.

2. Static part: $PPO2\_gas(t) = \dfrac{PPO2\_sens(t)}{T^{**2}(t)\times p3 + T^{**}(t)\times p2 + p1}$ – static temperature compensation transfer function output of the PPO2 sensor.

These transfer function equations can be represented with the following discrete-time form:

1. $i\_Tppo2_i = i\_Tppo2_{i-1} + Ki\_ts \times dTsys \times (Tppo2_i - i\_Tppo2_{i-1})$; $i\_Tppo2_0 = Tppo2_0$ [C]
2. $d\_Tppo2_i = i\_Tppo2_i + \frac{Kd\_ts}{dTsys} \times (i\_Tppo2_i - i\_Tppo2_{i-1})$;
   $d\_Tppo2_0 = Tppo2_0$ [C]
3. $s\_Tppo2_i = s\_Tppo2_{i-1} + Ki\_ppo2 \times dTsys \times (d\_Tppo2_i - s\_Tppo2_{i-1})$;
   $s\_Tppo2_0 = Tppo2_0$ [C]
4. $PPO2\_gas_i = \frac{PPO2\_sens_i}{\left((s\_Tppo2_i)^2 \times p3 + s\_Tppo2_i \times p2 + p1\right)}$ [ATA]

The implementation of the above functions would be expected to take the following general form:

1. Get the initial meanings of the following parameters: $Tppo2_0$, $PPO2\_sens_0$.
2. Calculate initial value of the $PPO2\_gas_0$ using the 4th equation above.
3. Get the next meanings of the following parameters: $Tppo2_i$, $PPO2\_sens_i$.
4. Calculate i_Tppo2_i, d_Tppo2_i, s_Tppo2_i and then $PPO2\_gas_i$.
5. Repeat the 3rd and 4th items.

7 VALIDATION OF THE FORMAL MODEL

An independent group led M. Evtukov measured the time constant of samples from an October 2009 batch of 230 PSR 11-39-DL sensors. These sensors are used in all Open Revolution rebreather oxygen monitors and oxygen controllers, including the Apocalypse O2 monitors, and the Rev D3 eCCR Base Card, as follows:

1. Four sensors were put into the fridge. Cooling time was much longer than estimated sensor's time constant.
2. Output voltage from individual sensor was measured when the sensor was moved to an ambient.
3. Data was approximated with the curve of the form A*exp(B*time)+C in MathCAD
4. Time constant was calculated from the approximation curve at 63.2% of the sensor's maximum value

The equipment used was the TTi 1906 Lab Precision Computing Multimeter s/n 111474 (Next cal December 2010) was connected to a PC through an RS232 interface. The meter was configured to measure Voltage DC, Autoranging.

The results are plotted below.

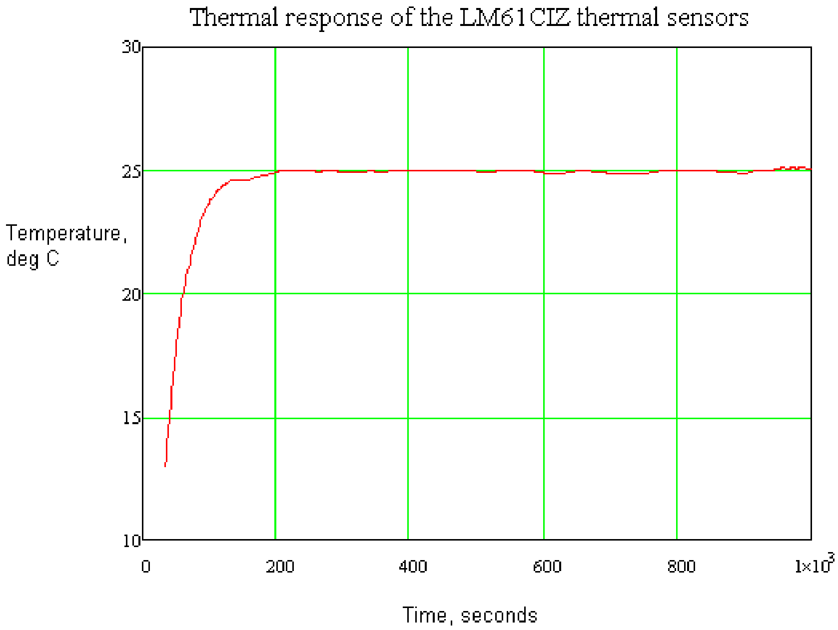


Figure 7-1. Thermal response of the LM61CIZ thermal sensors. Response time (1/e) is 29s.

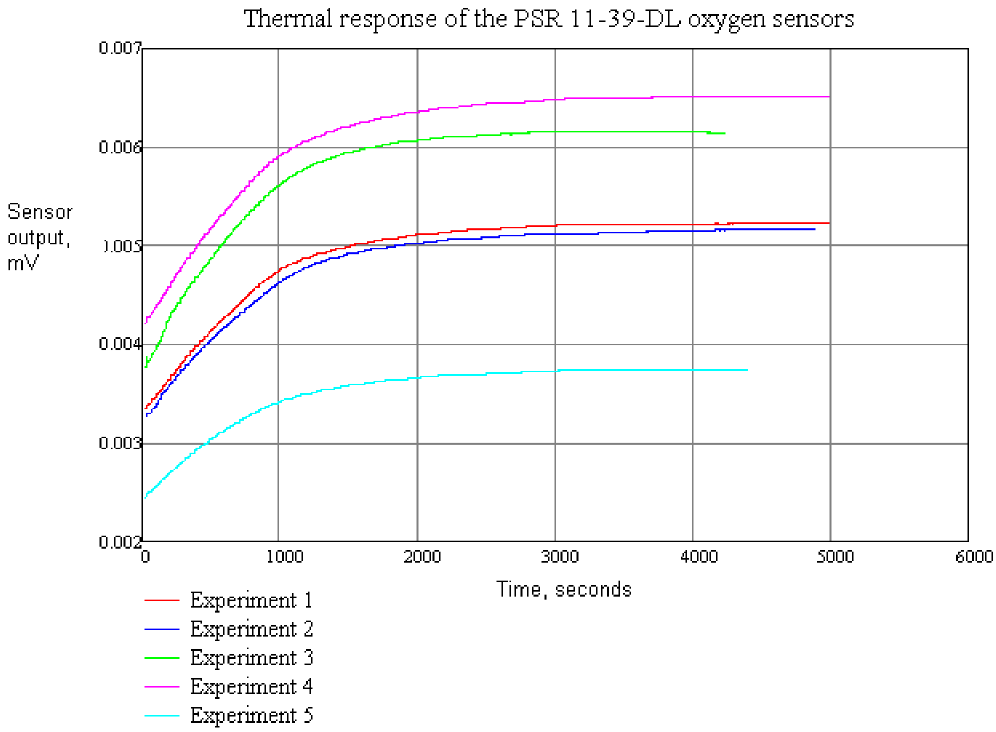


Figure 7-2. Thermal response of the PSR 11-39-DL oxygen sensors. Response is 714 seconds (1/e, or 63%) on average. Each experiment used a different sensor sample.

Sensors from a batch of 230 were sampled and measured. The average was 714 seconds, with a standard deviation of 31 seconds: 11 minutes 54 seconds.

The length of an IIR filter with a 12 minute response, is too long to implement. The Nyquist frequency from the fast temperature sensor itself is $1/20^{th}$ Hz, and sampled at $1/10^{th}$ Hz. The size of the IIR filter can be reduced to practical proportions if the data is pre-filtered. It is suggested that the simplest way to achieve this is for the input to the IIR filter to be taken as the 3 minute average of the fast sensor readings.

7.1 Variation in isolated and fitted sensors

It was observed that the thermal response of the oxygen sensors and temperature sensors, are significantly different when they are tested in isolation compared to when they are fitted to the monitor. This was factored into the formal model.

8 VERIFICATION OF IMPLEMENTATION

The formal model was reported to have been implemented, and the software team was able to show a full code, branch and condition test coverage. This means, the software implemented what they thought was specified, or what they intended to implement. Under the Quality Procedures Q-20 and QP_24, the safety functions specified for that software are verified independently. The software was tested exhaustively by being driven from the formal model, using the Rebreather Environment Emulator, but additional empirical tests had to be performed because it was not possible to emulate the entire environment defined by the specification, as the essence of this evaluation is to create a physical environment around the sensors and measure their accuracy and response.

Experiments were performed by M. Solovyev to determine coefficients for the thermal compensation used in the software on a black box basis. Apocalypse O2 monitor serial number 0102-B1 was used for the investigation, as there are no material differences in circuitry or accuracy between different monitor samples. The measurements are in the Table 7

Table 7

N	Time	H.W. Anemometer scope temp,C	O2 monitor temp,C	O2 monitor depth,m	General PPO2	1st sensor PPO2	2nd sensor PPO2_2	3rd sensor PPO2
1	9:40	26.2	25	0.02	0.221	0.219	0.221	0.221
2	9:45	19.7	24	0.00	0.217	0.217	0.217	0.214
3	9:50	14.8	22	0.01	0.204	0.203	0.202	0.199
4	9:55	13.4	19	0.00	0.191	0.191	0.190	0.188
5	10:00	12.6	17	0.02	0.182	0.182	0.179	0.178
6	10:05	13.5	16	0.01	0.175	0.175	0.174	0.173
7	10:10	13.5	15	0.03	0.169	0.168	0.169	0.166
8	10:15	12.5	14	0.04	0.164	0.162	0.164	0.160
9	10:20	11.9	13	0.03	0.156	0.157	0.159	0.155
10	10:25	10.6	12	0.02	0.156	0.153	0.156	0.152
11	10:30	11.1	11	0.04	0.153	0.150	0.153	0.150
12	10:35	11.0	11	0.03	0.151	0.148	0.151	0.147
13	10:40	10.5	11	0.03	0.150	0.148	0.150	0.146
14	10:45	10.8	10	0.03	0.148	0.145	0.148	0.144
15	10:50	10.4	10	0.03	0.147	0.143	0.147	0.143
16	10:55	11.7	10	0.04	0.148	0.144	0.148	0.143

17	11:00	10.2	10	0.04	0.146	0.143	0.146	0.142
18	11:05	10.5	9	0.03	0.145	0.142	0.145	0.141
19	11:10	9.7	9	0.03	0.144	0.141	0.144	0.140
20	11:15	10.3	9	0.04	0.144	0.140	0.144	0.140
21	11:20	9.5	9	0.03	0.142	0.138	0.142	0.139
22	11:25	8.5	8	0.03	0.140	0.138	0.140	0.137
23	11:30	8.8	8	0.03	0.139	0.137	0.139	0.136
24	11:35	8.7	8	0.03	0.137	0.135	0.137	0.135
25	11:40	8.8	8	0.03	0.137	0.135	0.137	0.134
26	11:45	9.0	7	0.03	0.137	0.134	0.137	0.134
27	11:50	8.4	7	0.03	0.136	0.134	0.136	0.133
28	11:55	8.8	7	0.03	0.136	0.133	0.136	0.133
29	12:00	9.1	7	0.04	0.135	0.133	0.135	0.133
30	12:05	8.9	7	0.04	0.135	0.133	0.135	0.133
31	12:10	9.2	7	0.04	0.136	0.133	0.136	0.133

Two coefficients were calculated, shown in the formula:

PPO2_compensated=PPO2_measured-**0.004747***Temperature_sensor_reading+ **0.11**

The results of the temperature compensation are shown in Figure 8-1.

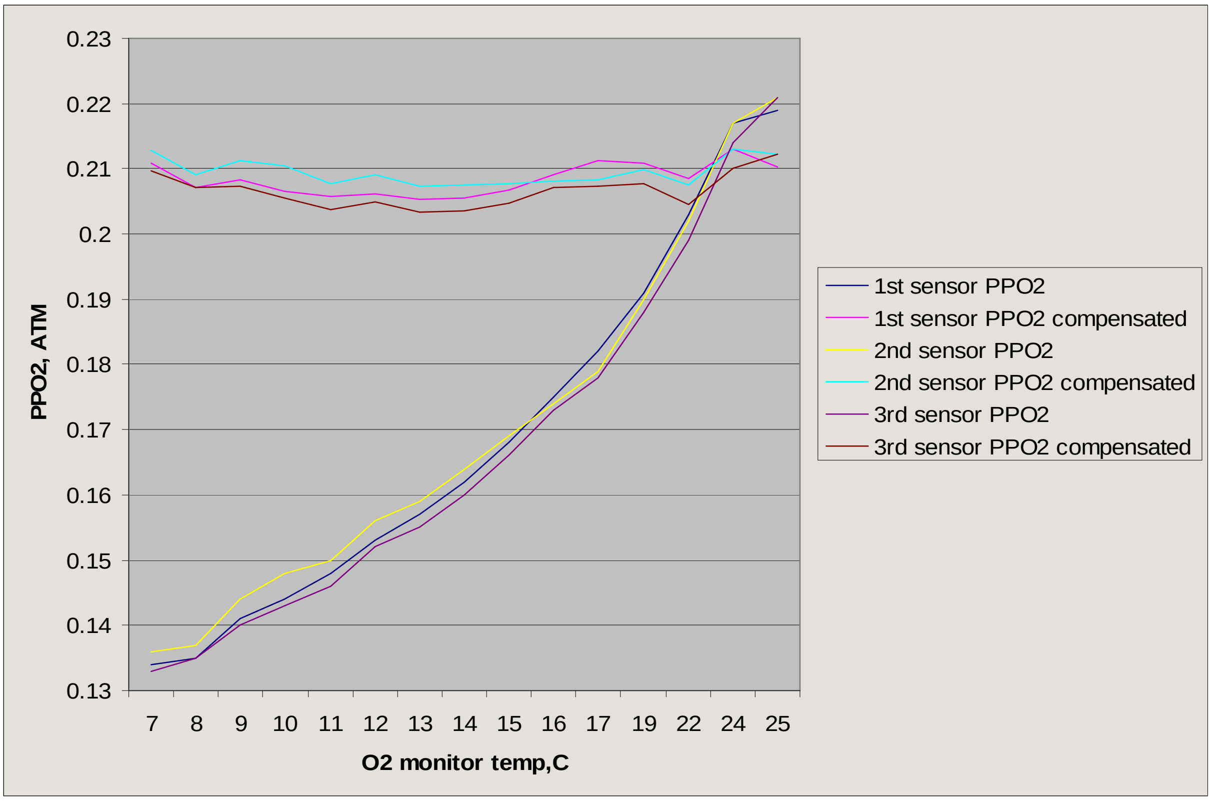


Figure 8-1. PPO2 readings, static portion of thermal compensation

The static compensation appears to be correct.

The dynamic portion of the algorithm was not implemented by the software as specified in the Formal Model. This was traced to the language of the Formal Model not being understood by the software team: it assumed knowledge of Z-transforms and DSP theory. That knowledge was appropriate to the electronics and control teams, but is not appropriate to the wider engineering community, including software teams. This non-conformance was reported in Deep Life Mantis system issues 954, 955, and 956.

The corrective action was to reword the description of algorithm above, resulting in issue A4 of this document.

The plain description of the compensation algorithm was implemented by the software team, and the verification results are reported below.

9 RE-VERIFICATION OF TEMPERATURE DEPENDENCE

Three PSR 11-39-DL O2 sensors selected at random from a November 2008 batch were placed in the O2 monitor serial number 105 (O2 monitor firmware version 5.1.12350). The PSR 11-39-DL sensors had the following serial numbers: 91053372, 91053357 and 91053368

The sensors were checked by calibrating them at five different temperatues, 4℃, 0℃, -2℃, -6℃ and -10℃, and then testing them for accuracy a t 34C. All the sensors passed this test, so were then subject to the full compliance tests below. The purpose of this check is to verify the worst case differences between calibration and operating temperatures. Note the sensors will fail if exposed to freezing conditions for an extended period: the exposure to cold temperatures was for 30 seconds only, simulating a diver performing a calibration in the open air..

Temperature compensation was re-verified for the operating temperature range of 0℃ to 38℃. The O2 monitor was calibrated at 24 °C and showed 0.210ATA in air. The sensors were then exposed to the temprature profile covering 0C to 40C shown in **Figure 9-1.**

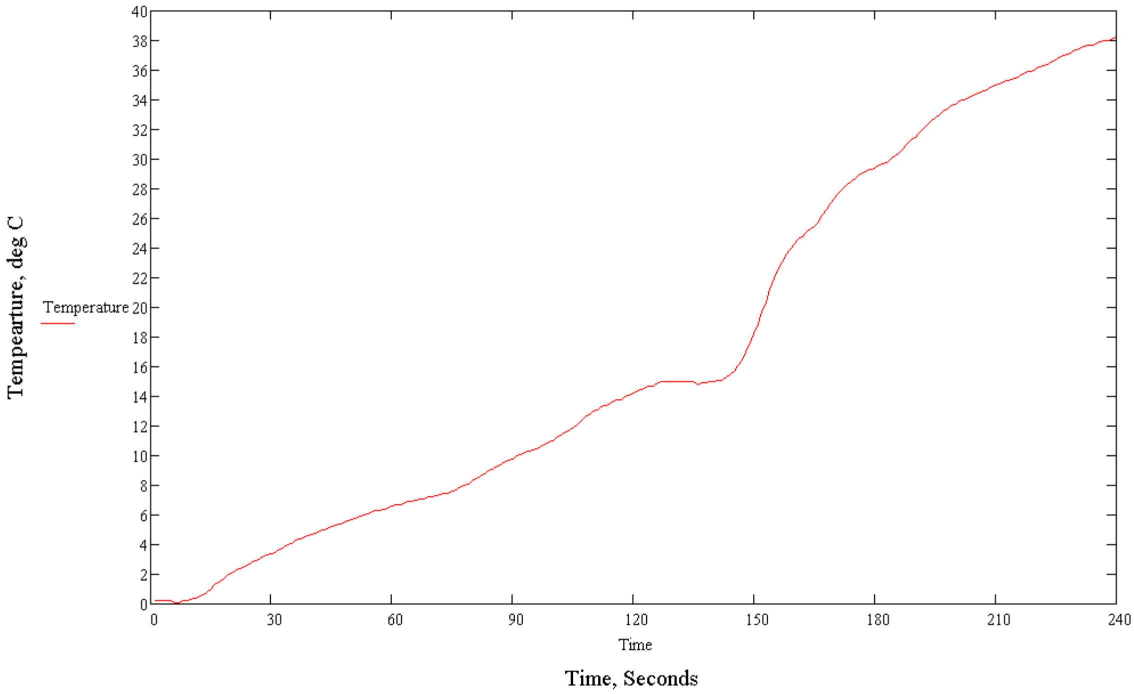


Figure 9-1. Temperature profile during temperature compensation re-verification.

PPO2 values were internally logged in the O2 monitor and read back after the re-verification.

The dependence of the PPO2 from the temperature is presented in Figure 9-2.

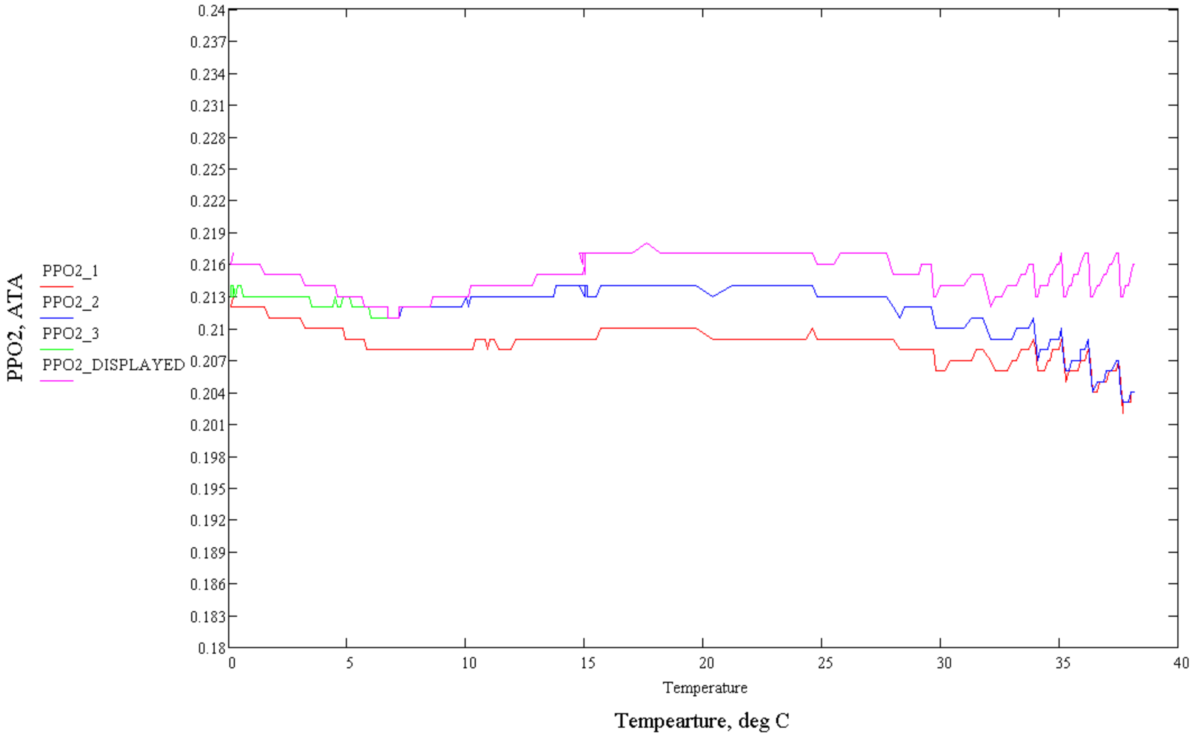


Figure 9-2. PPO2 readings from the sensors versus temperature, from 0C to 40C.

The PPO2_DISPLAYED (magenta in Figure 9-2) parameter is the figure that was displayed on the O2 monitor, and logged automatically. The average value of the PPO2_DISPLAYED over the full temperature range is 0.215 with maximum deviation 0.218, and minimum of 0.211 atm. These are within the permissible limits of +/-0.03 bar.

10 COMPLIANCE & DEPENDENCE ON PRESSURE

The dependence on pressure was assessed using the OR_Incursion and OR_Apocalypse monitoring pods by two methods:

1. Variable pressure; By placing the PPO2 monitoring part of the apparatus in a small pressure chamber, with an internal fan, and pressuring it using air to 8.9 bar.
2. Constant pressure; By placing the PPO2 monitoring part of the apparatus in a small pressure chamber, in Nitrogen and then in Helium, and sweeping the PPO2 by injecting oxygen through a needle valve and venting the chamber via a second needle valve to maintain the pressure. The PPO2 was monitoring using a Mass Spectrometer.

The Active Warning Devices were assessed at the same time as the PPO2 accuracy test using the first method above: for the iCCR monitors the chamber had a Lexan window that allowed the RF signal to pass through the window in the case. For the OR_Incursion a feedthrough from a 300mm I.D. chamber was used. In each case, the monitoring subassembly was tested, as permitted in EN 14143:2003.

All OR rebreather models use exactly the same processing of the oxygen data: i.e. the same firmware and the same software modules.

10.1 Accuracy of PPO2 Indicators under Variable Pressure

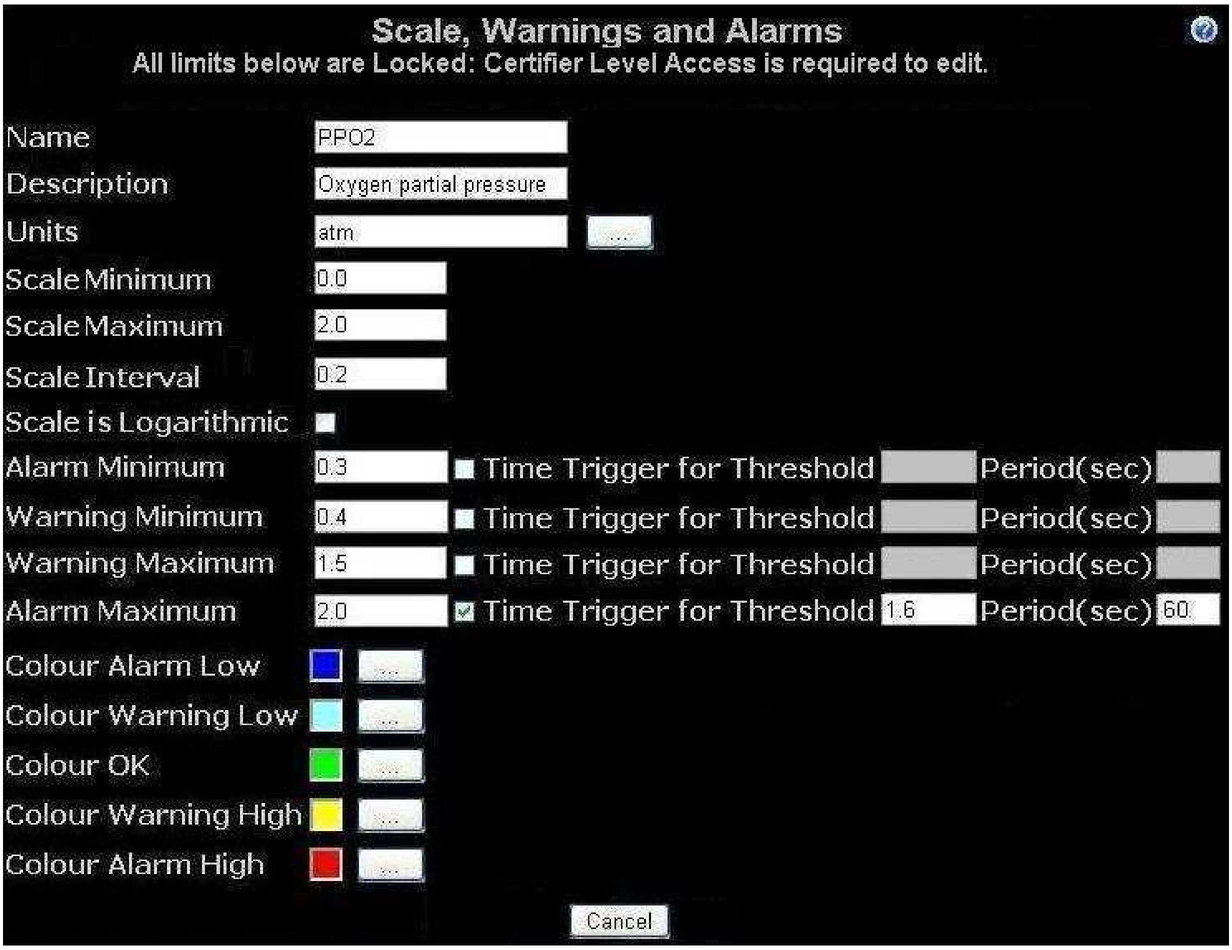
There are two PPO2 indicators in the Open Revolution rebreathers;

1. The oxygen monitoring pod on the iCCR
2. The oxygen monitoring display and system in the eCCR.

Both have the same code (as in exactly the same code modules) for all oxygen signal processing and sensor fusion.

The alarm levels are set as shown in the GUI below (on the Alarm Matrix screen of the Rebreather Utility (all models), and on the Rebreather Dive Monitoring (eCCRs), except that when the respirator rate is less than 1 bpm and the ambient pressure range is less than 1.089 bar the PPO2 alarm state is the greater of 0.16 atm AND 0.20 atm times the ambient pressure in atm: this suppression is necessary to avoid the rebreather alarming all the time while it is being set up predive – the warning is still 0.4 atm, the alarm shows “Oxygen low, Inject Gas”, and shows a yellow display on the iCCR, blue alarm condition on the computer monitor displays (eCCR).

The colour coding shown in the GUI is used only for computer displays (downloads, and monitoring of the eCCRs). The colour coding of the iCCR display is simplified: it uses red for alarm conditions, yellow for warnings and green for normal.



To test the accuracy the Oxygen Monitor was placed in a chamber with a fan ventillator and then pressurised with air. A digital precision manometer, a Keller LEX1 with accuracy of +/-

0.01 bar, displayed the pressure relative to atmosphere. The atmospheric pressure was 1.016Bar.

The oxygen percentage in the air is 20.09. Therefore to achieve 0.4; 0.6; 0.8; 1.0; 1.2; 1.4; 1.6; 1.8; and 2.0 Bar PPO2 the air pressure in the chamber was 1.88; 2.81; 3.75; 4.69; 5.64; 6.58; 7.51; 8.46 and 9.39 Bar respectively.

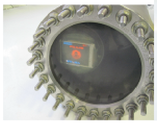
There is a deviation with humidity, as the gas used to pressurise the chamber was dry, this effect could be ignored. The gas cylinder was filled with a certified air cylinder (not a compressor), and the contents were checked using a mass spectrometer prior to the test.

Figure 10-1. Variable pressure test fixture for the PPO2 Pod

The test results are shown in Table 8. The deviation of the oxygen partial pressure display is less than the limit according to the standard EN14143.

Table 8: Oxygen monitor test results

Pressure (On right, Bar absolute)	Calculated PPO2, (Bar)	Oxygen monitor PPO2 reading (Bar)	PPO2 deviation (Bar)	% error
 1.0	0.212	 0.211 Warning active (as <=0.4 atm), Alarm suppressed (as ambient pressure <= 1.089 bar)	0.001	0.47
 1.88	0.4	 0.393 Warning active (as PPO2 <= 0.4 atm)	0.007	1.75

 2.81	0.6	 0.586	0.014	2.33
 3.75	0.8	 0.78	0.02	2.50
 4.69	1.0	 0.989	0.011	1.10
 5.64	1.2	 1.182	0.018	1.50
 5.58	1.4	 1.384	0.016	1.14
 7.51	1.6	 1.586 Warning indicated (as > 1.5 atm)	0.014	0.88
 8.46	1.8	 1.785 Alarms if >= 60s	0.015	0.83
 9.39	2.0	  2.003 Alarm activated instantly	0.003	-1.50

The deviation allowed in EN 14143:2003 is +/-0.03 bar for 0.1 to 0.4 bar and +/-0.06 bar for 0.4 to 2.0 bar. The measured deviation over the interval of the lower limit was +0.007 (which occurred with a pressure of 0.4 bar of O2), and the maximum deviation which occurred over the interval of the higher limit was +0.02 bar. All errors are well within the limits allowed by the standard.

The images in the above table show the display provides alarms and warnings at the pressures required by EN 14143:2003. All alarms and warnings were triggered within the accuracy of the PPO2 monitors.

The OR_Incursion was tested in a 300mm diameter chamber, and behaved similarly to the OR_Apocalypse, with a maximum error of 0.015 bar across the range 0.2 to 2.0 bar of oxygen.

10.2 Warning and Alarm Levels on eCCR models

The two eCCR models, the Incursion and Umbilical rebreathers, have identical electronics and have RS 485 telemetry ports. These ports provide a data stream providing the status and PPO2 levels twice a second. To test the Warning and Alarm levels, appropriate profiles were executed as shown in the images below. All superfluous data was removed from the display.

These profiles were incorporated into the regression suite, that is run on the rebreather controllers daily to ensure that no change or enhancement has a deleterious effect on critical functions.

The Umbilical rebreather has two controllers that are physically identical and independent. Data was captured from left and right controllers separately and then simultaneously from the Umbilical rebreather to ensure there was no interaction at the level where the data is combined for the Dive Supervisor and diver warnings.

As well as tests covering the normal upper and lower oxygen alarms and warnings, a series of tests were carried out to validate the special condition where:

1. the lower oxygen alarm is suppressed when the rebreather is on the surface, and
2. the PPO2 is more than 0.20 atm at 1.0 atm ambient pressure (the 0.20 atm level tracks ambient pressures linearly over the range 0.7 atm to 1.1 atm) and
3. the respiratory rate is zero continuously for more than one minute.

Due to the importance of any alarm suppression function there are three levels of redundancy to detect respiration:

1. the first level is a respiratory sensor in the ALVBOV;
2. if data from that is not available then an estimate is taken from the PPO2 fluctuations;
3. and there is an over-ride that respiration is occurring if there is a a reduction in PPO2 of more than 0.05 atm per minute.

When the respiratory rate is derived from PPO2 fluctuations (breath by breath), the indicated respiratory rate varies erratically around the true rate, but it does quickly and reliably detect that respiration is occurring. For example, at 10 bpm, the reading may vary from zero momentarily, up to 15bpm, or at 16 bpm, it may vary again from momentary readings of zero to 22 bpm. These fluctuations triggers the respiratory alarm indicating failure of the primary respiratory sensor or loss of that signal: the primary sensor is a fast response thermocouple in the actual mouthpiece. These fluctuations also occur in a small ambient temperature dead zone where water temperatures above 31C due to steady state between inhaled and exhaled gas temperatures: again the failure is Fail Safe in indicating a respiratory alarm condition. The fluctuations in PPO2 and the fall in PPO2 over time is used to prevent this condition suppressing the PPO2 alarm.

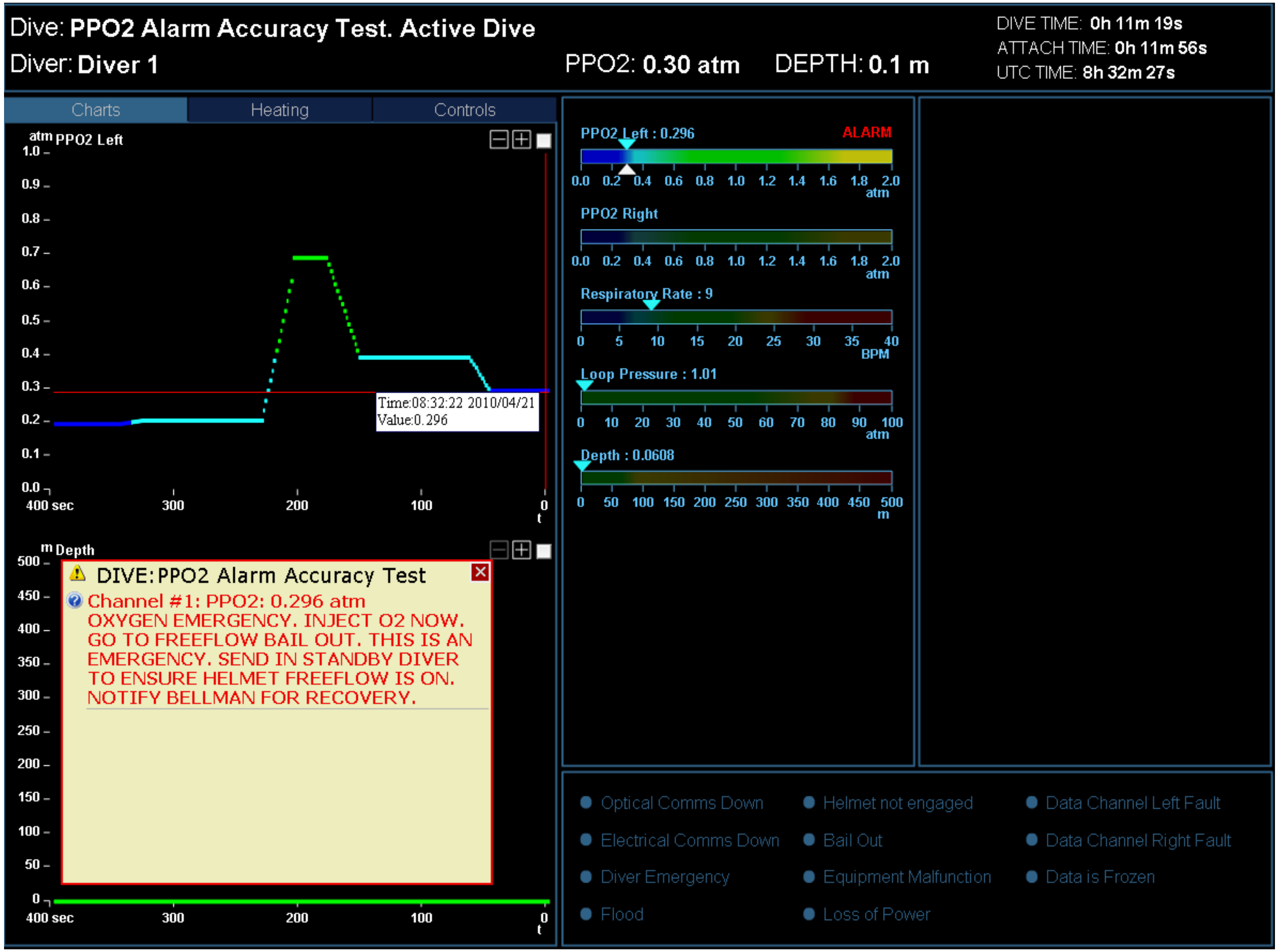


Figure 10-2. Test of Low oxygen alarm level of 0.3 atm. Alarm is triggered immediately because respiration is detected, even at normal atmospheric pressures.

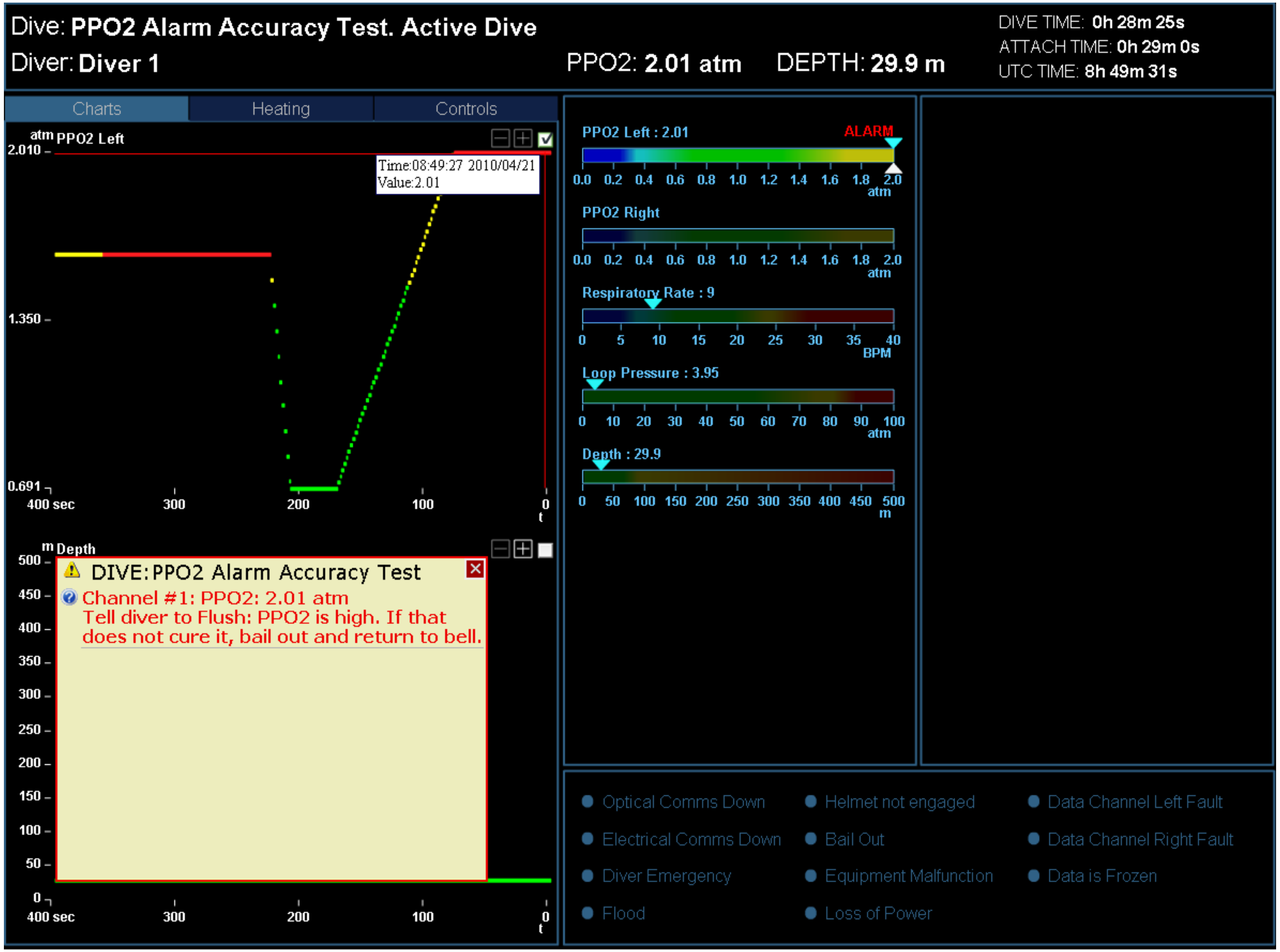


Figure 10-3. Test of high oxygen alarm level of 2 atm. Alarm is triggered immediately.

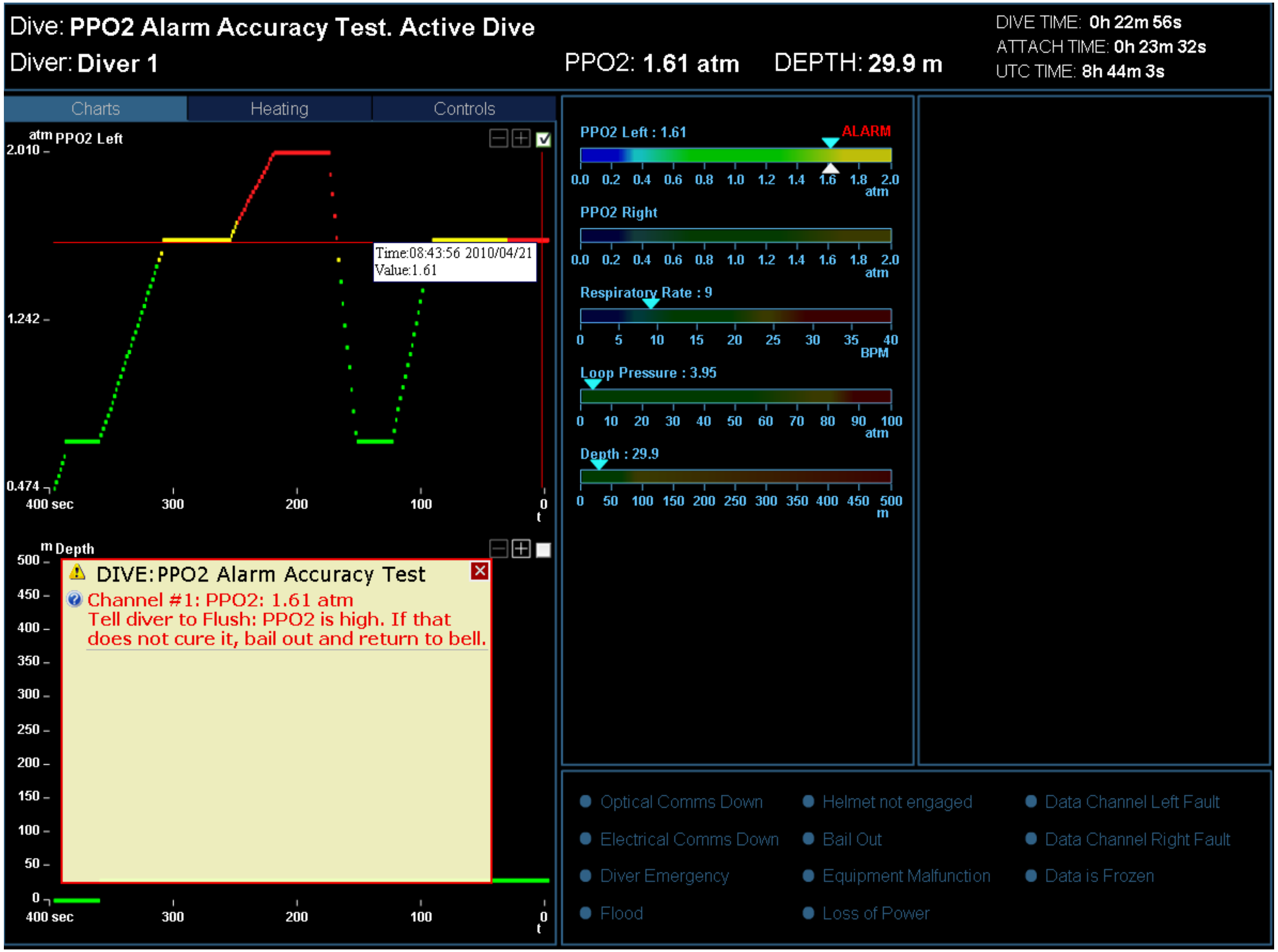


Figure 10-4. Test of high oxygen alarm level of 1.6 atm. Warning is activated at 1.5 atm in accord with Deep Life's Mantis safety requirements and alarm is triggered after one minute above 1.6 atm. See plot of time and alarms at top left.

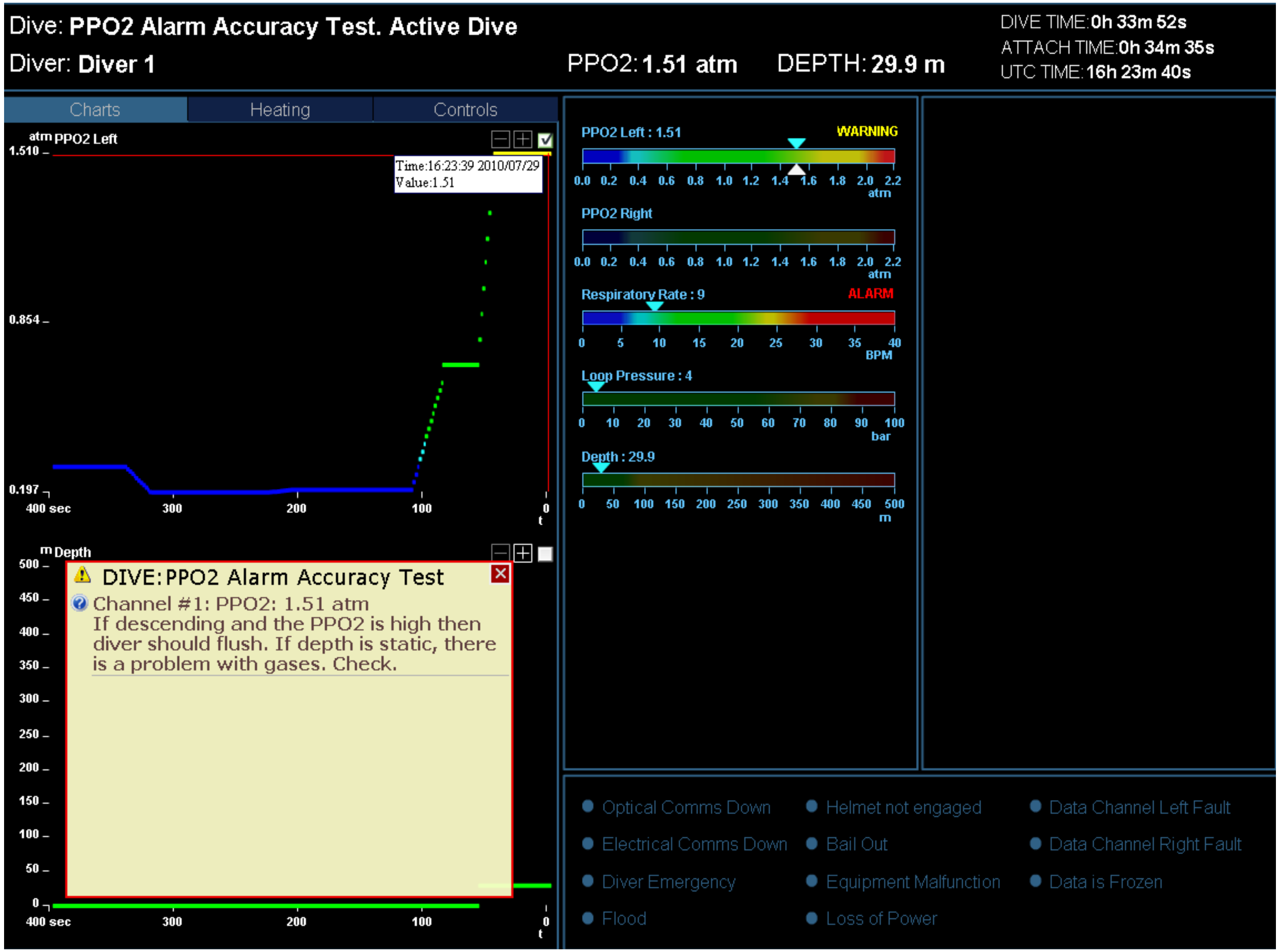


Figure 10-5. Test of high oxygen warning at 1.5 atm. Warning is triggered instantly the 1.5 atm threshold is reached.

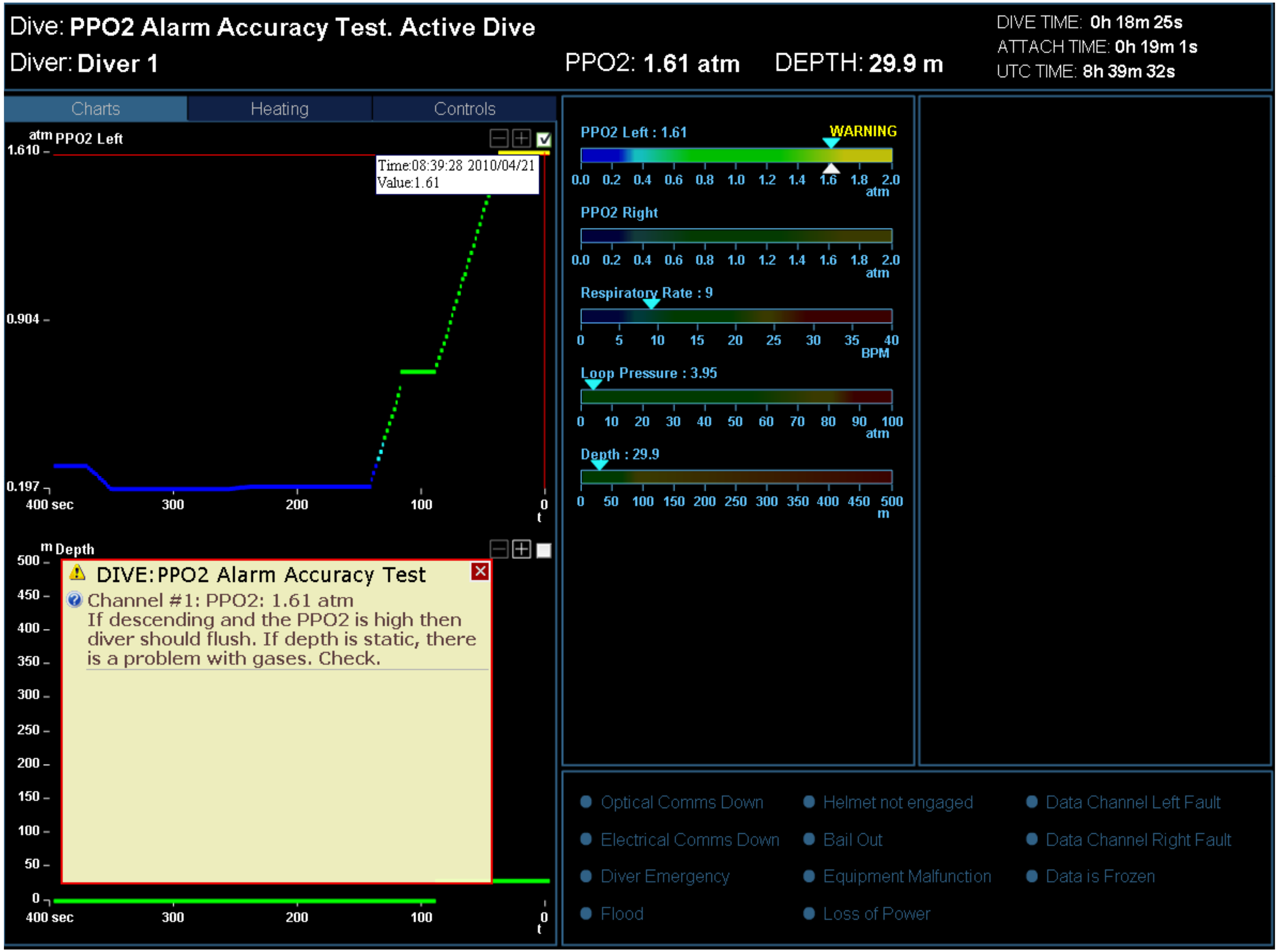


Figure 10-6. Test of EN 14143:2003 requirement for a high oxygen warning level of 1.6 atm. Warning has triggered already because the warning level is 1.5 atm in accord with Deep Life Mantis safety requirements. This complies with the EN 14143 requirement.

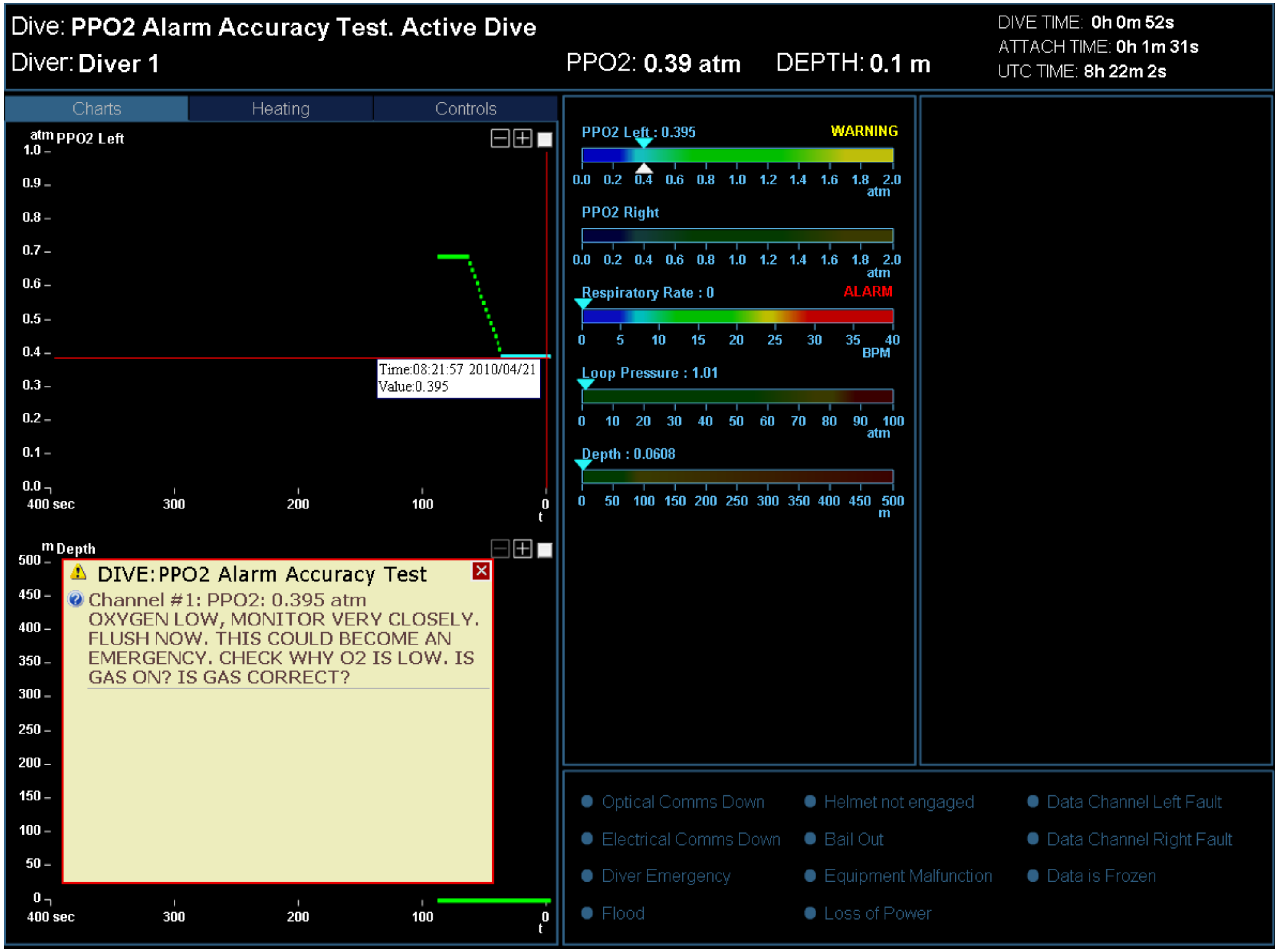


Figure 10-7. Test of low oxygen warning level of 0.4 atm. Warning is triggered immediately.

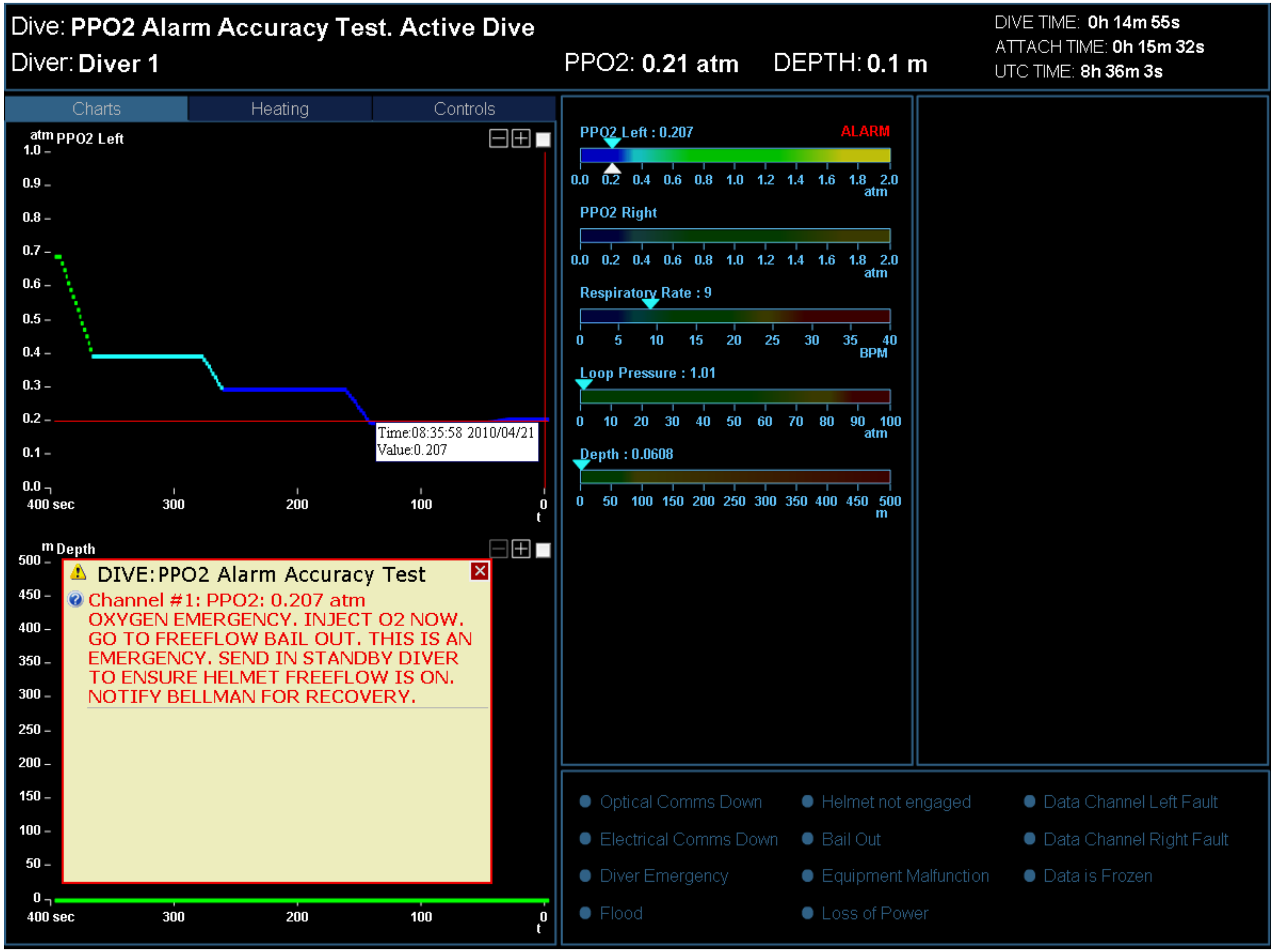


Figure 10-8. Test of low oxygen alarm level of when respiration commences (a level of down to 0.20 atm is permitted only on the surface without alarm if there Is no respiration to avoid spurious alarms when the equipment is in transit, or being set up or serviced). Alarm is triggered immediately respiration is detected.

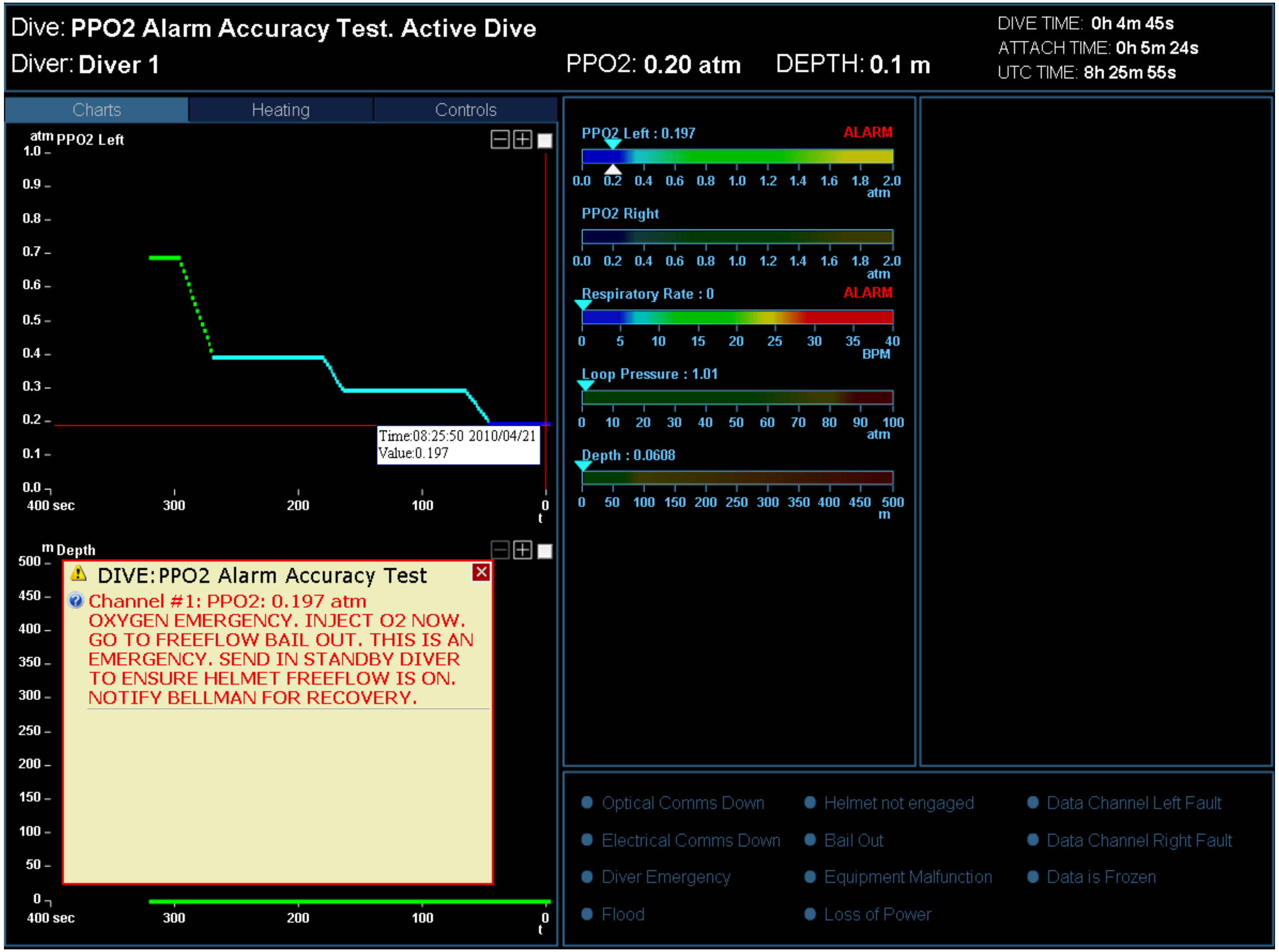


Figure 10-9. Test of low oxygen alarm level of 0.20 atm at normal atmospheric pressure when there is no respiration. Alarm is triggered immediately.

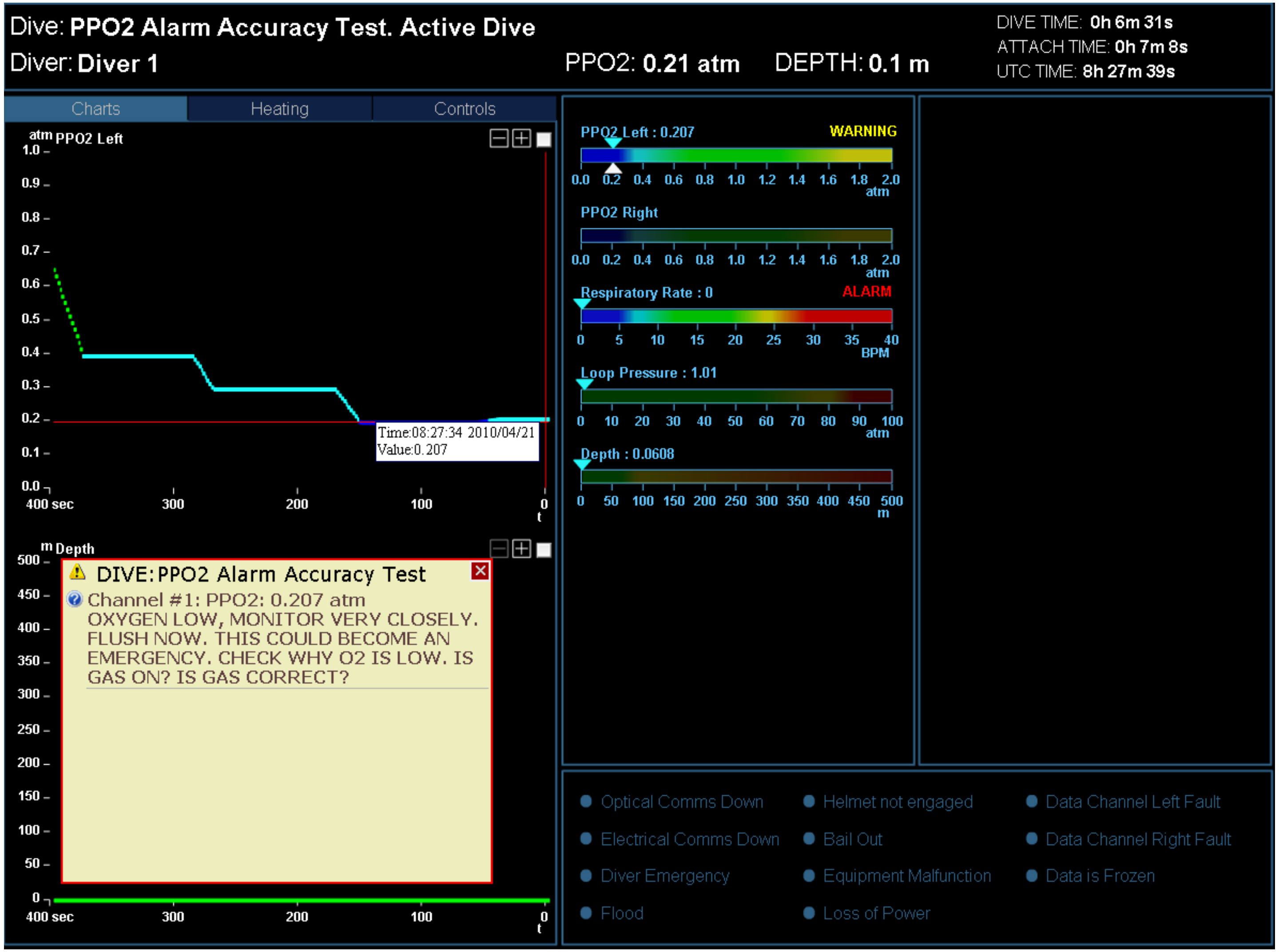


Figure 10-10. Test of low oxygen warning level of 0.3 atm, down to the lower limit of 0.20 atm when there is no respiration at normal atmospheric pressure. Warning is triggered immediately and remains on down to the alarm level of 0.20 atm at 1 atm ambient pressure.

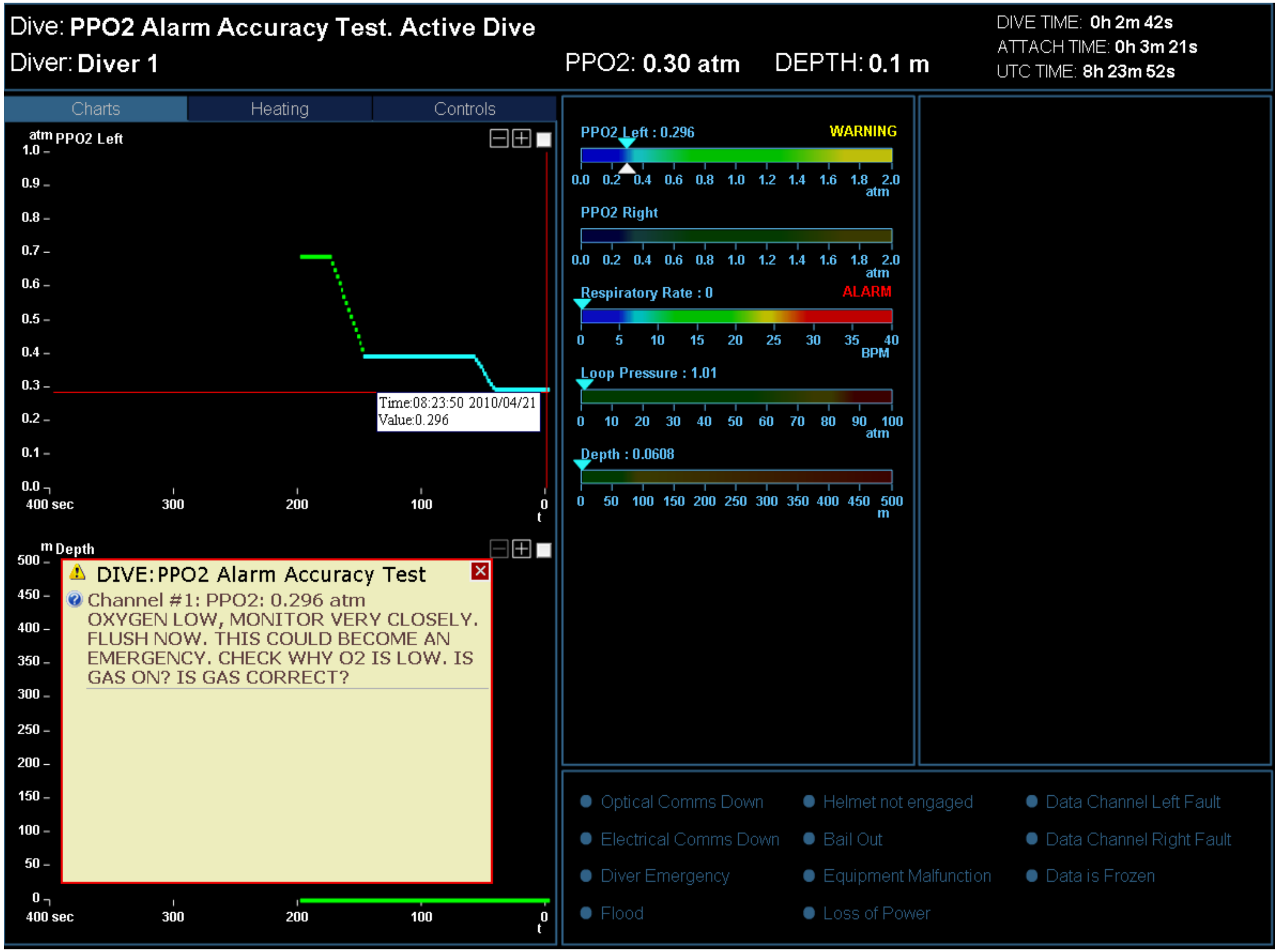


Figure 10-11. Test of upper low oxygen warning level of 0.3 atm when there is no respiration at normal atmospheric pressure. Warning is triggered immediately.

10.3 Accuracy of PPO2 Indicators under Constant Pressure

The test above was repeated using inert gas, first N2 then He, and oxygen was added. Tests were carried out at 8.9 bar for the OR_Apocalypse pods, and 11 bar for the OR_Incursion. The OR_Umbilical is identical to the OR_Incursion.

The test was difficult to perform, but resulted in values within an error band that encompasses the relationship established using pressurisation of the devices using a suitable gas mix.

10.4 Accuracy of Active Warning Devices

The ALVBOV actuated within 4 seconds of the alarm levels being set. It can be seen that the displays trigger at the levels stated in the figures above, which comply with EN 14143:2003. The low PPO2 alarm was tested by pressuring the chamber with N2, and again with He, without changing the PPO2: once the ambient pressure was > 1.089 bar, the alarm was triggered when the PPO2 was below 0.4 atm. Flushing the chamber with 99.998% pure No2 at atmospheric, caused the alarm when PPO2 crossed below the 0.20 atm threshold. An Innovision AMIS 2000 mass spectrometer was used to determine the oxygen concentration during tests with gases other than air.

One ALVBOV developed a fault during the entire sequence of tests, whereby in sudden exposure to cold temperatures (below freezing), it provided a warning that finished with “Bail out now” due to a fault in the assembly of the memory wire actuator. This failure mode was considered at length, and it was concluded by Deep Life and BAI that this was a safe failure mode: the display indicated no dive, the audio alarm indicated no dive. Once equalised at cold temperatures, the ALVBOV operated normally.

The behaviour of the ALVBOV when power is low, is to stop the voice but continue the LED alarms and normal functioning (including the actuator). The ALVBOV provides a “Batter Low” warning followed by “Bail out now”, then actuates the actuator. However, it can then be over-ridden by the diver but the voice annunciation will be off so it is clear the device is not functioning: the diver is conditioned to look to the ALVBOV and expect a voice annunciation of the PPO2 status. This failure mode was considered to be the safest of the possible options.

10.5 Audit of Apocalypse PPO2 Pod Accuracy

A comment appeared in the press from a Belgian competitor, claiming the PPO2 pod observed in Atersee, Austria had a significant error. Deep Life immediately took measures to obtain that pod, and without any update or change, took it to SGS United Kingdom Ltd, and demonstrated it to the Notified Body as an audit check.

The only preparation taken was to calibrate the pod prior to the test, by exposing it to light (i.e. opening it as per the User Manual), near a window in their Bradford office. The test was of the same form as that reported herein, and it demonstrated an accuracy of 0.08% at a PPO2 of 2.019 atm. A 12 point calibration was carried out. At all points the measured error was a small fraction of that allowed by EN 14143:2003. An overall accuracy of +/-0.03 atm is claimed.

The same test was used to demonstrate the ALVBOV limits, and that these confirm to the requirements of EN 14143:2003. The warnings and alarm limits test was also witnessed by the Notified Body.

10.6 Accuracy and Linearity to a PPO2 of 8 bar under simulated dive conditions

The oxygen cells are tested to be linear to a PPO2 of 5 atm (over 5.05 bar) when new and at each service interval. Deep Life have confirmed that the Analytical Industries cells of the Deep Life specification PSR-11-39-DL in a large batch purchased in November 2008 were still linear to 5 bar two years later, in December 2010. A test was made to 8 bar under dive conditions, which revealed further information on the performance of the PPO2 measurement system in the Deep Life Open Revolution rebreathers.

An Incursion model rebreather was fitted with four of the AII PSR-11-39-DL cells, all of which had previously experienced multiple scrubber endurance tests to 100m: this is much more demanding than normal diving conditions because the tests run for 3 hours with rapid compression and decompression from the heliox environment at that depth. The humidity and temperature simulate normal diving conditions, in 4C water.

There are many interesting features on this simulated test dive:

- During this test dive, 3 of the four sensors were extremely accurate, with no material difference between the PPO2 reading and a respiratory mass spectrometer reading, even at 8 bar of O2 (PPO2 of 8 bar[3]).
- The temperature compensation is perfect: there is no temperature error on any sensor, despite the equipment plunging suddenly from a normal room temperature to 4C water temperature, and then being compressed to 100m in helium almost immediately.
- One sensor (Sensor B, Green) suffers a small loss in output gain above 3 bar of PPO2, and then from an end-of-life ceiling fault (current limiting fault), once the PPO2 reaches 4 bar. This dynamics of how that sensor subsequently performs is typical of ceiling faults, including a negative PPO2 output function (falling output with rising PPO2), and sudden steps in its function. The sensor appears to operate completely normally at the PPO2 set point of 1.2 bar, and recovers once the PPO2 in the rebreather is brought back to close to the set point by using simulated metabolism (flushing).
- PPO2 control using the sensor data is extremely good during the periods where the set point control is active (i.e. when the flush rate is sufficient to simulate metabolism), even during the ascent at a rate far greater than a human could survive.
- There is no humidity droop: a common fault whereby poor cell placement or cell type allows a vapour trap or condensation on the cells, such that the PPO2 indicated by the mass spectrometer gradually diverges from that indicated by the rebreather apparatus, with the apparatus reading a lower PPO2 than actual.
- Self-test of the PPO2 monitoring system is highly effective at detecting which cell is the most accurate, and rejecting faulty cells. There are several different minor cell faults that were manifest during this dive, for example, the droop in cell C after 87 minutes.

There is an element of serendipity in these results: out of four sensors, one failed during the test and was rejected, and during the most extreme part of the test there was material differences between the different sensors that was resolved correctly by the sensor fusion algorithm used in these products. However, taking that into account, from the extensive cell testing carried out by Deep Life and BAI, the authors are not aware of any other galvanic PPO2 sensor (oxygen cell) type other then that specified for use in the O.R. rebreathers from Analytical Industries (PSR-11-39-DL) that could perform as well as this or indeed simply pass this testing.

[3] Bar was used for PPO2 in this test, to enable ambient pressure to be plotted on the same scale.

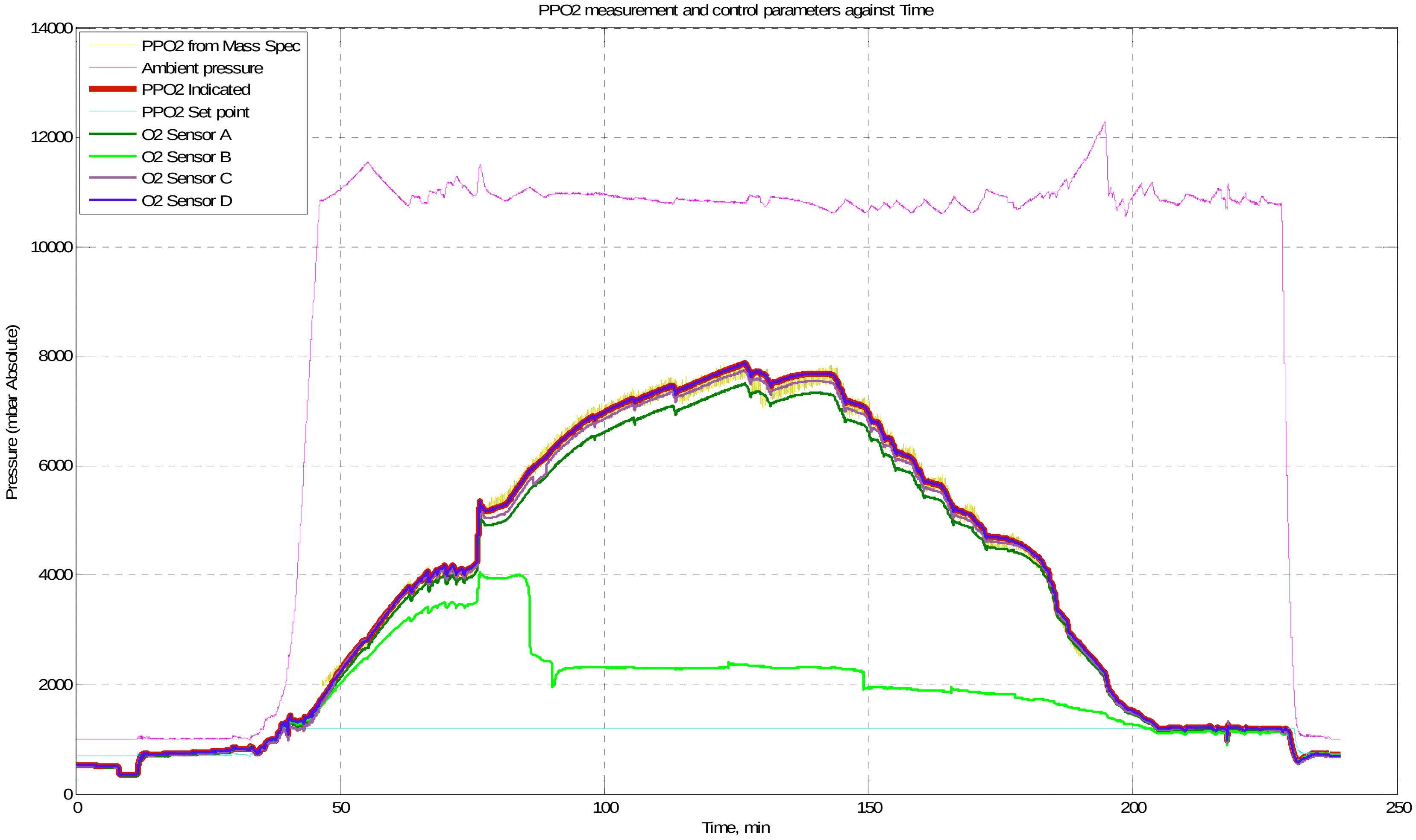


Figure 10-12. 100m test dive of 3 hours bottom time, with PPO2 indicated from four AII cells PSR-11-39-DL compared with mass spec.

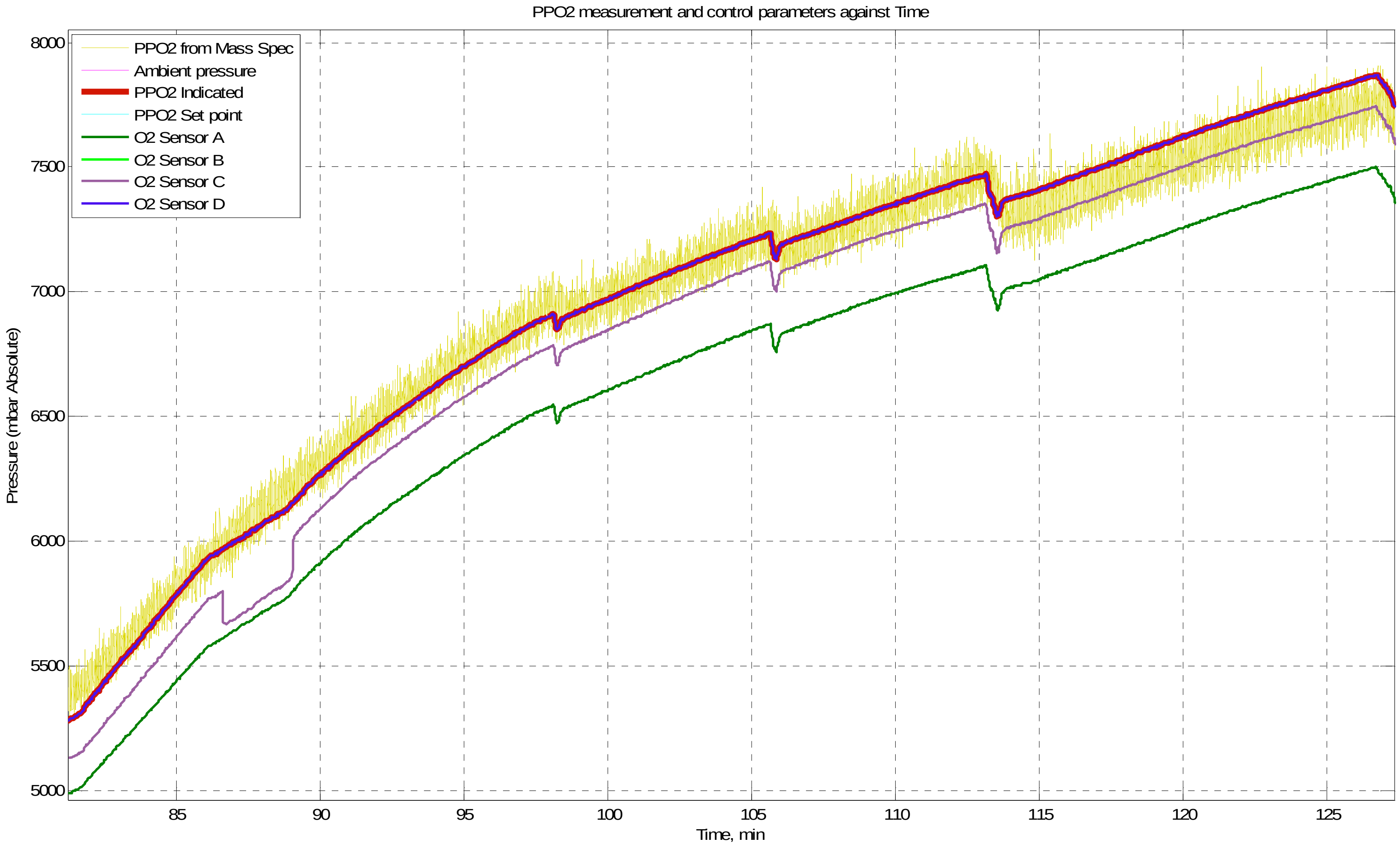


Figure 10-13. Zoom into the top portion of the curve, where the PPO2 was increased to 7.8 bar, The steps in the curves are due to self test movements of the injector. Three out of the four oxygen sensors had reasonable accuracy at this PPO2 level, even though all All sensors were more than 2 years old.

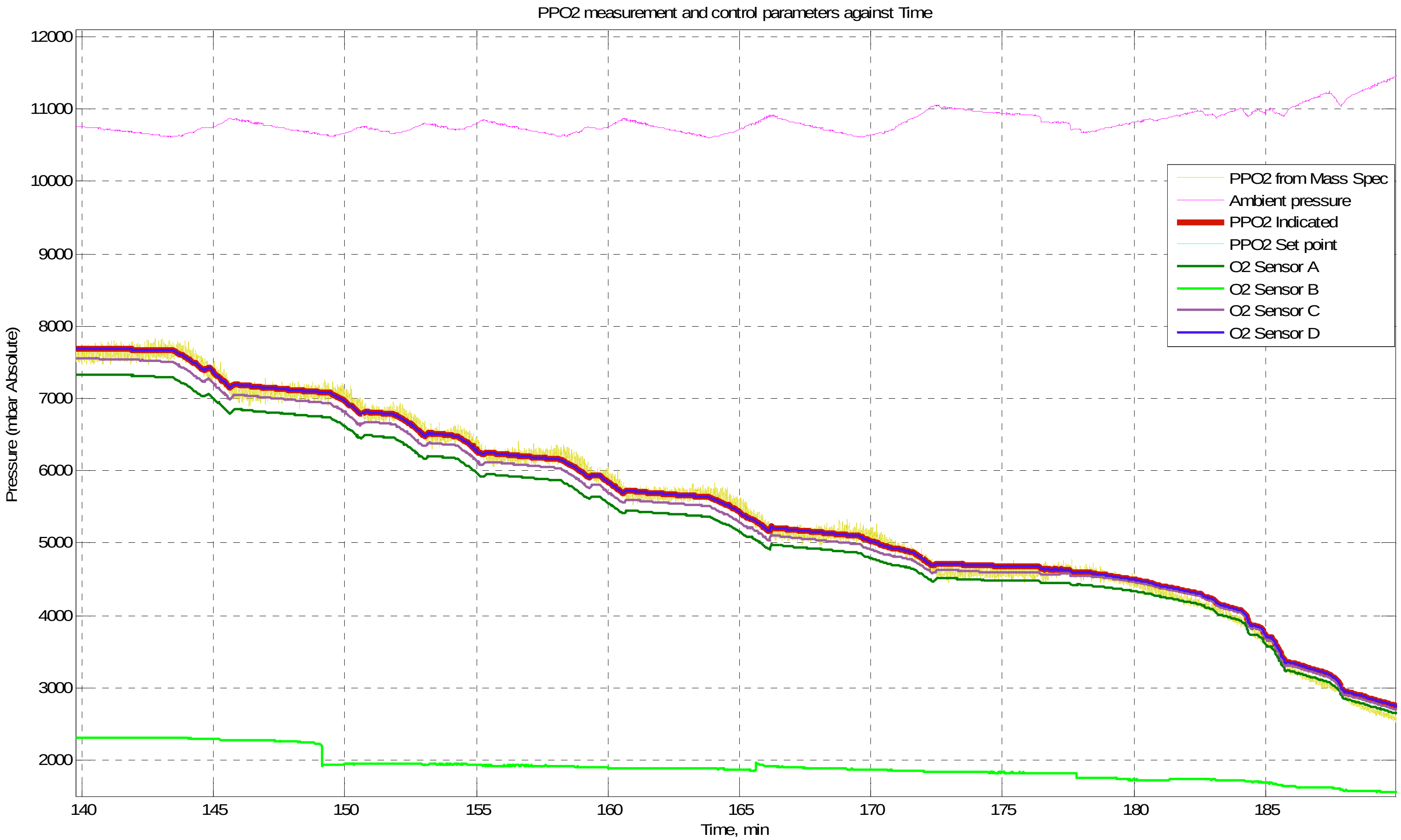


Figure 10-14. Zoom into the portion of the curve during the second part of the dive, where the PPO2 was drops gradually from 7.8 bar to eventually 1.2 bar. There is an excellent correlation with the indicated PPO2 and the actual PPO2 verified on the mass spectrometer.

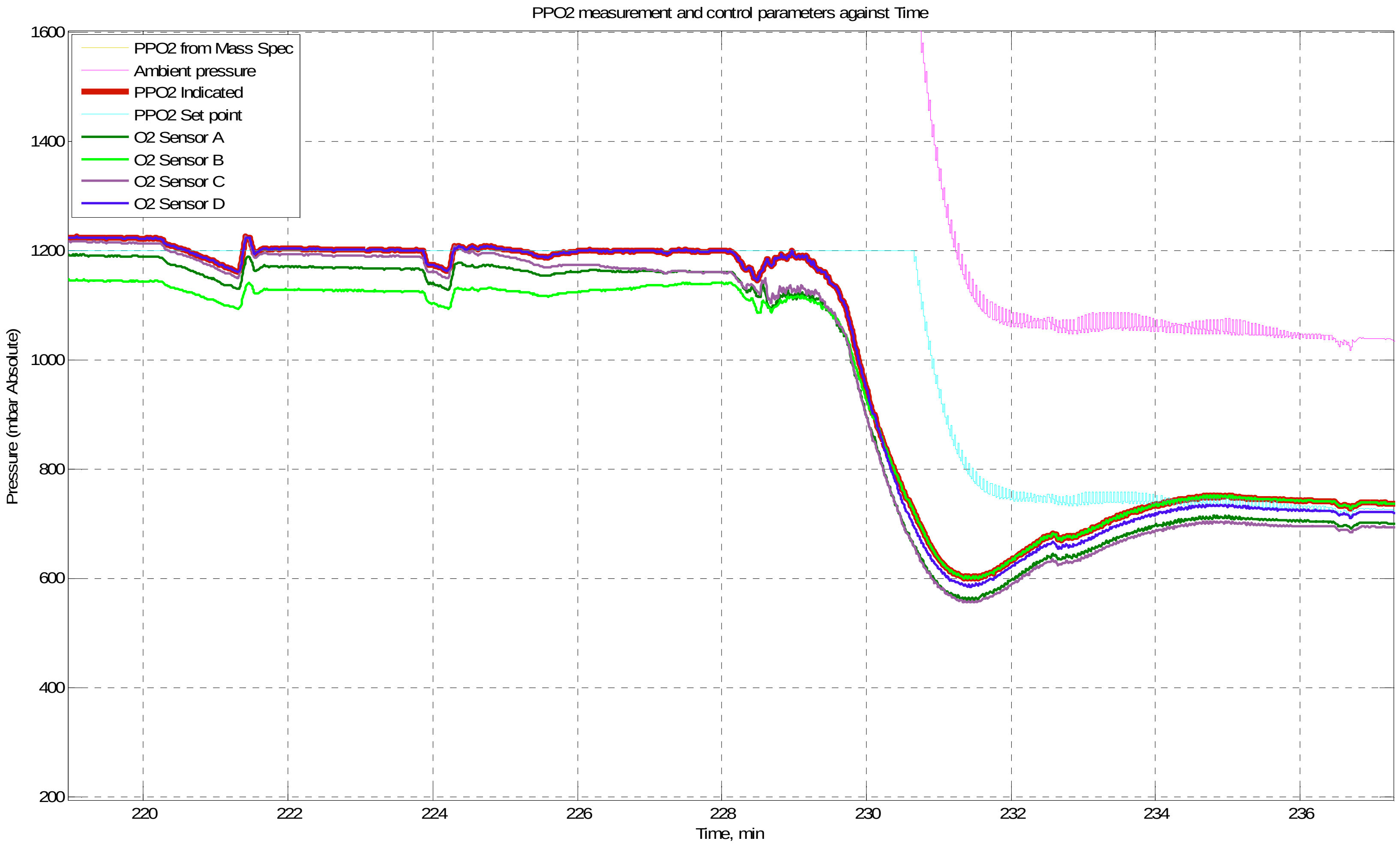


Figure 10-15. Zoom into the final part of the ascent portion of the dive. All sensors are now tracking each other closely, and again the actual PPO2 is indicated very accurately. The PPO2 setpoint reduces automatically in this rebreather from the chosen setting of 1.2bar at depth, to 0.7 at the surface. The PPO2 control is excellent even with this fast ascent rate and low oxygen supplies at this juncture.

11 CONCLUSIONS

The implementations of the above algorithm on both the OR_Apocalypse iCCR and OR eCCRs, comply with the safety requirements, functional requirements and with the EN 14143:2003 compliance requirements. The accuracy, warning and alarms of both the eCCR and iCCR oxygen monitors and active warning devices are within the limits required by EN 14143:2003.

The PPO2 monitors and PPO2 indications are extremely accurate, with a dynamic range that extends up to 8 bar even with cells up to 2 years old in the sample batch using the PSR-11-39-DL Galvanic PPO2 sensors.

The PPO2 monitors and PPO2 indicators manage ceiling failure of individual cells perfectly under the test conditions that were applied.

The All PSR-11-39-DL Galvanic PPO2 sensors (oxygen cells) exceed the performance of all other currently available oxygen cells on the market that are being used in a diving enviroment, based on extensive testing of cells from different manufacturers. The extremes of the conditions used and the limits tested to were considerably more demanding than would be expected to be survivable by a human diver.

The original formal model for sensor compensation neglected the difference between the response of the sensors in isolation and their thermal response when fitted to the application (where they are in a gas stream, and partially in a gas well). The formal model was updated for this effect. The compensation of the oxygen sensors is specified as:

1. PPO2 monitor temperature sensors' values readings taken every 10s shall be averaged for 3 minutes.

2. The averaged value shall be applied to a recursive filter:

   T_sensor_filt = **A***T_sensor_aver + **B *** T_sensor_filt_previously_calculated_value
   Where:
   A = **0.224**
   B = **0.776**
   These values correspond to a time constant of 3.94 samples * 180 seconds = 709.2 seconds

3. The temperature compensation shall be applied for the O2 sensor reading with the 5^{th} order polynom.

   Coeff_compensation = **A***T_sensor_filt^5 + **B*** T_sensor_filt^4 + **C***T_sensor_filt^3 + **D*** T_sensor_filt^2 + **E*** T_sensor_filt + **F**

   Where:

   A = -2.191074E-8

   B = 1.68277635E-6

   C = 1.64589955E-5

   D = -3.54557881E-3

   E = 0.04240762

   F = 1.46239202

   Thus O2 sensor compensated value will be:

   O2_compensated = **Coeff_compensation** * O2_sensor_reading

This formula is expressed as a formal model which acts as the formal specification for the oxygen sensor accuracy in all Deep Life safety systems using galvanic oxyen sensors.

This is a recursive mathematical function: it is implemented directly and not implemented using recursion because recursive calls are not permitted in the code of safety systems (MISRA C, SPARK Ada).