Characterisation of Oxygen Cells for Diving Rebreather Applications:

Sourcing, Performance, Safety and Reliability

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Revision History

Revision	Date	Description
A0 to A13	20th May 2000	Trial Initiation. Report updated every 6 months.
B0 to 2 C0 to C4	12th Feb 2007 29th Mar 2007	Added 2006 and 2007 batch retest data. Teledyne results removed to give opportunity for manufacturer to improve product. Prepared for release. Electrolyte test results included in the disclosure. C2 proof read for release. C3 & C4 includes final feedback from manufacturers
D0	18th June 2009	Teledyne R22D batch F7 test results are added.
E1	23rd Aug 2009	22nd July 2009 E0: Reporting of water entrapment issue, and vapour locking. 23rd Aug 2009 E1: Review and confirmation that all data on samples is present on standard production. Request for confidentiality to be lifted.
E2	17th Dec 2010	Updated fault investigations for cell load failure open, and cell contamination faults.
E3A	7th Jan 2011	Added cell accuracy to PPO2 of 8 bar. Added results from 2nd CO2 tolerance test, with linearity checks to 5 bar. E£A of same date corrected a typo (omission of milli) ad clarified maximum cell potential.
E3B	14th March 2013	Clarifications
E4	15th April 2016	Added explanation of how cells work, after discovery that some manufacturers were not aware of the fact that O2 must flow in and out of the cells freely, and if blocked by water, then the cell will continue to show the same PPO2 as before the water block occurred. See Sections 9.1.1, 9.1.2 and 10.1.8

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1 EXECUTIVE SUMMARY

O2 cells are required for design into rebreathers. A market search was carried out, followed by a formal laboratory and operational test programme to assess their stability, failure modes, shelf life and operating life for use in rebreather designs. The results are published in this report.

A short summary of the results is tabulated below, with cells rated by colour code for quick reference: black is complete failure, red is poor, orange is unsatisfactory, yellow is marginal, blue is acceptable, green is excellent. Where no test was carried out, or the value is simply being reported from tests without any good or bad outcome, the cell is white. The values of the cells contain the summary data. All conclusions are in respect of use for diving rebreather applications.

Manufacturer	Insovt	Analytical Industries	Analytical Industries	Teledyne	Teledyne
Sensor Model	DK-32	PSR-11-39-MD	PSR-11-39-MDR	R10, R17D, R22D Pre-F7, R22-2BUD	R22D-F7 Batch
Dimensions	Within limits defined	Within limits defined	Within limits defined	Within limits defined	Within limits defined
Median Output in air	5mV	11.9mV	4.5mV	11mV	10.0mV
Quality	Extremely narrow statistical spread. Adequate QA but error in internal circuit identified: resolved.	Consistent. Narrow statistical spread. Excellent QA in evidence. All samples complied with datasheet.	Consistent. Narrow statistical spread. Excellent QA in evidence. All samples complied with datasheet.	Not published as R22D-F7 sensors address the issues found. Significant problems were found with shock resistance with pre-F7 sensors.	Consistent. Narrow statistical spread. Excellent QA in evidence. All samples complied with datasheet.
Consistency	Excellent	Excellent	Excellent		Excellent
Connector improvement	Wire termination. Willing to adopt SMB.	Available.	Available		Are adopting SMB.
Sensor Life	All operated beyond 5 year life. No damage from tests.	18 months in dive applications.	2 years in dive applications.		18 months in dive applications
Error in temperature compensation	Miswired inside sensor	0.72 mV/60C	Digital Temp compensation extremely accurate. See DV_PPO2_Device_Accuracy_110105.pdf		Large errors. Devices pass only because no temperature compensation is fitted to DL sensors: DL

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					use digital compensation.
Linearity Error (PPO2 from 0.21 to 1.0)	-2%	-2.26%	0.08% error at 2 bar. Linear to 8 bar in DL model.		Time lag in sensor, thermal related
O2 materials compatibility	All pass	All pass	All pass		All pass
Hydrophobic membrane	Present	Present	Present		Present
Response time	20s rise, 25s fall	6s rise / 8s fall	6s rise / 8s fall		6s rise / 8s fall
Temperature range tested.	20C to 90C	20C to 90C	20C to 90C		20C to 90C
Stability with time	No drift	No drift	No drift		No drift
Shock	Pass	Original samples failed test. Manufacturer addressed this by design improvements. Improved sensors pass.	Same improvement as PSR-11-39-MD. Passes in –DL model.		Initial Pass but gradual failure within 6 months. Treated as a pass.
He susceptibility	Pass	Pass	Pass		Pass
Fast Decompression	Pass	Pass but changes observed	Pass but changes observed		Pass but changes observed
Chamber Lockout (Torpedo test)	Pass	Reversed polarity. 2 days to recover.	Reversed polarity. 2 days to recover.		Not performed. Previous batches passed.
Short-term CO2 susceptibility	No effect	200uV offset. Passed tests with 100% CO2 exposure for 24 hours: cells linear to > 5 bar following test.	190uV offset		190uV offset
Application test	Works but slow response	Good, except water collected on face. Membrane needs to be	Good, except water collected on face. Membrane needs to be		Good, except water collected on face. Membrane needs to be

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		flush.	**flush.**		**flush.**
Life test	**All still working after 5 years. Non-accelerated.**	**Passed accelerated and non-accelerated test**	**Passed accelerated and non-accelerated test**		**Passed accelerated test**
Electrolyte Loss (Stimulated fault)	**Increase in output voltage, reduction in capacitive impedance then fail low**	**Increase in output voltage, reduction in capacitive impedance then fail low**	**Increase in output voltage, reduction in capacitive impedance, then fail low**		**Increase in output voltage, reduction in capacitive impedance then fail low**
Storage test	**All pass 5 year test. Non-accelerated.**	**Passed accelerated test. Passed non-accelerated test.**	**Passed accelerated test. Passed non-accelerated test.**		**Passed accelerated test**
Offgassing	**No offgassing**	**No offgassing**	**No offgassing**		**No offgassing**
Marking	**Willing to mark date in large print**	**Correctly marked in –DL model**	**Correctly marked in –DL model**		**Needs to mark date in large print**
Cost	**2 x A, reducing to A**	**A**	**A**		**-**
Overall Suitability (Lowest mark)	**1**	**4**	**4, and 4.6 in the –DL model**		**4**
Weakest Area	**Slow response**	**Shock resilience**	**Shock resilience**		**Long term shock resilience, Thermal compensation**

Smaller batches were also tested of the PSR 11-33-NM sensor and a sample of the Teledyne R17D, and R22-A. Larger batches of these models would be needed for firm conclusions to be drawn, but from the data available:

1. The PSR 11-33-NM appears to be comparable to its Teledyne R10D equivalent, other than the PSR sensor appearing to have a higher level of quality control.
2. The R17D appears to be same as the R22-2BUD and R22-D other than having a different socket (a nickel plated audio jack socket instead of Molex pins). The R22-A is the same as the R22-D but without a membrane cover.

Teledyne R22-2BUD2, R22-D, R17-D and R22-A Sensors prior to June 2007 These were tested extensively, but found to be unsuitable for diving applications due to shock sensitivity and organic contamination giving unpredictable sensor life. The test results have been supplied to the manufacturer and was used as the basis for product improvements below.

Teledyne R22-F7 (i.e. July 2007) Sensors were found to be a good quality product suitable for dive applications subject to the modifications in the DL procurement specification (SMB

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socket, no well or outer case, electrical batch code, no temperature compensation, improved labeling, mechanical robustness). The standard sensor failed on the temperature compensation: external temperature compensation is required to ensure the temperature indicated by the sensor matches that internal to the cell and not the surface of the cell. Changes to packaging are proposed to improve resistance to water and vapour locking. Shock resilience is good in the very short term, but poor medium term.

It was concluded that the Analytical Industries PSR-11-33 and PSR-11-39 sensors are a good quality product suitable for rebreather applications, particularly the PSR-11-39- DL model as they has a suitable connector and can only fail low, as well as an absence of vapour traps. This particular sensor requires external temperature compensation and load testing to realise its benefits. For simple plug and go applications, the PSR-11-39-DC (DL with an SMB socket, no outer case, no temperature compensation, electrical batch coding), is a suitable sensor. **Analytical Industries are labelling the compensated sensor, with the improvements identified herein, the PSR-11-39-DC and the non-compensated sensor the PSR-11-39-DL.**

It was concluded the Insovt sensors are an excellent product but the slow response time precludes their use in rebreathers.

Sensors from other companies were also tested, but failed basic tests so were eliminated from the study early on. If this study is re-run, sensors from Maxtec and IT/Wismar should be included as these may have improved since the initial screening was carried out for this study in 2000 and 2001. There is a concern that the conclusion is tending towards a single vendor and efforts should be applied to qualify a second source of sensors for dive applications using the methods described herein.

Due to the long period of the study, fresh batches of sensors of each group were procured at the end of the study, in 2006, 2007 and 2009, and their key features retested. Where the new product showed improvements compared to previous batches, and the manufacturer confirmed this was due to product improvements that do not affect operating life or storage life, then the new results are published instead of those from the earlier batch.

2 SCOPE

This document reports a trial and study of oxygen sensors for diving rebreather applications.

3 PURPOSE

The purpose of the trials and study reported in this document is to determine:

1. Suitable vendor(s) and model of PPO2 cells for a diving rebreather.
2. All failure modes, for each sensor.
3. Failure probabilities for each mode, for each sensor.
4. Detailed performance characteristics of each sensor.

The number of sensors required to determine reliability is normally very large. In this study, batches were of 12 sensors of each type, to verify the data issued by the manufacturer based on a very much larger population. Within each batch, formal testing was carried out to identify the failure modes, as well as a literature search for different modes. Attempts were then made to reproduce those modes by reproducing appropriate environmental conditions.

The study worked with those sensor manufacturers that were willing to improve their performance in a rebreather environment. Where the manufacturer improved the product as a result of the test results, it is the improved version that is reported here.

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4 APPLICABLE STANDARDS

- EN14143:2003
- EN61508 (as a component in SIL 2 and SIL 3 systems)
- NORSOK U-101, and U100

5 ABBREVIATIONS

ATM: mean atmospheric pressure at sea level, 1.013bar

CCR: Closed Circuit Rebreather

DL: Deep Life Ltd

ESD: Electro-Static Discharge

KOH: Potassium Hydroxide, a very caustic compound used as an electrolyte in O2 cells

PPO2: Partial Pressure of Oxygen

RHIB: Rigid Hull Inflatable Boat

6 REQUIREMENT SPECIFICATION

Rebreather applications place the following demands on an oxygen sensor.:

- Linear within 1% over PPO2 range from 0.1 to 2.0, and within 0.5% over range of 0.21 to 1.4
- Maximum size is 50mm high and 33mm wide, except for within 6mm of the socket, where the maximum width is 17mm. This is to allow it to be fitted to DL designed electronics.
- Conformal coating of the internal pcb as a minimum.
- Hydrophobic front membrane without any well around the membrane that may trap water or vapour.
- Consistent performance from sensor to sensor.
- Resistance to shock in a dive environment, such as by transport on an RHIB, measured using twenty 1.5m and 3m drop tests.
- Connector must be reliable. This is ideally a male SMB coax connector. Sensors can be tested with a Molex 2 or 3 pin connector, but then arrangements made with the vendor to install an SMB connector for production quantities. The Molex connector is not suitable for life critical applications.
- Maximum response time to 90% of final value of under 10 seconds, measured by moving a sensor from pure O2 at 1ATM to air at 1ATM at room temperature (Requirement added May 06).
- If the temperature compensation is integral to the sensor, then it must provide temperature equalisation to within 3% over the whole operating temperature range.
- Operable in 10% to 100% relative humidity, non-condensing (condensing is treated separately, with hydrophobic membrane, water trap and immersion requirements).
- Should not be damaged by short term immersion in salt water.
- Operating temperature range 4℃ to 50℃, and no da mage at up to 90℃. This requirement is due to warm exhaust from scrubber, when pre-breathed after storage in a tropical environment.

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- Storage temperature range -30℃ to +90℃. Note th at EN14143:2003 requires -30C to +70℃ storage and -20C to 50C operating temperatures. but there are plausible circumstances where the temperature can rise about +90℃, such as if the equipment is left in a car in a hot desert climate, or during shipment of the sensor, if it is left in an aluminium air crate awaiting loading onto the aircraft in a subtropical climate. A minimum upper temperature limit is 50C: the CE EN 14143:2003 operating requirement.
- Should not be damaged by chamber lockout processes.
- Output should not change in the presence of helium or nitrogen mixes, subject to PPO2 being constant.
- Should not be damaged by short term exposure to CO2.
- Low cost, suitable for medium volume applications.
- Traceable QA system in place (ISO 9000 or equivalent).
- Devices must be serial numbered, including a batch number, and clearly labeled with the date of manufacture.
- A detailed procurement specification with other features, including packaging, marking, sealing with a gel on the rear face, connectors and batch load resistance coding is provided to each manufacturer who's sensors achieve a grade of 4 or more here, for production procurement purposes.

7 TYPES OF O2 SENSOR

There are eight types of O2 sensor available:

1. Paramagnetic. These are bench instruments which depend on the orientation of the magnetic field in relation to gravitation field, so are not suitable for use in rebreathers.
2. Sol-gel fluorescence. These do not respond to PPO2s above 1.0: they detect the absence of oxygen rather than the presence of oxygen. Sol-gel sensors are used as an hypoxia warning sensor by Deep Life Ltd, for dive applications.
3. Gas Spectrographic. Gas spectroscopic and chromascopic analysers are large with high power consumption and unsuitable for use in a rebreather. Gas spectrometers are used with saturation dive systems to analyse the chamber gas via sample lines.
4. Mass Spectrometry. This is too large and expensive for rebreather applications. Mass spectrometry is used as a reference measurement by BAI and Deep Life for oxygen measurements for test purposes.
5. Heated zirconia. These are very accurate and high speed sensors, using two Zr)2 discs with a small hermetically sealed chamber in between. Once of the discs functions as a reversible oxygen pump, which is used to successively and empty the chamber. The second disc measures the ratio of the partial pressure difference and generate a corresponding voltage. Unfortunately these zirconia sensors are not suitable for dive applications because helium gradually leaks into the heated chamber, severely affecting the response of the sensor. The sensing chamber is maintained at 700C in the Honeywell KGZ-10 Series sensors, though some micro-machined zirconia sensors are available using a 350C heater. Helium affects the temperature that can be obtained for a given power dramatically.
6. UHP Pico Ion, used by Analytical Industries for very low O2 levels
7. Galvanic. These are micro fuel cells, derived from NASA work on powering space craft. It is galvanic cells that are used in all rebreathers to measure PPO2.
8. Laser absorption. These suffer spectral spreading with depth and in noble gases, as well as being power hungry.

This study focuses exclusively on galvanic oxygen cells.

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8 SOURCES OF GALVANIC O2 CELLS

Table 1: Companies manufacturing galvanic O2 cells (bold) and branding

1. **Alphasense UK**
2. Alphamed
3. Ametek
4. **Analytical Industries (USA(**
5. Analox
6. Atom
7. BCI
8. BMD
9. BCI
10. BMD
11. Bertucci
12. BIO MS
13. BioMed
14. Bio-Tek
15. Biotest
16. Bird
17. BMD
18. Burke & Burke
19. Caradyne
20. Catalyst Res. (See MSA)
21. Ceramatec (See Maxtec)
22. Cheiron
23. CIG Healthcare
24. City Technologies
25. CR
26. Criticare Systems
27. Critikon
28. Dameca
29. Datascope
30. Datex Ohmeda (GE)
31. Diversified Diag.
32. DP Medical
33. Drager
34. Drager (North America)
35. Emerson
36. Engstrom (Datex)
37. EnviteC
38. F. Stephan
39. Fresenius
40. Hamilton
41. Henleys
42. Hewlett Packard
43. Heyer
44. Hill-Rom AS
45. HP
46. Hudson RCI / Ventronics
47. Imed
48. Infrasonics
49. Inmed
50. International Tech
51. **Insovt (Russia)**
52. **IT/Wismar (Germany)**
53. Ivac
54. Libra
55. Lifecare
56. Marquette/ Hellige/ GE
57. **Maxtec (USA)**
58. Medigas
59. Megamed
60. MSA
61. NarkedAt90
62. Newport Medical
63. Nivaco
64. Norco Med
65. Novametrics
66. Ohmeda (Datex)
67. Omni (See IT/Wismar)
68. Oxyquip
69. Oxitron
70. Pacifitech
71. Patient Tech
72. PPG
73. PPG Hellige
74. Prolab
75. Puritan Bennet
76. Respironics
77. Schoch
78. Sechrist
79. Sensor Tech
80. Shock
81. Siemens
82. Spacelabs
83. Sun Medical
84. Taema (France)
85. **Teledyne (USA)**
86. Toptronics
87. Vandergraph UK
88. Ventronics (See Hudson)
89. Vickers
90. VTI
91. Wardray Premis

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Eighty-eight (88) companies brand or claim to manufacture galvanic O2 cells. These are listed in Table 1 above. The reality appears to be that there are around 6 to 8 actually manufacturing their own sensors; the remainder appear to buy their sensors from one of these sources and brand label them.

Of these manufacturing companies, only three appear to produce sensors suitable for dive applications: Teledyne, Insovt and Analytical Industries[1]. This assessment is based on reports of the reliability of the vendor's product, and an initial screen test to determine their resistance to moisture, pressure and degree of temperature compensation. This is a broad brush assessment based on what is used in rebreathers in different parts of the world, a scan over web sites of the above companies and removal of some companies from the list based on persistent issues raised in public internet forums.

Galvanic O2 cells are produced for four main applications:

1. Process Industries: brewing, industrial chemistry, petrochemical, welding etc
2. Aviation: monitoring of cabin PPO2
3. Medical: monitoring of patient or specimen respiratory O2
4. Diving: monitoring of diver PPO2

The detailed characterisation described in this report is specific to the use of O2 cells for diving applications, in a rebreather or diving PPO2 monitor.

The initial screening of suppliers was carried out in the year 2000. Reconsideration of IT/Wismar and Maxtec sensors would be made if this study were to be repeated.

For this study, batches of the following sensors were procured, and tested.

1. Analytical Industries PSR 11-33-NM
2. Analytical Industries PSR 11-39-MD
3. Analytical Industries PSR 11-39-MDR
4. Analytical Industries PSR 11-39-DL
5. Teledyne R22-2BUD
6. Teledyne R22-D
7. Teledyne R22-A
8. Teledyne R17-D
9. Insovt ДК-32

The tests took up to five years per model of sensor, as this is the rated operating life of the Insovt sensor.

Late into the study a PSR-11-33-NM was also obtained and examined: use of that sensor would have to rely heavily on NEDU testing due to the available time.

9 CONSTRUCTION OF GALVANIC OXYGEN CELLS

Before embarking on the test programme, the design and construction of the sensors was studied carefully, and the manufacturers questioned extensively (in the case of Teledyne, their representatives). The purpose of this was to gain the benefit of the manufacturer's experience of their failure modes and ensure the test regime was a reasonable one in checking their performance against the requirements for dive applications.

9.1 Principle of Operation

The galvanic oxygen sensor is a battery that uses oxygen to oxidise lead to produce a voltage with a source impedance of several kilo ohms: as it is virtually DC, this is the same as resistance.

[1] City Industries's sensors may be suitable for diving: they will be included into the next round of tests.

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The chemistry, construction and safety of the sensors are described in literature from their manufacturers. Examples include (Internet links are provided to the document in the text in blue):

Advanced Instruments, Inc. at http://www.aii1.com/ give the chemical reactions in the cell, their limitations, stability and tradeoff of response time to cell life.

http://www.btinternet.com/~madmole/DiverMole/lauer.pdf General Information on the workings of Oxygen Fuel cells

http://www.electricfilm.com/HH_manual_30.PDF on failure modes observed by another vendor of CCR controllers.

Should any of these sites change the material, the documents can be found by entering the above link addresses to the Internet archive at www.archive.org.

In 2016, the editor to this FMECA became aware that some rebreather manufacturers did NOT know the following facts about oxygen cells. The following has been added to this document, and also further information in the Water Blocks later in this document to disseminate this key information.

9.1.1 Principles of the Galvanic Oxygen Sensor

The galvanic fuel cell sensor is an electrochemical transducer that generates a current (µA) signal output that is both proportional and linear to the partial pressure of oxygen in the sample gas.
Oxygen diffuses freely IN and OUT through the front sensing membrane of the oxygen sensor so the concentration of oxygen in the sensor is the same as the concentration in the surrounding gas. A tiny portion of the oxygen molecules that enter the sensor come into contact with the cathode where it is reduced by electrons furnished by the simultaneous oxidation of the anode. The flow of electrons from anode to cathode via the external circuit results in a measurable current proportional to the partial pressure of oxygen (PPO_2). The sensor has an inherent absolute zero, therefore, if there is no oxygen present the output is zero.

9.1.2 Demonstration that Cells MUST be allowed to "breathe" in and out

The essential operation can be demonstrated by allowing water to cover a cell membrane. An O2 sensor tolerates small droplets of water on the sensing membrane. If the membrane is covered with water then oxygen molecules cannot get in or out of the sensor. This true of all gas sensors that have membranes.

If a galvanic oxygen sensor is covered with water, its output will "freeze": the sensor will produce the same output as before the water covered the membrane. The consumption of oxygen by the sensor is so low, that the PO2 output will drop by less than 1% per minute when in this frozen state. There is no damage to the sensor: once the water is removed, after a short period of time, the sensor will operate normally.

For example, if the sensor was in pure oxygen showing a PO2 of 1.0, then water is allowed to cover the membrane, it will keep producing an output showing a PO2 of 1.0 even if it is then moved to air where the PO2 is 0.21 bar. If the water is shaken off, after a few minutes the sensor will show a PO2 of 0.21 and respond in seconds to changes in the gas environment.

In a rebreather, if water is covering the membrane then the displayed PO2 will be unrelated to the actual PO2 of the breathing gas. This is an extremely hazardous condition in a rebreather that can result in either hypoxia or hyperoxia, depending on what the cell output was when the water covered the membrane. It is an essential duty of the rebreather designer to ensure that water can never cover the sensor membrane at any time.

The membrane on rebreather oxygen sensors is hydrophobic but remember that when scrubber salts are dissolved into water, the liquid may not run off even a vertical hydrophobic membrane. The possibility of this occurring depends on the specific rebreather design, so should be taken into account by the rebreather manufacturer.

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9.2 Differences in Construction Amongst Galvanic O2 Cells

There are very important, albeit subtle, differences in construction between the various vendors. Some of these are a result of the tradeoffs in design; some are due to refinement of the sensor to improve reliability.

In design, the primary trade-off is response time versus sensor life: this is determined by the thickness of the Teflon membrane at the sensor face. There are also fundamental distinctions between sensors designed to detect ppm O2 levels and percentage O2 (the former having a lot of electrolyte and a small anode, the latter having little electrolyte and a large anode). The Insovt has a large reservoir of KOH solution to prevent the sensor drying out and a moulded front which gives better mechanical protection than on other sensors.

In design for reliability, Analytical Industries identified organic contaminants as the primary reason for production yield issues and for cell drift. As a consequence their cell does not use epoxy resins, soldering or welding (to eliminate fluxes and ensure even plating).

In another example of the differences in construction, the Teledyne sensors are liable to rear membrane failure and to pressure lifting the hydrophobic membrane (Zitex or Teflon). Analytical Industries and Insovt did not exhibit these rear membrane problems.

A third area where design differences are apparent is the method used to prevent off-gassing lifting the front membrane on the sensor. Insovt divide the sensor face into small areas and protect the sensor face from lifting using a clear potting process to give a cover. The approach in Analytical Industries and Teledyne is to protect the face using a screen sandwiched between hydrophobic membranes.

Cells which produce a higher output, due the internal load resistor having a higher value, will fail earlier due to electrolytic transfer of material inside the sensor. Some sensors have an output as high as 32mV, others as low as 4.5mV in air. This study uses low and medium output sensors for the longest operating life.

The sensor chamber must be absolutely free of organic contamination. The ability of different companies' processes to achieve that is a further differentiator.

Other differences can be found in the cell housing material (potted for Insovt and High Density Polyethelyne for Analytical Industries).

These differences give rise to the difference in results and also in the quality level each company can support.

10 SENSOR FAILURE MODES

10.1 Failure Modes Common to all Galvanic O2 cells

10.1.1 Ceiling or Current Limiting

This is the normal end of life failure mode for cells, and the mechanisms behind it are usually consumption of the lead anode or cathode contamination below, though other failure modes have the same effect.

There is a good example of a ceiling fault occurring during a dive in Section 19.8.3 of this report.

Some of the key features to note for ceiling faults are:

1. They can occur suddenly and without warning
2. The reduction in the PPO2 ceiling can be very large
3. The reductions can occur in large steps

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4. When the PPO2 is above the ceiling, the sensor can display a mild negative characteristic, i.e. increases in PPO2 cause a reduction in output voltage. This can cause interesting behaviour in badly designed eCCR PPO2 controllers.
5. The ceiling can rise temporarily.

10.1.2 Drying Out

Unused sensors in storage will fail eventually due to the water carrying the KOH electrolyte evaporating. This results in a zero output from the sensor. This fault is predictable. It can be eliminated by the manufacturer determining the rate of evaporation and amount of electrolyte in reserve, then calculating the shelf life. For example AI both states a 60 month life for their sensors with a 6 month shelf life. This is specific to the packaging: if the package is opened then the stated shelf life no longer applies, but the sensor service life then comes into effect.

The maximum life of a sensor is the maximum of the service life and the operating life. For example, if the Insovt sensor with a 5 year shelf life and 2 year operating life is stored for 4 years before being opened and used, then it must be discarded after one year.

10.1.3 Consumption of the lead anode

Exhaustion of the anode surface occurs because the reaction consumes the lead anode in the presence of O2. The result is an increase, first in the response time of the sensor, then in the voltage limit from the sensor. That is, the voltage output from the sensor is linear to a particular PPO2 level, then flattens off and becomes fixed, not increasing with increasing PPO2. This fault is tagged the "Ceiling fault".

The service life for oxygen sensors published by manufacturers is based on use at 1 ATM pressure in air at 20C, and must be down-rated for pressure, temperature and increased PPO2. A 2:1 down-rating of the service life from that published by the manufacturers for diving is appropriate, increased to a 3:1 ratio for sensors which may remain in a high PPO2 environment for their whole life: this figure is based on discussions with several manufacturers.

10.1.4 Loss of Electrolyte from shock or pin holes in the membrane

Mechanical shock causing loss of electrolyte or dislocation of the cathode or anode. This results in the following:

- The loss of electrolyte can cause the output to rise erratically, then over a period of days or weeks, to fall below the correct level. This effect is measured in the tests reported herein.
- A temporary reversal of the cell polarity can occur, with the output voltage attenuated as a function of PPO2. This normally ceases after a few days, and cells can recover to show normal polarity by are damaged and will tend to fail low within a few months.
- The capacitance of the sensor is changed by loss of electrolyte.

10.1.5 Decompression faults

If the diver makes a fast ascent, or if the cells are locked out from a hyperbaric environment, bubbles form in the electrolyte, producing faults similar to those from loss of electrolyte, but with a recovery of the cell over a period of a few days.

10.1.6 Load Resistor failure

This produces a high output if the resistor fails high or open, and a low or zero output if the resistor fails low or short.

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10.1.7 Thermal Compensation Failure

O2 cells are as sensitive to temperature as they are to oxygen.

This means that a temperature drift can occur of up to 2.5% per degree Celsius if the temperature compensation circuit fails. This generally results in the output voltage falling; that is, the sensor reads low, but a sudden temperature drop can cause a cell to read high, depending on the fault.

Failure of the temperature compensation circuit can cause four different effects:

- High output. O2 cells generate a charge, which if it is not drained constantly, will build up and express itself as a higher and higher voltage on the O2 sensor output. The internal load within an O2 sensor is very low: typically a few hundred ohms, so the 40 to 70uA output is expressed as an 8 to 13mV output in air (or 20mV to 32mV output, for high output devices which have a higher resistor value). Ideally the resistor would be 100 Ohms, which means the sensor would produce a 4mV to 7mV output in air. If the load resistor fails, then the sensor output will increase until current leakage is sufficient to dissipate the charge generated: this can several volts, equal to a PPO2 of hundreds of atm This failure mode can be detected by the output failing to fall when the O2 injectors are off, in an interval where other sensors show a fall in output value, as well as any sensor indicating a PPO2 greater than 4.0 atm at any time. Sensor electronics must be protected from this high voltage failure mode in addition to ESD.
- Temperature sensitive output. If the thermistor fails, the output from the O2 sensor will change as a function of temperature, by up to 2% per degree Celsius: the exact change depends on the sensor type and the nature of the failure.
- No output. If some components in the temperature compensation circuit fail open circuit, then the sensor will produce no output (open circuit).
- Zero output. If the load component or wires are short circuited, then the output will be zero volts.

Even without a total failure pf the temperature compensation circuit, cells with integral temperature compensation circuits have a very different time constant for the temperature compensation components and the electrolyte of the cells. A sudden temperature change can cauae very large errors in the cell output: cells with integral temperature compensation are not suitable for environments where sudden temperature changes can occur, such as in rebreathers.

10.1.8 The Lethal Danger of Liquid being allowed to pool on O2 Cell Membranes

If water covers part of the O2 cell membrane, a dramatic increase in the response time can occur. If the water blocks the whole membrane, then the sensor output will “freeze” at whatever it was before the block occurred. The output of a blocked sensor will reduce only very slowly over time. For example, if a sensor has water dropped onto the membrane in air, then the output will take around 20 minutes to drop from 0.21 atm to 0.17atm.

This problem occurs because the sensor membrane must allow the oxygen concentration in the gas to equalise with that in the cell: O2 molecules flow in and out through the membrane freely, and in fact, very rapidly.

If water is allowed to block the oxygen cell, then the O2 in the cell cannot flow out. The result is the cell will show the same PPO2 as before the water block occurred. If all cells have water on them the result will be either Hyperoxia or hypoxia of the diver. It should be obvious that this is an extremely dangerous fault mode that every rebreather designer must consider.

An example of this failure occurred in one test dive in the Bosforus Straits, where Teledyne R22 Batch F7 sensors were used in a simple PPO2 monitor: the cell drives a DVM, one DVM per cell. The cells were mounted on a cell holder in the inhale counterlung facing downwards when the diver is upright. After the dive, the cell holder was removed from the counterlung and all cells showed a PPO2 of 0.7 atm in air at sea level, taking over 5 minutes to change, and 30 minutes to show the correct reading of 0.21 atm. This was the first time this fault had been observed in such dramatic fashion: it is a very serious fault, so the cause was investigated.

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During test dives, the O.R. rebreathers frequently reject cells due to their transfer function moving out of specification. In some dives, 7 out of 8 sensors have been rejected at one time. This was believed to be overly tight limits on the cell acceptance, but examination of the dive logs suggests that it may be a mild variant of the Bosforus fault.

Some rebreather manufacturers share incident reports with Deep Life Ltd. In one of those incidents, a vapour lock occurred on the AII oxygen cells resulting in a diver passing out from hypoxia (but recovered on the dive boat).

This problem of water blocking the cells seems to be endemic with galvanic cells. Deep Life have accelerated the a programme for a supplementary sol-gel hypoxia warning device to provide additional diversity, but better water tolerance from the cells is highly desirable.

The procurement specification for oxygen cells for use in O.R. rebreathers (designed by Deep Life Ltd), require that cells have no well or lip around the membrane, specifically to avoid this failure mode.

This fault has a high probability of mortality if it is allowed to occur. To avoid this, this risk MUST be mitigated by good design, including consideration of the following:

1. Good positioning: the sensors should be mounted such that water falls off the face and cannot collect. During descent divers are often head down, but during descent PPO2 rises in the rebreather so this phase is not critical: if the sensor has a delay before showing rising PPO2 during descent it does not affect the diver's safety dramatically. During all other phases of the dive, the diver is either horizontal or head up, so orientation of the sensors downward, or ideally downward when the diver is on his back, head down at 45 degrees (the least likely position for a diver).
2. There should be no shroud around the cells. That is, the galvanic cell should have no outer case. The wires on the side of the cell are protected by the manufacturer's label.
3. The membrane should be flush with the surface of the cell. This prevents water building up, or vapour building up in any well around the face.
4. The cell holders should be held in a structure that does not have any well or cavity around the face of the cell.
5. Bump testing of the cells such as software monitoring to check that after injecting oxygen the cell output rises by the expected amount.
6. Ensuring the cells are not close to the scrubber (which generates water vapour when it absorbs CO_2). Provide a water trap between the scrubber outlet and the cells.
7. Ensure there is rapid enough gas flow over the cells that when scrubber salts are dissolved in water the resulting liquid cannot stick to the cell faces.
8. The rear side of the cells are covered with a dielectric gel to prevent water getting onto the circuit board and affecting readings. The gel is typically Dow Corning 3-4155: this is widely used in the automotive industry to provide environmental and shock protection of electronics in brake sensors, air bag sensors and engine management sensors.
9. The sensors are of different batches, and the batch code is read electronically, to ensure the maximum degree of diversity among the cells.

Fig 10-1: Deep Life injection moulded oxygen cell holders that take cells without case (e.g. R22 on left), and with a cell in a case (top, case in black), for comparison.

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10.1.9 Cathode Contamination failure

Any organic material introduced into the cell during manufacture will breakdown due to the strong base that forms the electrolyte, usually resulting in a black deposit over sections of the gold coated cathode. Some external contaminants may have a similar effect, if they permeate the membrane. This reduces the maximum output voltage from the cell into a fixed load, at high PPO2s: i.e. it is manifest as a ceiling type fault.

10.1.10 CO2 Contamination failure

CO2 will react with the electrolyte if it gets into the electrolyte, as the electrolyte is chemically similar to the action of a rebreather CO2 scrubber, however, tests of short term CO2 exposure has not revealed any cell degradation: five exposures of pure CO2 for 15 minutes has no effect, and exposure to pure CO2 for one week. These tests were carried out on sample cells from specific manufacturers: in a general sense the risk exists that CO2 that is present in rebreathers can affect cell life. This risk should be mitigated by regular testing of O2 cells using a suitable chamber to measure their ceiling voltage.

10.1.11 Connector failure Open Circuit or Short Circuit

Connectors and wires may fail open circuit or short circuit. The frequency of these failures depends on the connector type: the SMB connector used by Deep Life has modifications to seal the connector and the O-ring used in the seal applies pressure to the outer leaves of the connector to ensure a reliable ground connection. During testing many failures have been observed of Molex connectors and unmodified SMB connectors, but no failures have been observed in the modified SMB connector: the frequency of this failure mode with the Deep Life sensors is low. The self-tests used by Deep Life for cell resistance detects all cells that are open circuit or closed circuit and masks out those cells.

10.2 Failure Modes Arising from Design or Manufacturing Issues

The trial identified the following failure modes and rates that are specific to particular sensor designs and construction as follows:

1. Low shelf life. The reason for this is inappropriate packaging (the sensor bag should not be impervious to gas), and less than optimal design of the sensor allowing the water in the KOH solution to evaporate. To assess this, a control group of sensors in each batch was stored in an office environment, then half of the batch opened half way through the manufacturer’s stated shelf life. If those sensors still operated, the remainder were opened at the end of the stated shelf life and tested.
2. Drift. Good cells exhibit very little drift. For example, the Insovt cells tested here did not exhibit any measurable drift over a period of 5 years. In contrast, many of the Teledyne cells drifted every month, until they failed. Discussions with cell manufacturers exposed the reason for the drift to be organic contamination. The KOH solution is very aggressive and if it is contaminated by any organics, the result is usually a reduction in the cathode area. This results in a gradual reduction in the cell output. The cathode continues to be damaged by the contamination and the cell will fail early. Sources of contamination include soldering to the cathode, use of epoxy resin to seal the wires into the cell chamber and detritus introduced during assembly. AI and Insovt go to great lengths to eliminate this failure mode: down to use of a specific non-organic soap in the washrooms, clean room assembly, and good design.
3. Helium bubbles in the electrolyte causing fluctuations in output level. These fluctuations tend to cause the cell to read low. The cause can be either the front cathode being bonded to the sensor membrane, or being allowed to move, or the lack of a buffer before the membrane, causing the electrolyte to press on the membrane and causing it to dome.
4. Pressure migration of helium into the sensor, causing early rupture of the rear plastic film designed to contain moisture. This results in the sensor failing with a lower output than

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expected, due to drying of the electrolyte, damage to the circuit board or temperature compensation circuit. The plastic film is behind the sensor, and fills with gas during the dive. During the ascent the gas expands and normally diffuses back through the electrolyte and the hydrophobic membranes. If the ascent is too fast, the rear membrane can rupture, and the electrolyte dries out. This is a design defect caused by inadequate strength of the membrane and inadequate off-gassing pathways via the front membrane. The result is usually that the cell reads low, but can cause an increase in the cell output if the pressure pushes the cathode towards the anode, or vice versa.

5. Blockage of a pressure relief port. This caused a reduction in the output of the sensor in the sensor examined. The possibility of this fault is a design defect: it should not occur in the AI or Insovt designs. The result is the cell reads low.
6. Blockage of the rear pressure seal in some cells, can result in a displayed PPO2 that is higher than actual. Caps should not be fitted to O2 cells, that might cause air blocks in the rear of the sensor.
7. Tears or holes in the membrane can result in loss of electrolyte, and a temporary increase in cell sensitivity, before the cell output drops and the cell fails.
8. It is claimed on Internet forums that if the sensors are stored in a high O2 environment without a load attached, excess charge accumulates, resulting in the PPO2 reading higher than it is. On detailed investigation, this failure turned out to be dry joints: the bare micro fuel cells do not exhibit this behaviour – the fault is caused by faults in the temperate compensation circuit, such as dry joints or faulty components. The result is the cell reads low.
9. Environmental damage, particularly corrosion of contacts and the circuit board in an operational rebreather environment. This results in an open circuit or a zero output from the sensor. If that membrane leaks, then Potassium Hydroxide is deposited onto the circuit board, causing rapid degradation of the board and the components on the board, and failure of the cell. The other cells tested had either a solid wall behind the cell or an improved membrane to prevent this occurring.
10. Slow response. Wide variation in the response of Teledyne sensors was found: one had a 50s response when new, five times worse than the worst case in the data sheet. This can come from a number of different causes, including fitting the wrong membrane at the front surface, poor electrolyte composition and gross contamination of the electrolyte. This is a particularly hazardous failure mode for a rebreather, as although the sensor may pass calibration, the system will not inject enough oxygen during a fast ascent, causing the death of the diver. The existence of this mode means that the rebreather should test for the response time and if it is worse than 10s, reject the sensor. Preferably, sensor types that display this failure mode should be avoided.

11 RoHS and WEEE Compliance

RoHS refers to EC Directive 2002/95 Restrictions on Hazardous Substances, which bans the placing on the EU market of new electrical and electronic equipment containing more than agreed levels of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE) flame retardants.

Galvanic cells do not meet the RoHS objectives: they depend on a lead electrode. It is highly desirable to replace them by RoHS compliant sensors, but there is no physical means or phenomena to do so that is within ALARP.

All goods imported into, exported from, or manufactured in Europe after 6th July 2006 must be RoHS compliant, if they fall within the RoHS scope, unless the goods have an exemption. Very few exemptions are being issued. The scope of the RoHS regulations is electronic and electronic equipment in ten specific categories. Diving equipment is not in any RoHS category, and Category 9 of

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RoHS excludes Monitoring and Control Equipment for the time being(2). As diving equipment is not in any of the RoHS categories, rebreathers fitted with galvanic sensors do infringe RoHS regulations.

WEEE refers to EC Directive 2002/96 Waste from Electrical and Electronic Equipment, which aims to reduce the amount of WEEE going to landfill, by requiring all manufacturers and producers to take responsibility for what happens to the products they sell at the end of their lives. To comply with WEEE user manuals for rebreathers require a section stating the galvanic oxygen cells must be returned to the supplier for disposal, to meet WEEE requirements and the sensor must be labelled with a WEEE mark to indicate is should not be disposed of with household waste.

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[2] See http://www.rohs.gov.uk/DecisionTree.aspx?id=24 for the RoHS exemption, as of June 2009.

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12 MEASUREMENT EQUIPMENT

The following equipment was used to perform the tests. In describing the test results, further detail is given showing the exact configuration used: to minimise repetition, this is done for one sensor's test but where the same test is referred to then the configuration is the same unless otherwise stated.

12.1 Calibration

All equipment used in the tests have calibration records maintained by the Deep Life or BAI, as appropriate, as part of their ISO 9001 records.

Due to the long duration of this trial, equipment was calibrated several times during the trial and different instruments were used. The list of calibration serial numbers and the calibration intervals for that equipment, and calibrations, can be obtained from Deep Life Ltd on request.

12.2 General Instrumentation

Due to the long period over which these tests were carried out, the equipment has had multiple calibrations over the period of the tests and units with different serial numbers were used in many cases. The BAI calibration logs provide full traceability of those serial numbers and calibrations.

The following test and measurement equipment was used for the tests:

1. Test chamber 200msw rated, fitted with gas circulation control.
2. Test chamber 2000msw rated, fitted with DL Compact Breathing Simulator Rev D, Serial A.
3. Mini Test chamber 6100msw rated, for O2 and component testing.
4. Gas booster pump or adequate gas supply at 141bar.
5. Ultra high precision bench meter: TTi 5075
6. Keller LEO and BAI high pressure sensors
7. Druck LPM9381 Differential pressure sensors (2)
8. 10K and 100K external load resistors, 3 off.
9. Air, He and O2 supply to 141 bar.
10. Test fixture to heat the 2000msw test chamber to 90C.
11. Test fixture to cool the 2000msw test chamber to -4C.
12. BAI and Analox CO2 sensors.
13. Twelve samples of each of the sensor models to be tested, unless otherwise stated.
14. Innovision AMIS 2000 Respiratory Gas Real Time Mass Spectrometer
15. Temperature sensor, humidity sensor, pressure sensors and data capture system were component level items so are described below.

12.3 Humidity sensor

The humidity sensor requires a special note on its compensation, as follows.

Technical data:

1. Model: HIH4000-003
2. Wafer: t3
3. Channel: 403
4. MRP: t3
5. File: 36070406

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6. HYCAL Sensing Products
   Honeywell Inc.
   24B Concord Street, El Paso TX 79906
7. Calculated values at 5 V:
   Vout @0% = 0.808 @75.3% = 3.092
8. Linear output for 2% RH accy @25C:
   Zero offset = 0.808 / 0.0303
   Slope = 30.331 mV/%RH
   RH = (Vout – 0.808) /0.0303
9. Ratiometric response for 0 to 100%RH: Vout = Vsupply * (0.1616 to 0.7682)

In Test 5, when the temperature was 90 deg C, the humidity sensor showed a negative humidity of –2.2%RH. The formula used was RH = (V_{ADC} –0.808)/0.0303.

In Test 10, when the space around the PPO2 sensor was filled with dry CO2 from the cylinder and the mean temperature was 24.17 deg C, the minimum filtered humidity value was negative, -2.89%. The window size of the filter applied was 5. The formula used was RH = (V_{ADC} –0.808)/0.0303.

To remove the negative RH values from the test data as shown below, the offset of the humidity sensor was set at 0.7413 instead of 0.808. This increased the sensor output data by 2.2%RH. The updated formula was RH = (V_{ADC} – 0.7413)/0.0303.

12.4 Computer Data Capture interface

USB, L-CARD E14-440, 14 – bit ADC, 16 diff /32 single, calibrated against a TTi 8 ½ digit ultra high precision bench meter,

Scan: each second.

ADC range, V	Resolution, mV	Note
+/- 10	1.2 mV	For temperature and humidity sensors
+/- 2.5	305 µV	For pressure sensor
+/- 0.625	76 µV	
+/- 0.1562	19 µV	For PPO2 sensor

Sensor	Load
PPO2	100 kOhm
Temperature	1 MOhm (input of ADC)
Pressure	15 kOhm
Humidity	1 MOhm (input of ADC)

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13 DATA FILTERING

The output impedance of the O2 cells is from 82 Ohms to 270 Ohms.

In the rebreather the O2 cell is connected via a series resistor for ESD protection.

The appropriate level of ESD protection was considered. Given the moist environment in which equipment is generally used, operational protection is not an issue. The problem arises when the equipment is dry and new O2 cells are fitted. This may be in an office or home environment with synthetic flooring.

Category 3B+ protection was considered the most appropriate, as rated by ESD STM5.1-1998. US Standard MIL-STD-833C also refers. This is less than the requirement for some other safety critical applications; for example, a 25KV requirement exists for explosive devices in Mil Std 322B-1984, Mil Std 1512-1972 and Mil Std 1576-1984. A minimum level of 10KV was considered appropriate to this application, due to its SIL 4 rating.

ADCs generally have a 2KV HBM protection circuit on the input pads. Providing the appropriate level of protection requires, therefore, an external resistor and diodes to limit the ESD current. The external load of the sensor does not provide much protection, as the series inductance means any capacitors used have a self-resonant frequency well below the spectrum where the peak energy from an ESD event causes damage. The reason for adopting a 10KV requirement instead of 25KV, is that the O2 cells used by DL must be fitted with an SMB connector. The SMB connector also reduces the risk from ESD considerably, compared to the normal Molex 0.1" pitch connector or stereo jacks, by ensuring the ground is connected before the signal: the discharge is then into the ground of the equipment rather than into the chips. The SMB connector has other advantages, including better signal screening and less susceptibility to making an intermittent contact after exposure to a humid salt atmosphere.

To achieve the 10KV protection, a series resistor of 100K is used, followed by the usual dual reverse biased diodes to dump charge into the capacitance across the power supplies. The 100K resistor must also limit the current from an open circuit sensor: if the load resistor on any O2 sensor becomes open circuit for any reason, the output voltage can increase to hundreds of millivolts. The maximum theoretical voltage from the Lead-Oxygen reaction is 0.98V from the basic electrochemistry:

Pb + 2OH- -> PbO + H2O + 2e- (-0.58V)
O2 + 2H2O + 4e- -> 4OH- (0.40V)

The Lead-Gold potenital is up to 2V, which is the maximum potential from the cells.

For a sensor with a load resistor with a voltage of 10mV in air, this is 47mV per atmosphere pressure of O2, or an output equivalent to a PPO2 of 20. In reality, any load will reduce this, but sensors can record linear outputs up to around PPO2s of 10atm with a low valued load resistor. The current flowing from a cell is typically 50microA, in air.

For these reasons these tests were carried out with a 100K Ohm resistor in series with the cell, with comparison provided by a 10K Ohm resistor, as is common in contemporary rebreather equipment.

The effect of noise from the series resistor was measured and the results shown in the figures below.

This data shows the original data and the effect of passing the data through a moving average filter with a filter window of 5 samples, and 50 samples.

The PPO2 mean is 11.84 mV and the temperature mean is 24.94 deg C during the test.

The results enabled the noise from each resistor to be assessed, and confirmed that 50 times over-sampling and a moving average filter are close to optimal for signal conditioning.

A parallel resistor of 10K Ohms is used also, to prevent the output rising too high if the cell's internal load fails. This does not affect the results, except to reduce the output level by 1%.

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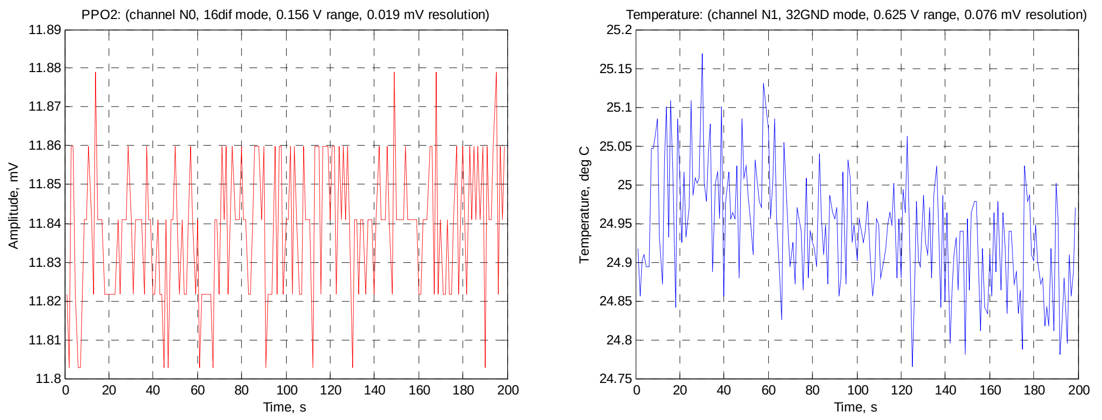

Fig 13-1: Original data.

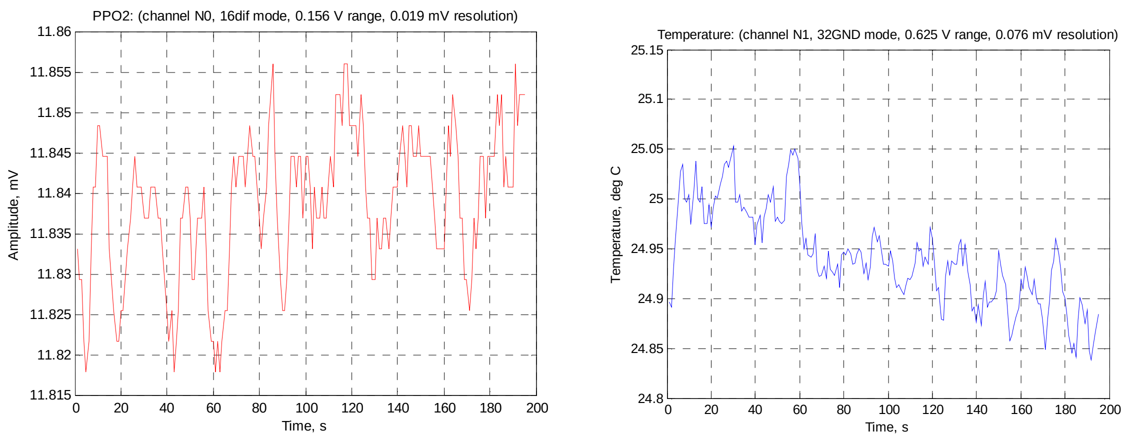

Fig 13-2: Original data filtered by moving average with window size of 5.

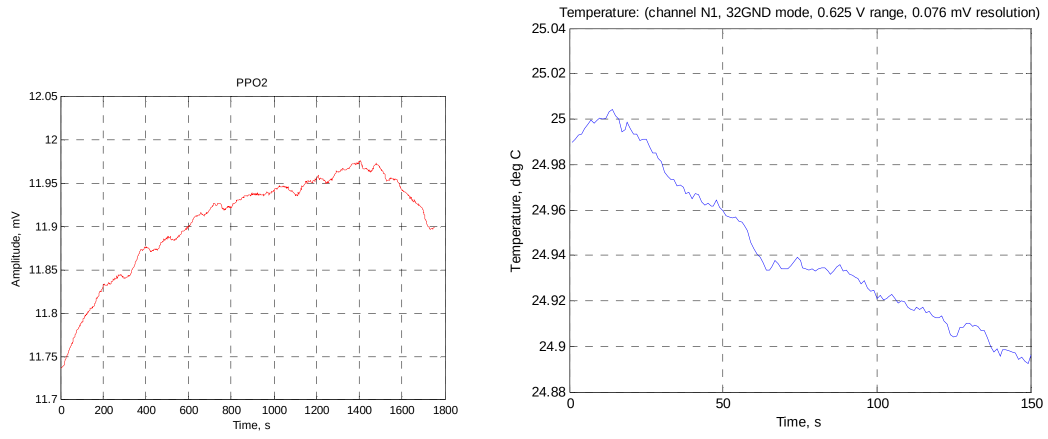

Fig 13-3: Original data filtered by moving average with window size of 50.

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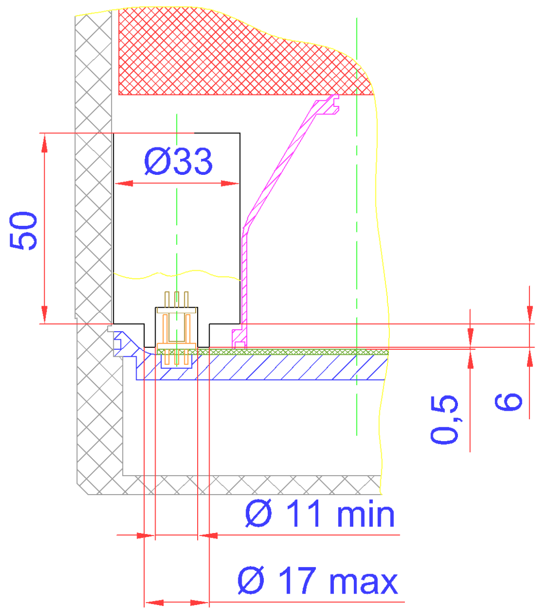
14 TEST SCHEDULE

Each batch of sensors was tested using a formal test schedule. The test plan is described by Table 2 below. Further information on the precise configuration of the test equipment and method is given, along with the report of the results, such as those of the PSR 11-39-MD sensors later.

The use of the formal test schedule is in addition to, and not a substitute for, any tests deemed prudent to understand the effects of any unique feature of a specific sensor design.

Prior to tests starting, model and serial numbers of sensors were documented, and a photographic record taken. All sensors were treated as Customer Supplied Material according to QP-05. The sensors were marked as samples 1 to 12.

Table 2. List of tests.

Test	Purpose	Method	Nonconformance Action
1. Confirm mechanical dimensions fit the space provided for in the design plan.	Mechanical compliance.	1. Use sensor 1. 2. Measure dimensions to confirm the sensor fits the space shown below, which is 33mm x 50mm + 6mm connector extension. 3. Check there is a means to hold the top of the sensor using a clamp, to prevent it shaking loose from the connector. 4. Check the active face is at the top in the drawing below (that is, the active face faces downwards in normal operation). 5. Place in position and check for interference. 	Reject. Abort tests.

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2. Examination of materials for O2 compatibility.	To avoid O2 fire hazards taking into account the flow rate over any surface and risk of adiabatic compression.	1. Use sensor 1. 2. Examine construction for all materials on the external surface, and for all metal parts identified, check their O2 compatibility against NASA document NSS 1740.15, Jan 1996: SAFETY STANDARD FOR OXYGEN AND OXYGEN SYSTEMS - Guidelines for Oxygen System Design, Materials Selection, Operations, Storage, and Transportation.	Reject. Discuss with manufacturer. Continue tests.
3. Hydrophobic membrane	Confirm that water is not retained by measurement membrane	1. Use sensor 1. 2. Measure sensor voltage, and record temperature. 3. Place sensor sideways in shallow water bath filled with 3cm depth of sea water at 20C +5C/-2C for 1 minute, then withdraw and position with the sensor face downward. 4. Check for any water held on the face. 5. Measure the output voltage every minute over a 30 minute period. 6. Verify that output does not change more than 3%.	Reject
4. Response time	Measure the time to respond, to 90% of final reading, on a change of PPO2 from 0.21 to 1.0	1. Use sensor 1 and allow output voltage to settle in air. 2. Apply a stream of oxygen to a sensor with a pressure of 30mbar +/-20mbar . Measure the readings every 100ms. 3. Compute response time to a 0.21 to 1.0 change, and from 1.0 to 0.21. 4. Verify that the response is less than 10 seconds to 90% of final value.	Reject. Discuss with manufacturer. Continue tests.
5a. Temperature range.	To verify linearity over full temperature range.	1. Use sensor 1 2. Place in the 300mm dia compression chamber immersed in saline, with the DL Compact Breathing Machine. 3. Cool chamber to -4C for 3 hours, then run breathing machine at 4x2.5l strokes per minute to mix the gas, record temperature, humidity. 4. Heat the chamber at 1C per minute to 90C. 5. Record temperature, pressure, humidity and measured PPO2 throughout test. 6. Correct results for pressure changes during test.	Review

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5b. Stability.	Confirm sensors are stable in air and confirm calibration interval required for their use	1. Use sensors 2 and 3. 2. Measure the output voltage with a 10K load, once per day, for six months. Record atmospheric pressure, temperature and humidity. 3. Correct data for temperature and pressure. 4. Confirm results are within 5% throughout the measurement period. 5. Extrapolate any trend to verify that operating life is not less than that quoted by manufacturer.	Reject, but continue tests.
6. Shock test Drop from 1.5m and 3m.	Test robustness. Test simulates effect of a sensor being mounted in a CCR transported by an RHIB.	1. Use sensor 1 and 5. Perform 3m drops first using sensor 1. 2. Photograph the sensor to be tested. 3. Measure the output voltage in air with a 10K load. 4. Drop 1.5/3m onto a hardwood surface 10 times. 5. Measure the output voltage in air after each drop. 6. The output voltage should not change more than 10% after 10 drops. 7. Drop 1.5/3m onto a wooden board laid on concrete 10 times and measure flow rates at 1ATM. 8. Photograph the external surfaces again. Repeat response time test (4) and note any differences. 9. Sensor then to be monitored for two weeks on a minute by minute basis to detect any changes relative to a reference group. 10. Repeat using sensor 5 from 1.5m	Design change
7. Linearity with pressure, and susceptibility to helium.	Confirm operation over required range of PPO2 and pressures.	1. Use sensor 4. 2. Fit sensor inside a DL Compact Breathing Machine, in a pressure chamber. 3. Set the breathing machine to 4x2.5l strokes per to mix the gas in the chamber. 4. Starting at 1ATM, measure output voltage, temperature, humidity and pressure with a 10K load, while increasing the pressure in the chamber by injecting air, to a depth of 100m, with a maximum rate of descent not	Must operate correctly over range 4 bar to 14 bar relative to ambient, otherwise design change.

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		exceeding 30m/min. 5. Bleed off air until the PPO2 falls to 1.3. 6. Add helium with a maximum rate of descent of 30m/m, recording output voltage, temperature, humidity and pressure, until the pressure is 141 bar absolute (2000msw). 7. Correct data for changes in temperature using the results from Test 5a. 8. Plot linearity with PPO2. 9. Plot linearity with Depth. 10. Do not decompress: move to Test 8.	
8. Uncontrolled ascent and test for cathode movement.	To verify the sensor is not damaged if decompressed at the fastest rate a human can ascend in sea water (120m/min).	1. Use sensor 4 2. From 2000msw, decompress linearly, at a rate of 120m/min. 3. Check output of cell in air at 1 ATM. 4. Recompress at 30m/min, then repeat test 10 times. 5. Examine cell for signs of leakage. 6. Store sensor for 6 months with face vertical and check no damage to rear PCB from leaking electrolyte.	Determine maximum safe ascent rate using a second sensor.
9. Chamber Lockout (Torpedo) test	Test effect of worst possible ambient pressure increase or decrease in a chamber lock. Test for gas entrapment leading to risk of explosion or implosion.	See Note on this test, below table. 1. Use sensor 1. This test is the last in the sequence for sensor 1. 2. Wrap sensor in single sheet of 80gms paper. 3. In a chamber rated to 600 bar, increase pressure from 1 ATM to 300 bar in under 1 second, using air. Wait five minutes for sensor to stabilise. Drop pressure from 300 bar to 1 ATM in 1 sec. 4. Check inside of chamber for particles thrown out from sensor. 5. Check paper for holes and leakage. Characterise the sensor after the test for internal damage.	Review
10. CO2 Susceptibility	To determine damage caused by sensor being in loop pre-breathed without scrubber. The PPCO2 can vary from 0.04 to 0.4 under these conditions.	1. Use sensor 3. Record ambient pressure and temperature. 2. Fit sensor to small chamber with an open port, and fill with CO2 so there is a 100% CO2 environment at ambient pressure around the sensor. 3. Measure the voltage produced by the sensor to verify it has fallen to zero.	Review

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		4. Leave the sensor in the chamber for 15 minutes. 5. Remove from the chamber and allow to stabilise in air for 1 minute and measure the voltage, temperature and ambient pressure. 6. Repeat steps 2 to 5 four times. 7. The sensor should be in air when it is not in CO2. 8. Record voltage, ambient pressure and temperature once per day for 5 days.	
11. Application Test	10 dives to recreational depths.	1. Use sensors 3, 8, 9, 10, 11, 12 2. Fit sensors to two PPO2 monitors: one a pure PPO2 monitor and the second to a rebreather head. 3. Perform 10 dives with a mix of RHIB and hardboard diving. 4. Measure the output voltage and record ambient pressure and temperature between each dive. 5. Store for 6 months, then take a further set of readings, and perform 10 more dives. 6. Correct the data for temperature and pressure. 7. Compare differences between units before and after use. 8. Examine carefully for signs of corrosion or other visible deterioration.	Review.
12. Life Test	Verify the manufacturer's quoted life test	1. This test is the penultimate in the sequence for all sensors, except sensors 1, 7, 8 and 9. 2. Record readings for all open oxygen sensors one per month, until 50% have failed. 3. Compare with manufacturer's stated sensor life.	Review
13. Storage life.	Verify the storage life of the sensor.	1. Use sensors 5, 6 and 7 2. Store at room temperature in unopened packages. 3. After 1/3rd, 2/3rd and the full storage life quoted by the manufacturer, open one sensor. 4. For the first two sensors, measure the output voltage for six months with the sensor in air, and compare with the results from Test 2.	Review.

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		5. For the final sensor, after measuring the voltage, disassemble the sensor and compare with sensors 8 and 9 which should be likewise disassembled. 6. Take a photographic record of any changes. 7. Particular attention should be paid to the size of the anode and any changes in the cathode. 8. Examine the housing for possible sources of contamination. 9. Examine the PCB for corrosion.	
14. Offgassing	Review MSDS for each material in the sensor. Off-gassing is not tested.	-	N/A
15. Effect of KOH Leak	Effect on output if KOH leaks from sensor, to understand the behaviour of the sensor under this sensor failure mode.	1. Measure the output voltage of a sensor. 2. Drill two 1mm holes in the sensor, plugging the first before drilling the second. 3. Measure the output of the sensor when the holes are unplugged, and air is injected into the sensor to slowly displace the electrolyte. 4. Note that the electrolyte is highly alkaline so protective gloves and goggles should be used. The electrolyte should be drained into water, and the solution disposed of after the experiment by neutralising it first with a mild acid.	
16. Storage at minus 30C	Required for EN14143:2003	1. Use new sensors. Measure output voltage. 2. Store sensors in rebreather for 3 hours at temperature of below minus 30C. 3. Measure sensor characteristics. 4. Compare sensor characteristics before and after storage.	

14.1 Note on deviations from test plan.

In many cases when a result will show some anomaly, further tests are carried out. This can include re-running the whole experiment or measuring other parameters during the experiment. When this occurs, this is indicated in the test results by a departure from the plan and the additional data measurements.

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14.2 Note on Test 1: Mechanical Dimensions

All the sensors were supplied with Molex connectors. These are entirely unsuitable for the application, being subject to corrosion and having poor reliability in a marine environment[3] and they are liable to destroy the sensing electronics because the signal can connect before the ground. This latter fault was found in an APV Inspiration tested after a fatal accident: it is a real fault condition and should be addressed by the sensor manufacturer, by providing a connector where ground connects before the signal, as well as providing ESD protection in the sensing circuitry.

In April 2000, Dr. Alex Deas touring the AP Valves factory in Cornwall pointed out the unsuitability of the connector to Martin Parker, APV's General Manager, and was asked, “What is a suitable connector?”. Dr. Deas replied, “an SMB connector with a hard gold finish, for example”. APV, now AP Diving, took up this suggestion and the SMB connector is now available for both APD Evolution and Inspiration products. There are other connector types that are suitable, provided the contacts are bifuricated or annular to provide reliability, protected from moisture in use and make contact with ground before the signal.

This study requires the vendor to supply either an SMB connector or another connector suitable for dive applications.

14.3 Note on Test 5: Temperature Range

Sensor manufacturers state the operating temperature range is -10C to 45C, or -5C to 50C, with exposure to 60C for 30 minutes, and do not recommend taking the sensor to 90C.

The purpose of Test 5 is to verify the accuracy of that range, and the effect of a sensor being in a rebreather in the sun, where it can be exposed to 90C. The test should determine if there is any dangerous off-gassing or leakage, or permanent damage.

14.4 Note on Test 6: Drop and Shock Test

In diving, equipment is subject to greater shock than a human. The largest shocks identified in normal use occur when equipment is laid on the floor of an RHIB (a Rigid Hull inflatable boat), which is driven at speeds of up to 60 knots. The occupants sit on the inflatable walls, but still complain of back ache after a journey: the shock to the equipment laid on the floor is similar to a drop of 3m. In rough seas the speed is reduced considerably, but the RHIB then powers off the peaks of the waves, falling into the trough of the following wave, with drops of up to 3m before the dive is cancelled: the Surface Marker Buoy used to locate the divers, in areas such as Scotland and Norway where these wave heights are considered diveable, have a height of 2 to 3m. Above 3m waves it is too difficult to locate the divers in the water. Again a 3m drop occurs, which the occupants are cushioned from because they bend their legs and sit on a 1m high inflatable cushion (the RHIB sides).

The sensors are checked with both a 1.5m and 3m drop test on to a block of wood.

14.5 Note on Test 9: Chamber Lockout Test (Torpedo Test)

Test 9 is a destructive test as part of a safety case required under European Regulations (to meet EN61508). The reason for this test is that sudden compression or decompression in a hyperbaric chamber is a “very likely” scenario, and it is necessary therefore to ensure that no serious injury is likely to be sustained by either the chamber occupant or the chamber technician in handling the sensor after it is withdrawn from an interlock. The sensor is not expected to function: the equipment tests for functionality as part of its calibration routine and the instructions issued with all equipment are that the

[3] The O2 cells in a rebreather operate in a condensing 100% humidity pure oxygen environment, and may be subject to flooding by highly caustic solutions from the scrubber. This causes corrosion to Molex pins.

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decompression should not be faster than 120m/m, as this is the fastest ascent a human can achieve in water and survive, assuming low tissue loading by aborting a dive close to the start.

14.6 Note on Test 12: Life test

A full storage life test is required in Test 12. Where possible, this should be exactly as stated in the table above, taking the period stated by the manufacturer: this can be up to 5 years.

One manufacturer's sensors entered the test late, so it is necessary to accelerate the test period. The sensor shall be maintained at a PPO2 of 1.0 by pressurising in air, in an open package, and stored at 50C. The sensor should be considered to have a 5:1 acceleration factor under these conditions. An O2 compatibility test chamber can be used for this purpose.

14.7 Manufacturing Review

Discuss with the manufacture their quality arrangements and certification. Pay particular attention to the implementation of the quality control, focusing on minimising the risk of contamination of the KOH solution in the sensor.

Discuss with the manufacture all known failure modes. Enter these modes into the safety case.

When disassembling the sensors in Test 12, inspect the sensor for signs of contamination and of hand assembly operations. This will show up as a blackening of the cathode, or areas of the cathode. Discuss with manufacturer.

Rate the manufacturer from 0 to 10, based on the result of this review.

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15 INSOVT ДК-32 SENSORS

Insovt is a Russian company with a long history of supplying Russian process industries, the Russian Navy and in diving in Eastern Block countries: the company web site is http://www.Insovt.ru/o2sensors/.

The ДК-32 is a high performance sensor, filled with KOH solution. The response time is 20 to 30 seconds, and was measured at 25 seconds for the batch. The sensor is rated to produce 5mV in air, and measured at 4.999mV. It has a hydrophobic membrane fitted. The sensor was of very good quality: consistent, robust and with an exceptionally long life. The temperature sensor for compensation is integral to the housing: actually inside the main cell housing to achieve a good thermal match physically.

The sensor was found to have too slow a response for diving applications. The tests and results reported are an extract out of the full test regime that was applied, to enable the merits of this sensor to be understood but without the detailed characterisation that might distract the reader from the main issues: the sensor is unsuitable so there is no purpose in publishing the full characterisation that would be needed for it to be used in this application.

15.1 Sensor Sampling

A batch of sensors was purchased and separated into a group stored for five years, and a group used in a rebreather for periods over the 5 years the sensor was studied.

Figures 15.1-1 to 15.1-5 show the Insovt DK-32 and the arrangements used for sea trials of the sensor.

Fig 15.1-1: Front face of Insovt DK-32 showing integral and thick shield in front of hydrophobic membrane to prevent membrane lifting when depressurised rapidly. Sensor serial number 171, shown after testing.

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Fig 15.1-2: Side view of Insovt DK-32 after testing, showing the hard wired temperature compensation circuit potted into housing.

Fig 15.1-3: Insovt DK-32 showing KOH solution fill: bubble can be seen behind anode and also in second compartment. This shows the two part potting process to avoid contaminants affecting the cell. Note the thick material in front of the cell to prevent depressurisation forcing electrolyte out.

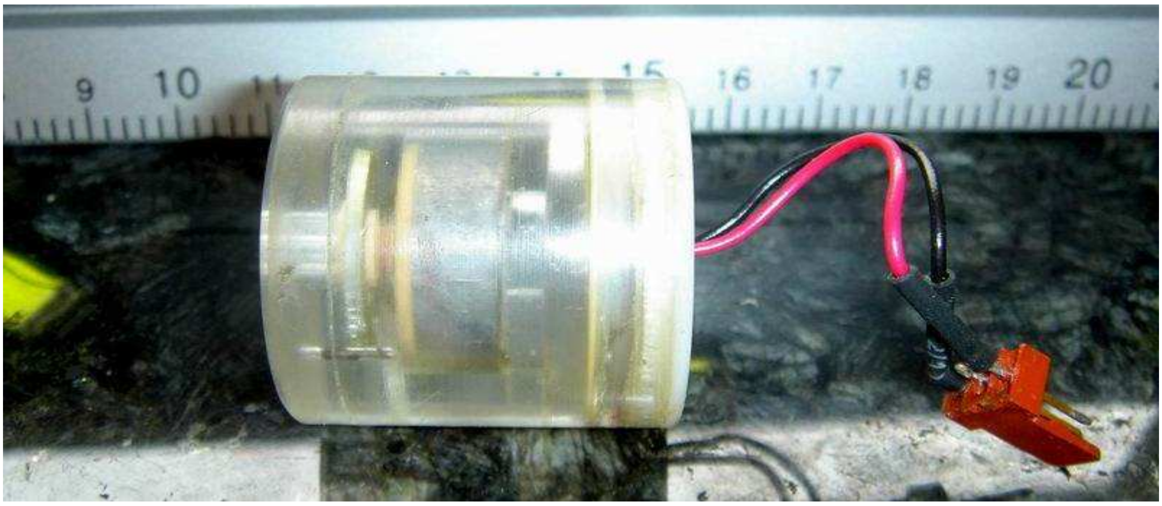

Fig 15.1-4: Insovt DK-32 with rule showing the thick hydrophobic membrane in front of the cell

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Fig 15.1-5: Test Rig using an improved AP Valves Inspiration Classic to test the Insovt DK.32s on dives. An ExtendAir scrubber was fitted, the batteries were replaced by rechargeable lithium ion cells and the failure point at the top of the lid was removed by Deep Life. Note that cells within the breathing loop are not used in any rebreather design by Deep Life, other than in this test fixture.

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15.2 Results

At the beginning of the trial, the sensors were tested and found to produce 5mV in air (as specified), but the temperature compensation was not functioning. Considerable care was taken to ensure all measurements were taken at the same temperature (21.0C). Variation between the sensors when new was less than 20mV.

At the end of the 5 year period, no difference was observed between sensors that had been stored and those in use. All sensors were still operational; all produced the same output voltage in 100% O2 and in air. There was no corrosion visible except slight corrosion of the contacts.

The ДК-32 sensor seems accurate to within 1% over the 20C to 90C range when the temperature and pressure are compensated properly, but the sensors supplied had a circuit fault due to a design error. This had to be remedied to provide this improved result.

15.3 Observations

The temperature compensation for the ДК-32 as supplied was completely inadequate, with 2% per degree Celsius changes being observed during the tests. The manufacturer has been contacted and would work with Deep Life to correct this issue if the other parameters are acceptable. The resolution of this problem is very simple: a wiring correction was needed.

The ДК-32 is a high quality product, but needs additional production engineering to meet the volume requirements anticipated by the project.

No failure of any sensor was observed in the batch during the 5 years the Insovt sensors were tested; however, examining the construction of the sensor, it is noted that all failures should result in the output falling below the voltage that is expected as the electrodes are consumed. In the sixth year, ceiling faults started to occur: this is the correct failure mode.

No failure modes that are caused by design or manufacture were found in the Insovt sensors, other than the above noted error in the temperature compensation circuit.

The fact that cells always fail low could be used to improve the tolerance of PPO2 circuitry by taking only the highest reading cell: the reading must be after normalisation (after calibration) – often the highest absolute voltage is the cell that will fail early.

Hazard found during the HAZOP Study in the O.R. Project using the formal model of the rebreather. If the sensor response is more than 10 seconds, and the diver is using a set point of 0.4 or below, then the diver can ascend fast enough for the PPO2 to drop below 0.12, causing loss of consciousness. This hazard was considered serious enough by the HAZOP Study Group to rule out all sensors with a response time of less than 10s (to 90% of final value).

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16 ANALYTICAL INDUSTRIES PSR-11-33-NM

An April 2004 NEDU study, "Evaluation of Analytical Industries Inc. Model Number PSR-11-33-NM Oxygen Sensors for Use With the MK 16 MOD 1 Underwater Breathing Apparatus", Document available on http://handle.dtic.mil/100.2/ADA443585, approved the PSR-11-33-NM for Navy use to replace the Teledyne R10D. It is noted the standard deviation of the error of the PSR-11-33-NM is approximately half that of the R10D.

The PSR-11-33-NM has no components on the reverse side of the circuit board, so does not require conformal coating. The trial carried out indicates that both sides of the board will still corrode, but the cause of the corrosion, the leaking KOH, is deemed much less likely to occur with the Analytical Industries diving sensor than some other devices tested.

The overall construction of the PSR-11-33-NM was very similar to the R22, but the shelf life does appear to be longer. The reasons for this are being discussed with the manufacturer, and include:

- Elimination of organic contaminants by good design practice, in particular a weld free and epoxy free construction.
- 100% testing of every sensor four times during production
- Differences in the rear membrane to avoid gas bubbles
- Differences in the rear membrane to avoid leakage of electrolyte
- Difference in design to avoid drying of the electrolyte. This gives Analytical Industies PSR-11-33-J2 sensors a storage life of 60 months.

Examination of the sensors did not reveal any quality control problems, though some are reported on internet forums. A portion of these may be caused by incorrect loading of the sensor.

Only a limited number of the failure modes identified in Section 10 apply to the Applied Industries sensors, due to differences in design compared to the R22D.

As a result of the above interim conclusions, a high-level close dialogue was opened with Analytical Industries. That dialogue conveyed a strong impression of the company having an effective quality system, and a passion for quality that results in high-quality sensors free of some of the failure modes common to their competitors.

17 ANALYTICAL INDUSTRIES PSR-11-39-MD, MDR AND DL

Inspection of the PSR-11-39 indicated the same quality and construction as seen earlier with the PSR-11-33. The full O2 Sensor Test Plan was applied to a batch of 12 of the PSR 11-39-MD and 12 of the PSR 11-39-MDR sensors.

The PSR-11-39-MD is a plug replacement for the Teledyne BUD2 and R22D.

The PSR-11-39-MDR is a special sensor fabricated for Deep Life with the following changes to the MD:

1. The Molex connector on the MD is replaced by an SMB Male on the MDR for a more reliable connection, with better signal integrity. Note that Analytical Industries are also providing an SMB equipped version of the MD in due course, but the samples tested had the Molex connector.
2. The Temperature Compensation circuit is removed, to remove all failure points connected with that circuit. Temperature compensation is carried out more accurately by the digital electronics on the CCR controller.
3. The output has a 100Ohm internal load, 1% tolerance, that prevents any charge storage in the sensor and allows the presence of the load to be measured by the CCR controller to verify that the load is present and the correct sensor is installed. This arrangement allows all failure

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modes that result in the output from the sensor being higher than the correct output, being eliminated.

4. The output voltage is 4.5 to 5mV typically in air, this giving the longest cell life.

This document reports the results for the Analytical Industries PSR-11-39-MD and PSR-11-39-MDR sensors against the formal test schedule. These two sensors differ only in the pcb: in the latter the temperature compensation circuit is removed and replaced by a precision 100 Ohm load, to give a typical output voltage in air of 4.5mV, compared to 12mV for the –MD device.

The numbering of the tests in this document refers to the test numbering in the Test Plan.

The DL sensor is a sensor developed by Analytical Industries for Deep Life following Deep Life's assessment of the MDR sensor. The main improvements to the DL sensor compared to the MDR are:

- removal of the outer-case to remove the well that could form a vapour or moisture trap,
- improved marking,
- an SMB male socket,
- gel coating of the circuit board,
- and ruggedness features.

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18 PSR 11-39-MDR TEST RESULTS

The PSR 11-39-MDR is a sensor specially created by Analytical Industries for Deep Life Ltd, to remove all sources of failure that can result in the sensor output being higher than expected.

The sensor has a 4.5mV output rating in air, to provide the maximum cell life while keeping sufficiently far above the electrical noise floor to allow accurate measurements to be made quickly.

The sensor does not have any temperature compensation. Instead it has a fixed precision (1%) load. The sensor normally uses an SMB connector, but the test batch was supplied with 0.1” pitch pins. It will normally be coloured Green to avoid confusion with other sensors.

The protocol in using the sensor is to test that the output level is within the correct range in air, and to check the 100 Ohm resistor is present. The latter operation involves driving the sensor with different loads using a DAC and measuring the response. In this manner, the equipment can check that the correct sensor is fitted, and if the load is present, then it cannot produce a higher output than the true PPO2 level.

18.1 Sensor data

The initial outputs of the oxygen MDR sensors without temperature compensation are shown in Table 3 below.

Table 3. Sensor initial output.

Sensor No	Output, mV	Serial number
1	4.1	60741634
2	4.5	607425
3	5.3	60741628
4	4.9	60741632
5	5.5	607424
6	4.5	60741629
7	4.6	607428
8	4.4	60741633
9	4.2	607435
10	4.0	607426
11	5.5	60741630
12	4.2	60741625

The acceptance band for the sensor, by the electronics, is 3.9mV to 5.6mV. All sensors were within this band.

Fig 18.1-1: Part of the test batch of MDR sensors.

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18.2 Test 1: Dimensions

The sensor meets the dimensional requirements imposed by the test plan.

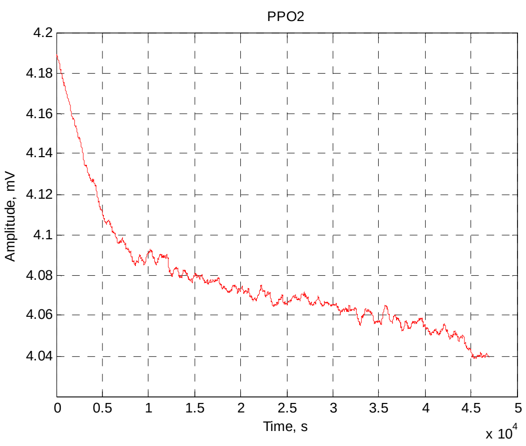
18.3 Test 2: Materials compatibility

Discussion with the manufacturer indicated an acute awareness of the need to avoid plasticisers and organic compounds. The sensor does not have any known materials compatibility issues.

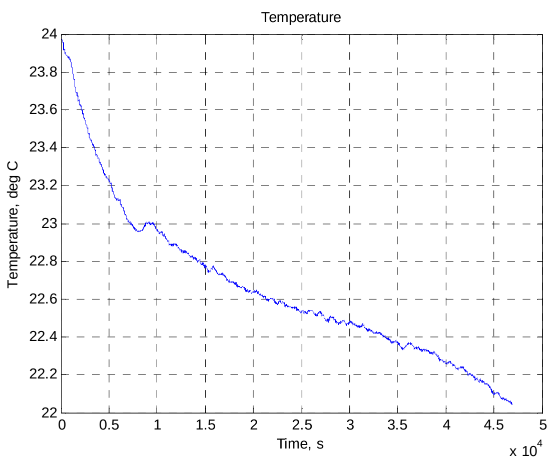
18.4 Test 3. Hydrophobic membrane

Test	Purpose	Method	Result
3. Hydrophobic membrane	Confirm that water is not retained by measurement membrane	1. Use sensor 1. 2. Measure sensor voltage, and record temperature. 3. Place sensor sideways in shallow water bath filled with 3cm depth of sea water at 20C +5C/-2C for 1 minute, then withdraw and position with the sensor face downward. 4. Visual inspection using magnifier for any water held on the face. 5. Measure the output voltage every minute over a 30 minute period. 6. Verify that output does not change more than 3%.	The sensor output change is 1.7%. Accept as a pass.

Step 2: Measure sensor voltage, and record temperature.



PPO2 mean = 4.08 mV



Temperature mean = 22.67 C

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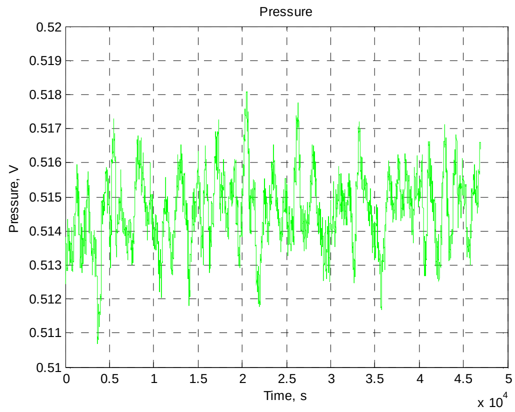
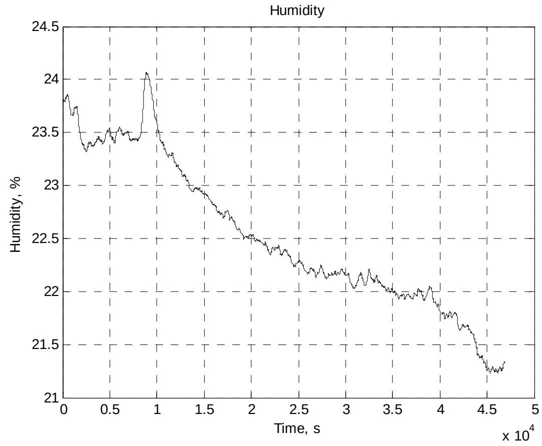
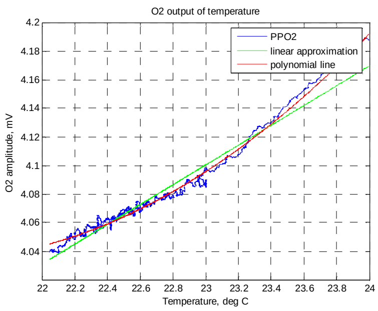


Pressure mean = 0.5146 V

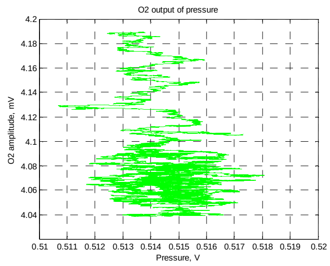


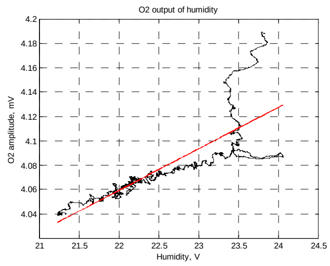
Humidity mean = 22.53%



p = [0.0693 2.5065]

0.07mV/K





p

= [0.0341 3.3097]

Fig 18.4-1: Sensor characteristics before immersion in water (filter: 500).

Step 3: Place sensor sideways in shallow water bath filled with 3cm depth of sea water at 20C +5C/-2C for 1 minute.

Artificial sea water was made by adding1 teaspoon to a cup of still drinking water.

Fig 18.4-2: Sensor in water.

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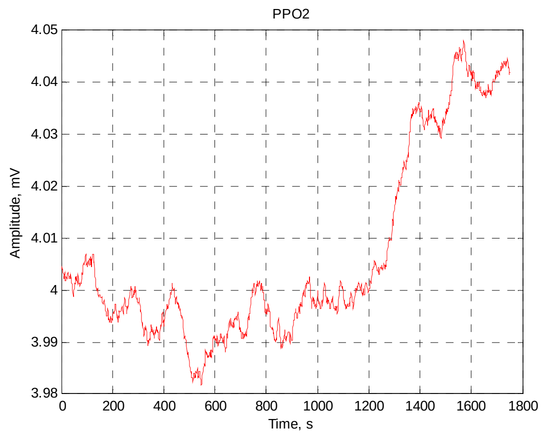
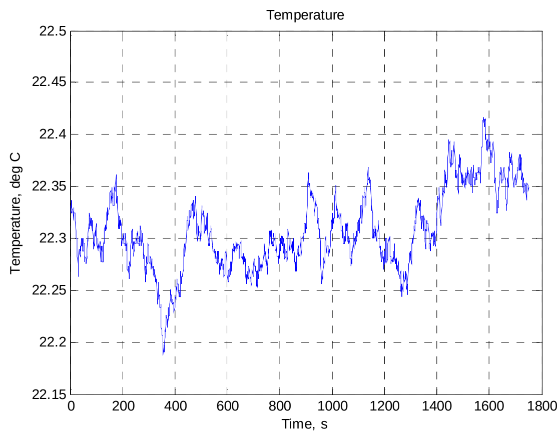
Step 4: Visual inspection using magnifier for water held on the sensor face. There was none visible.

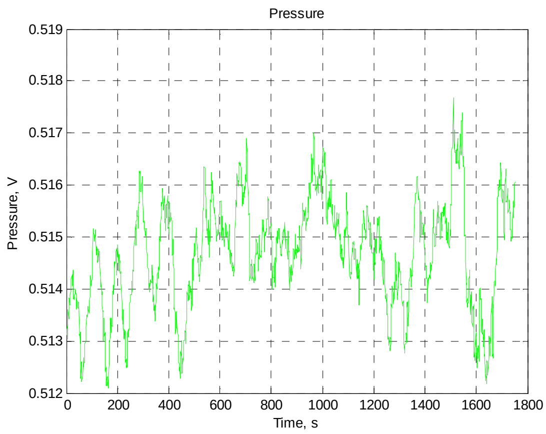
Step 5: Measure the output voltage every minute over a 30 minute period.



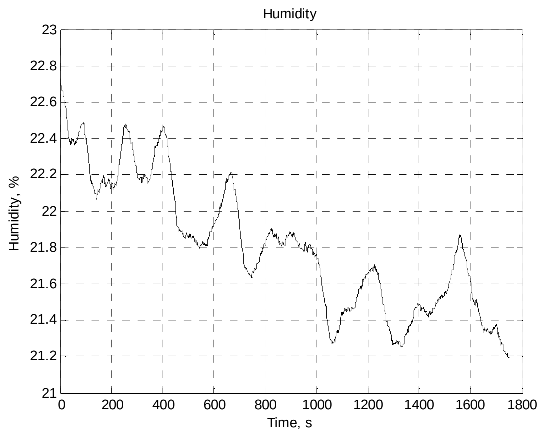
PPO2 mean = 4.01 mV



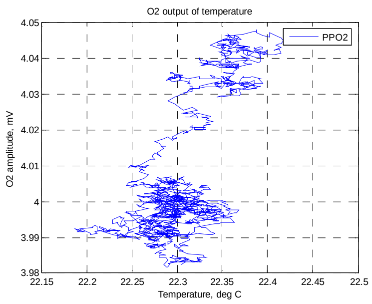
Temperature mean = 22.31 C

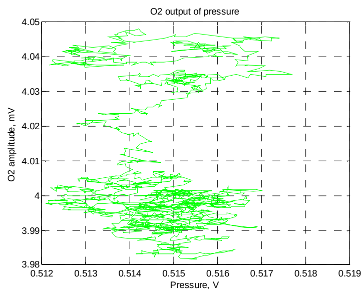


Pressure mean = 0.5147 V



Humidity mean = 21.81%





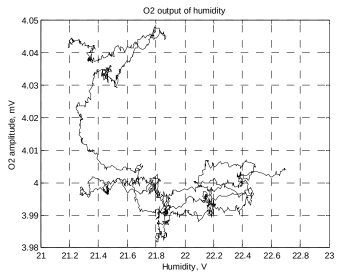


Fig 18.4-3: Sensor after immersion in water (filter: 50). The sensor output change is 1.7%. The ideal figure is under 1%, but after review, the result was acceptable.

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18.5 Test 4. Response time.

Test	Purpose	Method	Result
4. Response time	Measure the time to respond, to 90% of final reading, on a change of PPO2 from 0.21 to 1.0	1. Use sensor 1 and allow output voltage to settle in air. 2. Apply a stream of oxygen to a sensor with a pressure of 30mbar +/-20mbar. Measure the readings every 100ms. 3. Compute response time to a change from 0.21 to 1.0, and from 1.0 to 0.21. 4. Verify that the response is less than 10 seconds to 90% of final value.	Pass.

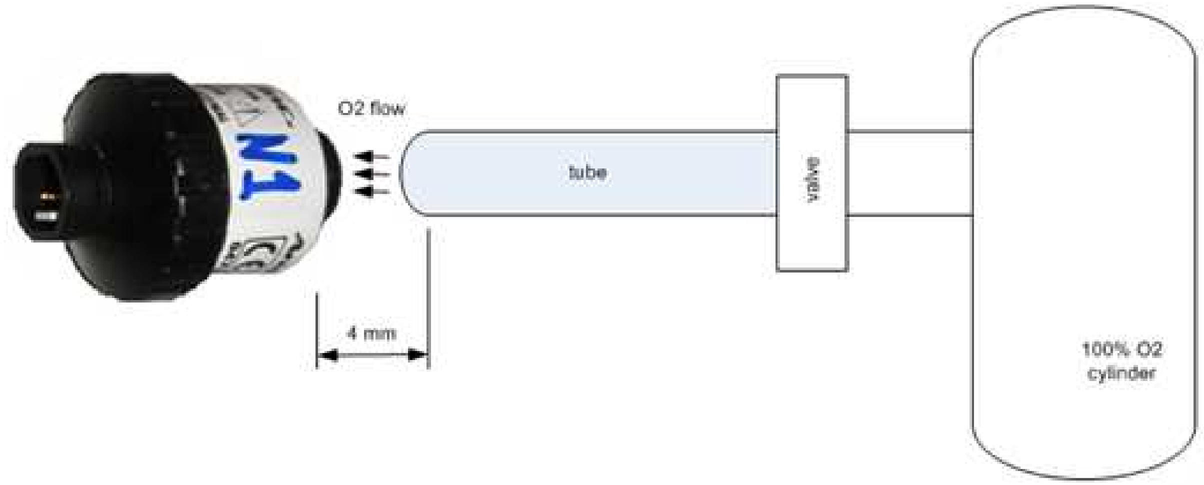

Fig 18.5-1: Test structure for sensor response test.

Step 2: Sensor 1. Apply a stream of oxygen to a sensor with a pressure of 30mbar +/-20mbar. Measure the readings every 100ms.

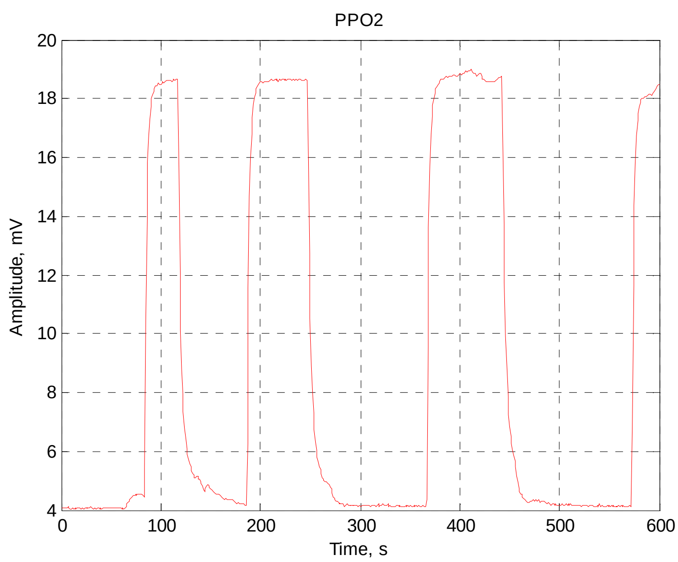

Fig 18.5-2: Output from sensor with pulsed O2 flow.

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Step 3 & 4: Sensor 1. Compute response time to a change from 0.21 to 1.0, and from 1.0 to 0.21. Verify that the response is less than 10 seconds to 90% of final value.

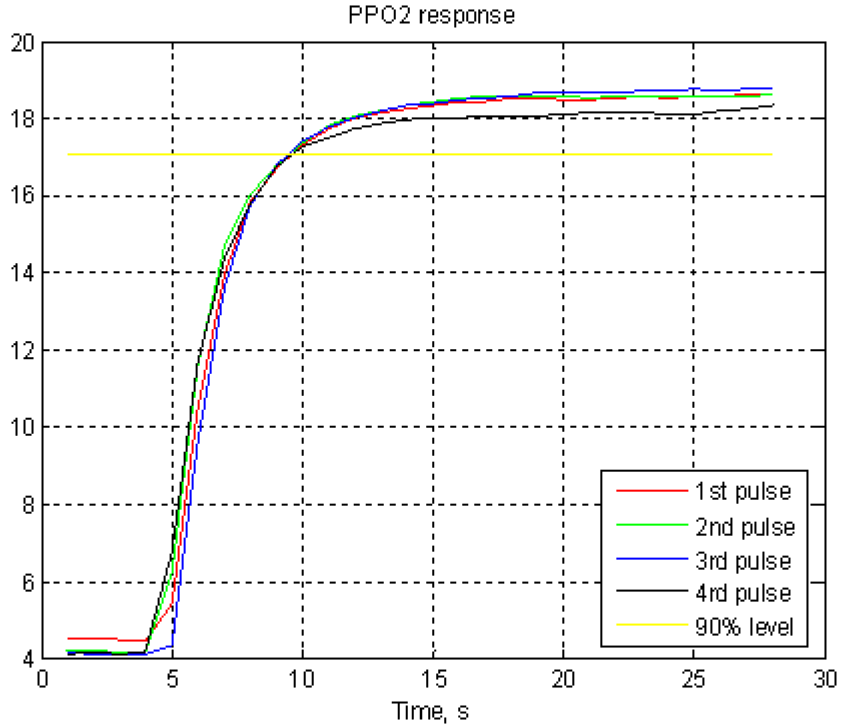

Fig 18.5-3: PPO2 time response. 90% level is 17.07 mV: (18.5-4.2)*0.9+4.2. Rise response is 6 s. The sensor output is about 18.5 mV when the sensor is in 100% O2.

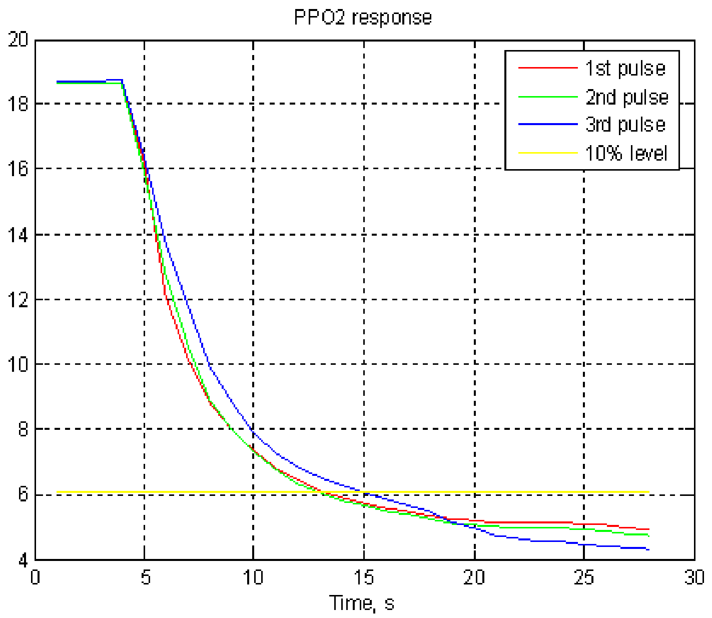

Fig 18.5-4: PPO2 time response. 10% level is 6.1 mV: (18.7-4.7)*0.1+4.7. Fall response is 10s. There is some retained O2 in the measurement fixture, so this figure equates to a fall response time of 6s.

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Step 2: Sensor 3. Repeat of Experiment. Apply a stream of oxygen to a sensor with a pressure of 30mbar +/-20mbar. Measure the readings every 100ms.

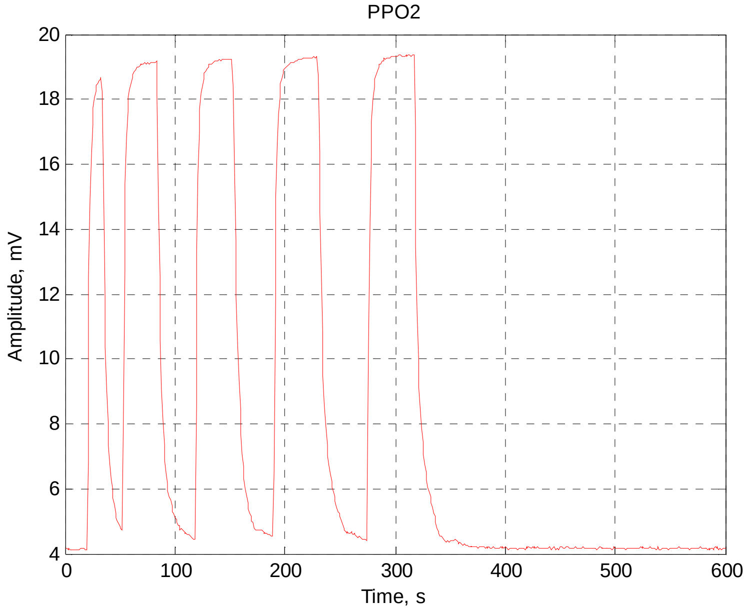

Fig 18.5-5: PPO2 of CO2 pulse flow.

Step 3 & 4: Sensor 3. Repeat of Experiment. Compute response time to a change from 0.21 to 1.0, and from 1.0 to 0.21. Verify that the response is less than 10 seconds to 90% of final value.

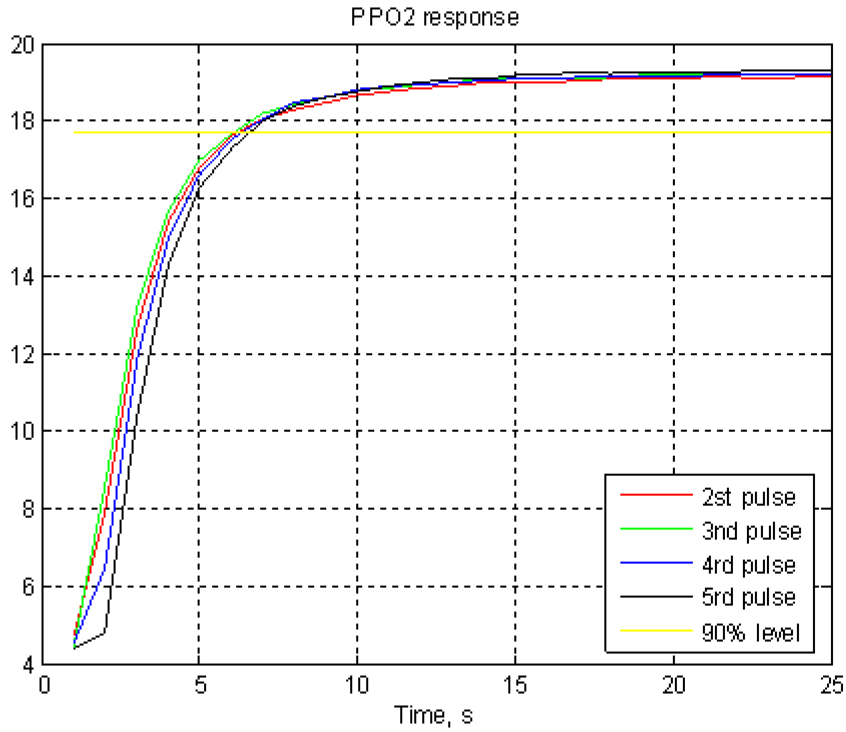

Fig 18.5-6. PPO2 time response. 90% level is 17.75 mV: (19.2.5-4.7)*0.9+4.7. Rise response is 6s.

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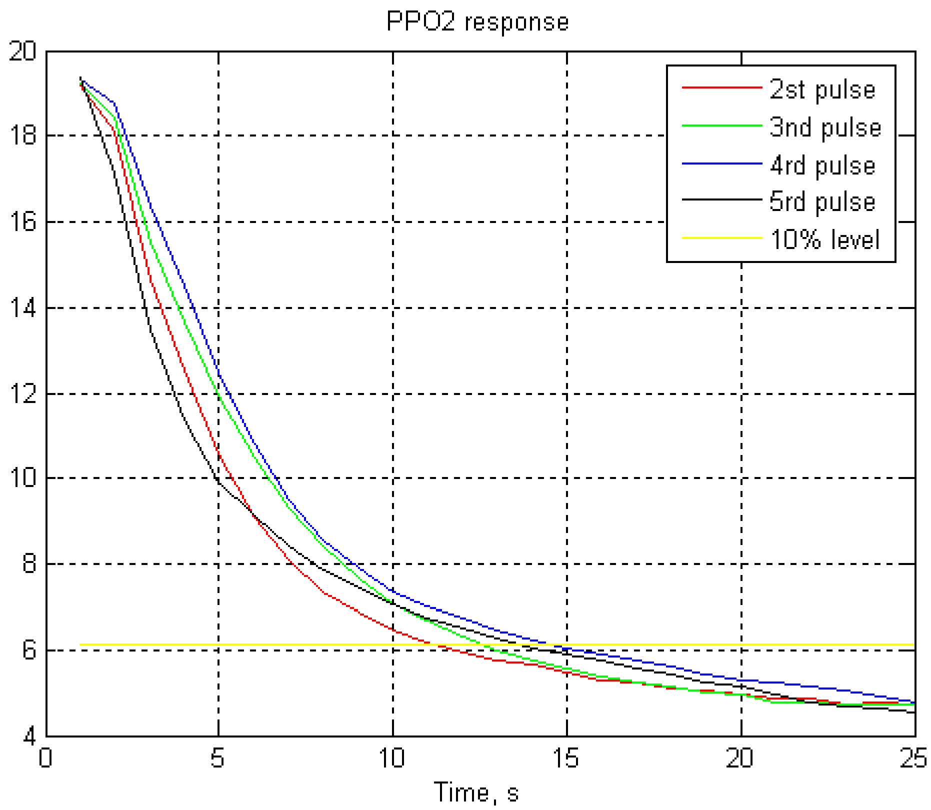

Fig 18.5-7: PPO2 time response. 10% level is 6.15 mV: (19.2-4.7)*0.1+4.7. Fall response is 13s, which equates to an actual response of under 10s due to the O2 retained in the cavity around the sensor face and in the tube.

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18.6 Test 5a. Temperature range.

Test	Purpose	Method	Result
5a. Temperature range.	To verify linearity over full temperature range.	1. Use sensor 1 2. Place in the 300mm dia compression chamber immersed in saline, with the DL Compact Breathing Machine. 3. Cool chamber to -4C for 3 hours, then run breathing machine at 4x2.5l strokes per minute to mix the gas, record temperature, humidity. 4. Heat the chamber at 1C per minute to 90C. 5. Record temperature, pressure, humidity and measured PPO2 throughout test. 6. Correct results for pressure changes during test.	Pass, noting the compensation coefficients

Note: Sensor manufacturers state the operating temperature range is -10C to 45C, or -5C to 50C, with exposure to 60C for 30 minutes, and do not recommend taking the sensor to 90C.

The purpose of Test 5a is to verify the accuracy of that range, and the effect of a sensor being in a rebreather in the sun, where it can be exposed to 90C. The test should determine if there is any dangerous off-gassing or leakage, or permanent damage.

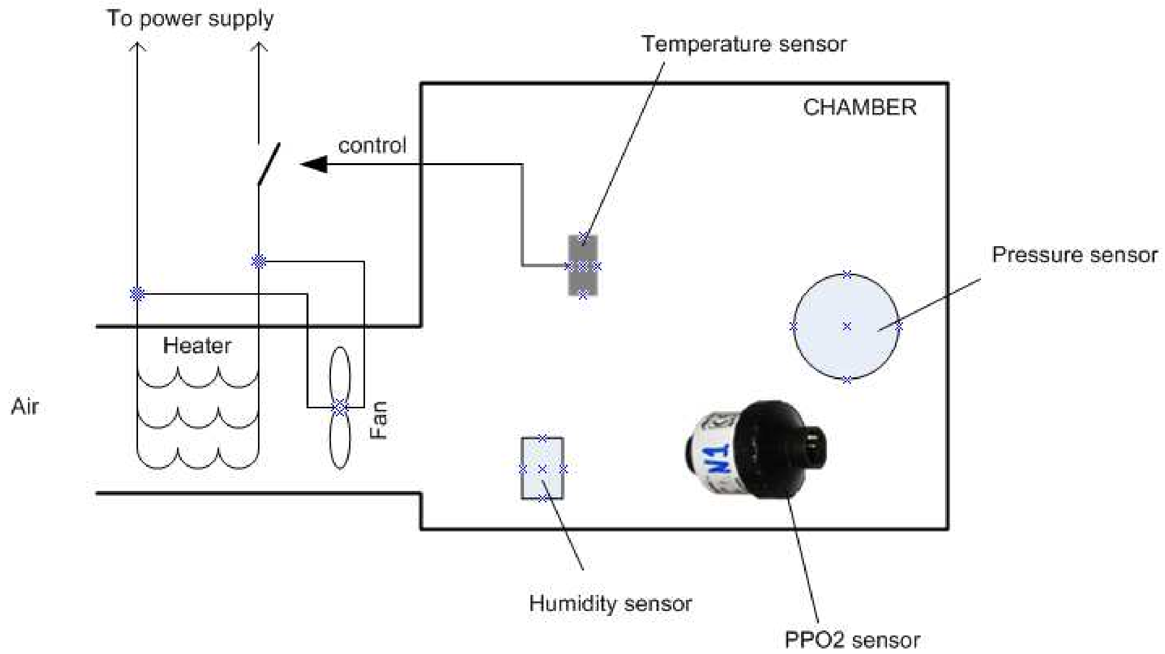

Fig 18.6-1. Test fixture for Test 5a

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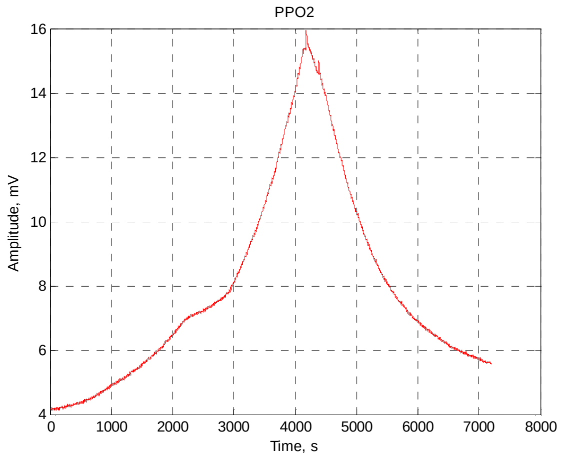
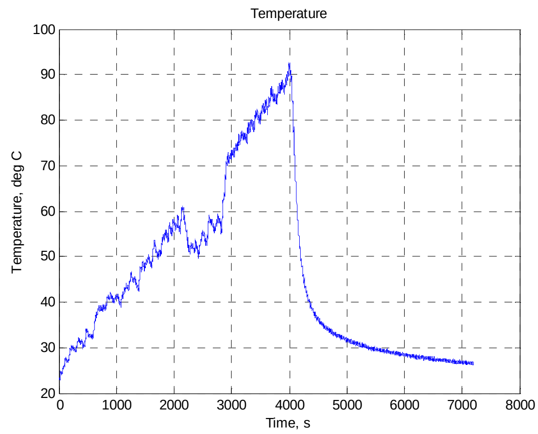
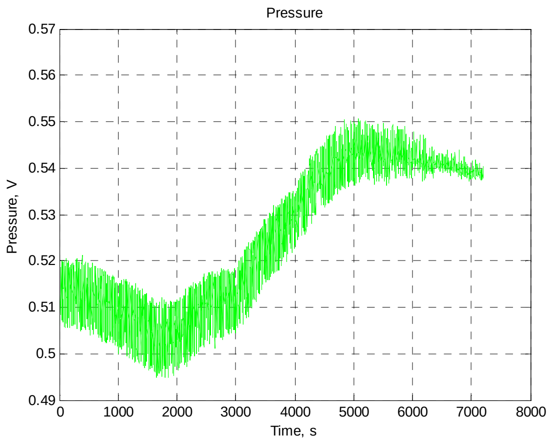
Up/down temperature.



Peak is at 4175s.



Peak is at 4002s.



Peak is at 5074s.

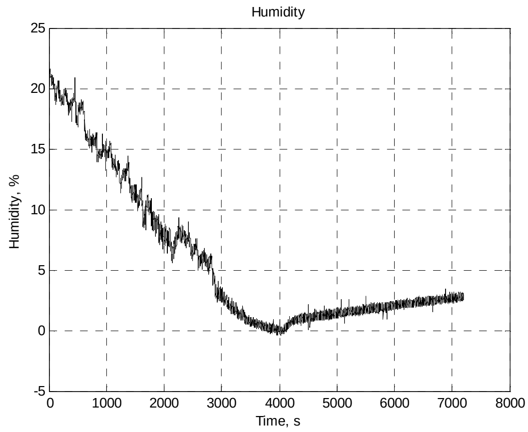


Fig 18.6-2. Maximum output from sensor is reached 173 s after the temperature starts to fall from 90 deg at 4002s. The probable reason for the delay in reaching the maximum of the oxygen sensor output is the temperature capacitance of the sensor and the temperature resistance between the sensor and environment.

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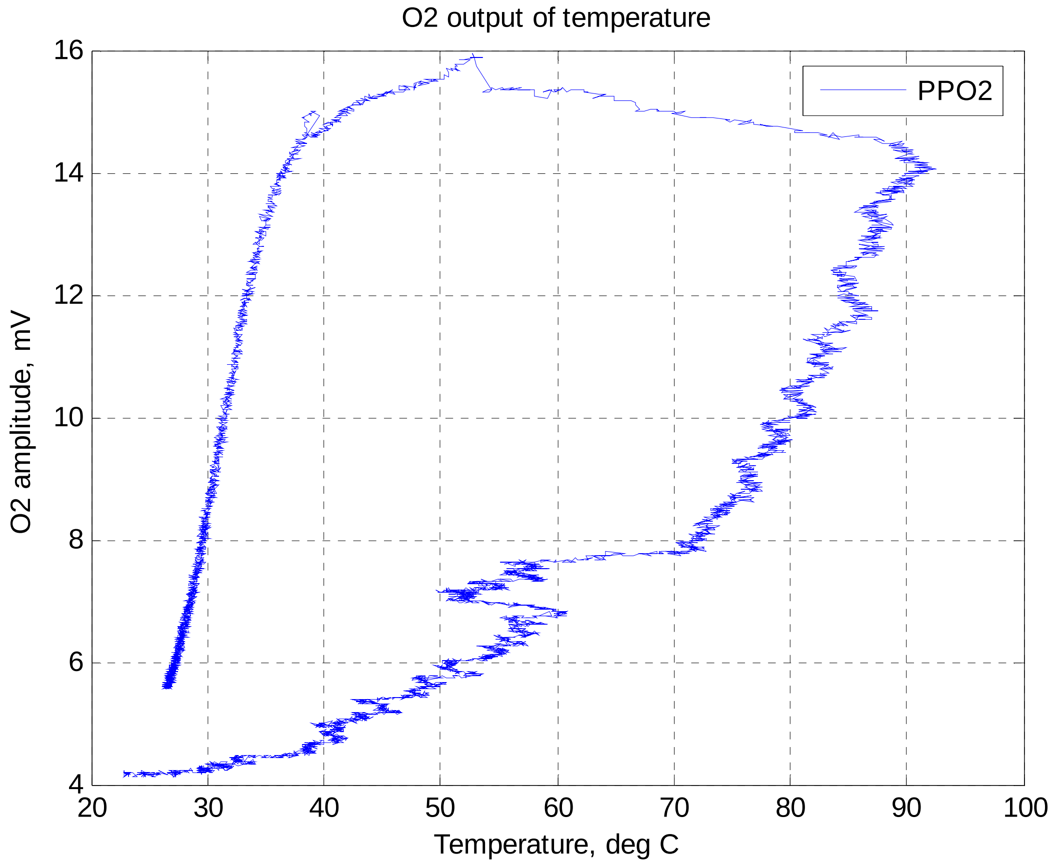
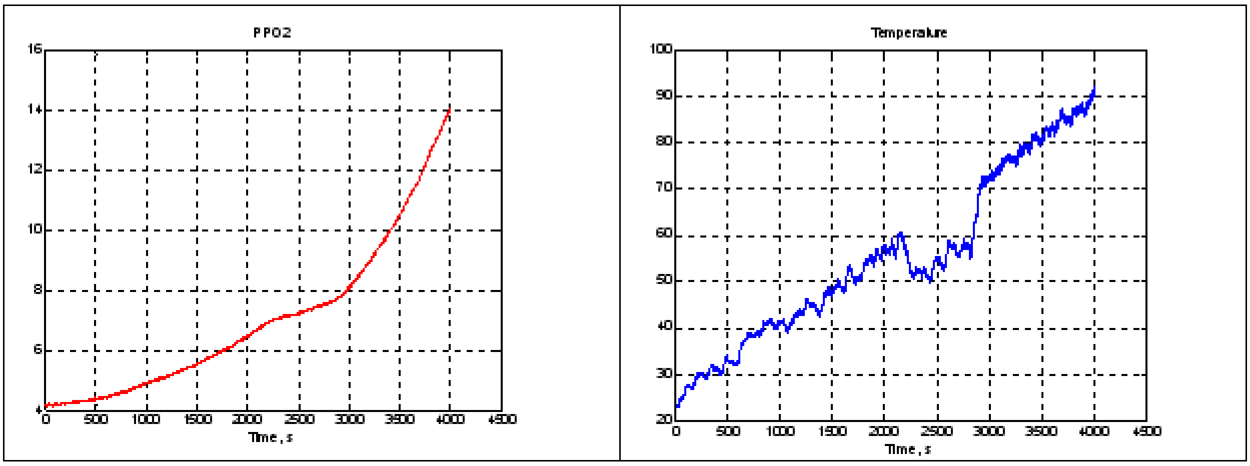


Fig 18.6-3. Output of cell as a function of temperature (PPO2 label is of apparent PPO2 voltage, PPO2 was constant during the test).

Step 4: Raise temperature for 4002 seconds.



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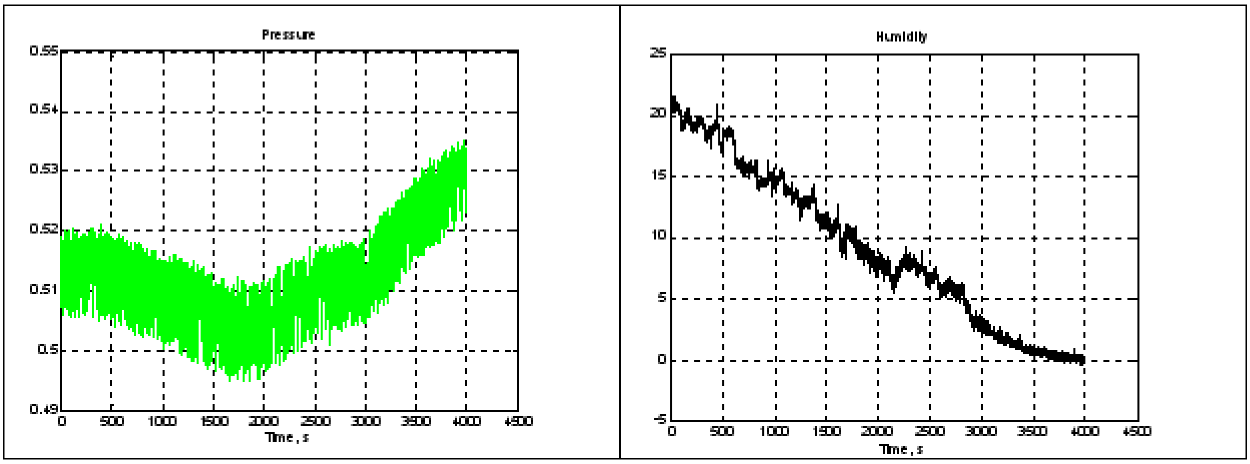

Fig 18.6-4. Effect of temperature, pressure and humidity.

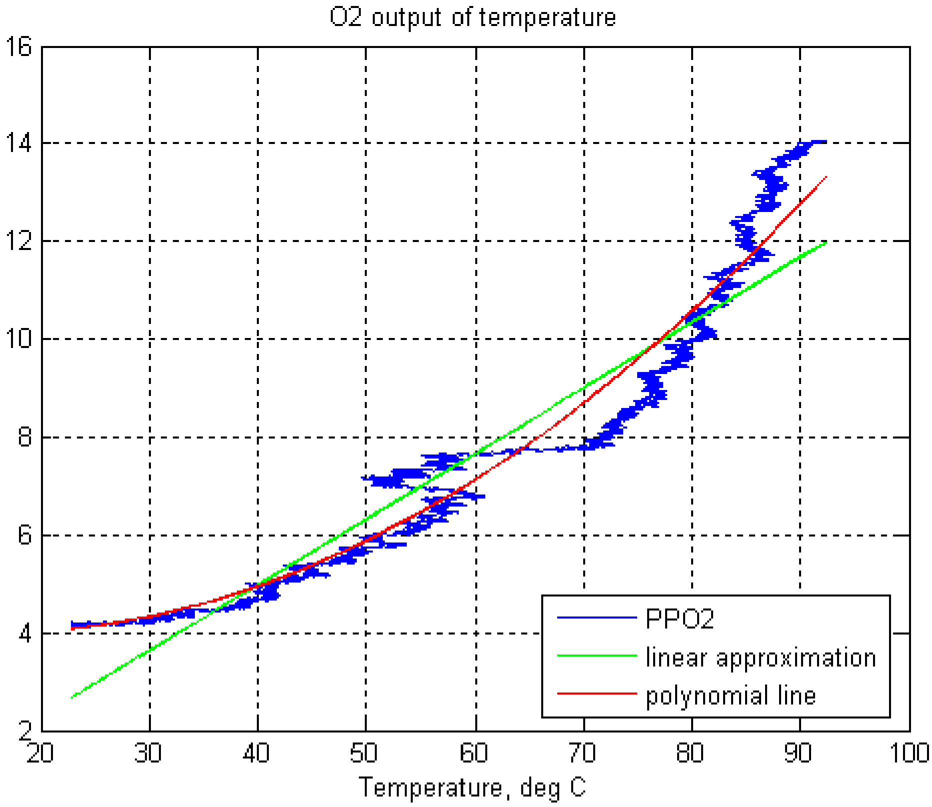

Fig 18.6-5. Cell output in mV as a function of temperature during the positive temperature ramp. Label of PPO2 is apparent PPO2 voltage, that is the actual cell output: PPO2 itself was constant during the test. The linear approximation of the temperature dependence of the cell is PPO2 = 0.1341*t - 0.3835, and a better second order polynomial approximation is PPO2 = 0.0016*t^2 - 0.0490*t + 4.3827. The cell error due to temperature is about 0.2ATA/30K.

The following graphs show the cell performance during the drop in temperature between 4175 seconds (at the peak of PPO2 reading) and 7200 seconds into the test.

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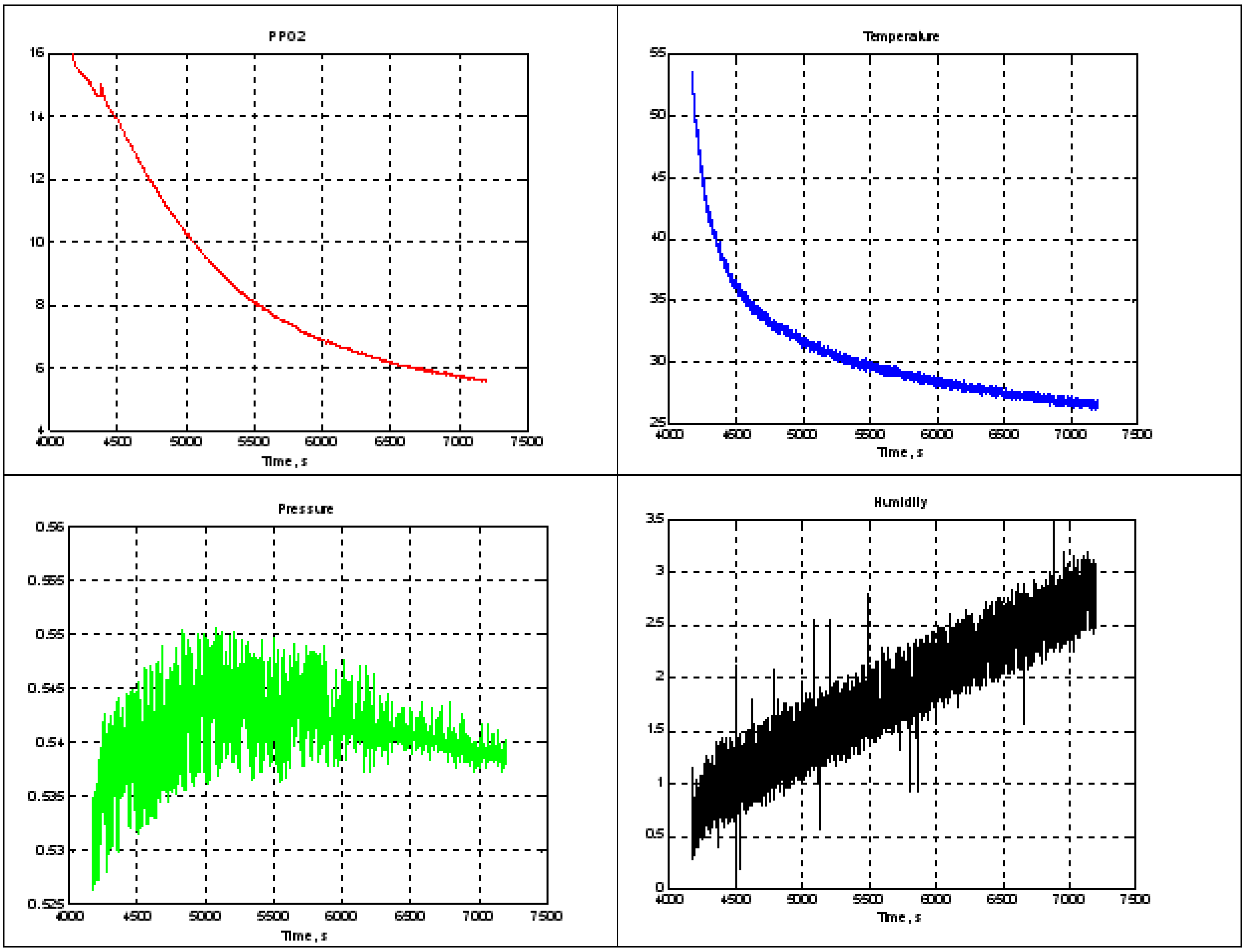

Fig 18.6-6. Apparent PPO2 while the sensor is cooling. All conditions are otherwise the same as for the previous test.

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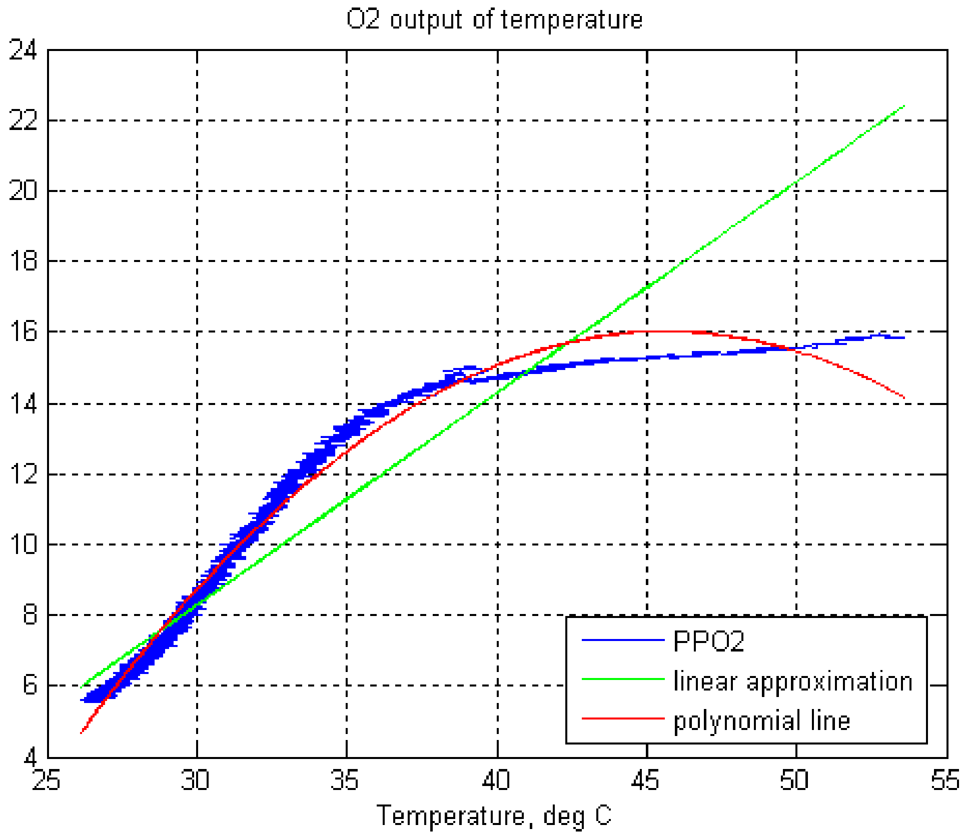

Fig 18.6-7. Cell output in mV as a function of temperature during the cooling phase. The label of PPO2 is apparent PPO2 voltage, that is the actual cell output: PPO2 itself was constant during the test. The linear approximation of the temperature dependence of the cell is PPO2 = 0.5977*t - 9.6380, second order polynomial approximation is PPO2 = -0.0296*t^2 - 2.7073 *t - 45.8348

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18.7 Test 5b. Cell Stability.

Test	Purpose	Method	Result
5b. Stability.	Confirm sensors are stable in air and confirm calibration interval required for their use	1. Use sensors 2 and 3. 2. Measure the output voltage with a 10K load, once per day, for six months. Record atmospheric pressure, temperature and humidity. 3. Correct data for temperature and pressure. 4. Confirm results are within 5% throughout the measurement period. 5. Extrapolate any trend to verify that operating life is not less than that quoted by manufacturer.	Pass

The sensors are still undergoing testing, but have passed since the start of the tests to date.

18.8 Test 6. Shock test from 3m and 1.5m

The following tests identified a weakness in the sensor design, which was addressed by the manufacturer. Results are described for the sensors as received, then again for a further batch of twelve sensors incorporating design changes to overcome this deficiency.

Test	Purpose	Method	Result
6. Hard Drop test from 3m.	Test robustness. Test simulates effect of a sensor being mounted in a CCR transported by an RHIB.	1. Use sensor 1. 2. Photograph the sensor to be tested. 3. Measure the output voltage in air with a 10K load. 4. Drop 3m on to a hardwood surface 10 times. 5. Measure the output voltage in air after each drop. 6. The output voltage should not change more than 2% after 10 drops. 7. Drop 3m onto a wooden board laid on concrete 10 times and measure flow rates at 1ATM. 8. Photograph the external surfaces again. Repeat response time test and by comparison with the image from Step 2 and with other physical samples, note any visible damage. 9. Sensor then to be monitored for changes against the reference group.	Acceptable but requires careful design of fixture around sensor. Recommend design changes to sensor manufacturer.

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Note: In diving, equipment is subject to greater shocks than the human diver. The largest shocks identified in normal use occur when equipment is laid on the floor of an RHIB (a Rigid hull inflatable boat), which can be driven at speeds of up to 60 knots. The occupants sit on the inflatable walls, but still complain of back ache after a journey: the shock to the equipment laid on the floor is similar to a drop of 3m. In rough seas the speed is reduced considerably, but the RHIB then powers off the peaks of the waves, falling into the trough of the following wave, with drops of up to 3m before the dive is cancelled: the Surface Marker Buoy used to locate the divers, in areas such as Scotland and Norway where these wave heights are considered diveable, have a height of 2 to 3m. When waves are above 3m, it is too difficult to locate the divers in the water. Again a 3m drop occurs, which the occupants are cushioned from because they bend their legs and sit on a 1m high inflatable cushion (the RHIB sides).

Steps 3-7: Sensor drop test results (Sensors prior to product improvement)

The initial output voltage in air with a 10K load is 5.1mV.

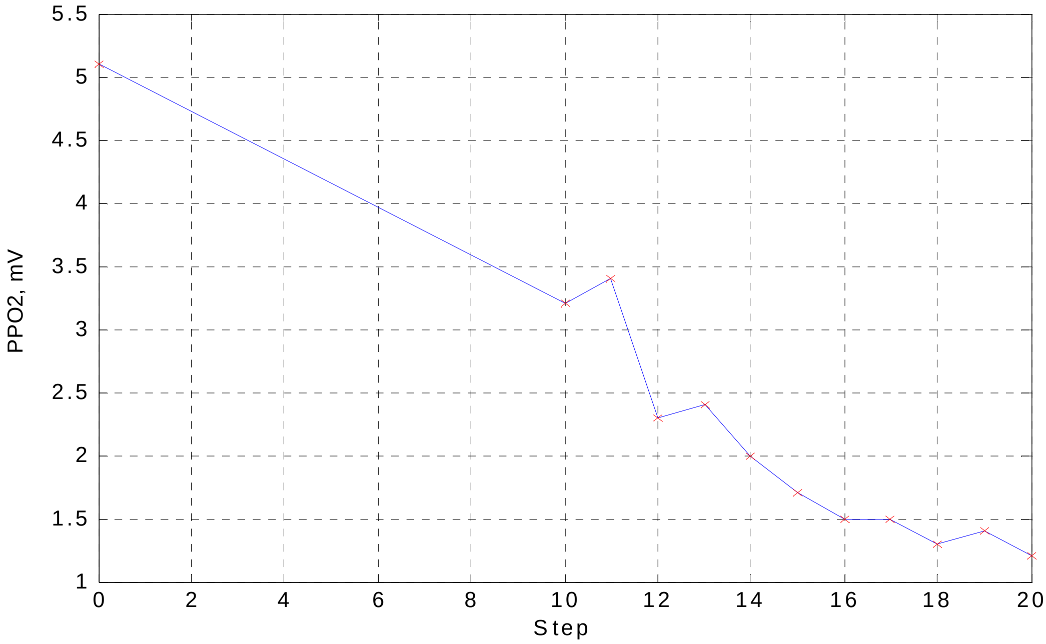

Fig 18.8-1. The apparent PPO2 voltage, i.e. the cell output. The cell output of 1.2 mV is after 20 drops onto two types of surface as specified by the test plan. Each drop decreases the initial output by about 3%. After the ninth drop, with the output at 3.2, a component became loose inside the sensor; that is, the damage became visible.

Step 8: Photograph the external surfaces again. Repeat response time test and note any differences.

Fig 18.8-2. Broken PPO2 sensor. Part of the membrane is out of the housing.

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18.8.1 Detailed analysis of first drop in experiment

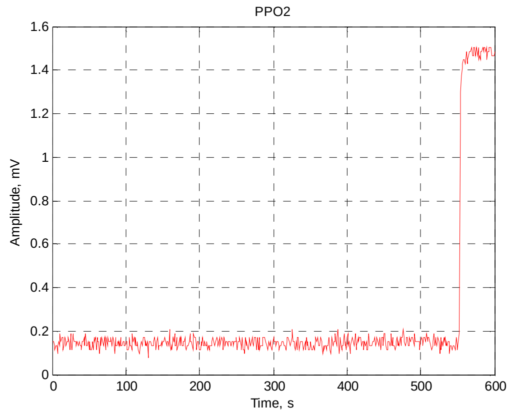

Fig 18.8.1-1. PPO2 sensor in 100% O2 flow. Before the drop test, the PPO2 in air was 4.17mV. It is less than 1.2 mV after the drop test. After the drop test, the PPO2 sensor does not respond to a pulse of 100% O2 flow (the two drops in humidity are noted to confirm the timing of the O2 pulse, from 40-100s and from 160-240s). Suddenly (in air at 550s) the PPO2 sensor increases its output to 1.44 mV. Before the drop test the output of the sensor in 100%O2 was 18.5mV.

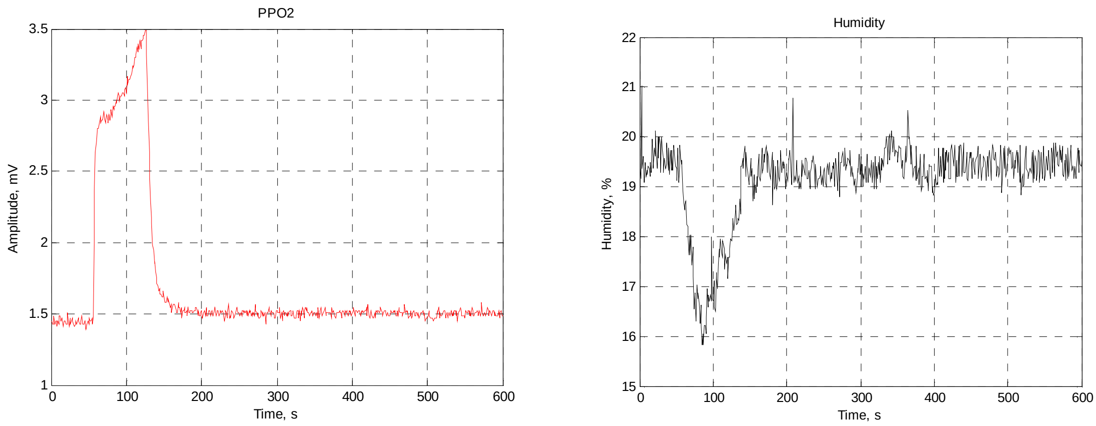

Fig 18.8.1-2. PPO2 sensor in 100% O2 flow. Drop in humidity from 60-130s shows the time of O2 flow pulse.

18.8.2 Steps 2-7: Sensor 5 drop results, from 1.5m (sensor prior to product improvement)

A hard drop from 1.5 meters was carried out on sensor 5. The data from the test is shown in the following table.

Drop number	Output voltage, mV	Note
	5,6	Before the drop
1	3.5	
2	3.6	
3	3.2	

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4	-1..+1.2	Floating output. No visible changes.
5	16.9..+24	Floating output. No visible changes.
	4.4	Stable output two days later

When damage does occur, the sensor changes its calibration point, then fails completely. The damage was visible to the naked eye when this complete failure occurred in one instance but not the other. The batch of twelve sensors were therefore deemed unsuitable for rebreather use due to insufficient mechanical robustness. The results from these tests were sent to the manufacturer, who responded with a commitment to carry out research to find the causes of the mechanical problems and address these with the highest priority.

The manufacturer's response was from the highest level in the company and the action was well resourced. A series of improvements were identified and implemented by the manufacturer. An example of the manufacturer's test results on these improved sensors is shown in the chart below. A batch of twelve further sensors with these improvements was sent to Deep Life for independent verification.

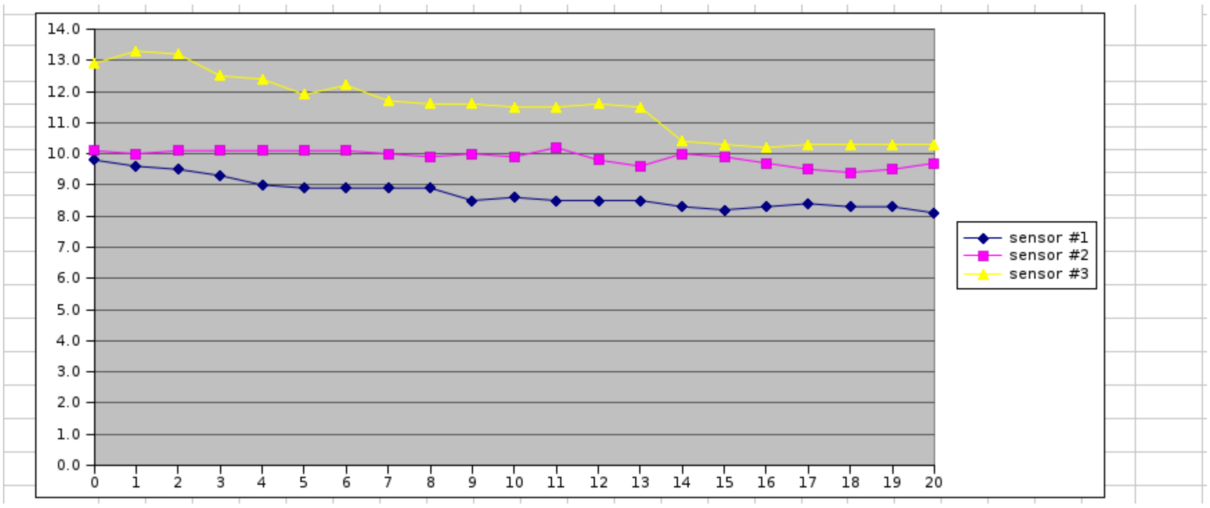

Fig 18.8.2-1: Manufacturer's results on a sample of three sensors with the mechanical improvements to improve robustness. Note the sensors show small rises, of a few percent in value, in the worst case, from 9.4mV to 9.7mV, a 3.19% change. This may be due to temperature changes or mechanical creepage.

Twelve sensors were retested by Deep Life with these improvements, labeled 13 to 24.

18.8.3 Shock tests on improved sensors

The sensors with the improvement to the mechanical resilience were tested and found to support the manufacturer's data above. The mechanical improvements that have been made have been disclosed by Analytical Industries to Deep Life Ltd, and appear to be effective.

18.9 Test 7. Linearity with pressure, and susceptibility to helium

Test	Purpose	Method	Result
7. Linearity with pressure, and susceptibility to	Confirm operation over required range of PPO2 and pressures.	1. Use sensor 4. 2. Fit sensor inside a DL Compact Breathing Machine, in a pressure chamber.	Pass: operates correctly over range 4 bar to

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helium.		3. Set the breathing machine to 4x2.5l strokes per minute to mix the gas in the chamber. 4. Starting at 1ATM, measure output voltage, temperature, humidity and pressure with a 10K load, while increasing the pressure in the chamber, by injecting air, to a pressure equivalent to a depth of 100msw with a maximum rate of descent not exceeding 30m/min. 5. Bleed off air until the PPO2 falls to 1.3. 6. Add helium with a maximum rate of descent of 30m/m, recording output voltage, temperature, humidity and pressure, until the pressure is 141 bar absolute (2000msw). 7. Correct data for changes in temperature using the results from Test 3. 8. Plot linearity with PPO2. 9. Plot linearity with Depth. 10. Do not decompress: move to Test 8.	14 bar relative to ambient.

Steps1 and 2:

Fig 18.9-1. O2 sensor test fixture. Gauge on top of chamber is for safety only: pressure readings were taken digitally (electronically).

The initial state of the sensor in air was recorded as shown below.

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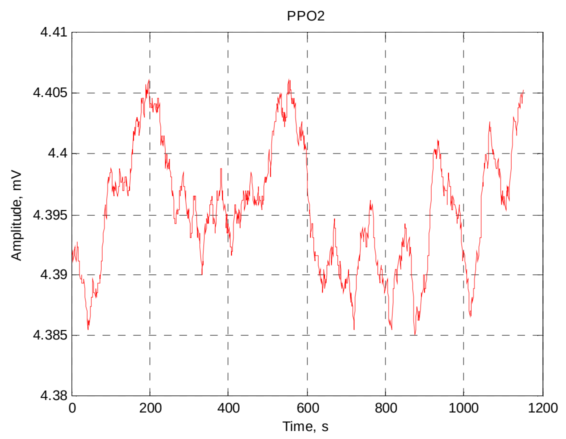
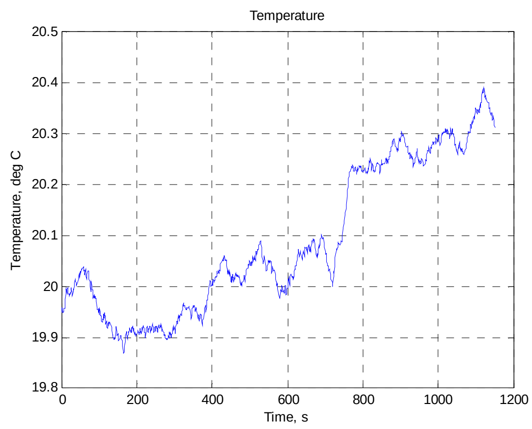
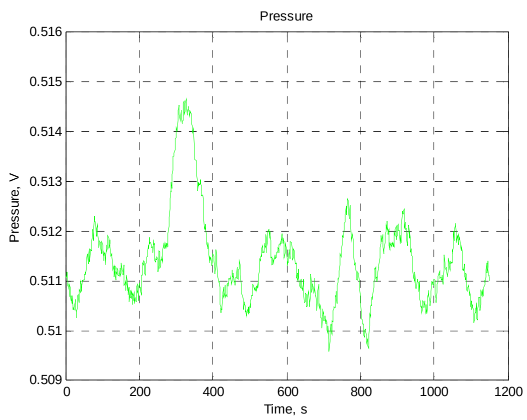


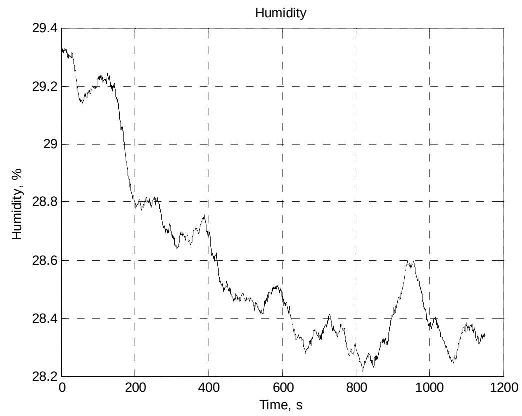
PPO2_mean = 4.40 mV



Temperature mean = 20.09 C



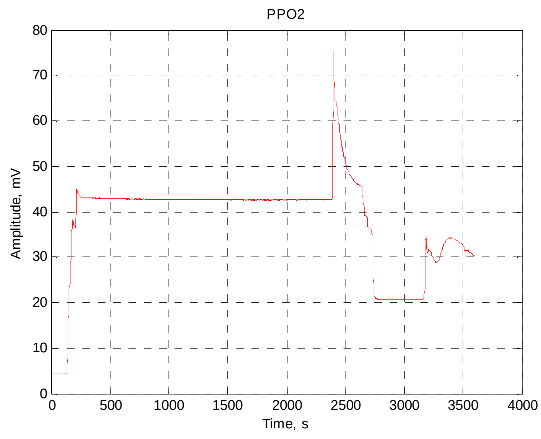
Pressure mean = 0.5114 V

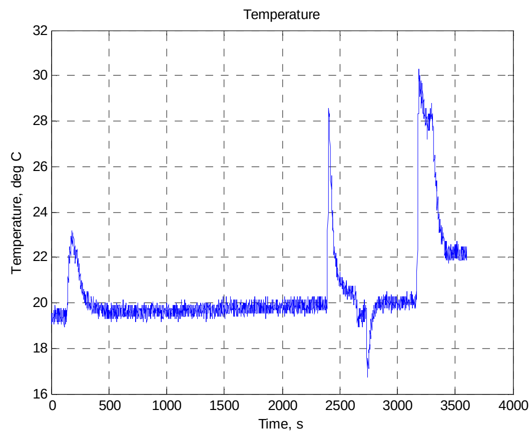


Humidity mean = 28.59

Fig 18.9-2. Initial state of the sensor in air. Filter window is 50.

Step 4 onwards.





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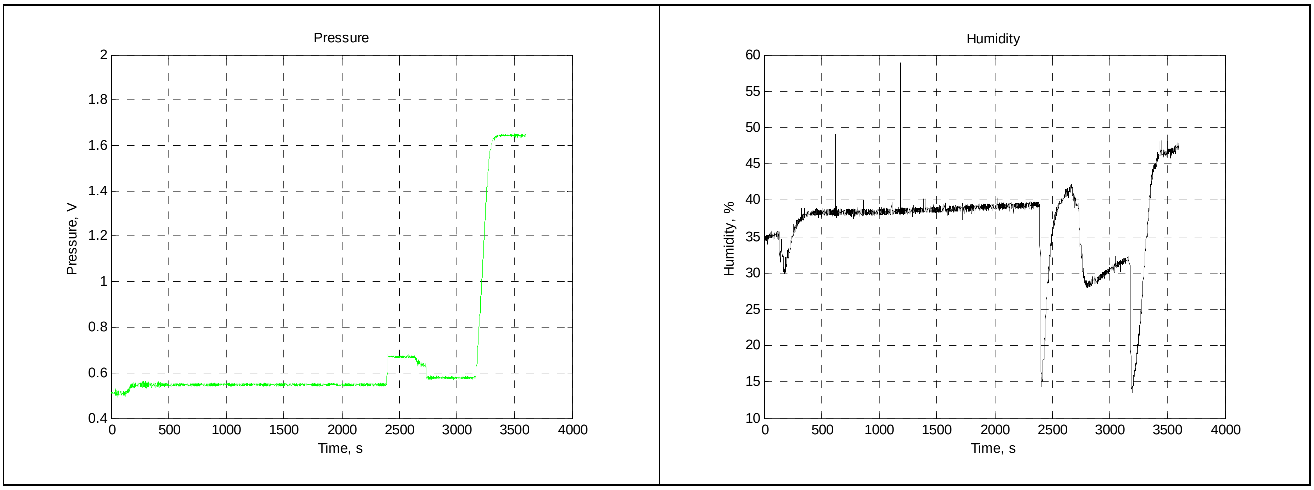

Fig 18.9-3. Sensor in O2 and then in He. Filter window is 0. These results were analysed carefully. The sensor has a lower output sensitivity when under high pressures of helium. The graphs show the raw voltage levels from the sensors, other than for humidity.

18.10 Test 8. Uncontrolled ascent and test for cathode movement

Test	Purpose	Method	Result
8. Uncontrolled ascent and test for cathode movement.	To verify the sensor is not damaged if decompressed at the fastest rate a human can ascend in sea water (120m/min).	1. Use sensor 4 2. From 2000msw, decompress linearly, at a rate of 120m/min. 3. Check output of cell in air at 1 ATM. 4. Recompress at 30m/min, then repeat test 10 times. 5. Examine cell for signs of leakage. 6. Store sensor with face vertical and check no damage to rear PCB from leaking electrolyte.	Determine maximum safe ascent rate using a second sensor.

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Fig 18.10-1. Test chamber showing attachment point below for pressure sensor

The experiment was run repeatedly due to inconsistent results in the first experiment. The first run is not recorded for this reason: results below are for the second, third and fourth runs.

Step 2: Experiment run 2. After second Test 7.10, shown above, place under high pressure for 24 hours.

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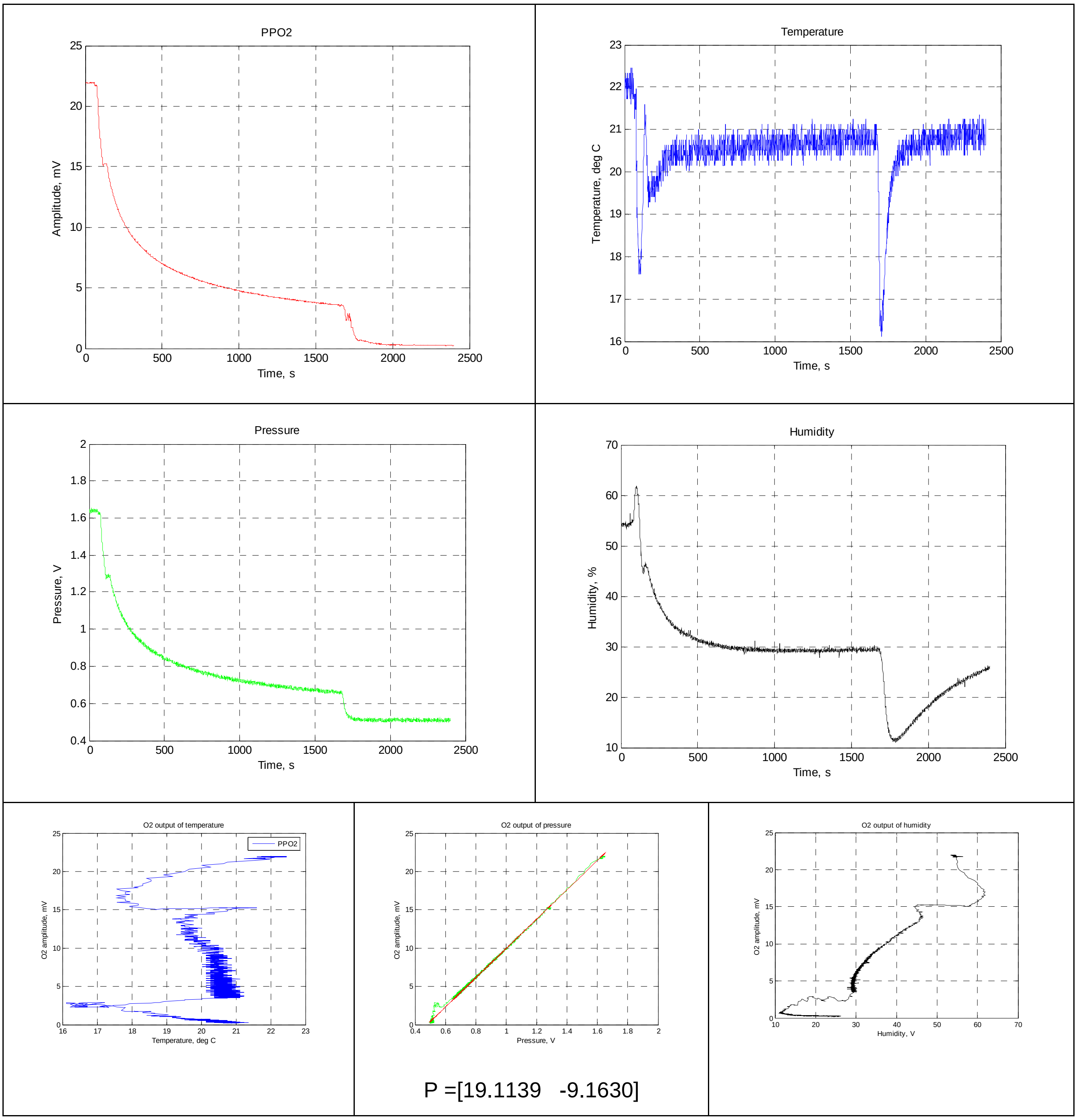

Fig 18.10-2. PPO2 is proportional to the O2 concentration.

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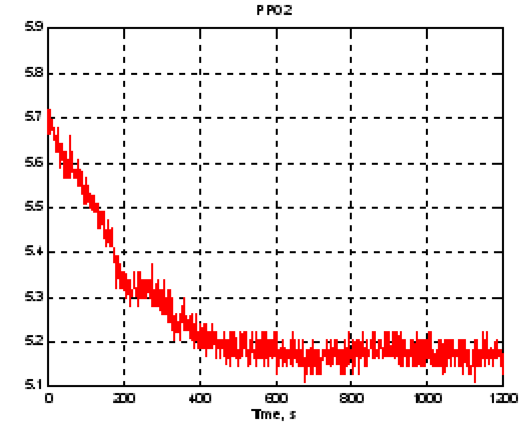
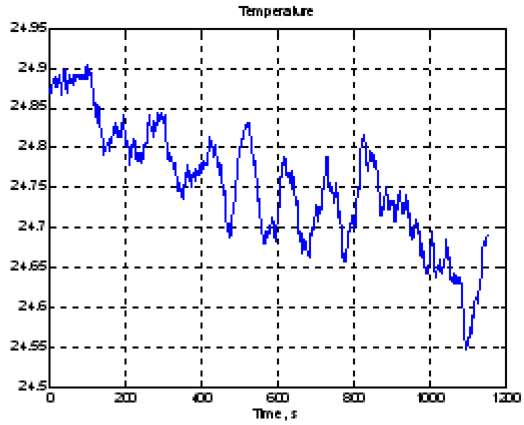
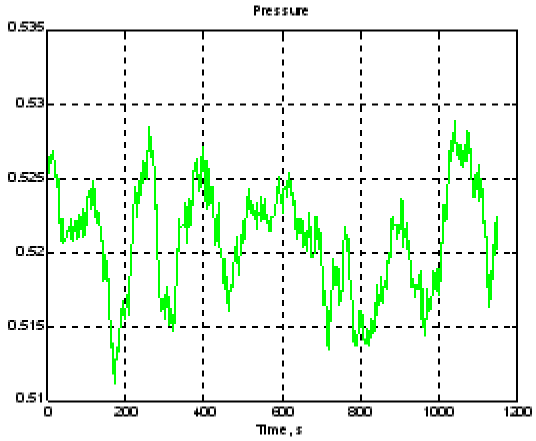


Filter window is 0



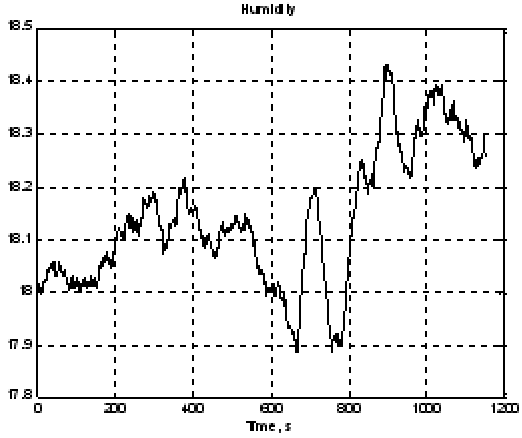
Filter window is 50

Temperature mean = 24.75 C



Filter window is 50

Pressure mean = 0.5208 V



Filter window is 50

Humidity mean = 18.14%

Fig 18.10-3. Long PPO2 sensor output restoration in air.

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Step 2: Experiment Run 2. Immediately after first test 7.10.

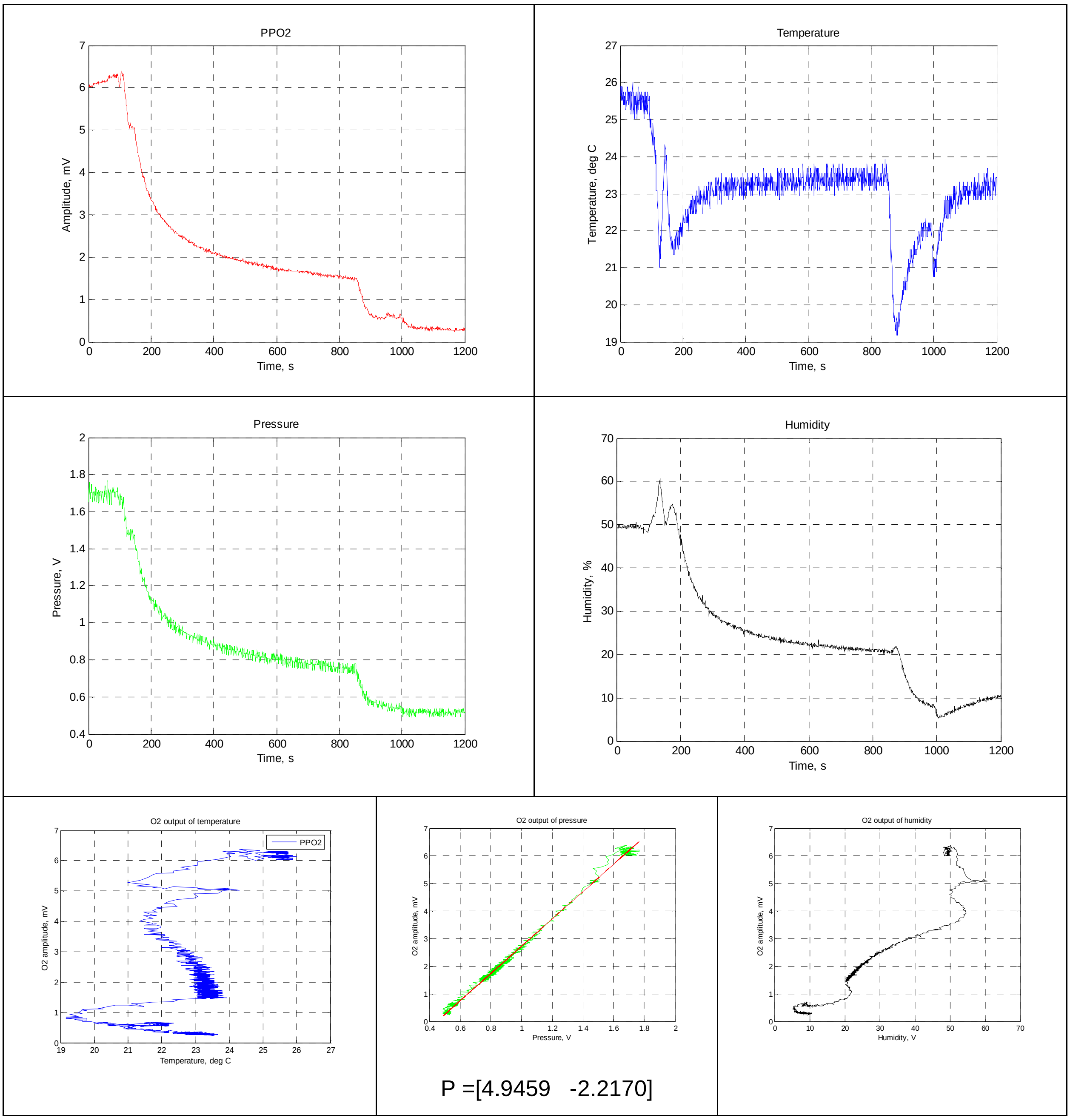

Fig 18.10-4. Run 2, following Test 7.

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Step 4 and repeat of 2: Experiment run 3.

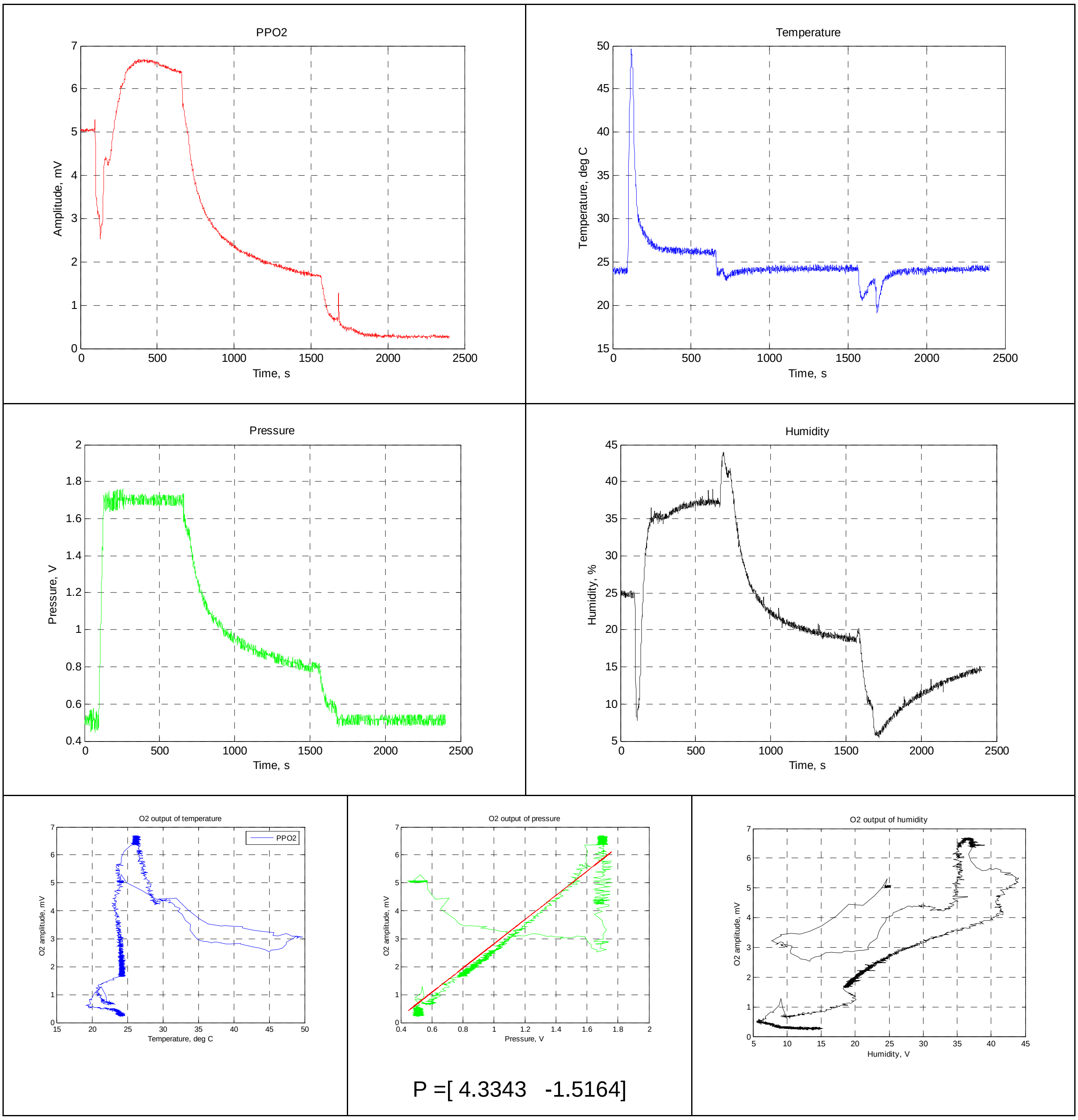

Fig 18.10-5. Rise and fall pressure.

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Steps 4 and 2: Experiment run 4.

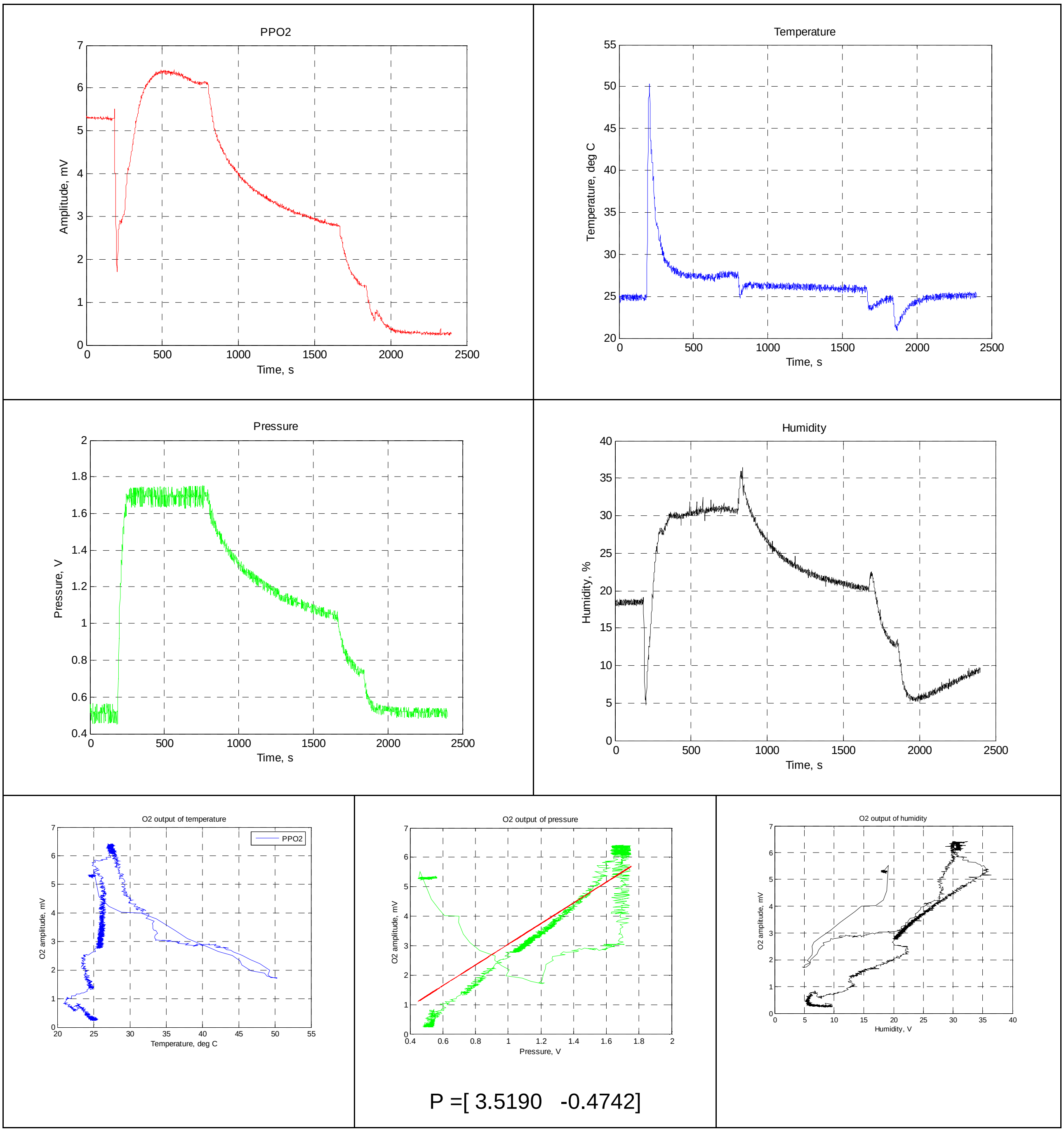

Fig 18.10-6. Rise and fall pressure.

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Steps 4 and 2: Experiment run 5.

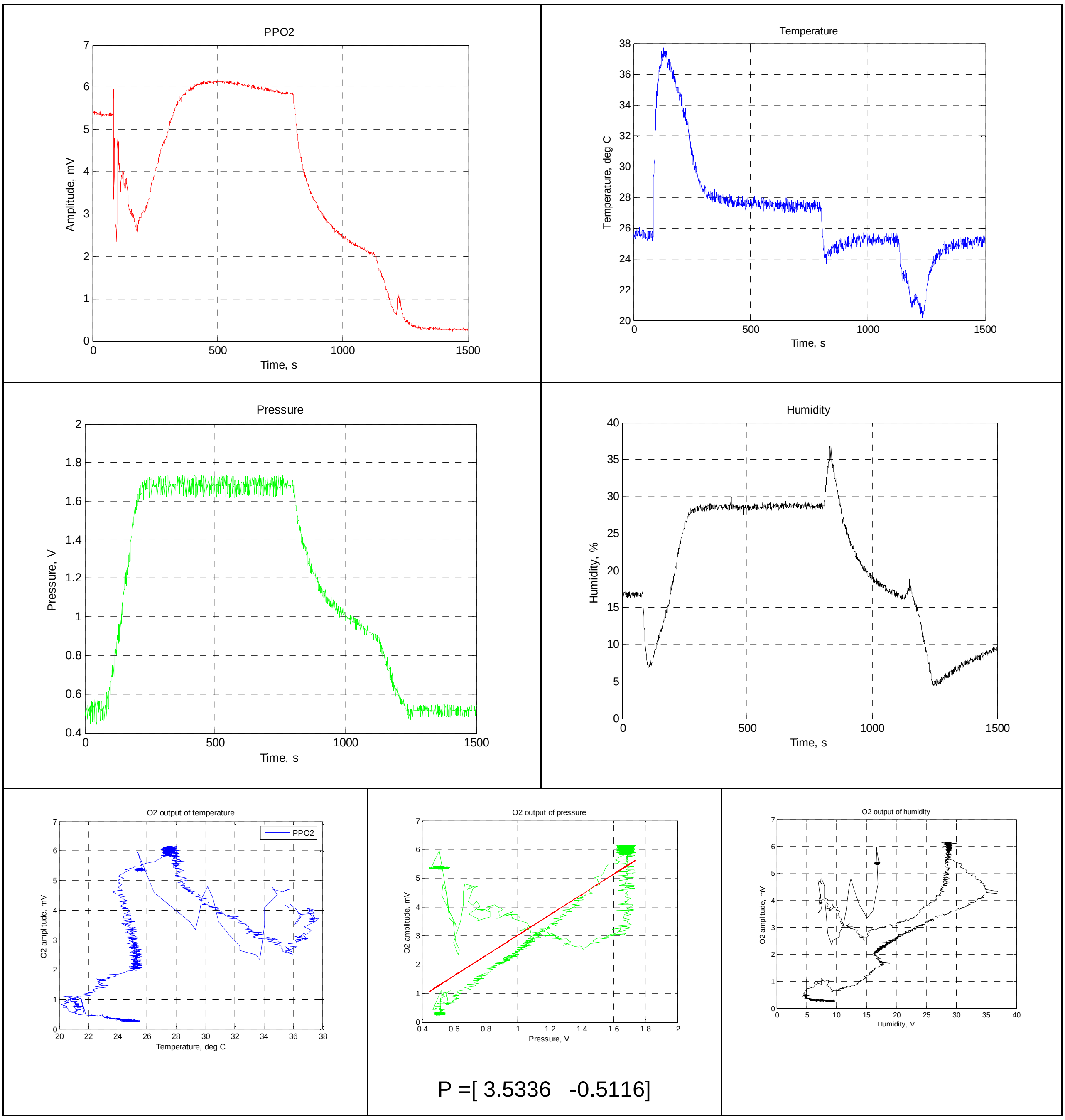

Fig 18.10-7. Rise and fall pressure. PPO2 mean after the test is 0.27 mV

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18.11 Test 9. Chamber Lockout Test (Torpedo Test)

Test	Purpose	Method	Result
9. Chamber Lockout (Torpedo) test	Test effect of worst possible ambient pressure increase or decrease in a chamber lock. Test for gas entrapment leading to risk of explosion or implosion.	See Note on this test, below table. 1. Use sensor 1. This test is the last in the sequence for sensor 1. 2. Wrap sensor in single sheet of 80gm paper. 3. In a chamber rated to 600 bar, increase pressure from 1 ATM to 300 bar in under 1 second, using air. Wait five minutes for sensor to stabilise. Drop pressure from 300 bar to 1 ATM in 1 sec. 4. Check inside of chamber for particles thrown out from sensor. 5. Check paper for holes and leakage. Characterise the sensor after the test for internal damage.	Perfect pass.

Note: Test 9 is a destructive test as part of a safety case required under European Regulations (to meet EN61508). The reason for this test is that sudden compression or decompression in a hyperbaric chamber is a “very likely” scenario, and it is necessary therefore to ensure that no serious injury is likely to be sustained by either the chamber occupant or the chamber technician in handling the sensor after it is withdrawn from an interlock. The sensor is not expected to function: the equipment is tested for functionality as part of its calibration routine and the instructions issued with all equipment state that the decompression should not be faster than 120m/m, as this is the fastest ascent a human can achieve in water and survive, assuming low tissue loading by aborting a dive close to the start.

Sensor 4 was used in this test instead of the sensor 1 because sensor 1 was damaged when dropped during Test 6.

Fig 18.11-1. Chamber for Test 9. The gauge is for safety purposes only: all readings are taken via the digital sensors.

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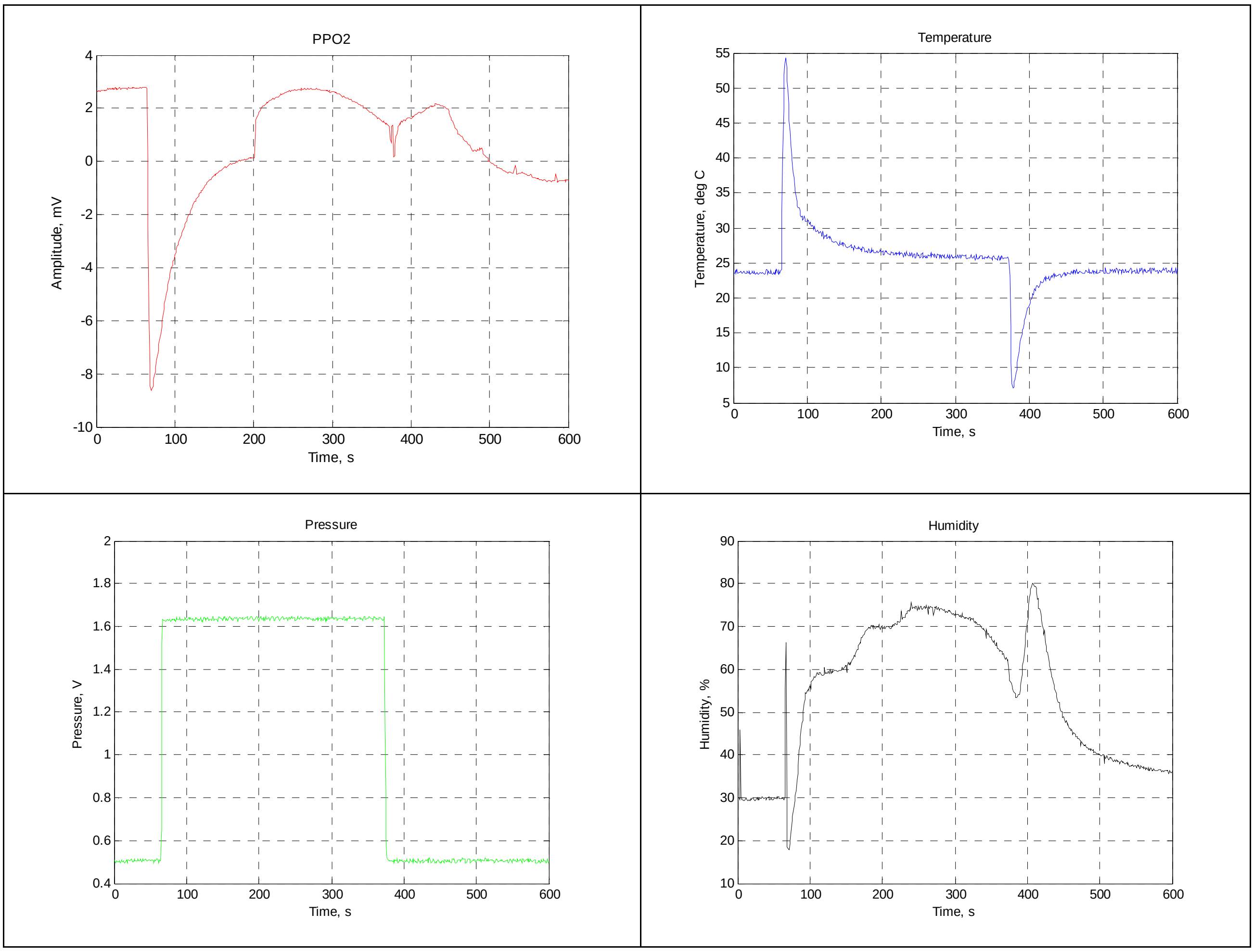

Fig 18.11-2. The test results. Pressure from 1 ATM to 130 bar in under 1 second, using He**.** No particles or liquid were thrown out from the sensor inside the chamber.

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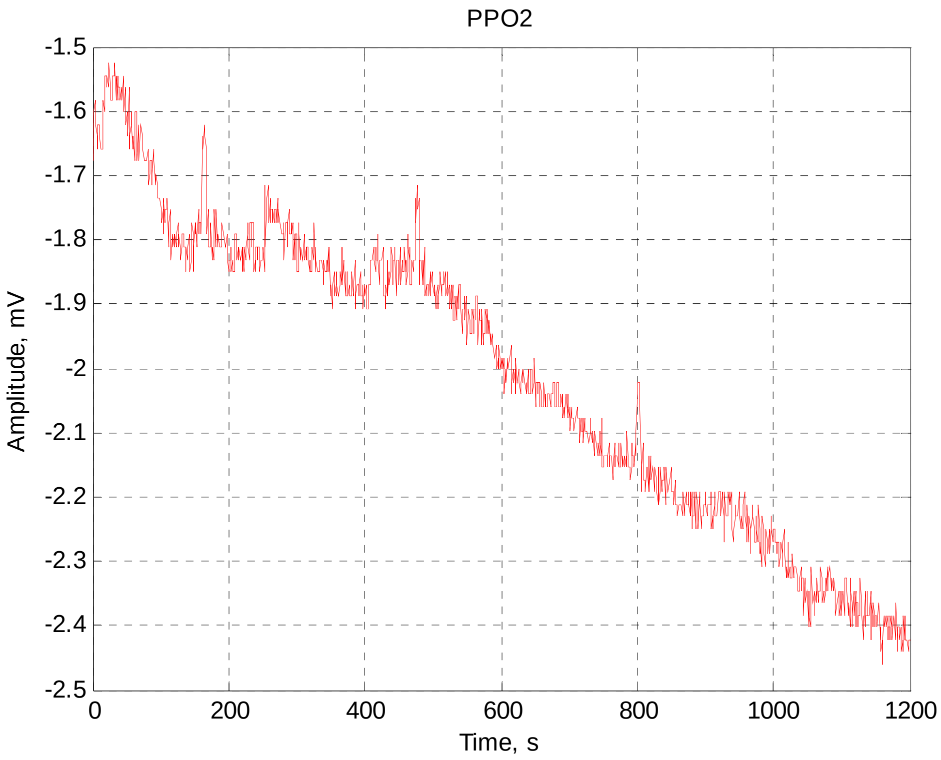

Fig 18.11-3. After the test. The sensor in atmosphere over 20 min. The filter window is 0. PPO2 mean is negative of -2.01 mV, temperature mean = 23.13 C, pressure mean = 0.5045 V, humidity mean = 24.69%. Note the sensor output polarity is reversed.

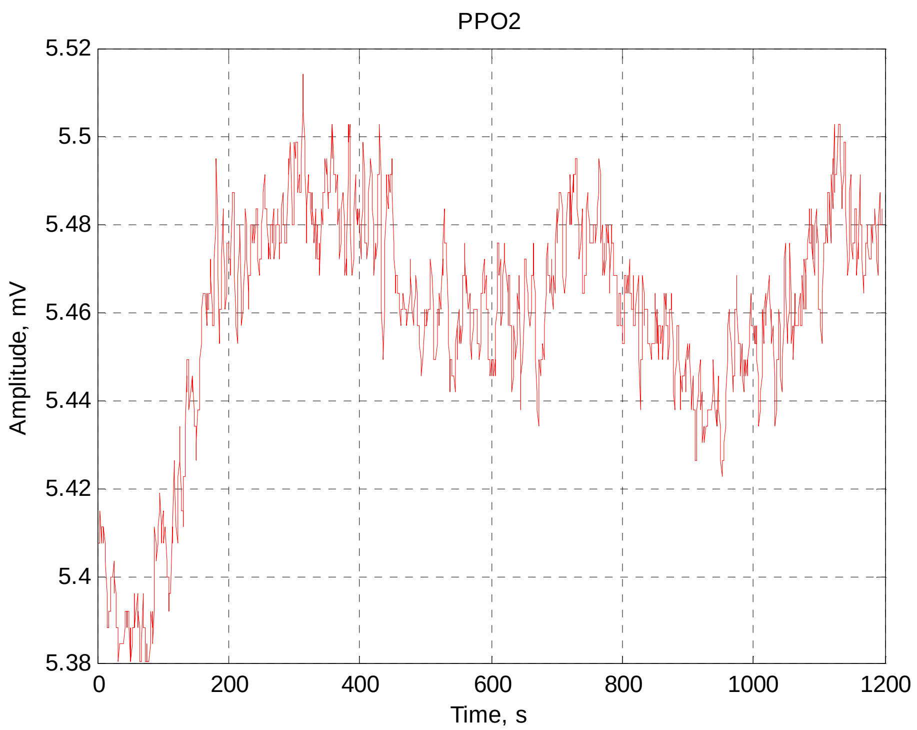

Fig 18.11-4. Two days later. The positive output of the sensor is restored.

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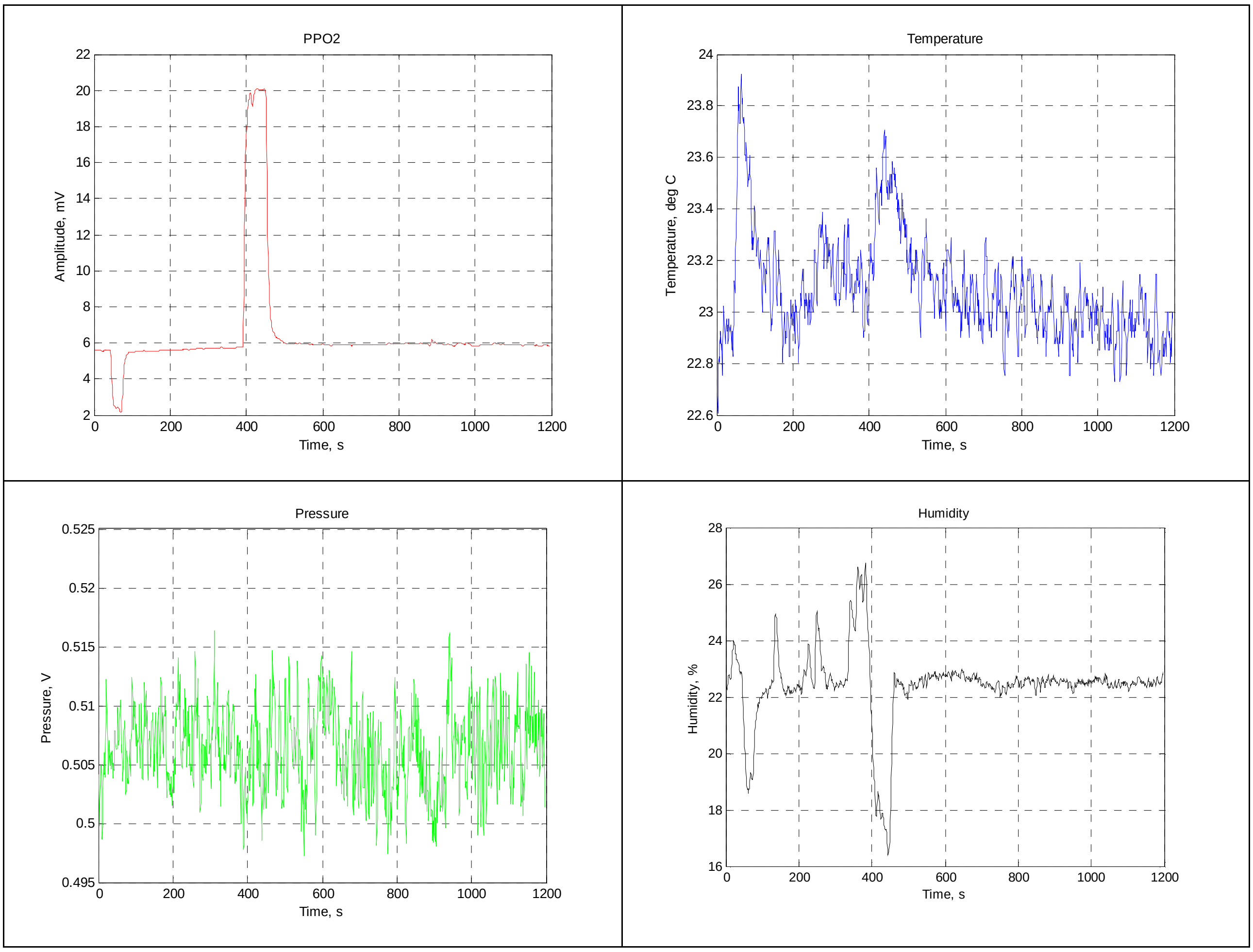

Fig 18.11-5. Check of the sensor gain after restoration of the output signal. First the sensor is placed in a CO2 flow, then in 100% O2 flow. The output of the sensor in CO2 increases from 0.19 mV (see test 10) to 2.1 mV. The output of the sensor in 100% O2 increases from 18.5 mV (see test 4) to 20.4 mV. The apparent offset of the sensor is about 0.2 mV.

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18.12 Test 10. CO2 Susceptibility.

Test	Purpose	Method	Result
10. CO2 Susceptibility	To determine damage caused to the sensor by being in a loop which has been pre-breathed without a scrubber. The PPCO2 can vary from 0.04 to 0.4 under these conditions.	2. Use sensor 3. Record ambient pressure and temperature. 3. Fit sensor to small chamber with an open port, and fill with CO2 so there is a 100% CO2 environment at ambient pressure around the sensor. 4. Measure the voltage produced by the sensor to verify it has fallen to zero. 5. Leave the sensor in the chamber for 15 minutes. 6. Remove from the chamber and allow to stabilise in air for 1 minute and measure the voltage, temperature and ambient pressure. 7. Repeat steps 2 to 5 four times. 8. The sensor remains in air for the remainder of this test. 9. Record voltage, ambient pressure and temperature once per day for 5 days.	Review

Step 2: Fit sensor to small chamber with an open port, and fill with CO2 so there is a 100% CO2 environment at ambient pressure around the sensor.

Fig 18.12-1. PPO2 sensor in/out of plastic bag with CO2 feed.

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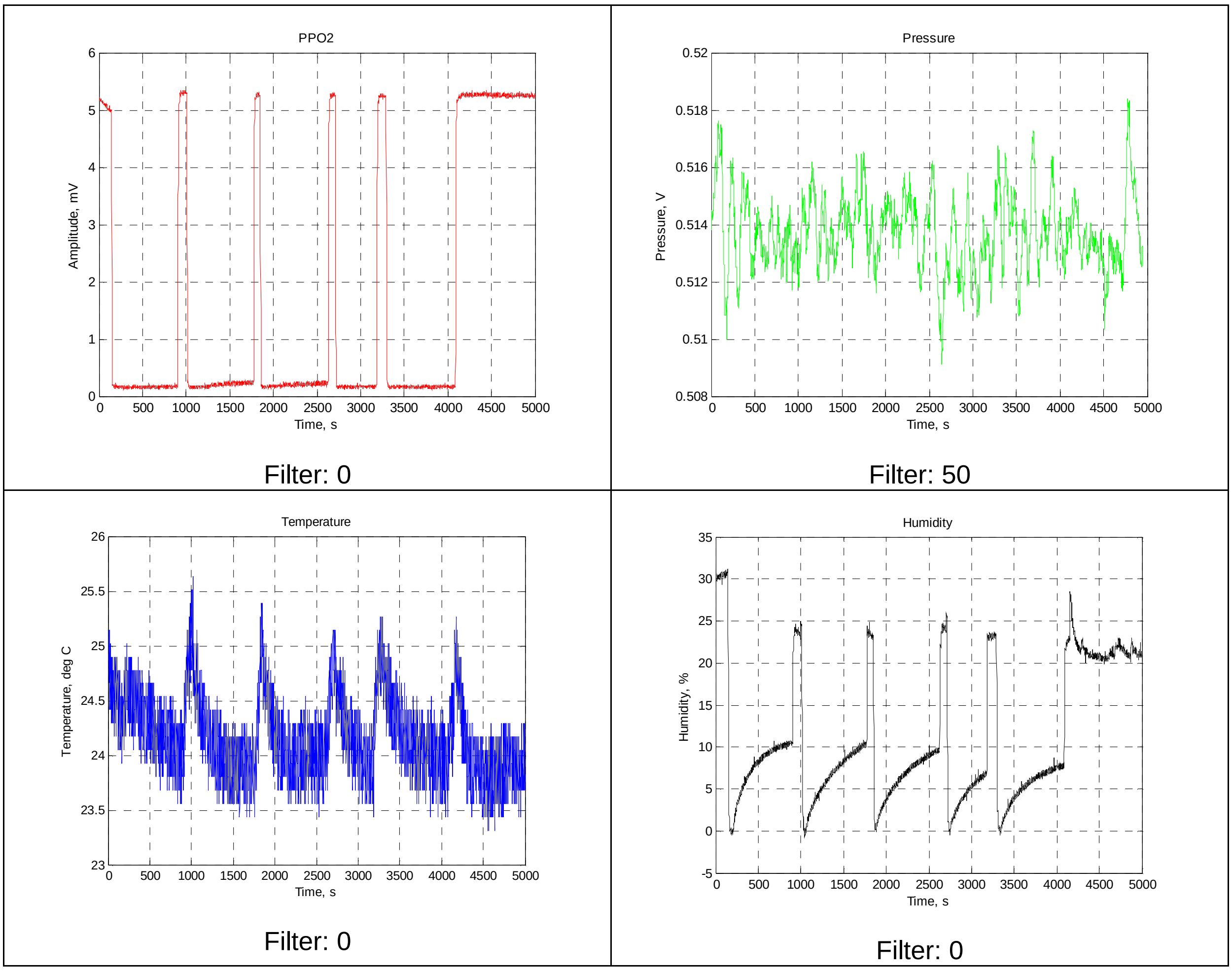

Fig 18.12-2. Sensor when five pulses of pure CO_2 are applied. Note there is a small offset to the sensor reading in a CO_2 environment. This may be due to imperfect flushing of the bag.

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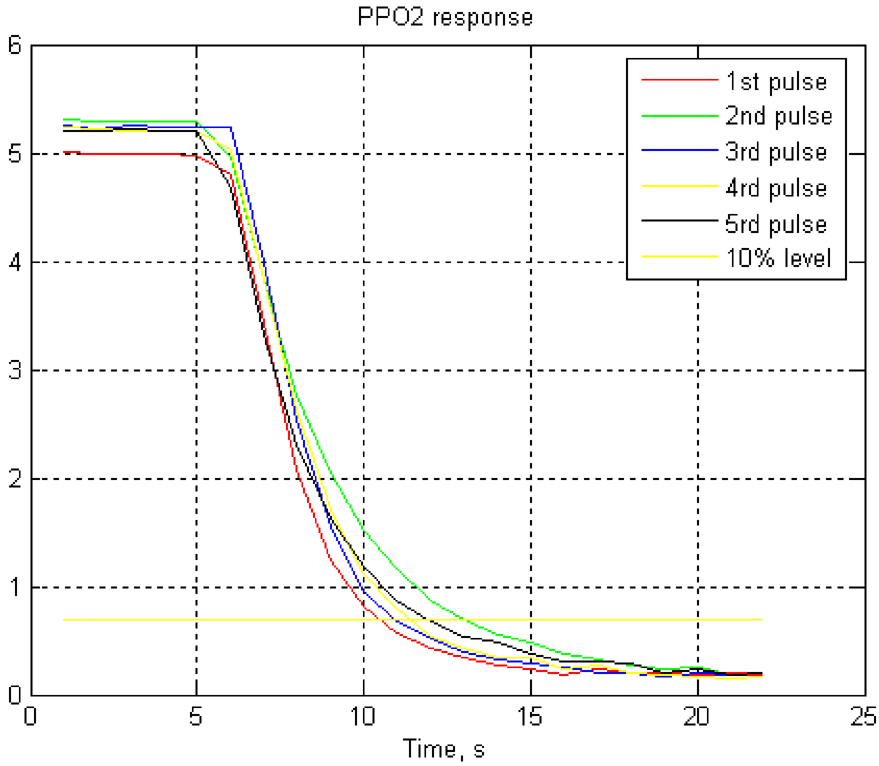

Fig 18.12-3 Sensor response at onset of CO2 pulse. 10% level = 0.696 mV, ((5.25-0.19)*0.1+0.19). Time of response is 7s.

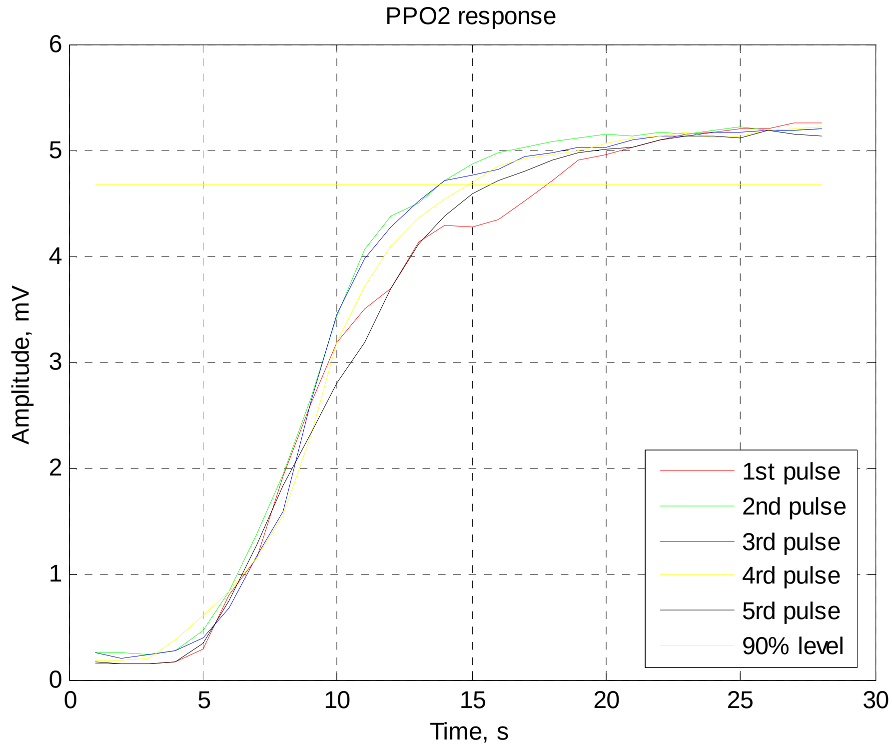

Fig 18.12-4. Sensor response when returned from CO2 to air. 10% level = 4.673 mV, ((5.17-0.2)*0.9+0.2). Time of response is 12s.

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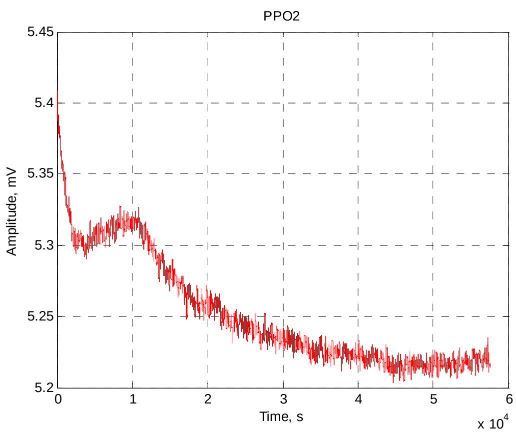
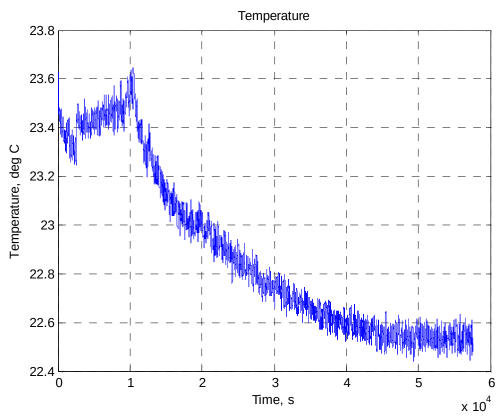
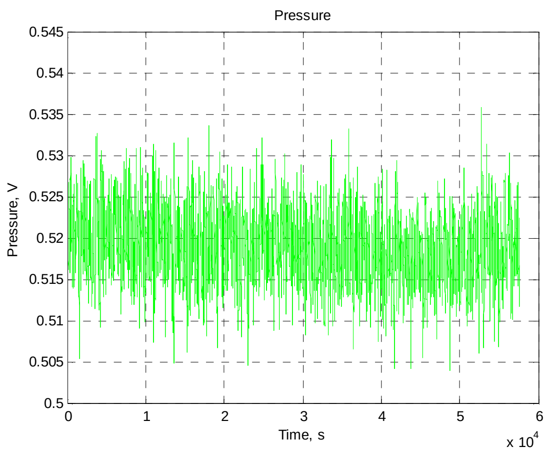
Step 8: 1st day.



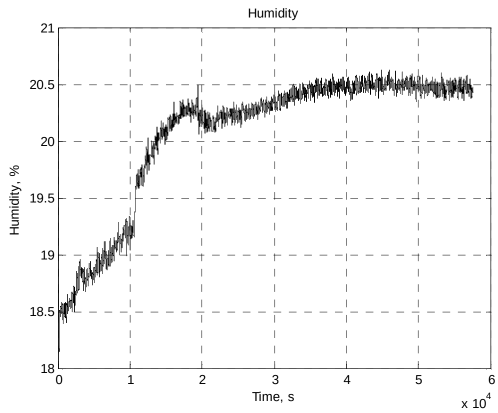
PPO2 mean = 5.25 mV



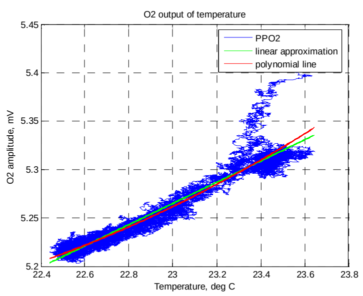
Temperature mean = 22.89 C



Pressure mean = 0.5191 V

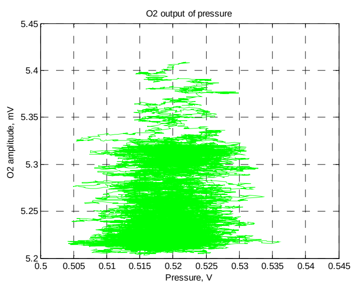


Humidity mean = 20.06%



P 1st order = [0.1096 2.7448]

P 2nd order = [0.0255 -1.0617 16.2056]



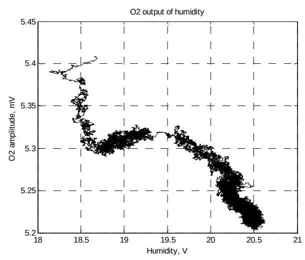


Fig 18.12-5. Sensor response on 1st day after CO2 experiment. Filter window: 50.

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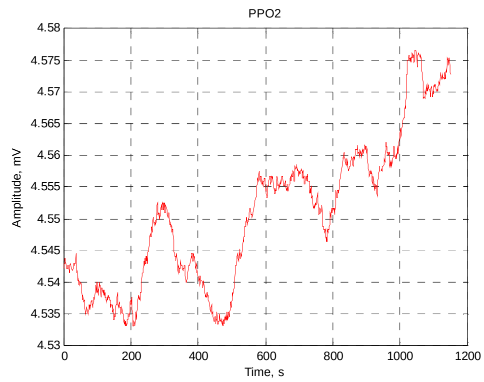
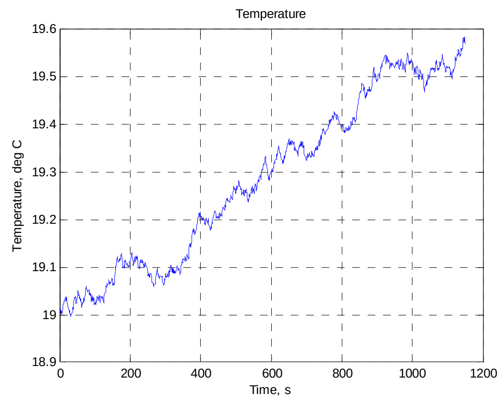
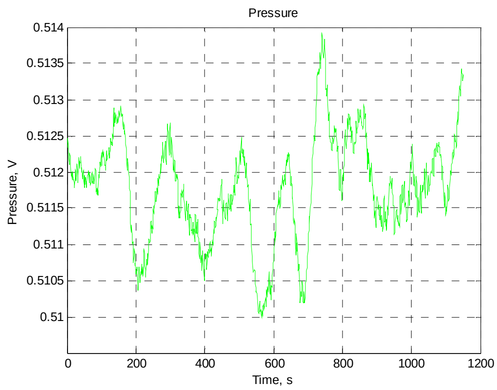
Step 8: 2nd day.



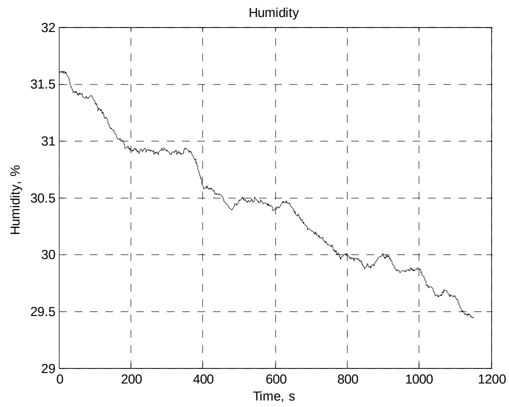
PPO2 mean = 4.55 mV



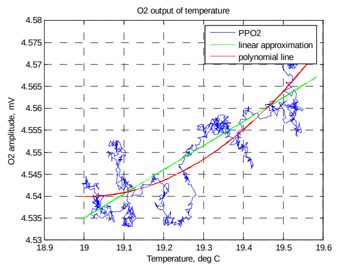
Temperature mean = 19.29 C



Pressure mean = 0.5118 V

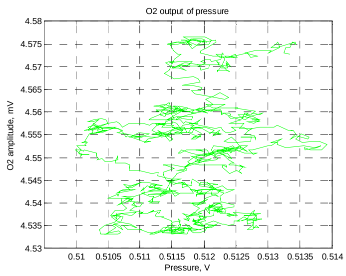


Humidity mean = 30.44 %



P 1st order = [0.0549 3.4924]

P 2nd order = [0.0989 - 3.7593 40.2706]



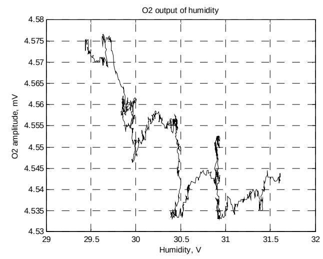


Fig 18.12-6. Sensor response on 2nd day after CO2 experiment. Filter window: 50.

Step 8: 3rd day.

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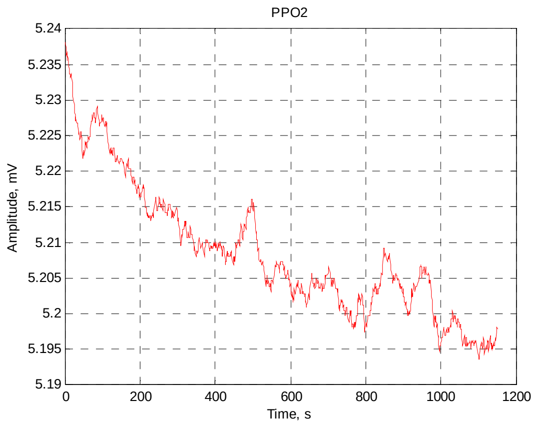
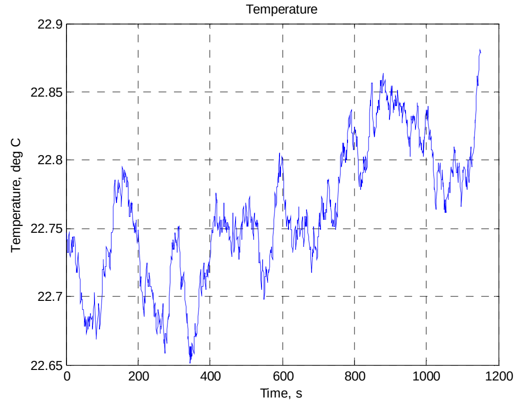
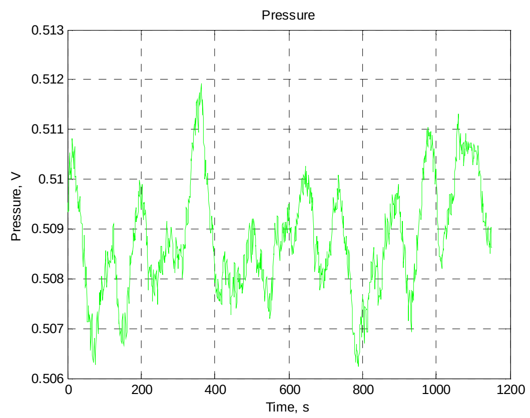


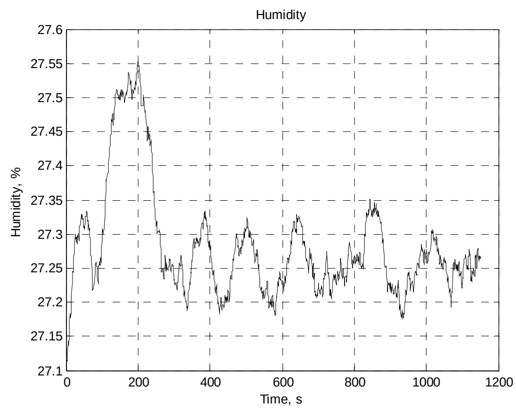
PPO2 mean = 5.21 mV



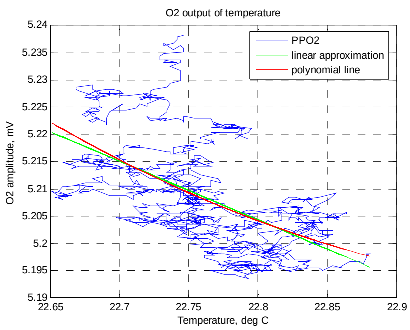
Temperature mean = 22.76 C



Pressure mean = 0.5088 V

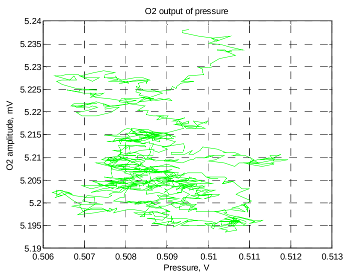


Humidity mean = 27.28%



P 1st order = [-0.1076 7.6579]

P 2nd order = [0.1764 -8.1361 99.0309]



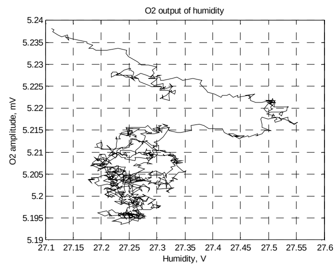


Fig 18.12-7. Sensor after 3rd day after CO2 experiment. Filter window: 50.

Step 8: 4th day.

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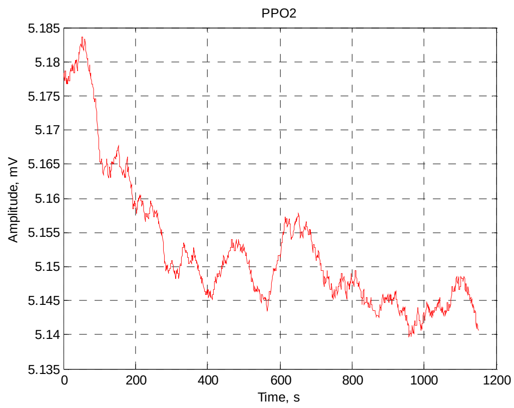
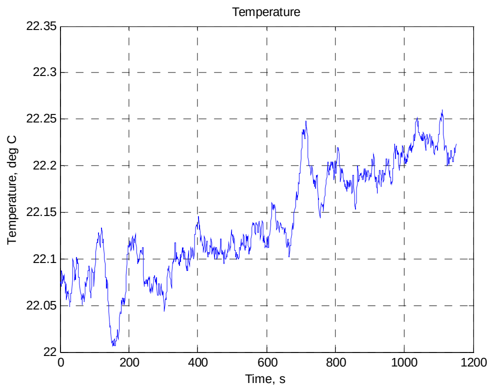
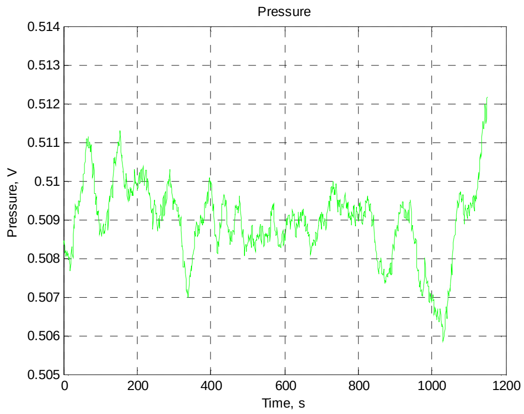


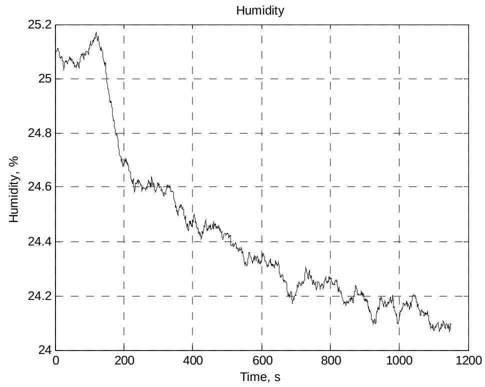
PPO2 mean = 5.15 mV



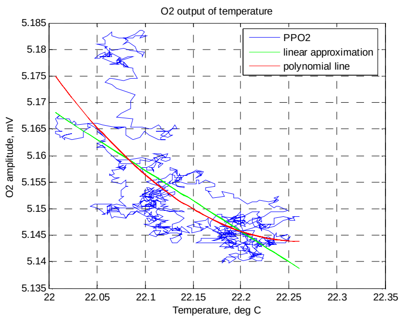
Temperature mean = 22.14 C



Pressure mean = 0.5089 V

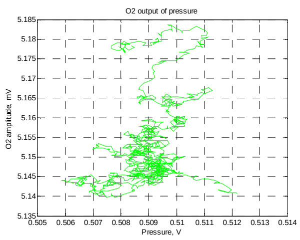


Humidity mean = 24.44%



P 1st order = [-0.1155   7.7095]

P 2nd order = [0.4701 -20.9319 238.1589]



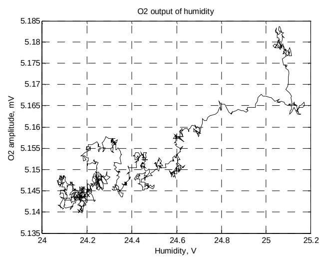


Fig 18.12-8. Sensor on 4th day after CO2 experiment. Filter window: 50.

Step 8: 5th day.

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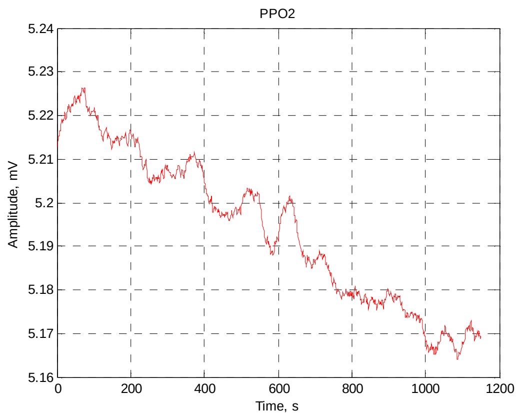
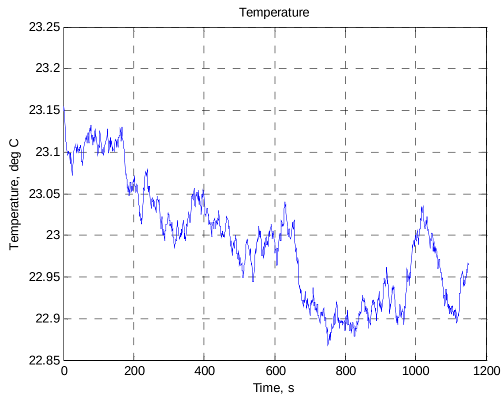
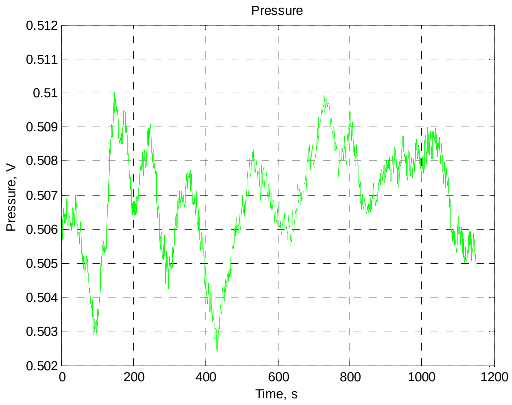


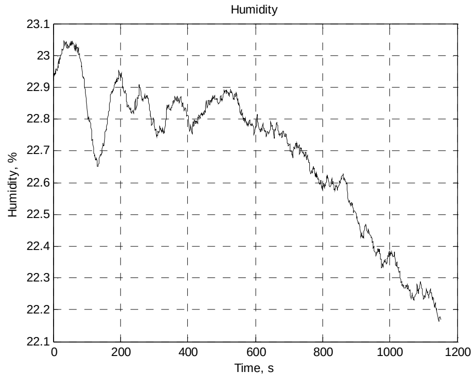
PPO2 mean = 5.19 mV



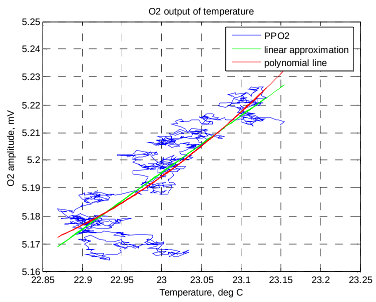
Temperature mean = 22.99 C



Pressure mean = 0.5069 V

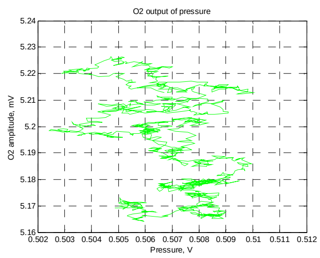


Humidity mean = 22.69%



P 1st order = [0.2043 0.4960]

P 2nd order = [0.2839 -12.8572 150.7073]



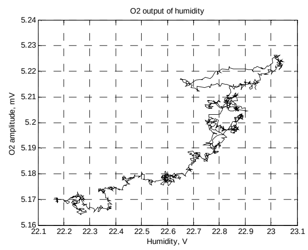


Fig 18.12-9. Sensor response on 5th day after CO2 experiment. Filter window: 50.

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18.13 Test 11. Application Test

Test	Purpose	Method	Result
11. Application Test	10 dives to recreational depths.	1. Use sensors 3, 8, 9, 10, 11, 12 2. Fit sensors to two PPO2 monitors: one to a pure PPO2 monitor and the second to a rebreather head. 3. Perform 10 dives with a mix of RHIB and hardboard diving. 4. Measure the output voltage and record ambient pressure and temperature before each dive. 5. Store for 6 months, then take a further set of readings, and perform 10 more dives. 6. Correct the data for temperature and pressure. 7. Compare differences beween units before and after use. 8. Examine carefully for signs of corrosion or other visible deterioration.	Pass

No drift at all was observed in any of the sensors used for the dives during the period of the dives, from the time of the initial inspection of the sensors.

Water on the cell faces was found to be a problem: the membrane should be flush with the outside of the cell to prevent water collecting in the well around the sensor face.

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18.14 Test 12. Life test.

Test	Purpose	Method	Result
12. Life Test	Verify the manufacturer's quoted life test	1. This test is the penultimate in the sequence for all sensors, except sensors 1, 7, 8 and 9. 2. Record readings for all open oxygen sensors once per month, until 50% have failed. 3. Compare with manufacturer's stated sensor life.	Review

The life test is still underway. No drift has been observed from any sensor in the test.

The fixture used for this test is an automatic test system which measures the output voltages and records atmospheric pressure, temperature and humidity once per day, recording data for one hour with 2 sec between samples. After each recording the system calculates the average values and saves them in a csv file. The format of the data file is shown in the table below.

The same algorithm is used to fix the sensor Life Time in test 12.

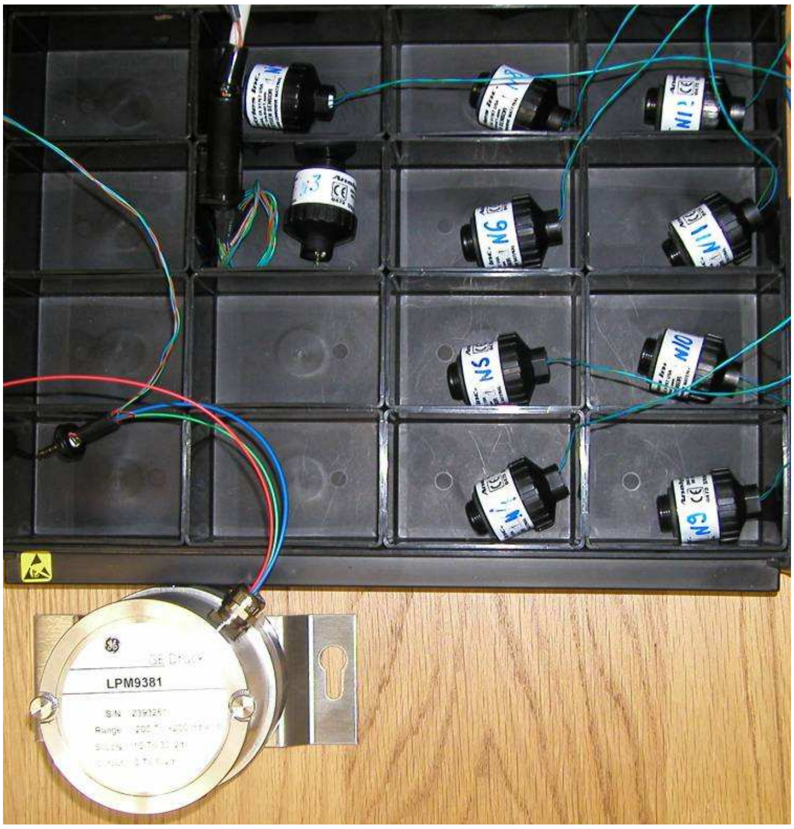

Fig 18.14-1. MDR sensors tested in air. Druck pressure sensor shown below tray. Temperature sensor is on left of tray.

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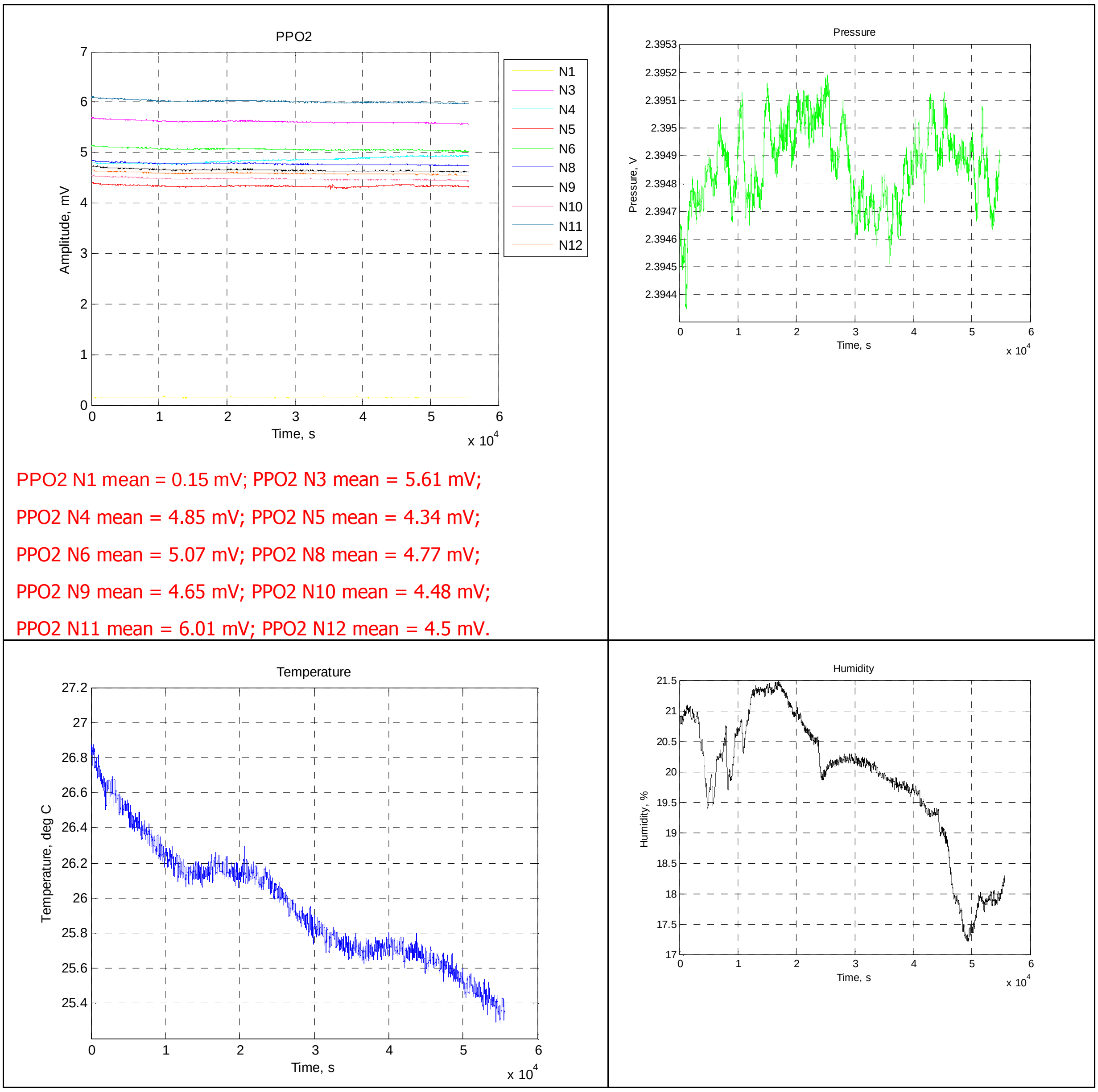

Fig 18.14-2. Example of sensor output, temperature, pressure and humidity, measured during 15 hour 30 min. The database stores this data for the entire duration of the trial. Note the horizontal scale is second to the 10^4 in the extracted plots above.

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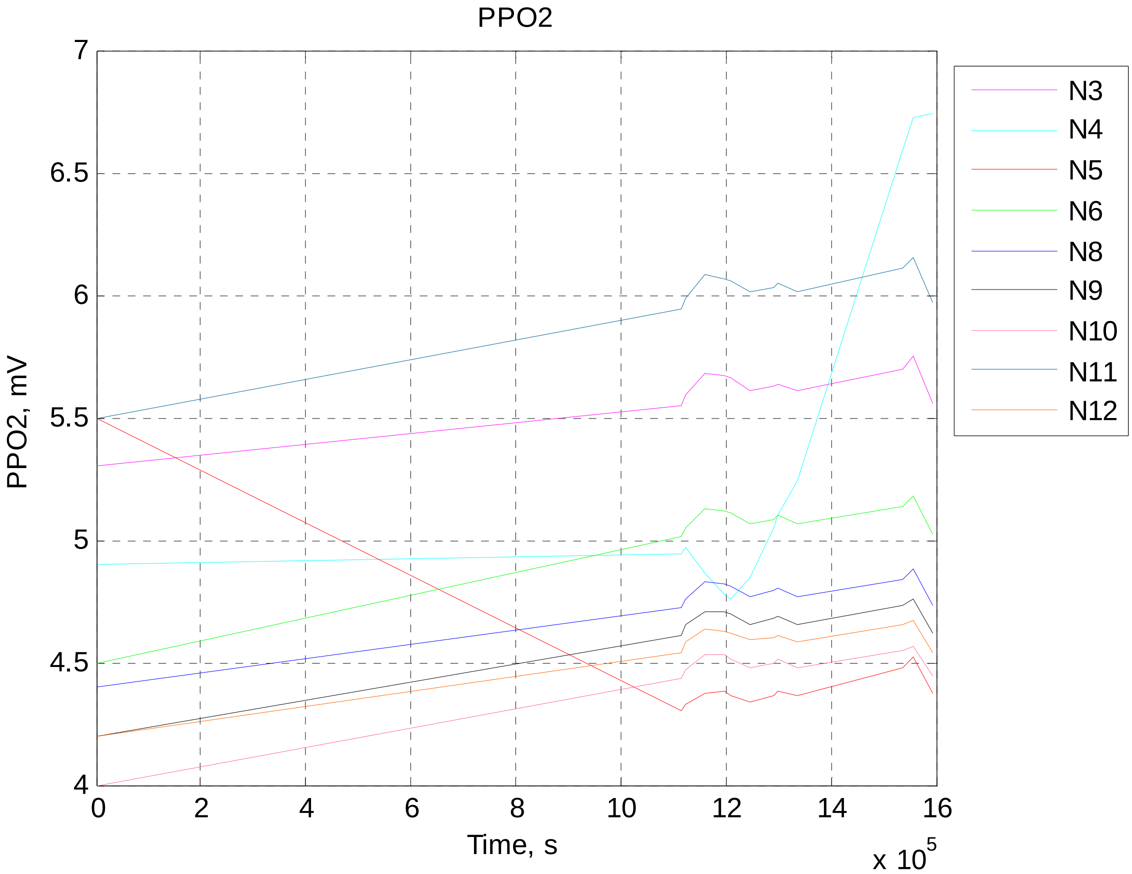

Fig 18.14-3. PPO2 averages of time during 18 days. Lines are used to connect the average points. The output of sensor 1 of 0.15 mV is not shown. Note the scale is seconds to 10^5. The general drift is due to changes in temperature and pressure: the sensors themselves are not drifting, except for those damaged by testing.

The long test shows that the dynamics of sensors 1, 4 and 5 are different from the other sensors in the group. Tests 3, 4, 5a and 6 (Drop test) are applied to sensor 1, resulting in it being damaged. Sensor 4 is used for tests: 7, 8 and 9 (Torpedo test), resulting in it being damaged. Test 6 is applied to sensor 5 (Drop test), resulting in it being damaged. There is no significant drift of the sensors other than that due to this damage.

Table 18.14-1. Format of the mean values database.

Date, Start	Date, finish	Tem-pera-ture	Pres-sure	Humi-dity	PPO2 sensor									
					N1	N3	N4	N5	N6	N8	N9	N10	N11	N12

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18.15 Test 15: Storage at -30C

This requirement arises from EN14143:2003, which states:

EN14143:2003 Section 5.14.1 Storage: Trouble free operation shall be ensured after storage at temperatures ranging from -30 °C to + 70 °C.

Testing shall be done in accordance with Section 6.13.2.

6.13.2 Testing after storage at - 30 °C and + 70 °C: Before performing the following test the apparatus shall, where required, be calibrated and shall be breathed from for a period of 5 minutes.

On completion of the above procedure (both - 30 °C and + 70 °C) for a period not less than 3 h allow the

temperature of the apparatus to return to standard laboratory conditions.

Switch on the apparatus and calibrate, if required.

Test at a pressure of 1,0 bar and a ventilation rate of 40 l min-1 with an oxygen consumption of 1,78 l min-1 for the duration of the apparatus as specified in the manufacturers information, during which time the performance shall remain within the limits specified.

The temperature of -30C is below that which the test chambers available to Deep Life can reproduce without use of dry ice.

To achieve -30C, the equipment was put into a biomedical freezer at the St Petersburg City Blood Bank Cold Store for 3 hours below -30C. This freezer was located at Hospital 2, Kostushko St, Saint Petersburg and is used for storing blood at minus 38C.

Both the twin scrubber and single scrubber configurations were tested and both mouthpiece configurations (conventional and combined ADV and BOV).

The test involved breathing for five minutes from the equipment, then putting it into the cold store with a min-max thermometer.

The equipment was then moved to a test chamber, in which an electrical heater had been placed. This was heated to 70C for 3 hours. This test at 70C was in addition to the previous characterisation which was carried out at +90C.

Fig 18.16-1. Biomedical freezer for testing of the equipment. The freezer power is 220W. Effective capacity is 426 litres.

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Fig 18.16-2. Control panel of the freezer showing it achieving -35C.

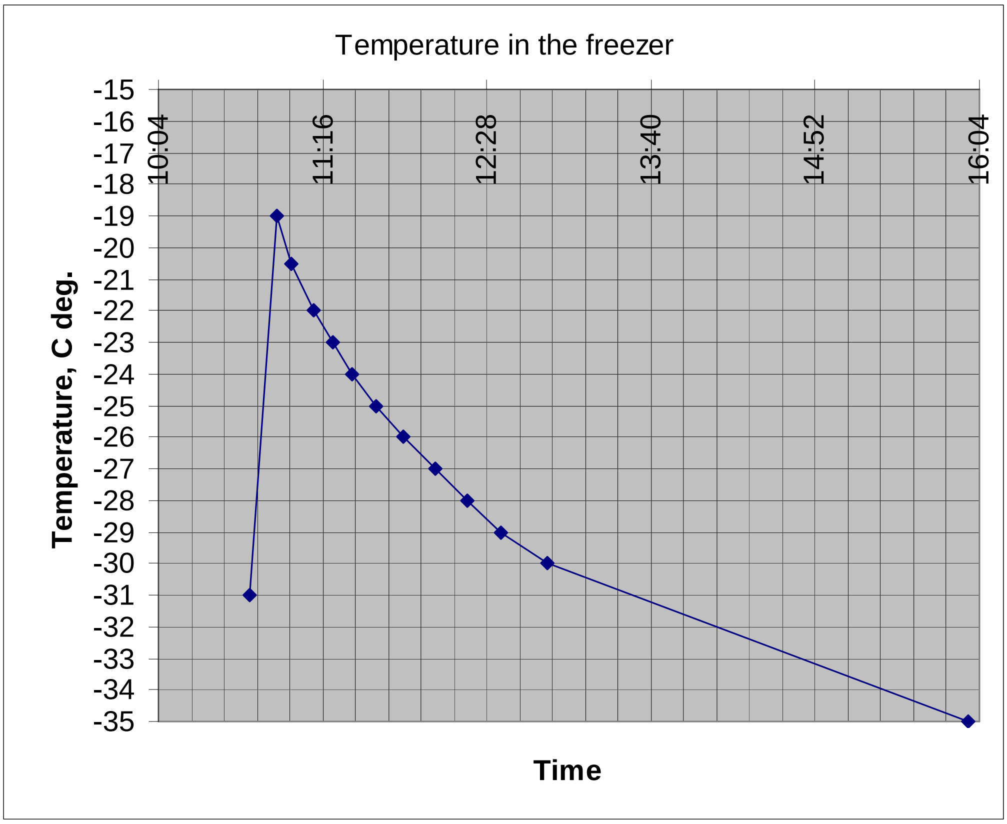

Fig 18.16-3. Temperature after putting the units into the freezer. Total time of the test was 5 hours 15 minutes including 2hours and 15 minutes for getting below -30 C.

Both the twin scrubber and single scrubber configurations were tested and both mouthpiece configurations (conventional and combined ADV and BOV). The single scrubber was tested as an assembly and the dual scrubber as a whole, so all parts were in the freezer for the same time.

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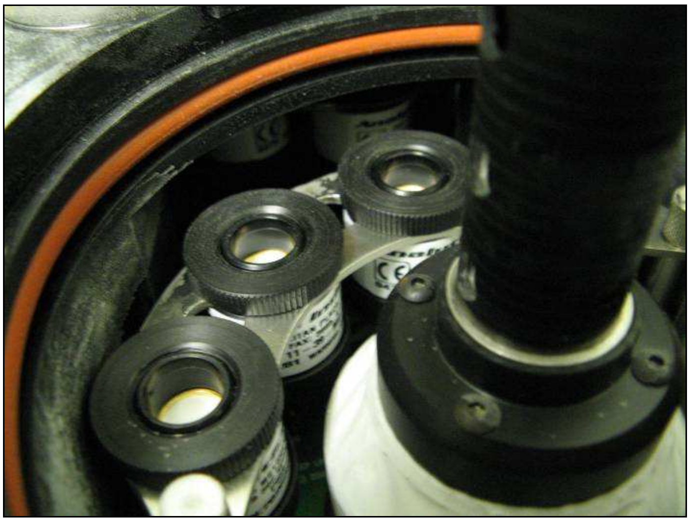
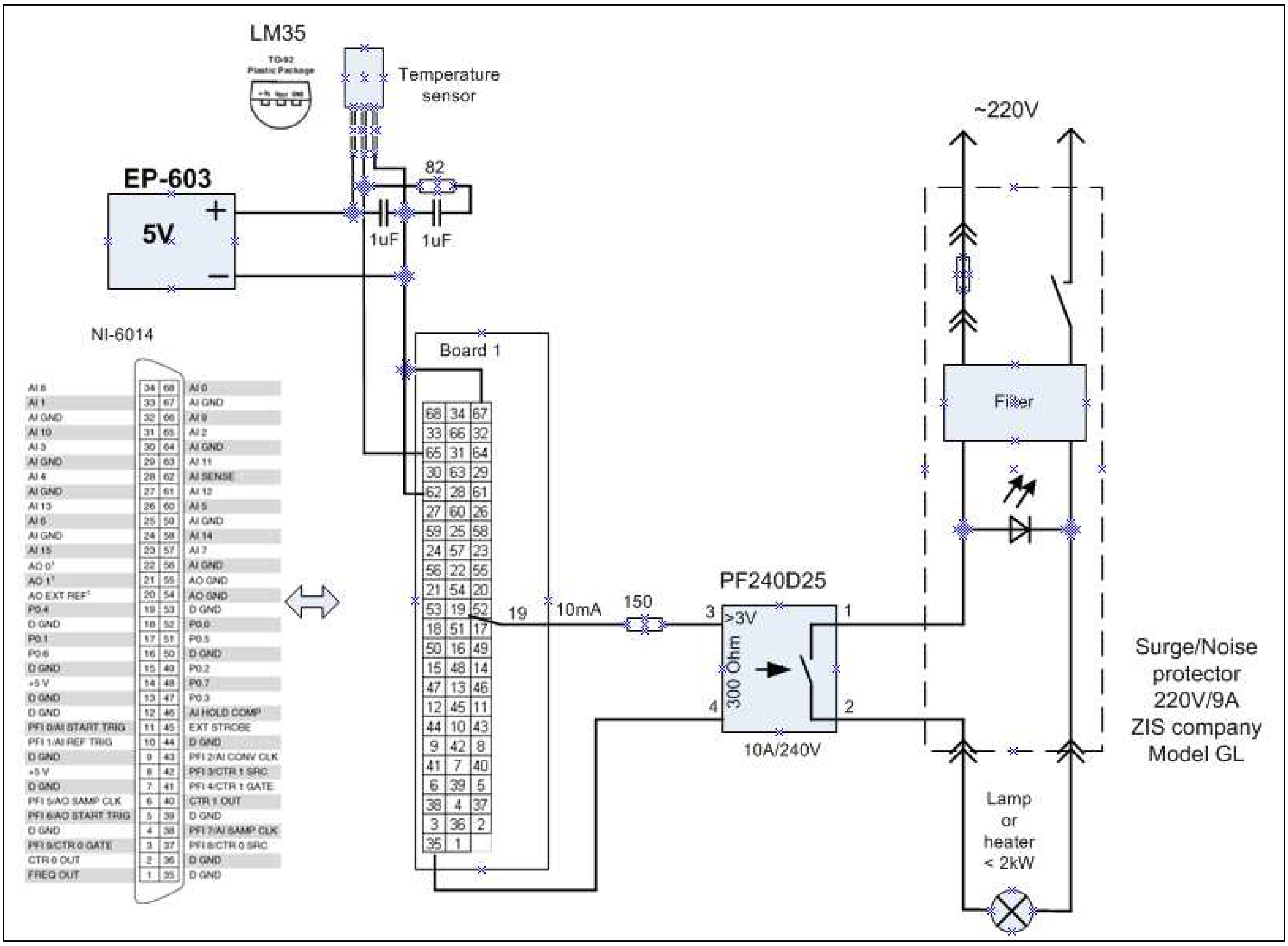


Fig 18.16-7. PPO2 cells after the cold test.

The equipment was then moved to a test chamber, in which an electrical heater had been placed. This was heated to 70C for 3 hours.



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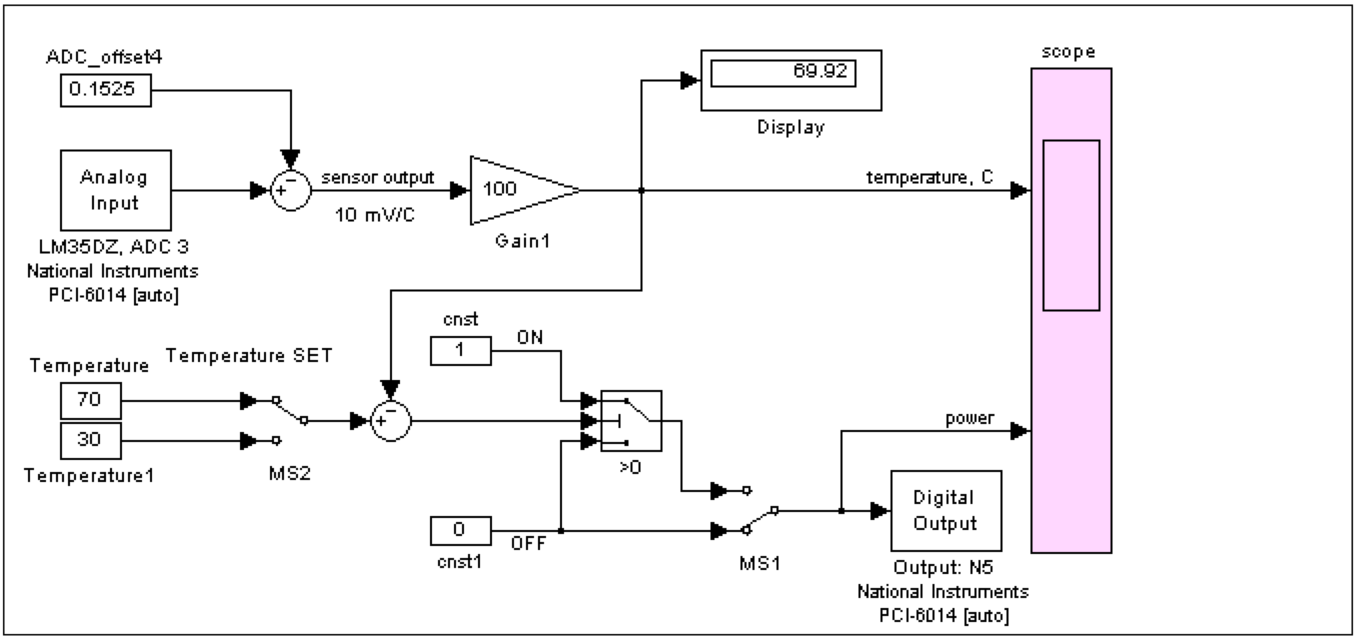

Fig 18.16-8. Structure of the temperature control system for the hot soak test.

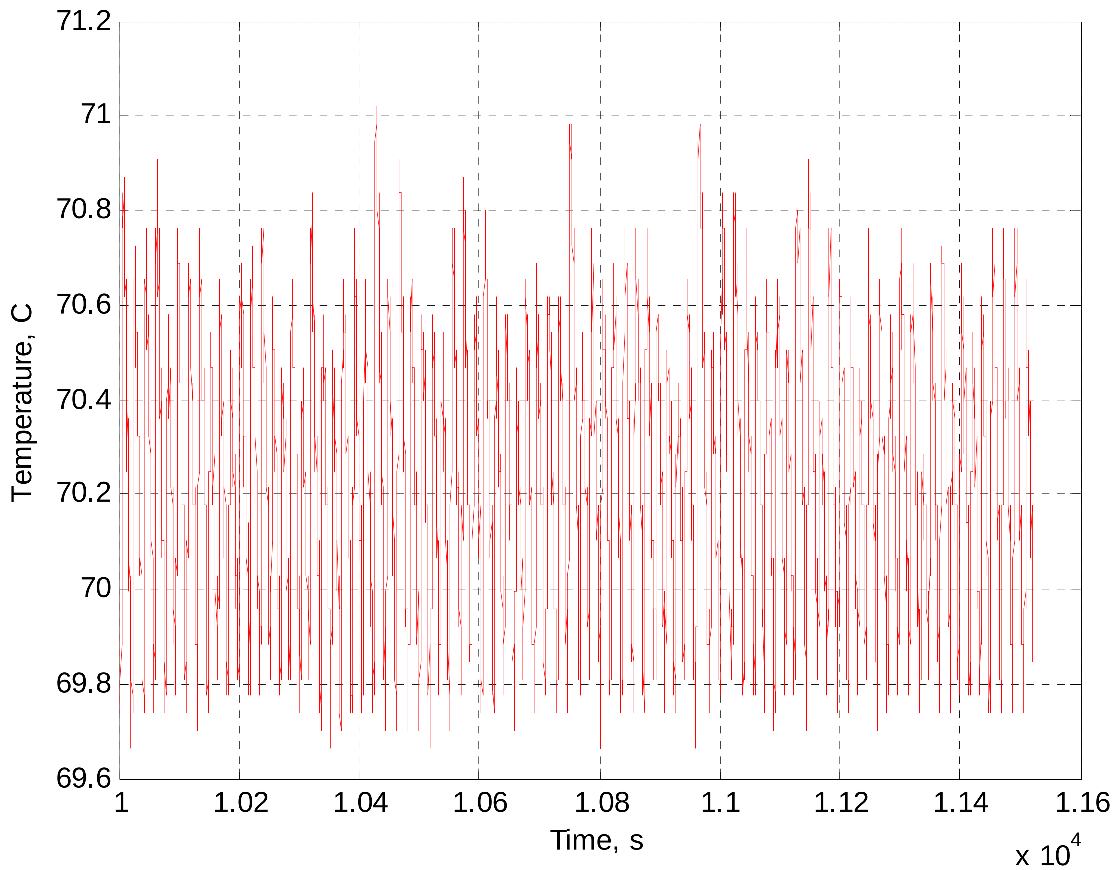

Fig 18.16-9. The temperature during the 3 hour hot soak test.

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18.16 OUTPUT vs PPO2, AFTER EXPOSURE TO -30C and +70C

Table 18.16-1. Sensor output after exposure to –30C and +70C

	MD Sensor N13	MD Sensor N14	MD Sensor N15	MD Sensor N16
After –30C	12.2 mV	11.9 mV	14.7 mV	11.9 mV
After +70, five minutes later	13.2 mV	13.6 mV	16.2 mV	12.8 mV
Two hours later	12.4 mV	12.6 mV	15.4 mV	12.4 mV

18.17 Hard Drop test from 1.5 and 3m of improved sensors

Note: All drop tested sensors passed -30C and +70C storage test.

A hard drop from 1.5 and 3 meters was carried out on sensors 14, 15, 16. The data from the test is shown in the following Tables 1 & 2 and Fig 18.18-1 & Fig 18.18-2.

Table 1 1.5m drop test

Drop №	before the tests	1	2	3	4	5	6	7	8	9	10	mV drop	% drop
Sensor №16	12,2	12,0	12,1	12,0	12,1	11,9	12,0	6,4	11,8	11,5	11,6	0,6	6%
Sensor №15	14,9	15,2	15,0	13,8	13,4	12,8	12,3	12,0	11,7	11,3	11,5	3,4	34%
Sensor №14	12,3	12,1	12,2	11,8	11,6	11,5	11,2	10,9	11,2	10,7	10,1	2,2	22%

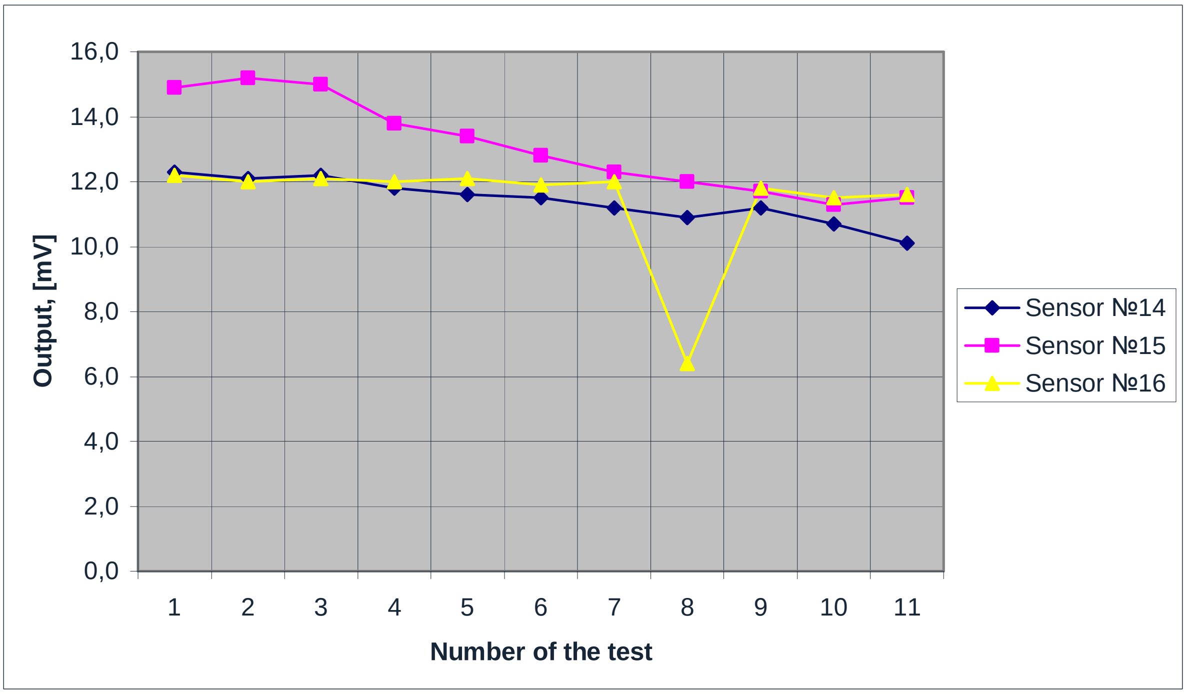

Fig 18.18-1: PPO2 sensor output at 1.5m drop tests.

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Table 2 3m drop test

Drop №	1	2	3	4	5	6	7	8	9	10	mV drop	% drop
Sensor №16	10,9	10,9	10,6	10,2	8,0	7,6	7,0	6,1	5,7	5,9	5,0	50%
Sensor №15	10,7	Damage at the 2nd drop (resulting behaviour is explained below)										
Sensor №14	9,7	9,3	9,2	8,5	8,0	7,2	7,5	7,1	6,6	6,3	3,4	34%

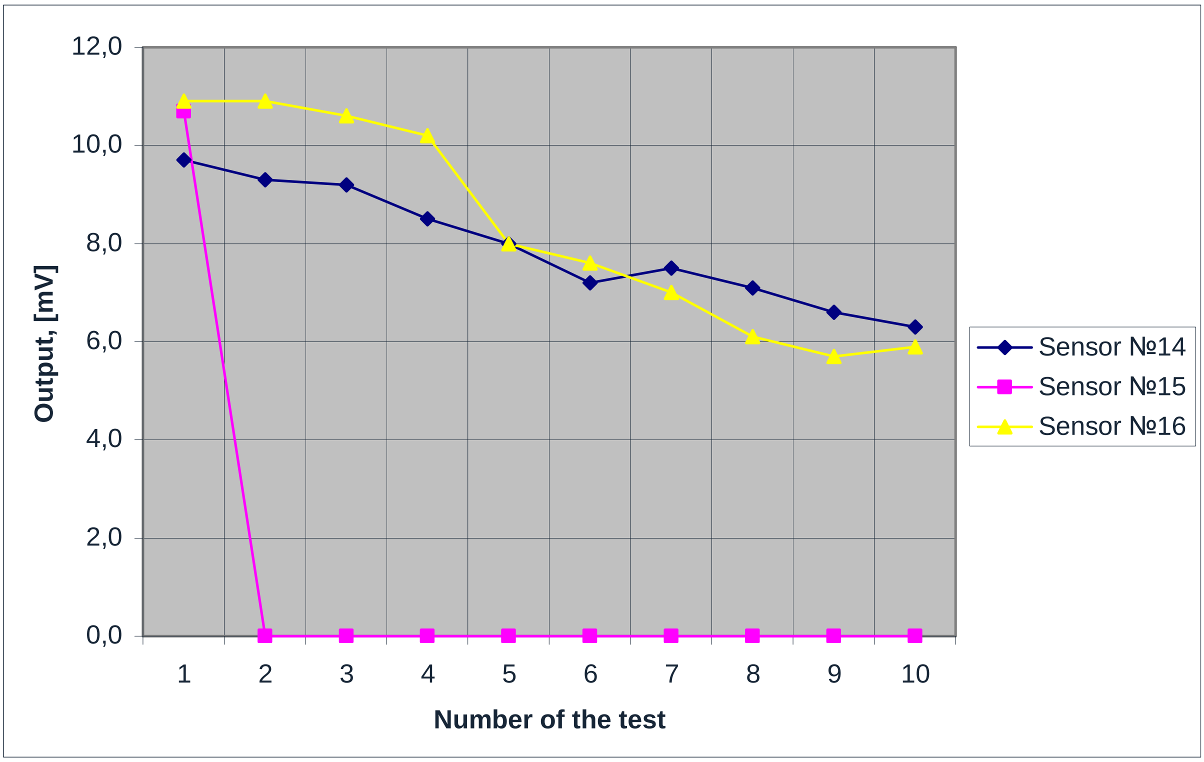

Fig 18.18-2: PPO2 sensor output with 3m drop tests.

Sensor 15 lost electrolyte from the connector side, as shown in Fig 18.18-3. The leakage of the liquid drops was found when the sensor was shaken. Sensor 15 also had a ‘knocking’ noise when it was shaken.

Fig 18.18-3: Drops of electrolyte from the N15 sensor after -30 and +70 storage and drop tests

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The output signal from sensor 15 is unstable after the 2nd 3m drop test. This sensor output is negative in the range of -1..-40 mV with approx. period of 0.5s. This was measured with a Mastech M890F multimeter. After two minutes, the output range is 0..0.2mV, then after four minutes the range is 0..0.7mV. Note. There is no visible damage to the sensor.

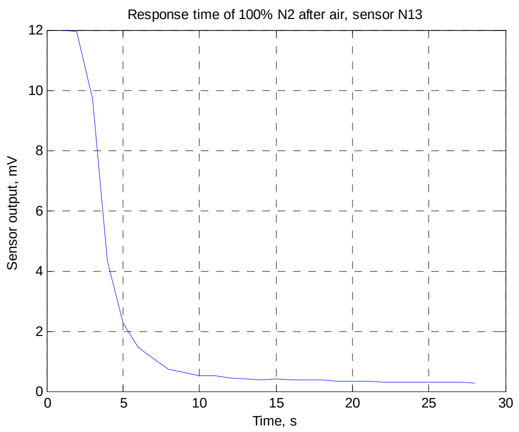
Sensors 14 and 16 both have a ‘knocking’ noise when shaken after the 3m drop test. Sensor 16 has no visible damage, unlike sensor 14, which has a small dent near the connector hole (Fig 18.18-4).

Fig 18.18-4: A small dent can be seen is near the connector hole of the N14 sensor

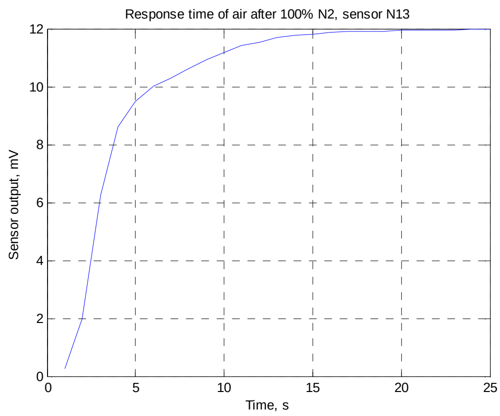
18.18 Response time after environmental tests

The history of the sensors used in this test is:

1. MD sensor 13 passed -30C and +70C storage test
2. MD sensor 16 passed -30C and +70C storage test and 1.5/3m drop test
3. MD sensor 17 is fresh (untested)



from air into 100%N2



from 100%N2 into air

Response is 9 s

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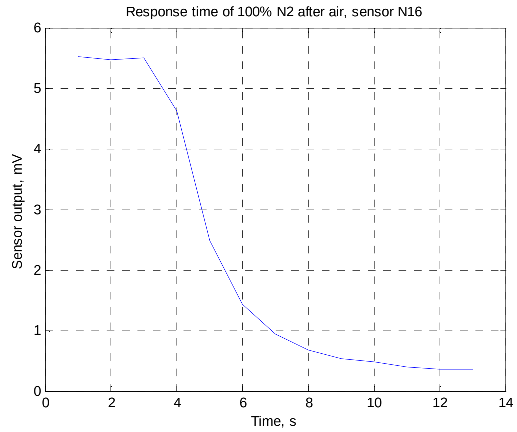
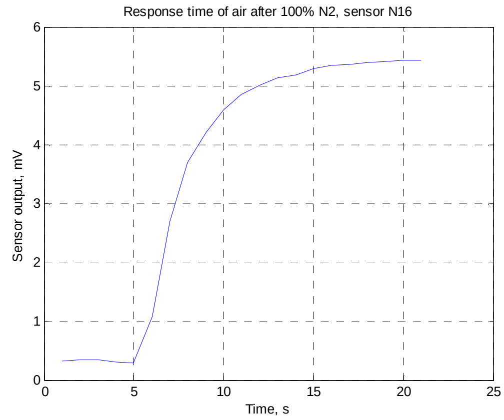
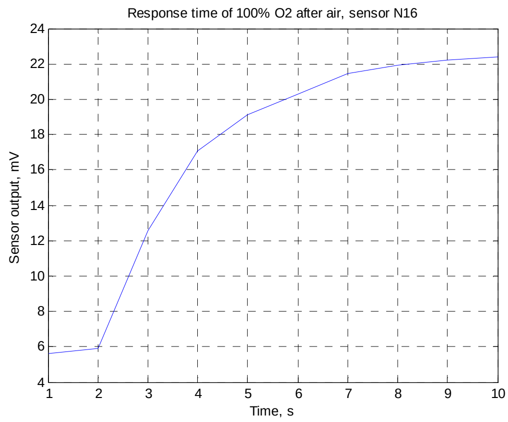
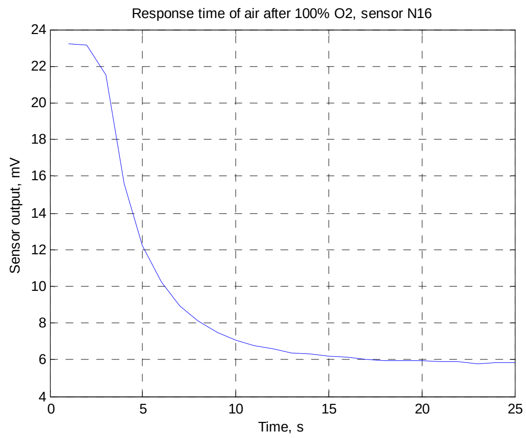
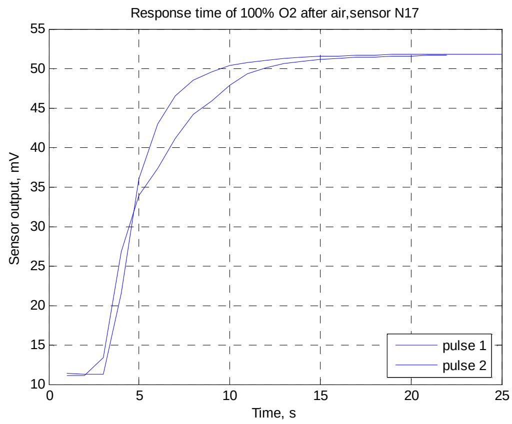
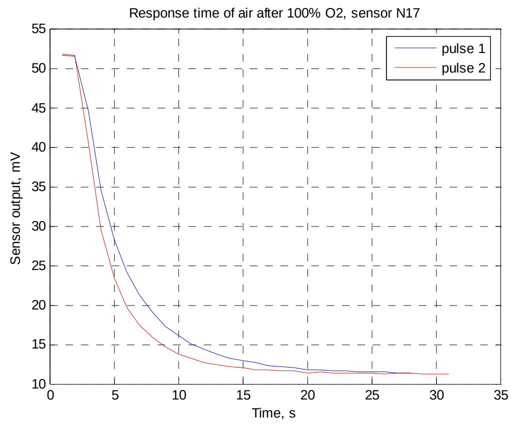
<table>
<tr><td>Response is 7 s</td><td></td></tr>
<tr><td>


from air into 100%N2
Response is 6 s
</td><td>


from 100%N2 into air
Response is 9 s
</td></tr>
<tr><td>


from air into 100%O2
Response time is 6 s
</td><td>


from 100%O2 into air
Response time is 9 s
</td></tr>
<tr><td>


from air into 100%O2
Response time is 7 s
</td><td>


from 100%O2 into air
Response time is 9 s
</td></tr>
</table>

Fig 18.19-1: Response time for each sensor following environmental testing

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18.19 Effect of losing electrolyte (Stimulated fault)

The case where there is a loss of electrolyte is of special interest in the safety case, as it tracks the highest sensor output. Loss of electrolyte is known to cause the output of the sensor to increase.

18.20 Test 15: Effect of Loss of KOH

15. Effect of KOH Leak	Effect on output if KOH leaks from sensor, to understand the behaviour of the sensor under this sensor failure mode.	1. Measure the output voltage of a sensor. 2. Drill two 1mm holes in the sensor, plugging the first before drilling the second. 3. Measure the output of the sensor when the holes are unplugged, and air is injected into the sensor to slowly displace the electrolyte. 4. Note that the electrolyte is highly alkaline so protective gloves and goggles should be used. The electrolyte should be drained into water, and the solution disposed of after the experiment by neutralising it first with a mild acid.	

Sensor 14 was used for this test: it had already passed -30C and +70C storage tests and 1.5m and 3m drop tests. Sensor output before the test was 6.4mV.

Two 1mm holes were drilled into the sensor body to cause a loss of electrolyte. The sensor output rose to 24mV after leaking the quantity of electrolyte shown in Fig 18.20-1. 40minutes after drilling the holes, the sensor output increased to 47mV, then after a further 20 minutes the output rose to 57mV. The cell value then falls to zero over a period of days to weeks.

Small losses in electrolyte cause a change in cell output as a function of orientation.

The loss of electrolyte, strangely, causes a reduction in the source impedance of the cell. This reduction can be detected by applying a load on the cell and checking whether the reduction in output voltage is within the range expected. For example, a 100 Ohm load should halve the output voltage, but in the case of loss of electrolyte the reduction is considerably less. The risk of electrolyte loss is high, because risk of severe mechanical shock is high. The equipment should therefore include suitable DAC and switching circuitry to test for this mode whenever there is a substantial difference in the cell outputs, before selecting the highest output cell.

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Fig 18.20-1: Sensor losing electrolyte.

The oxygen cell verification circuit of the base unit with 12-bit DAC is shown in **Fig 18.21-1**

18.21 Auto Detection of Electrolyte Loss

The Deep Life rebreather designs include a circuit to detect if the correct sensor is fitted and to detect electrolyte loss. That circuit is shown in the figure below. Tests were carried out to characterise the sensors under the electrolyte loss conditions to enable operating limits to be assigned to that circuit.

The circuit that was used to characterise the sensor under electrolyte loss conditions is shown in Fig 18.21-2.

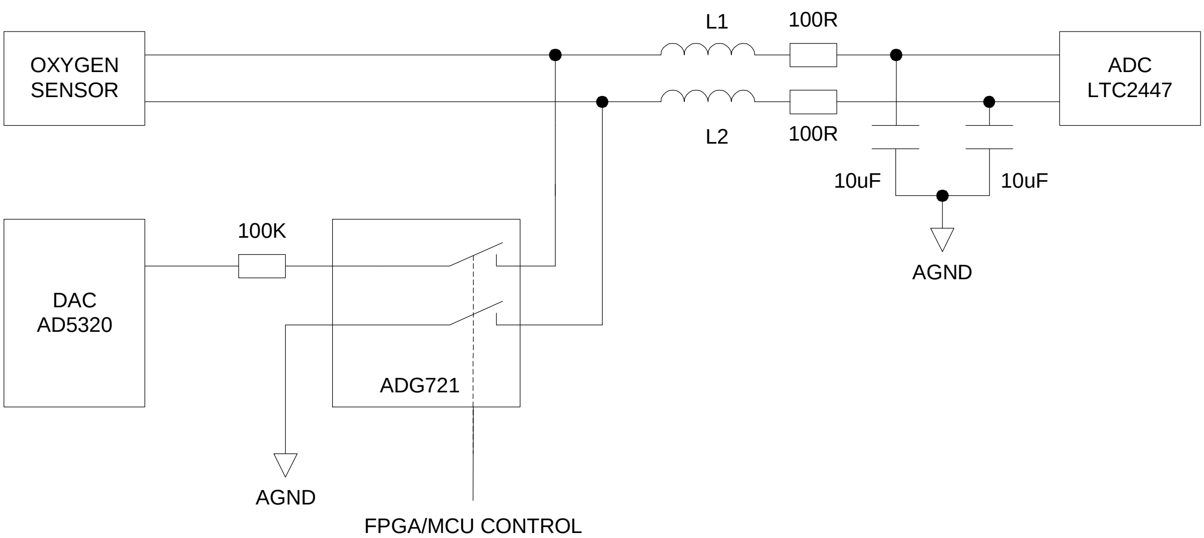

Fig 18.21-1: DAC circuit used to screen O2 sensors in all safety critical applications designed by Deep Life Ltd.

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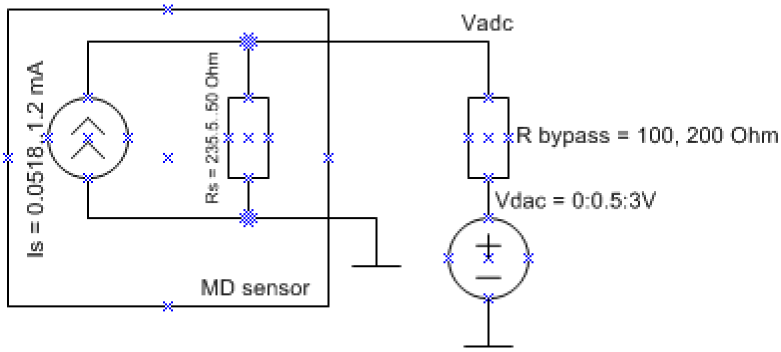

Fig 18.21-2: Sensor impedance test circuit.

Table 18.21-1. Sensor test parameters

Sensor type and number	Output resistance	Output voltage, mV	Note
MD, N13	Rs	12.2	Is = 0.0518 mA, as 12.2/Rs or 12.2/235.3
	Rs || 100 Ohm	3.7	
	Rs || 100 Ohm + 100 Ohm	5.7	Rs = 235.3 Ohm, as (200/(3.7-5.7/2))
MD, N14 (after electrolyte losses)	Rs	58.4	Is = 1.2 mA, as 58.4/Rs or 58.4/50
	Rs || 100 Ohm	17.3	Rs = 50 Ohm, as (200/(17.3-26.6/2))
	Rs || 100 Ohm + 100 Ohm	26.6	

Table 18.21-2. Sensor test and calculated parameters

	With the electrolyte	With electrolyte loses
Sensor impedance, Rs, Ohm	From 235.3	To 50
Sensor current, Is, mA	From 51.8 uA	To 1.2 mA
Sensor output, mV	From 12.2	To 58.4 mV

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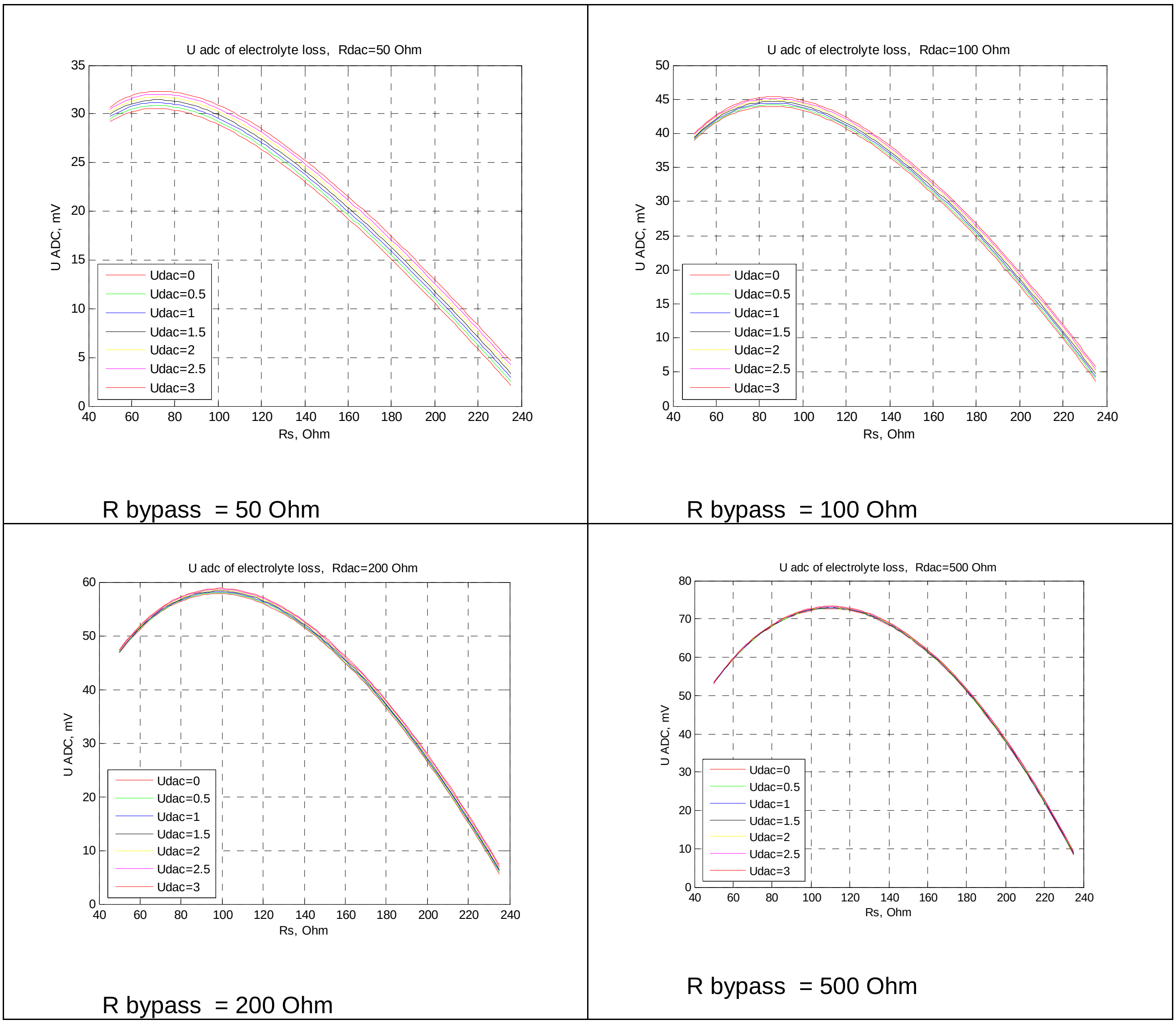

Fig 18.21-3: Sensor characterisation against bypass resistance and ADC output.

18.22 Review of quality and materials

In discussions with the manufacturer, it became clear that Analytical Industries have a passion for quality of their product.

Design faults found in other sensors were noticeably absent during these tests.

There was excellent consistency from sample to sample. No sample suffered drift other than due to damage from testing.

The manufacturer has taken every measure to remove organic contaminants from the design.

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19 PSR 11-39-MD TEST RESULTS

The test plan requires 12 sensors of each type. Sensors used in tests are numbered 1 to 12.

The test numbers below refer to the test number in the test plan.

Where the MD sensors produced results which were the same as for the MDR sensor, then the detailed graphs are shown only for the MDR sensor.

19.1 Sensor Characteristics

The output of the MD oxygen sensor air is 11.9 mV, with an internal temperature compensation circuit. All 12 MD sensors in the test were between 11.85 and 12.0mV in air at 1 ATM under lab conditions.

Fig 19.1-1. Sensor marking. Sensor 1 had an output mean of 11.94 mV in air at a mean temperature of 24.91 C. All others were in the range 11.85 to 12.0mV under similar conditions.

19.2 Test 1: Dimensions

The sensor meets the dimensional requirements imposed by the test plan.

19.3 Test 2: Materials compatibility

Discussion with the manufacturer indicated an acute awareness of the need to avoid plasticisers and organic compounds. The sensor does not have any known materials compatibility issues.

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19.4 Test 3. Hydrophobic membrane

Test	Purpose	Method	Result
3. Hydrophobic membrane	Confirm that water is not retained by measurement membrane	1. Use sensor 1. 2. Measure sensor voltage, and record temperature. 3. Place sensor sideways in shallow water bath filled with 3cm depth of sea water at 20C +5C/-2C for 1 minute, then withdraw and position with the sensor face downward. 4. Check for any water held on the face. 5. Measure the output voltage every minute over a 30 minute period. 5. Verify that output does not change more than 3%.	

Step 3: Place sensor sideways in shallow water bath filled with 3cm depth of sea water at 20C +5C/-2C for 1 minute.

Fig 19.4-1. Sensor in artificial sea-water.

Step 4: No water was held by the face.

Step 5: Measure the output voltage – results below.

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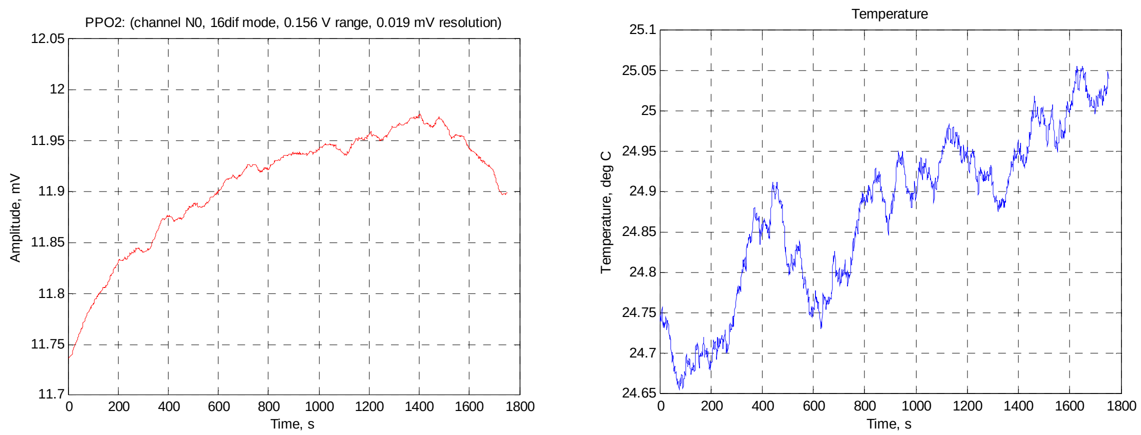

Fig 19.4-2. Cell output and temperature after water bath. Filter window is 50. PPO2 mean = 11.90 mV. Temperature mean = 24.87 ^{o}C. Output change is 0.34% (less than1%).

19.5 Test 4. Response time

Test	Purpose	Method	Result
4. Response time	Measure the time to respond, to 90% of final reading, on a change of PPO2 from 0.21 to 1.0	1. Use sensor 1 and allow output voltage to settle in air. 2. Apply a stream of oxygen to a sensor with a pressure of 30mbar +/-20mbar. Measure the readings every 100ms. 3. Compute response time to a change from 0.21 to 1.0, and from 1.0 to 0.21. 4. Verify that the response is less than 10 seconds to 90% of final value.	Pass

The result of applying each measurement step is listed below.

Step 2: Apply a stream of oxygen to a sensor with a pressure of 30mbar +/-20mbar. Measure the readings every 100ms.

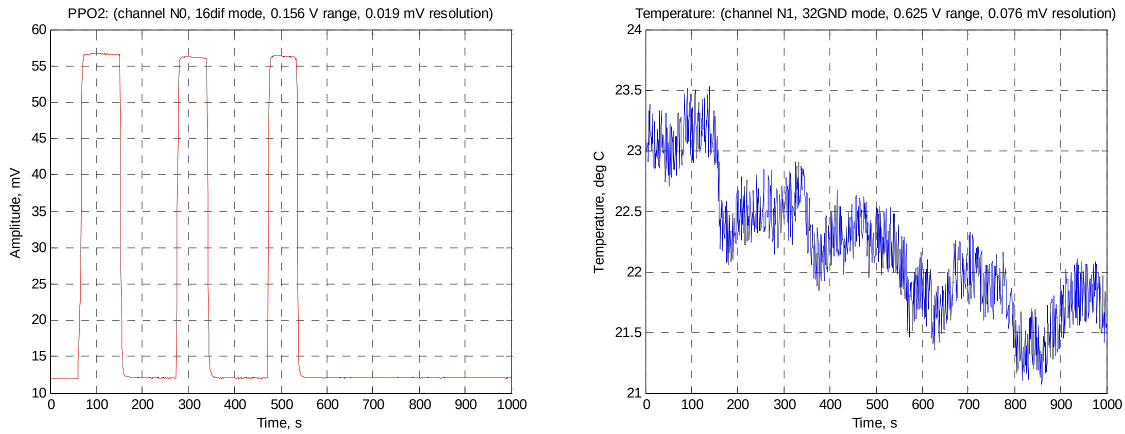

Fig 19.5-1. Step 2. Filter window = 0.

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Steps 3 and 4: Compute response time to a change from 0.21 to 1.0, and from 1.0 to 0.21.

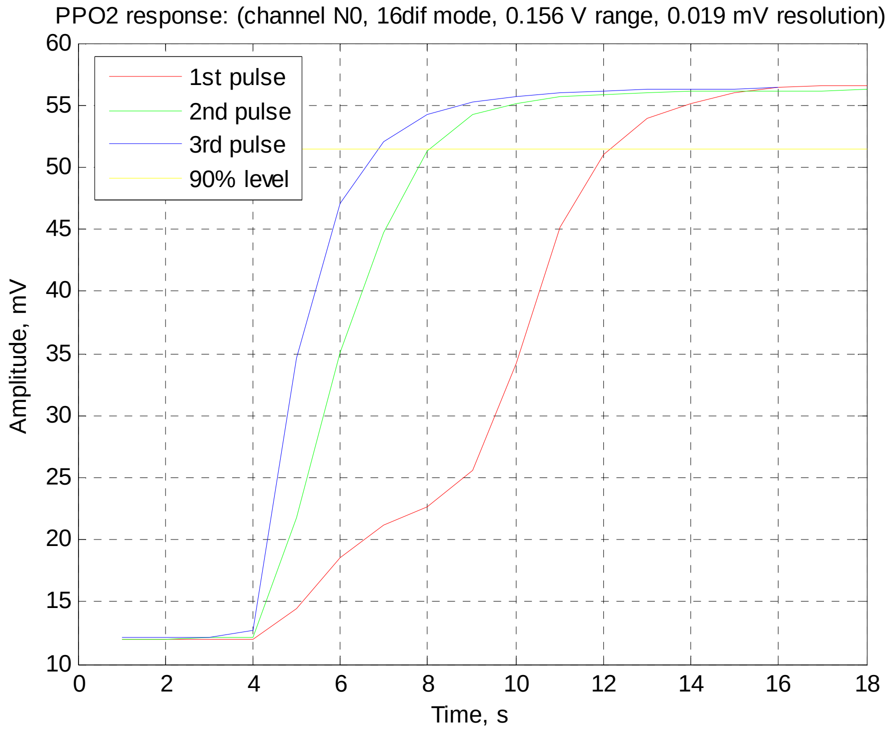

Fig 19.5-2. It seems that the less steep start of the red plot is due to a slow O2 flow. Rise time response is otherwise 4 to 6 seconds. The sensor output is 57 mV when the sensor is in 100% O2.

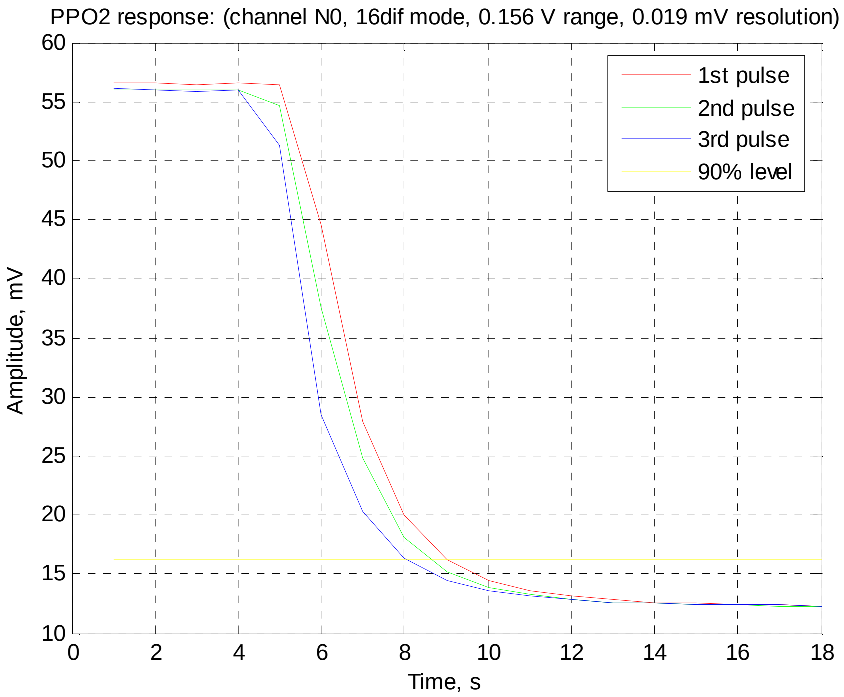

Fig 19.5-3. Fall response is 5 s (less than 10 s).

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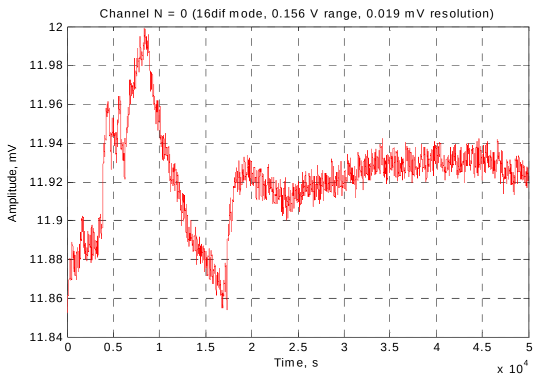
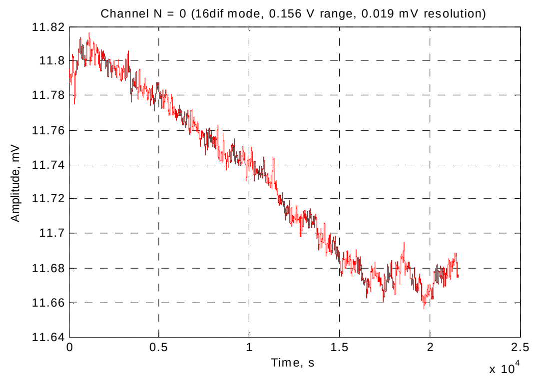
19.6 Test 5b Stability

Test	Purpose	Method	Result
5b. Stability.	Confirm sensors are stable in air and confirm calibration interval required for their use.	1. Use sensors 2 and 3. 2. Measure the output voltage with a 10K load. Record atmospheric pressure, temperature and humidity. 3. Correct data for temperature and pressure. 4. Confirm results are within 5% throughout the measurement period. 5. Extrapolate any trend to verify that operating life is not less than that quoted by manufacturer.	Pass. Correction equations shown with results

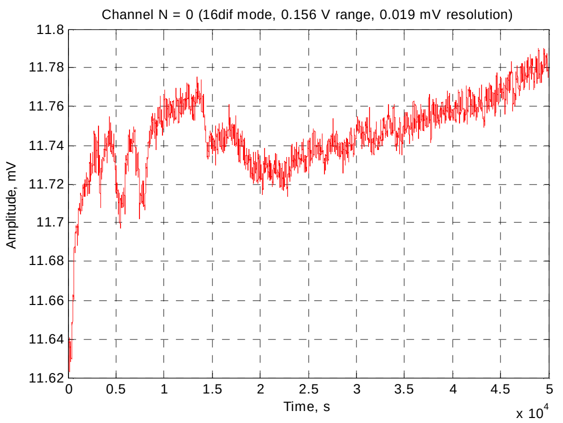
Steps 2 and 3, Sensor 2: Measure the output voltage with a 10K load. Record atmospheric pressure, temperature and humidity.



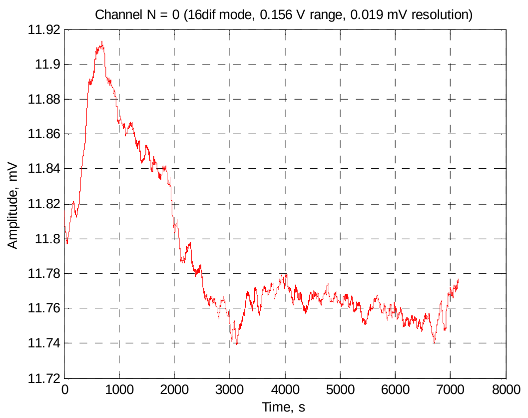
PPO2 mean = 11.92 mV



PPO2 mean = 11.73 mV



PPO2 mean = 11.74 mV



PPO2 mean = 11.79 mV

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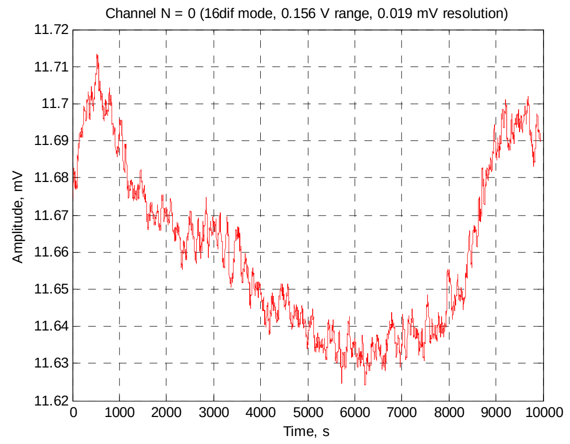
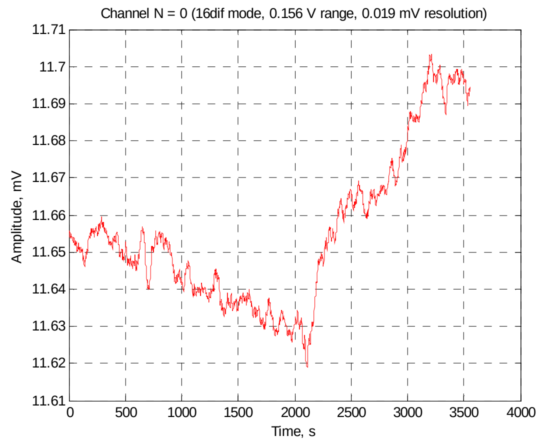
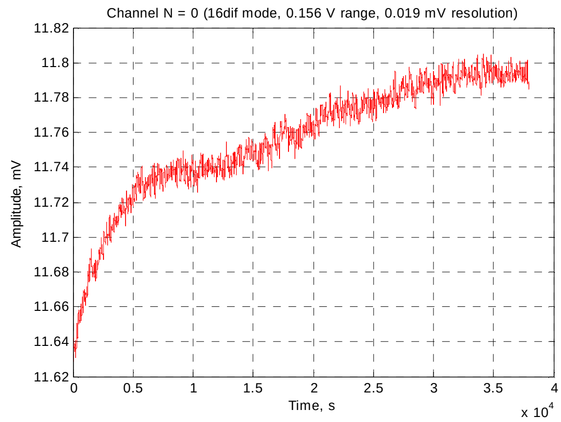


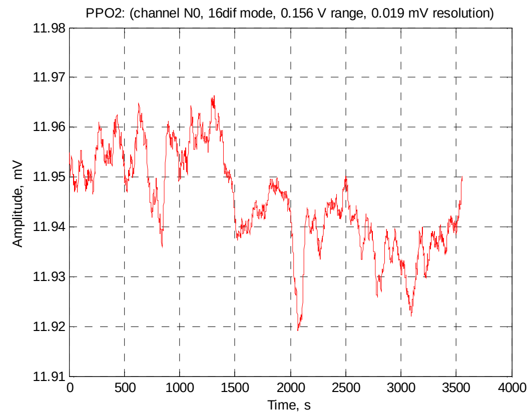
PPO2 mean = 11.66 mV



PPO2 mean = 11.66 mV



PPO2 mean = 11.76 mV



PPO2 mean = 11.95 mV

Fig 19.6-1. Stability of the two sample MD sensors under laboratory conditions, exploring dependency on small scale changes in pressure and humidity. The method of waiting until there is sufficient change in other parameters to allow the correlation between each parameter change and the cell output to be determined, is used throughout these tests.

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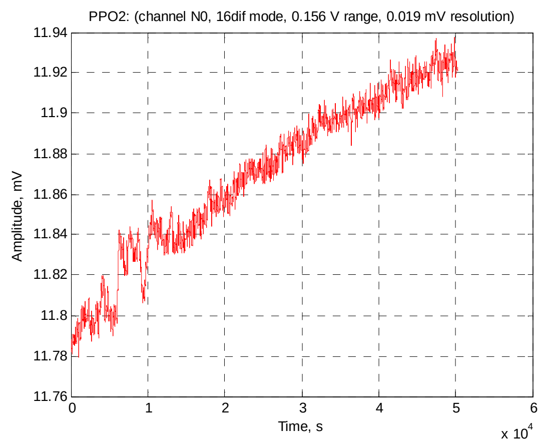
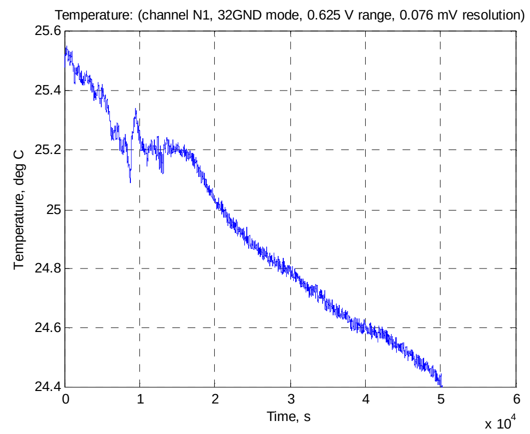
Steps 2 and 3, Sensor 3: Measure and compensate for changes in temperature and pressure.

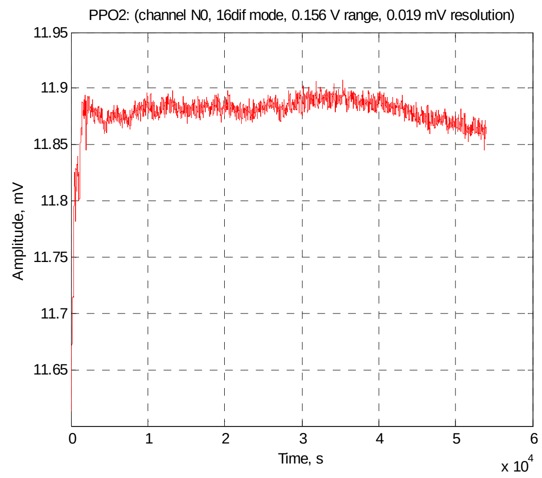


PPO2 mean = 11.87 mV

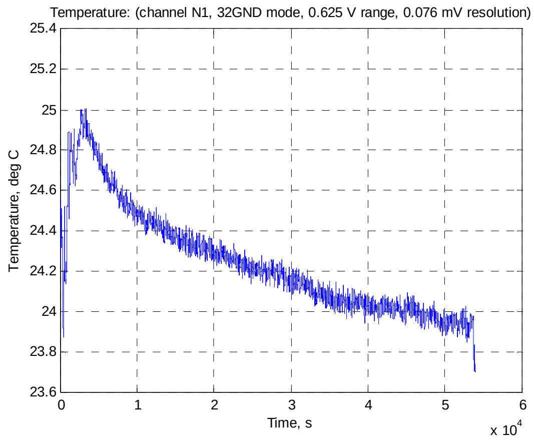
-0.14 mV/K



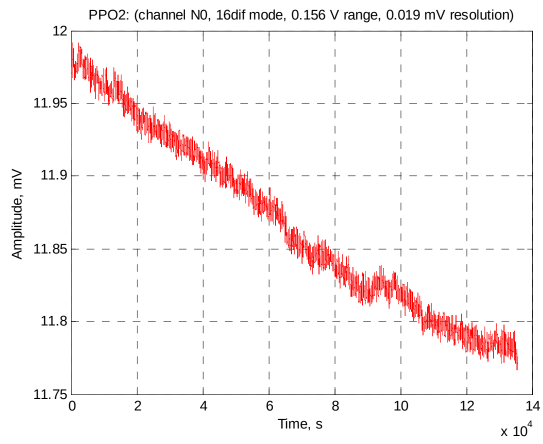
Temperature mean = 24.92 C



PPO2 mean = 11.88 mV

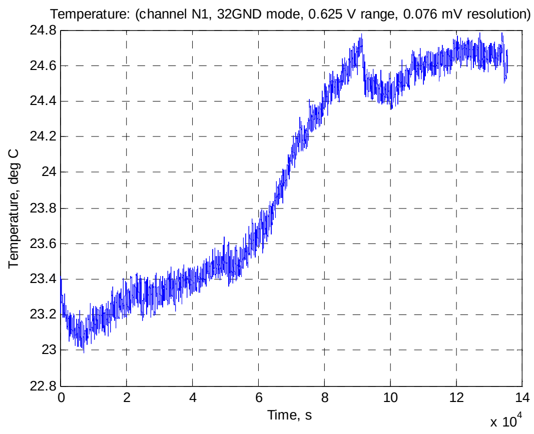


Temperature mean = 24.25 C



PPO2 mean = 11.87 mV

+0.12 mV/K



Temperature mean = 23.95 C

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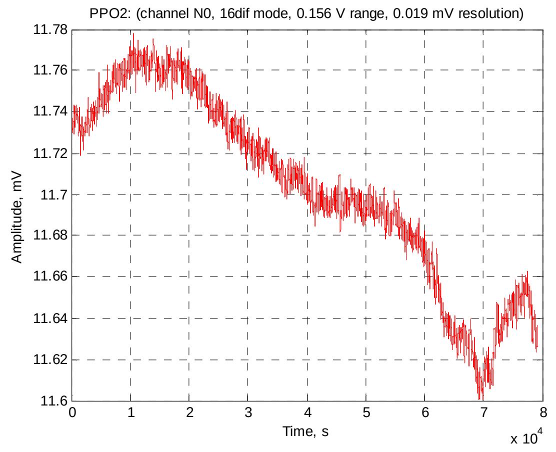
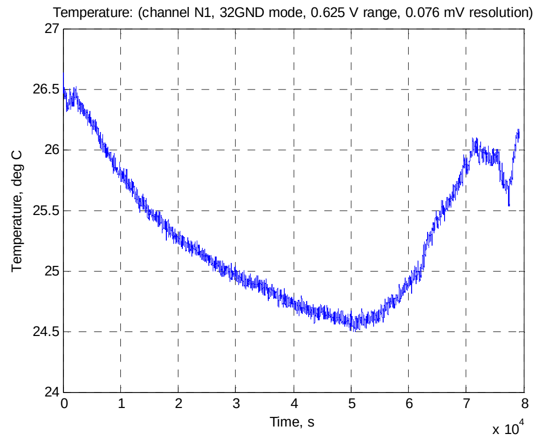


PPO2 mean = 11.7 mV



Temperature mean = 25.28 C

Fig 19.6-2. Stability of N2 MD sensor in laboratory conditions. Sensitivity to temperature is within the range -0.14 mV/K to +0.12 mV/K.

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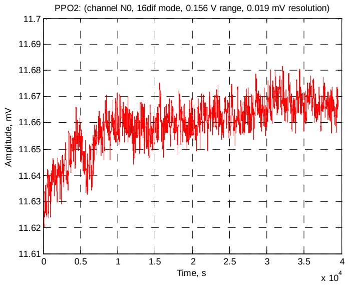
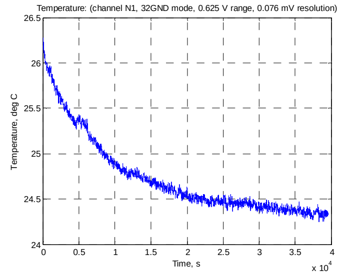
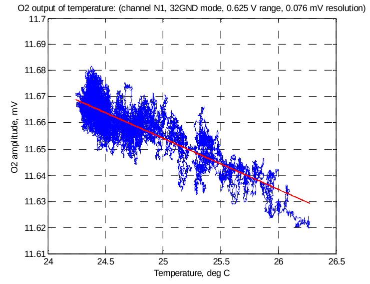
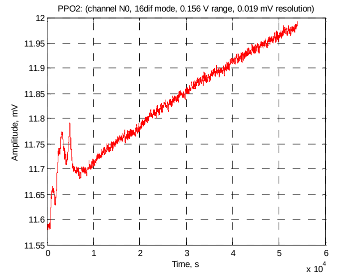
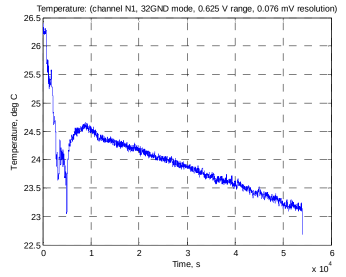
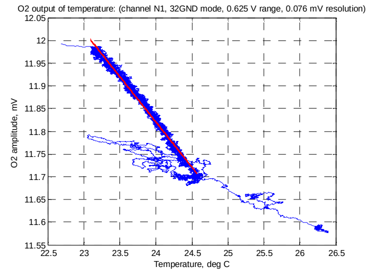
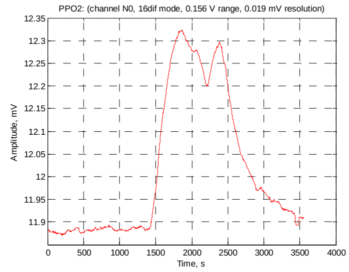
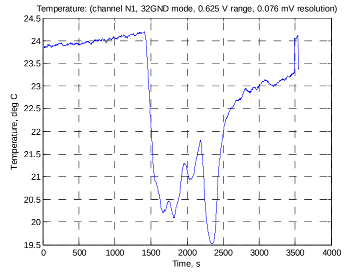
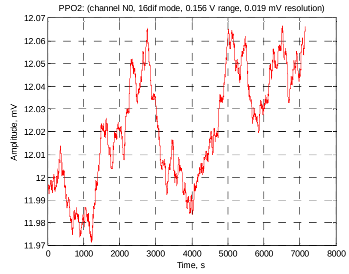
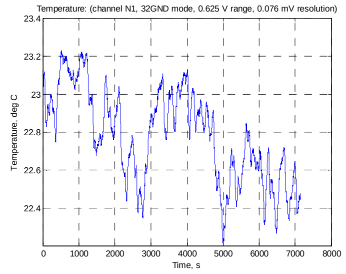
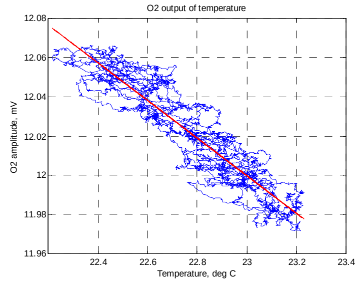
 PPO2 mean = 11.66 mV	 Mean = 24.73 C	 p = [-0.019545 12.143] ∆PPO2=-0.019545mV/∆C
 PPO2 mean = 11.83 mV	 Mean = 23.95 C	 p = [-0.1990 16.5972]
 PPO2 mean = 12.01 mV	 Mean = 22.76 C	← O2 sensor inversely tracks the temperature change
 PPO2 mean = 12.02 mV	 Mean = 22.78 C	 p = [-0.0961 14.2090]

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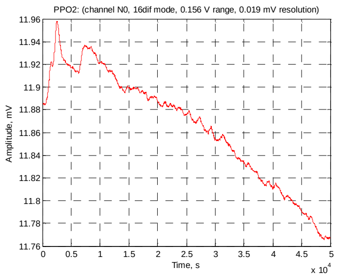
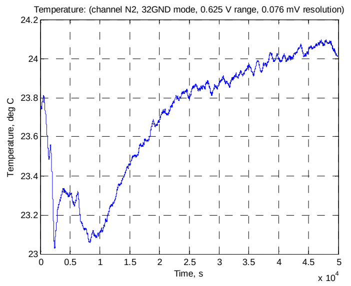
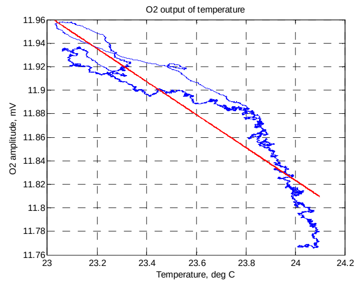


PPO2 mean = 11.86 mV



Mean = 23.7 C



p = [-0.1403 15.1894]

Fig 19.6-3. Dependency on the rate of change of temperature. As a function of temperature, the sensitivity is within the range –0.09 to -0.19 mV/K. It is also a function of the rate of change of temperature: the faster the temperature change, the lower the PPO2 sensitivity. The lower end of the range, –0.09 mV/K, is reached when the rate of temperature change is 1K/2hour. The upper end of the range, –0.19 mV/K, is reached when the rate of temperature change is 1K/12hour.

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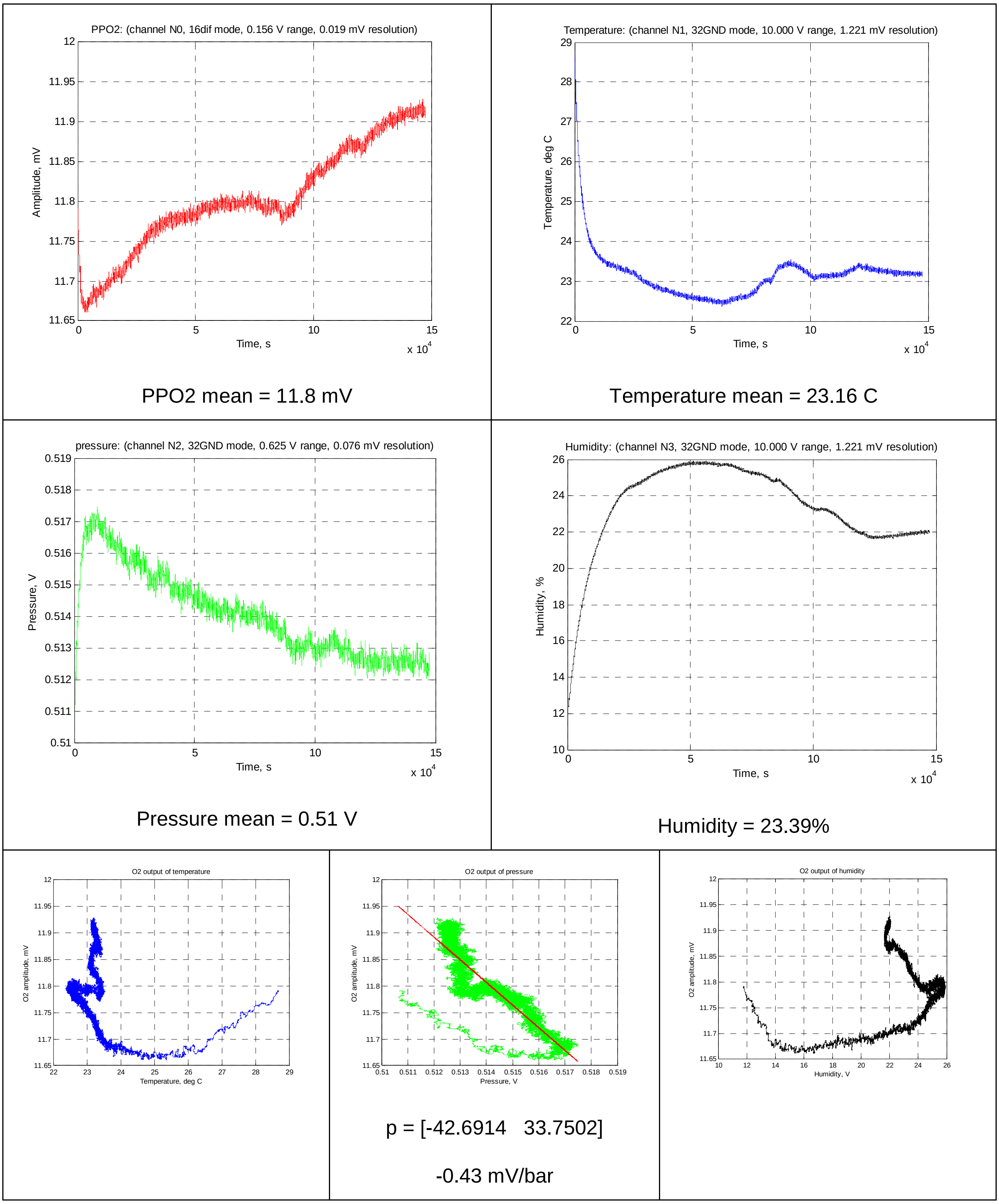

Fig 19.6-4. Sensor stability. When the temperature and humidity are constant, the oxygen sensor output is inversely proportional to the pressure as a linear function of -0.43 mV/bar.

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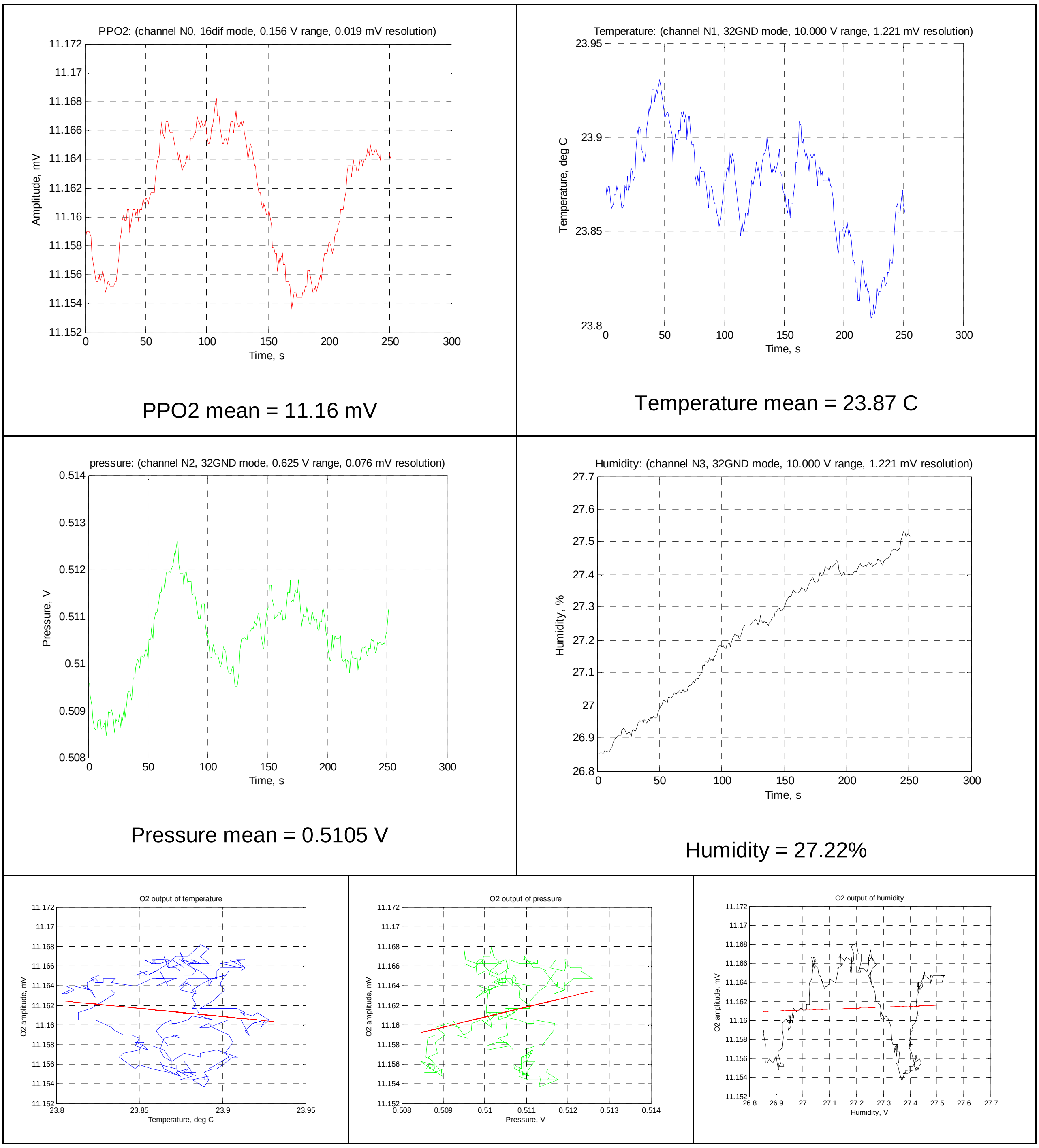

Fig 19.6-5. Stability of PPO2 sensor. Fluctuation of pressure and temperature make it difficult to determine the dependence of PPO2 sensitivity for very small changes.

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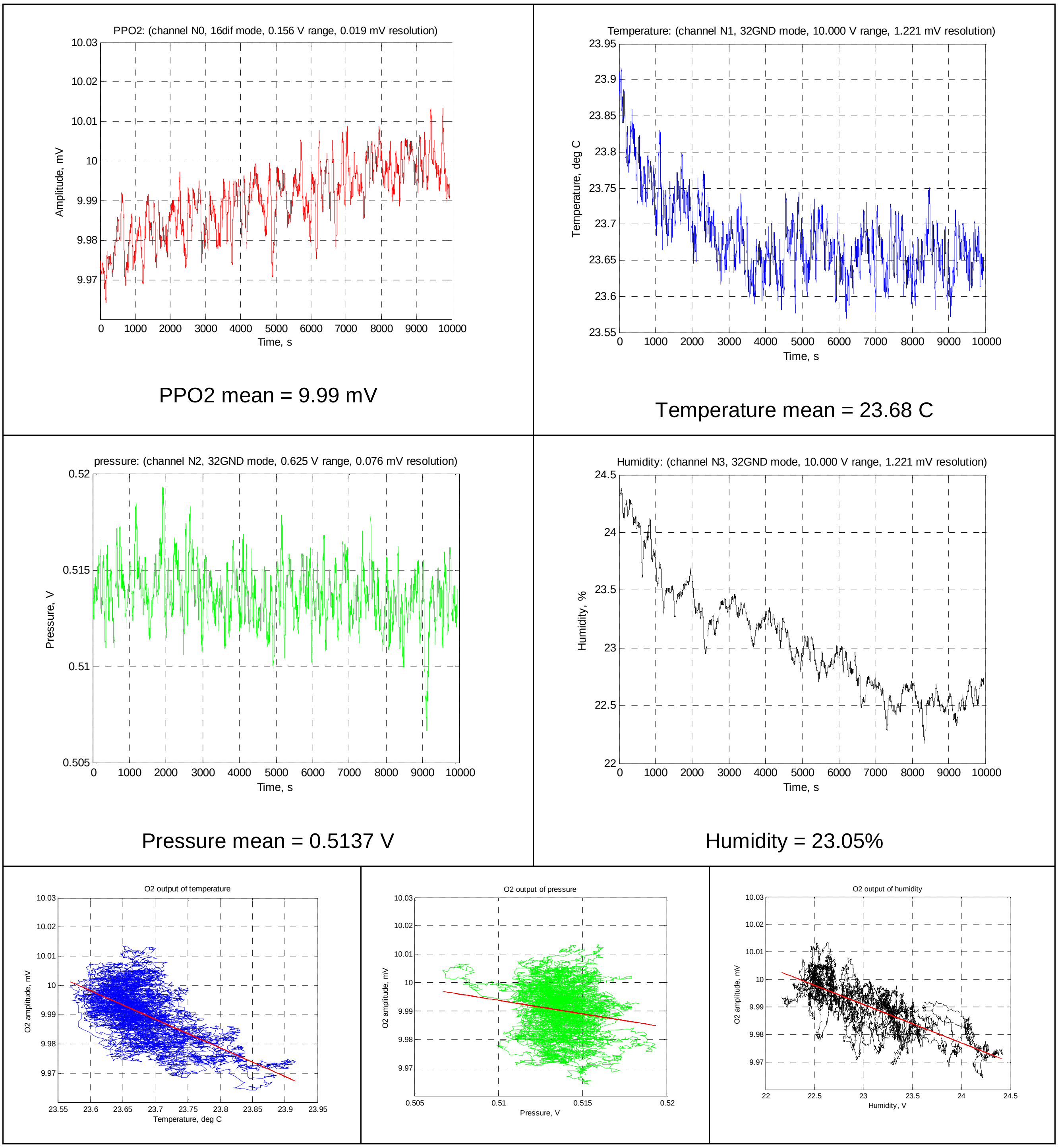

Fig 19.6-6. When the pressure is constant, the PPO2 sensor output inversely depends on temperature.

Steps 4 and 5: The extrapolation equations are described with the above results.

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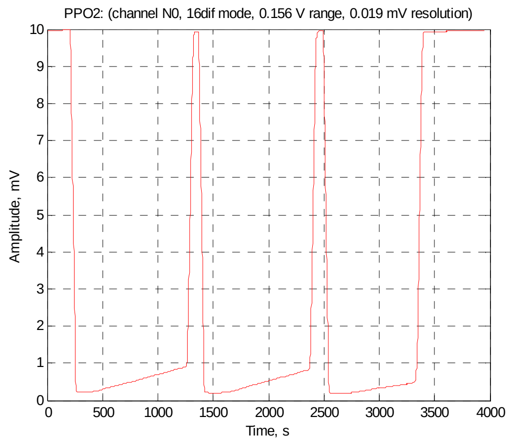
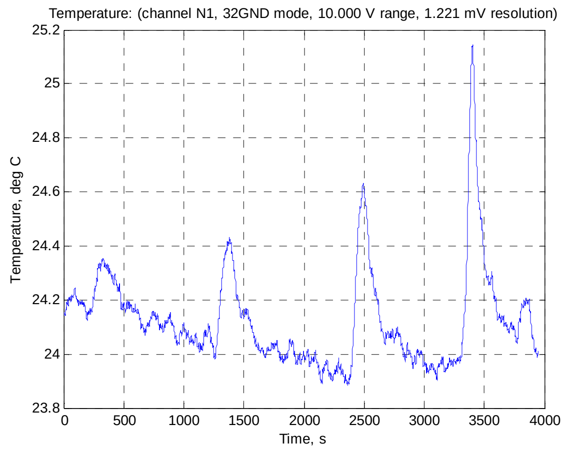
19.7 Test 10. CO2 Susceptibility

Test	Purpose	Method	Result
10. CO2 Susceptibility	To determine damage caused to the sensor by being in a loop which has been pre-breathed without a scrubber. The PPCO2 can vary from 0.04 to 0.4 under these conditions.	1. Use sensor 3. Record ambient pressure and temperature. 2. Fit sensor to small chamber with an open port, and fill with CO2 so there is a 100% CO2 environment at ambient pressure around the sensor. 3. Measure the voltage produced by the sensor to verify it has fallen to zero. 4. Leave the sensor in the chamber for 15 minutes. 5. Remove from the chamber and allow to stabilise in air for 1 minute and measure the voltage, temperature and ambient pressure. 6. Repeat steps 2 to 5 four times. 7. The sensor should be in air when it is not in CO2.	Pass





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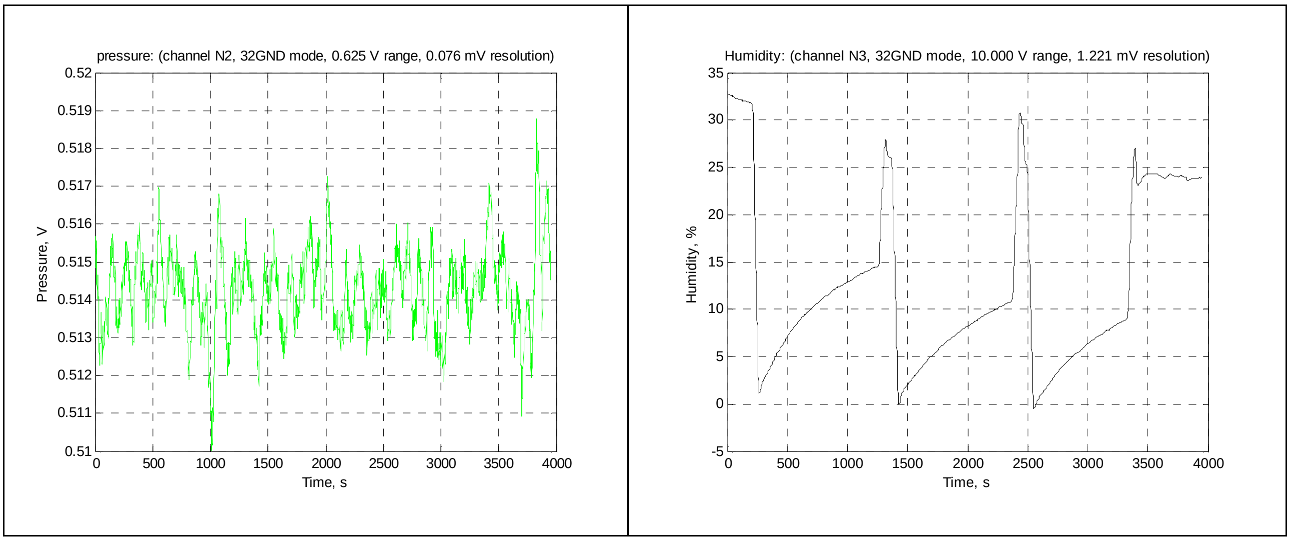

Fig 19.7-1. The offset (minimum reading) from the oxygen sensor in dry CO2 is 0.2 mV.

The DL model of the PSR 11-39 sensors were also tested for CO2 tolerance, and withstand at least 31 hours exposure to pure CO2 without any observable change. The exposure was of 1 hour, 2 hours, 4 hours, 8 hours, and 16 hours, with a PPO2 linearity test before and after each of these exposure periods. The cells were linear, within their 1% accuracy specification, to 5 bar of O2 in every case.

19.8 DL model variant

The PSR 11-39-DL is a variation of the MDR sensor manufacturing by Analytical Industries. It differs from the MDR in that the outer case removed to eliminate vapour traps, external digital compensation, with ruggedness features and marking specified by Deep Life.

19.8.1 Temperature Compensation Accuracy of the DL model variant

The report DV_PPO2_Device_Accuracy_110105.pdf describes the temperature compensation of the DL cells, and their accuracy. The DL model cells are the most accurate galvanic cells that have been tested as part of this programme.

19.8.2 CO2 Tolerance and Linearity to 5 bar of O2

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.

19.8.3 Linearity to 8 bar of O2 under realistic diving conditions to 100m

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:

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- 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[4]).
- 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.

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

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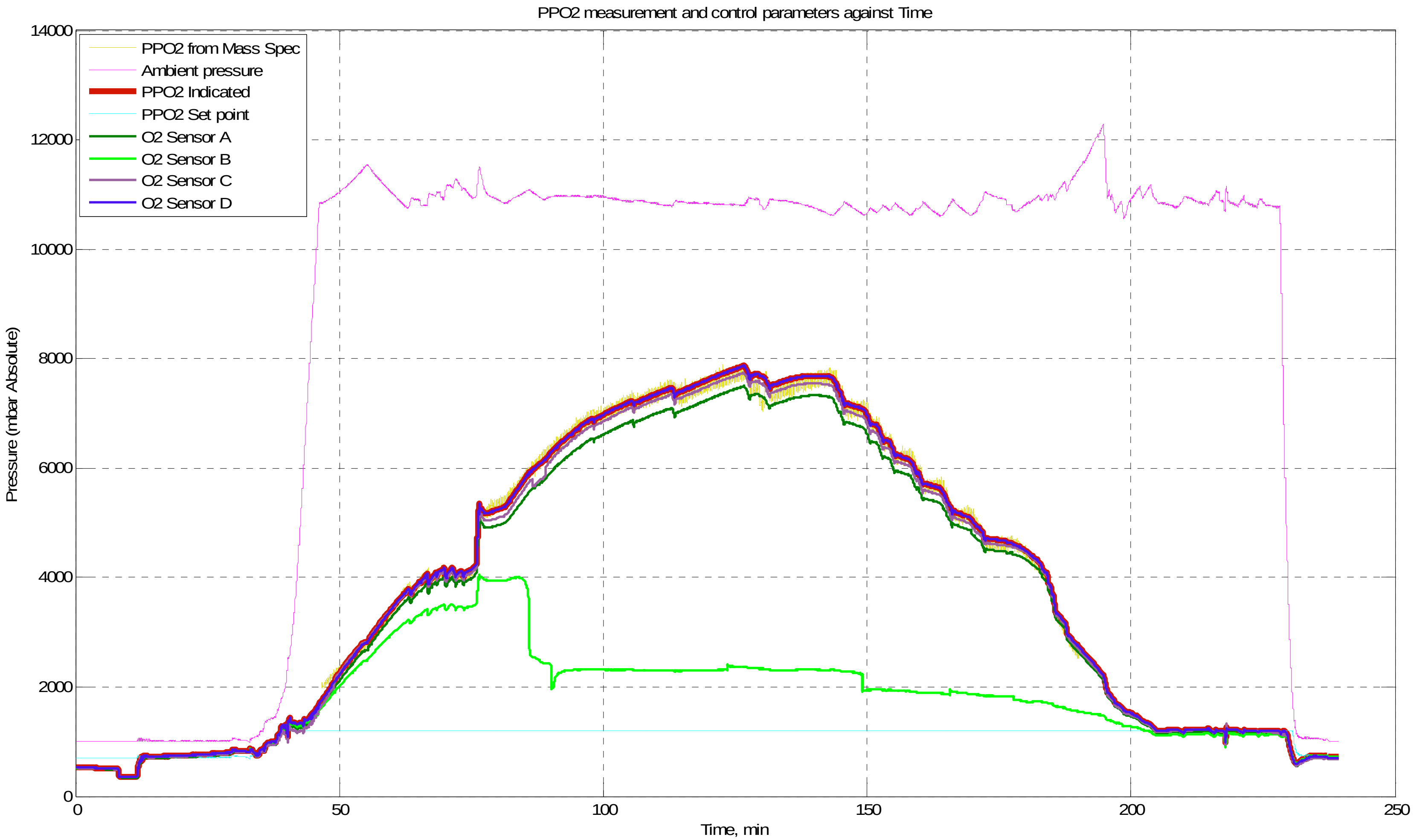

Figure 19-1. 100m test dive of 3 hours bottom time, with PPO2 indicated from four AII cells PSR-11-39-DL compared with mass spec.

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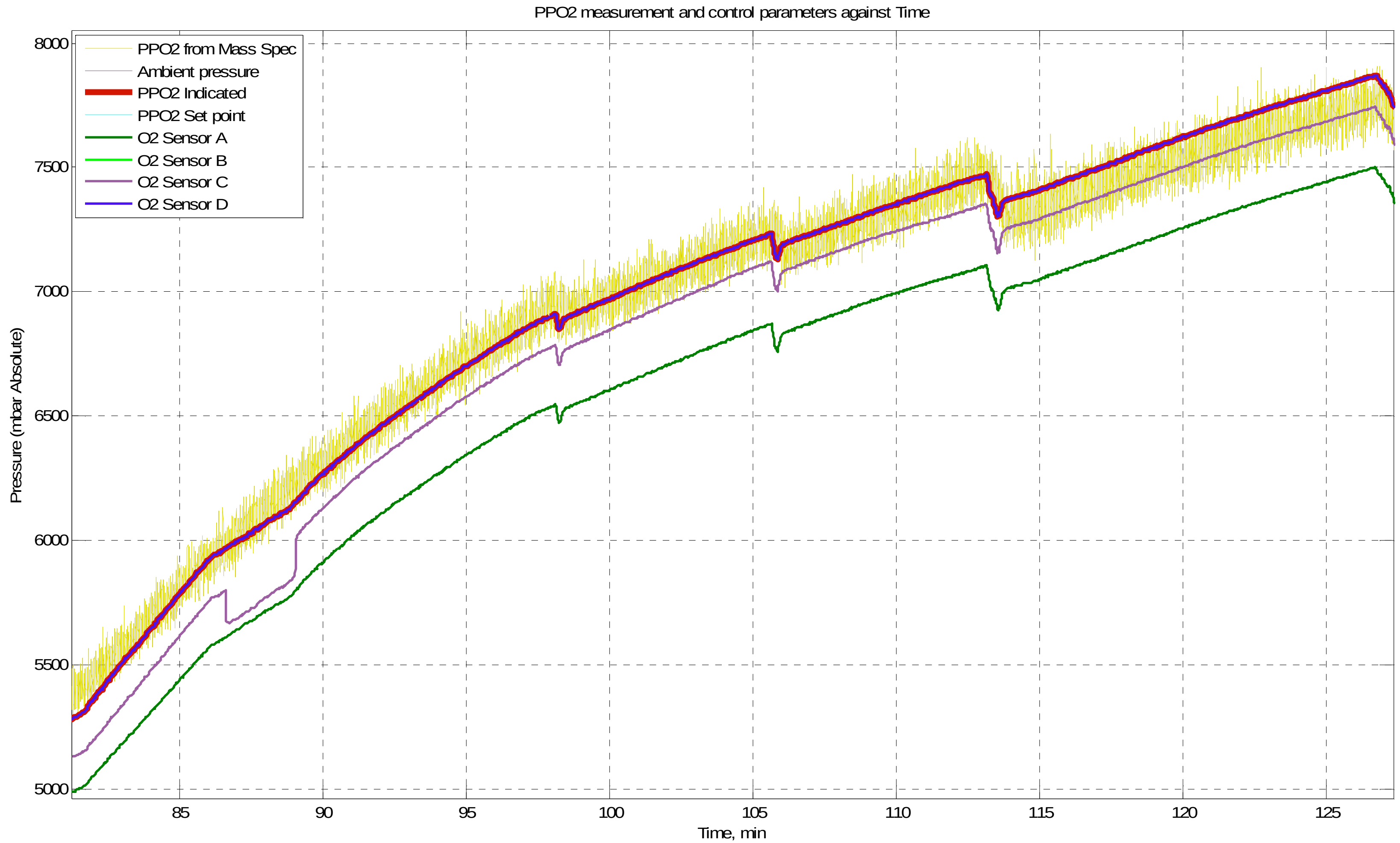

Figure 19-2. Zoom into the top portion of the curve, where the PPO2 was increased to 7.8 bar, The steps in the curves are due to self test movements of the injector. Three out of the four oxygen sensors had reasonable accuracy at this PPO2 level, even though all All sensors were more than 2 years old.

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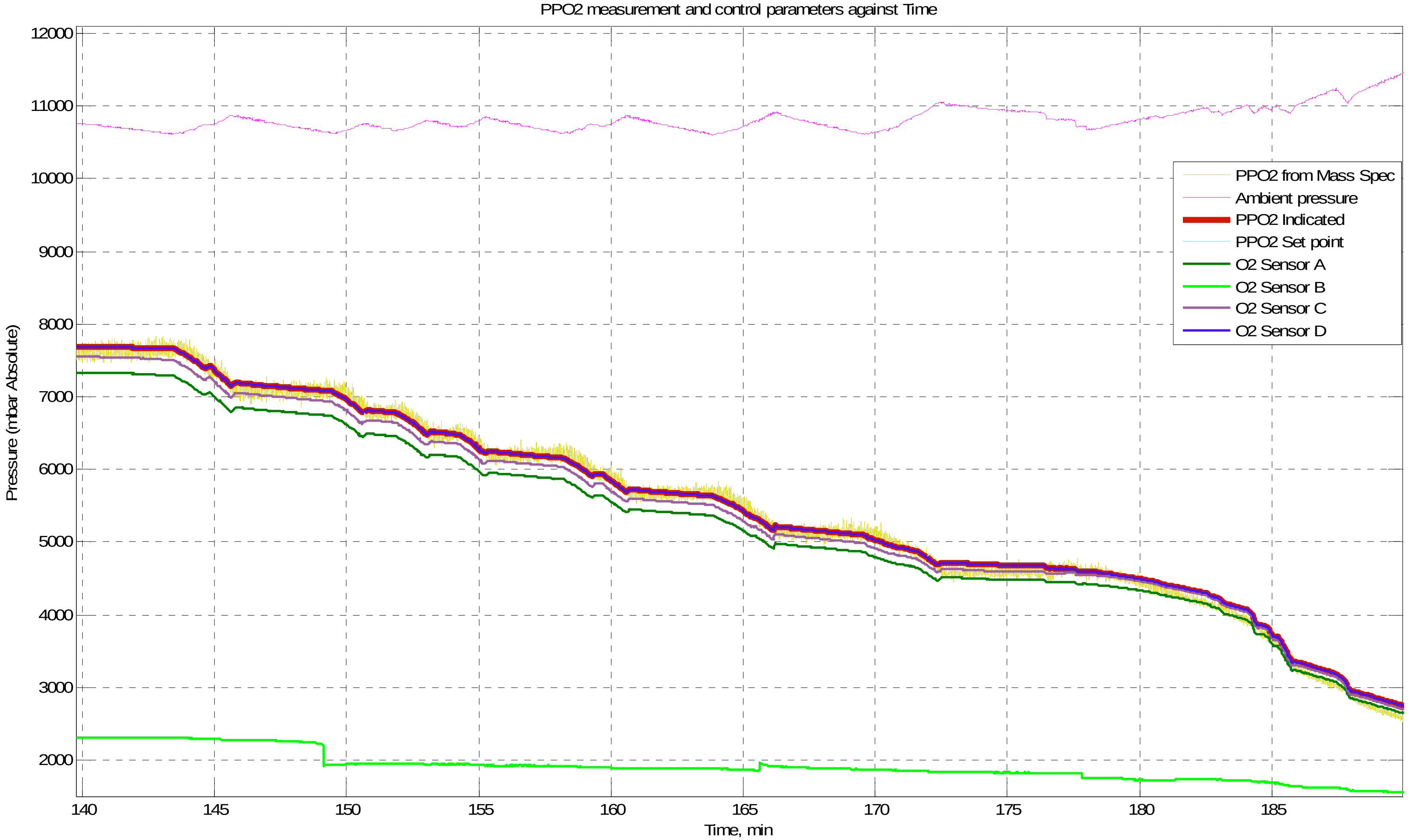

Figure 19-3. Zoom into the portion of the curve during the second part of the dive, where the PPO2 was drops gradually from 7.8 bar to eventually 1.2 bar. There is an excellent correlation with the indicated PPO2 and the actual PPO2 verified on the mass spectrometer.

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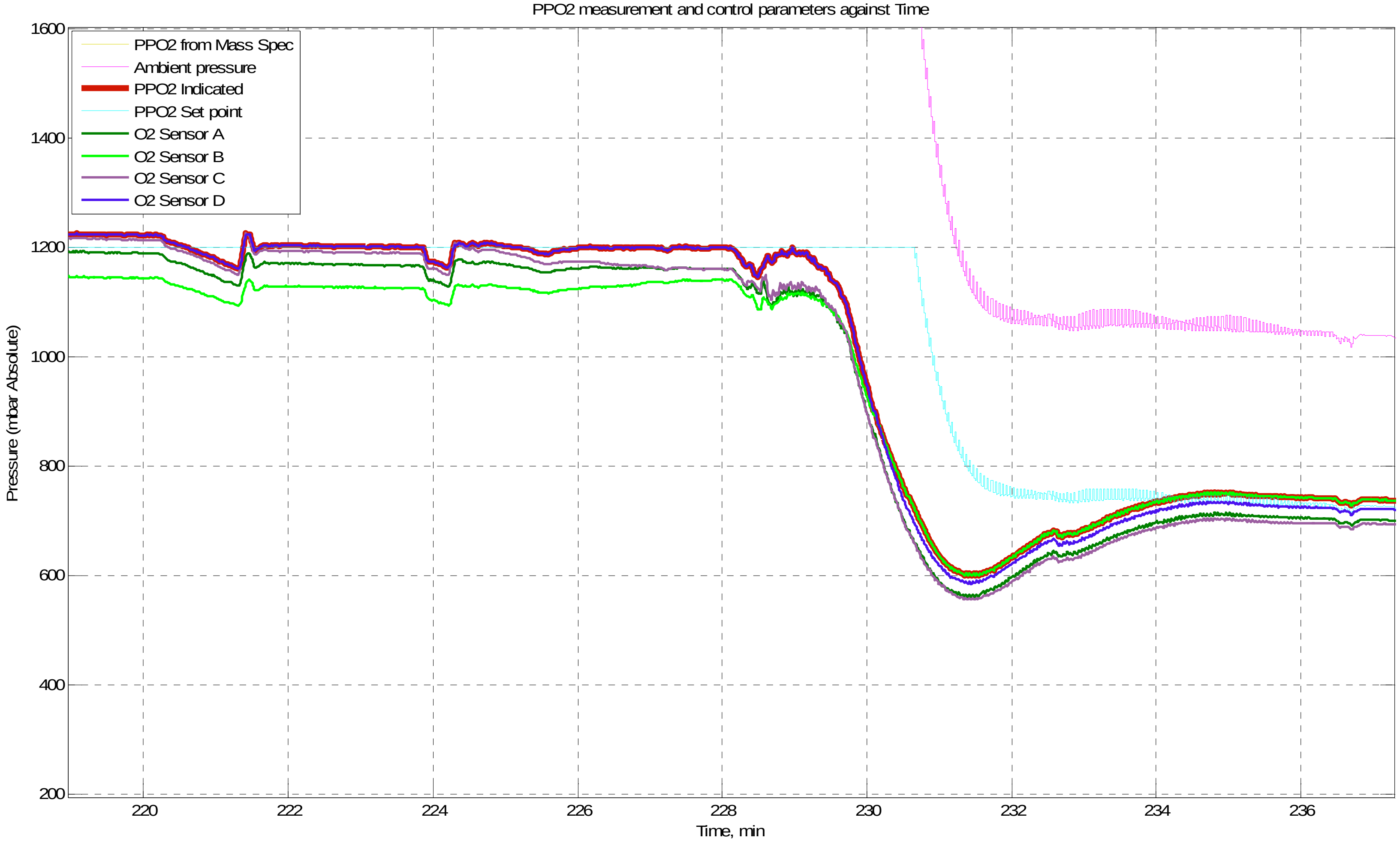

Figure 19-4. Zoom into the final part of the ascent portion of the dive. All sensors are now tracking each other closely, and again the actual PPO2 is indicated very accurately. The PPO2 setpoint reduces automatically in this rebreather from the chosen setting of 1.2bar at depth, to 0.7 at the surface. The PPO2 accuracy and group accuracy of the cells excellent even following this fast ascent.

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19.9 Conclusions of test of PSR 11-33 model MD, MDR and DL sensors

The following conclusions are made:

1. The PSR 11-33-MD, MDR and DL sensors are not damaged by exposure to pure CO2 for up to 24 hours. There may be effects at different cell temperatures: this is a matter for ongoing study.
2. None of the safety concerns from leaking KOH arose during these tests, except after a 3m drop, in which case electrolyte was lost from one sensor from the group tested. The sensor is significantly more robust in that respect than the market leader, Teledyne.
3. The output of the MD sensor at 1 ATM is typically 0.25 mV/0%O2; 11.9mV/20.9%O2; 57mV/100%O2; which is modified by temperature, pressure and other parameters examined in this report. This is within the specified range for this sensor.
4. The output of the MDR sensor at 1 ATM is typically 0.19 mV/0%O2; 4.9mV/20.9%O2; 18.5mV/100%O2. The outputs of the tested MDR and DL sensors are in the range from 4.0 mV to 5.5 mV: this is within the specified range for this sensor.
5. The change in output after being placed in a shallow salt water bath is less than 2%.
6. The response time of the MD sensor upon an O2 step from 21% O2 to 100% O2 is 5 sec. The response time of the MDR and DL sensor on a step increase of O2 from 21% to 100% is 6 to 7 seconds. The response time of each of three sensors is sufficient for the use of the cell in a rebreather.
7. The MD sensor is sensitive to temperature and to the derivative of the temperature. The sensitivity is in the range from –0.012 mV/K to -0.19 mV/K. The sensitivity increases the slower the change in temperature is, contrary to what was expected.
8. The MDR sensor is sensitive to temperature and to the derivative of the temperature. The sensitivity is about 0.14 mV/K. The sensitivity to long temperature changes is 0.11 mV/K. The DL sensor is digitally compensated, and this appears to produce an ideal compensation.
9. The response time of the MDR sensor on a step decrease of O2 from 100% to 21% is under 10 sec (11 measured, with retained O2 in fixtures, and 9 seconds from the improved sensors in the second batch).
10. The response time of the MDR sensor on a step decrease of O2 from 21% to 0% in CO2 flow is 7 to 9 sec. The recovery response of discontinuing the CO2 flow and allowing an O2 step from 0% to 21% (1 ATM) is 12 s.
11. The sensitivity of the MDR sensor to temperature depends on gas flow rate, the temperature capacitance of the sensor and the temperature resistance between the sensor and the environment.
12. Increasing ambient pressure increases the MDR output from 5mV/1bar to 6mV/130bar even when the PPO2 is constant. This correction is much less than for some other sensors tested (from other manufacturers) but it means that for extremely deep dives, a polynomial correction should be used. The deepest dives the rebreathers are planned to be used in are to 600m (60 bar).
13. After explosive compression and decompression in a torpedo test, where the pressure is increased from 1 ATM to 130 bar in under 1 second using He and then from 130 bar to 1ATM, the output of an MDR sensor at 1 ATM was observed to be negative (less than –2.5 mV). Two days later the sensor sensitivity and polarity were restored. This failure mode is preferred as in this case the failure is obvious and the sensor would be screened by the electronics.
14. The effect of worst possible ambient pressure (Chamber lockout/Torpedo test N9) could change the sign, gain, output value, stability of the O2 sensor and generate a floating output, but does not cause leakage of electrolyte or explosive breakup of the sensor which would pose a health and safety hazard to the chamber operator.

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15. On finding the weakness to be mechanical robustness, Analytical Industries responded quickly and carried out a design change to improve this aspect of their performance: all other parameters were already acceptable. Following the design change, Analytical Industries PSR-11-39-MD and MDR sensors are suitable for diving applications.
16. The MDR sensor is sensitive to drops (high acceleration). Each 3m drop of the MDR sensor decreases its output by 3% on average and its response to O2 drops from 18.5mV/100%O2 to 1.5 mV/100%O2. A 3m drop can cause immediate destruction of the sensor and loss of electrolyte. After a drop, the sensor does not respond to O2 changes immediately. 9 drops of 3m generally destroy the sensor. The initial batch tested found that after 1.5 m drops in 1 ATM the sensor output varies in the range from –1 to 2.4 mV. This performance is better than some other sensors tested, but given the use of rebreathers in RHIBs, the electronic assembly was improved by the manufacturer. The second batch of sensors show a reducing output after multiple drops from 1.5m, but all sensors worked after this test.
17. The risk of electrolyte loss is high, because risk of severe mechanical shock is high. It is strongly recommended that the equipment include suitable DAC and switching circuitry to test for a change in cell source impedance whenever there is a substantial difference in the cell outputs, before selecting the highest output cell. This involves placing a known resistance across the output of the cell and checking the output drops by the expected amount as a percentage of its normal output.
18. AII is approved as a supplier of O2 cells, meeting Deep Life's Procurement Specification.
19. The DL sensor appears to be fully compliant with the requirement specification. These differ from the MD and MDR cells by the removal of outer housing to prevent water traps, gel coating circuit board, electrical coding, SMB male socket, labelling to provide traceability and better identification.

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20 TELEDYNE R22D BATCH F7 TEST RESULTS

Batches of Teledyne R22D sensors have been tested since this test programme began. The R22D batch F7 is an improved diving sensor by Teledyne, addressing issues highlighted by Deep Life Ltd, in particular, improvements to the mechanical robustness of the product . This sensor has an internal temperature compensation circuit. It normally uses an MOLEX connector: this should be the SMB male connector in dive applications.

A prototype batch of 12 of the F7 sensors were tested.

Specifications:

1. Output - (8-13mV) in air at 25C, sea level
2. Range – 0 – 2.3 ATM PPO2
3. Accuracy – within +/-1% of full scale at constant temperature and pressure (0-1ATM),+/1 2% full scale at constant temperature and pressure (0-2 ATM PPO2) when calibrated with 100% oxygen.
4. Response time - less than 6 seconds for 90% of final value .
5. Offset – less than 0.5% of oxygen equivalent at 25C in zero gas after 36 seconds
6. Humidity – 0 to 99% R.H. (non-condensing). Note application is condensing.
7. Operating temperature range - 0 to 40C
8. Storage temperature – 0 to 50C
9. AVG expected cell life – 36 month in air at 25C and 50% R.H.
10. Shelf life – 24 month
11. Weight – 32 grams
12. Load 10K required
13. Temperature compensation error specification is +/-5% of full scale over the temperature range. Worst case tracking error (within the first hour after a maximum temperature step)is+/-7.5% of full scale. (Gas samples must be brought to ambient temperature.) Percent readout is only within+/-1% at constant pressure (e.g. a 10% increase in pressure will result in a 10% in reading)

20.1 Sensor data

The initial outputs of the oxygen R22D batch F7 sensors with temperature compensation are shown in Table 20.1-1 below.

Table 20.1-1 Sensor initial output

All values are within the specified range.

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Figure 20.1-Example of sensor marking. Sensor 8 had an output mean of 9.743 mV in air at a mean temperature of 24.62C. Date code is F7 rather than JULY 2007 but otherwise is clear.

20.2 Test 1: Dimensions

The sensor meets the dimensional requirements imposed by the test plan.

20.3 Test 2: Materials compatibility

The sensor does not have any known materials compatibility issues, though the shell is made from ABS.

20.4 Test 3. Hydrophobic membrane

Test	Purpose	Method	Result
3. Hydrophobic membrane	Confirm that water is not retained by measurement membrane	1. Use sensor 8. 2. Measure sensor voltage, and record temperature. 3. Place sensor sideways in shallow water bath filled with 3cm depth of sea water at 20C +5C/-2C for 1 minute, then withdraw and position with the sensor face downward. 4. Visual inspection using magnifier for any water held on the face. 5. Measure the output voltage every minute over a 30 minute period. 6. Verify that output does not change more than 3%.	The sensor output change is 0.54%. Accept as a pass.

Step 2: Measure sensor voltage, and record temperature.

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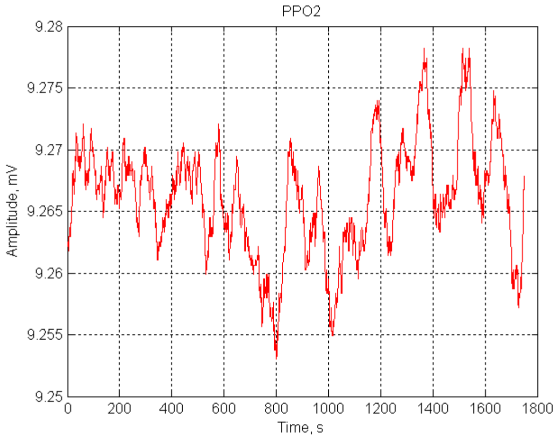
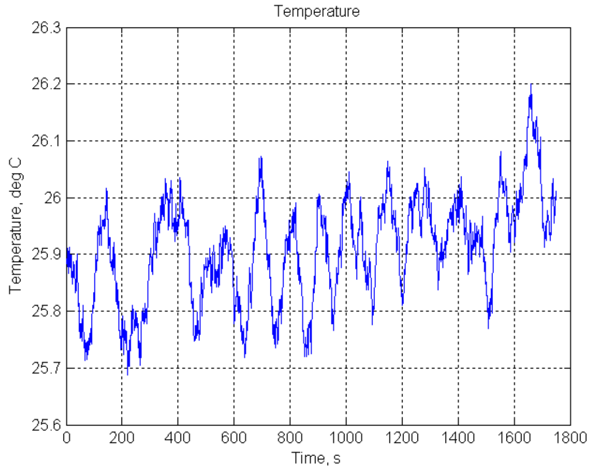
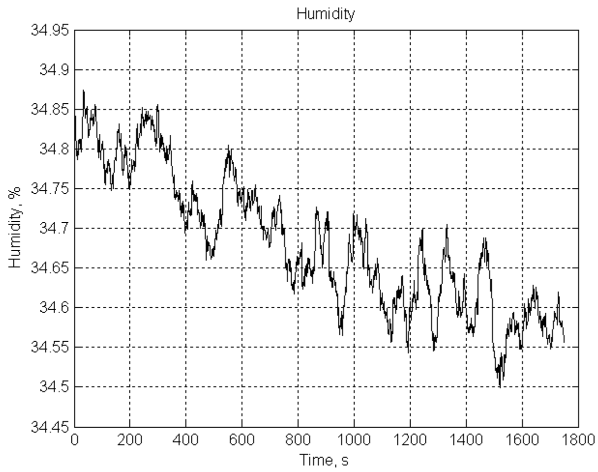


PPO2 mean = 9.266 mV

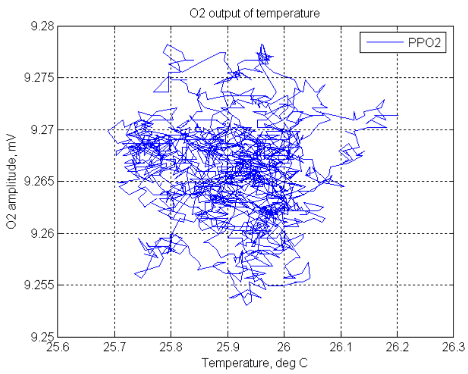


Temperature mean = 25.91C

Pressure mean = 1005 mBar



Humidity mean = 34.68%



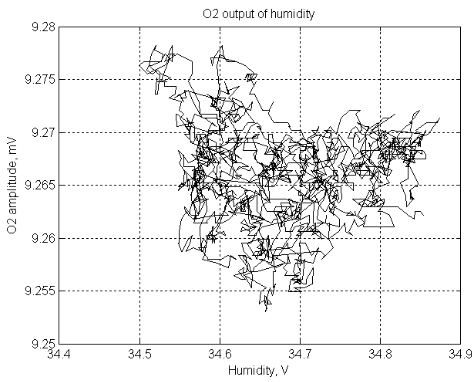


Figure 20.4-Sensor 1 characteristics before immersion in water (filter: 50). Multi-variate analysis shows good temperature compensation, and the sensor is not affected by humidity.

Step 3: Place sensor sideways in shallow water bath filled with 3cm depth of sea water at 20C +5C/-2C for 1 minute.

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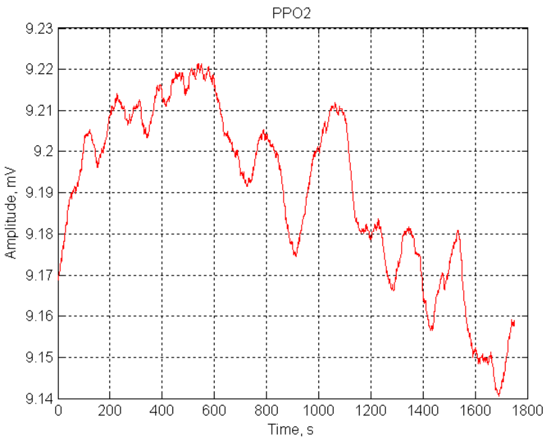
Artificial sea water was made according to EN14143.

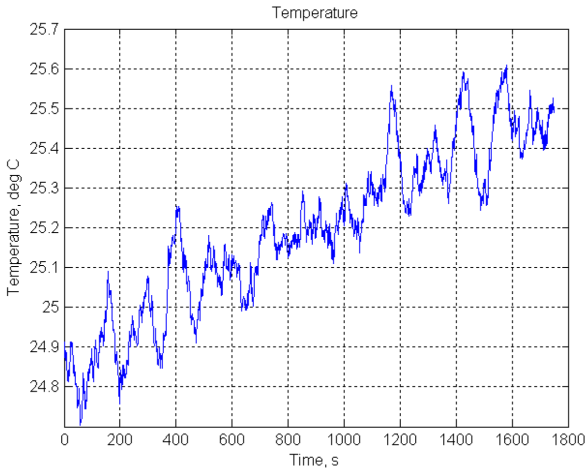
Figure 20.4- Sensor 2 in sea water.

Step 4: Visual inspection using magnifier for water held on the sensor face. There was none visible.

Step 5: Measure the output voltage every minute over a 30 minute period.

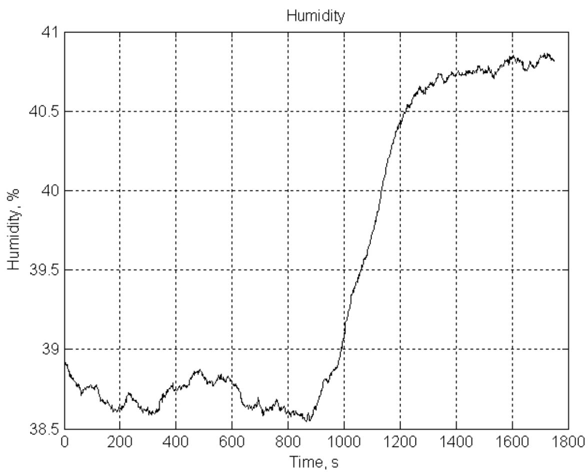


PPO2 mean = 9.19 mV



Temperature mean = 25.19 C

Pressure mean = 1005 mBar



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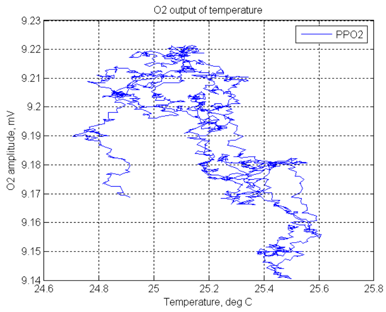
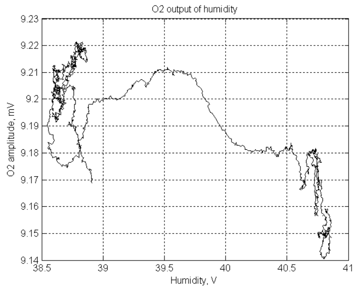
	Humidity mean = 39.47%
	

Figure 20.4-1 Sensor 2 after immersion in water (filter: 50). The sensor output change is 0.54%, which is insignificant (i.e. under 1%).

20.5 Test 5a. Temperature range.

Test	Purpose	Method	Result
5a. Temperature range.	To verify linearity over temperature range.	1. Use sensor 8 2. Heat the chamber at 1C per minute to 90C. 3. Record temperature, pressure, humidity and measured PPO2 throughout test. 4.Correct results for pressure changes during test.	Permanent damage

Note: Sensor manufacturers state the operating temperature range is 0C to 40C, and storage temperature 0C to 50C and do not recommend taking the sensor to 90C.

The purpose of Test 5a is to verify the accuracy of that range, and the effect of a sensor being in a rebreather in the sun, where it can be exposed to 90C. The test should determine if there is any dangerous off-gassing or leakage, or permanent damage.

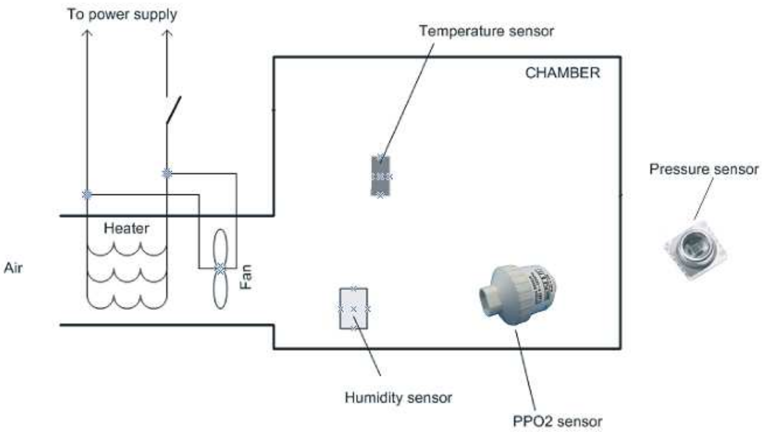


Figure 20.5-1 Test fixture for Test 5a

Effect of Increases and decrease of temperature.

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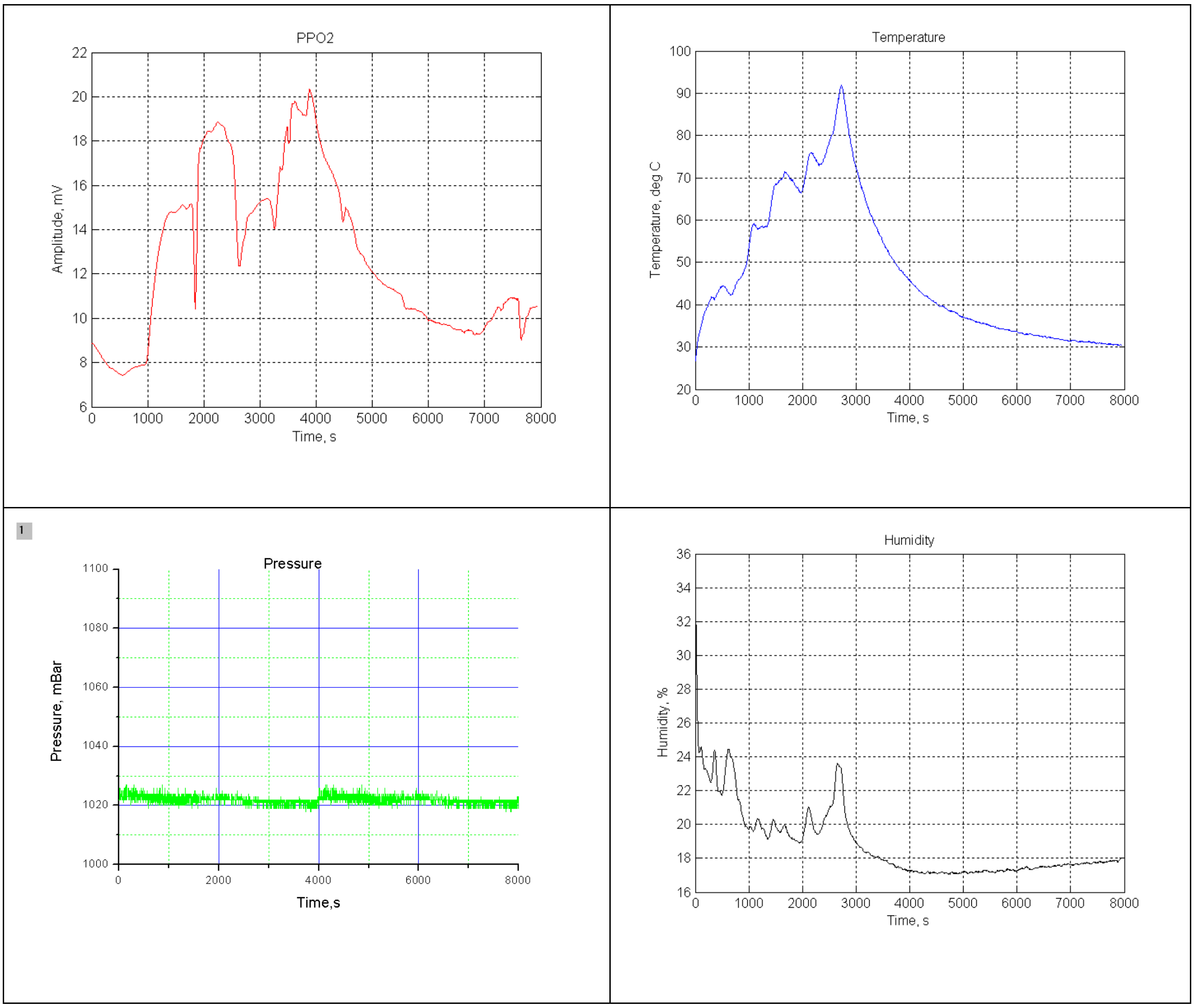

Figure 20.5-2 High PPO2 fluctuation are observed during temperature changes.

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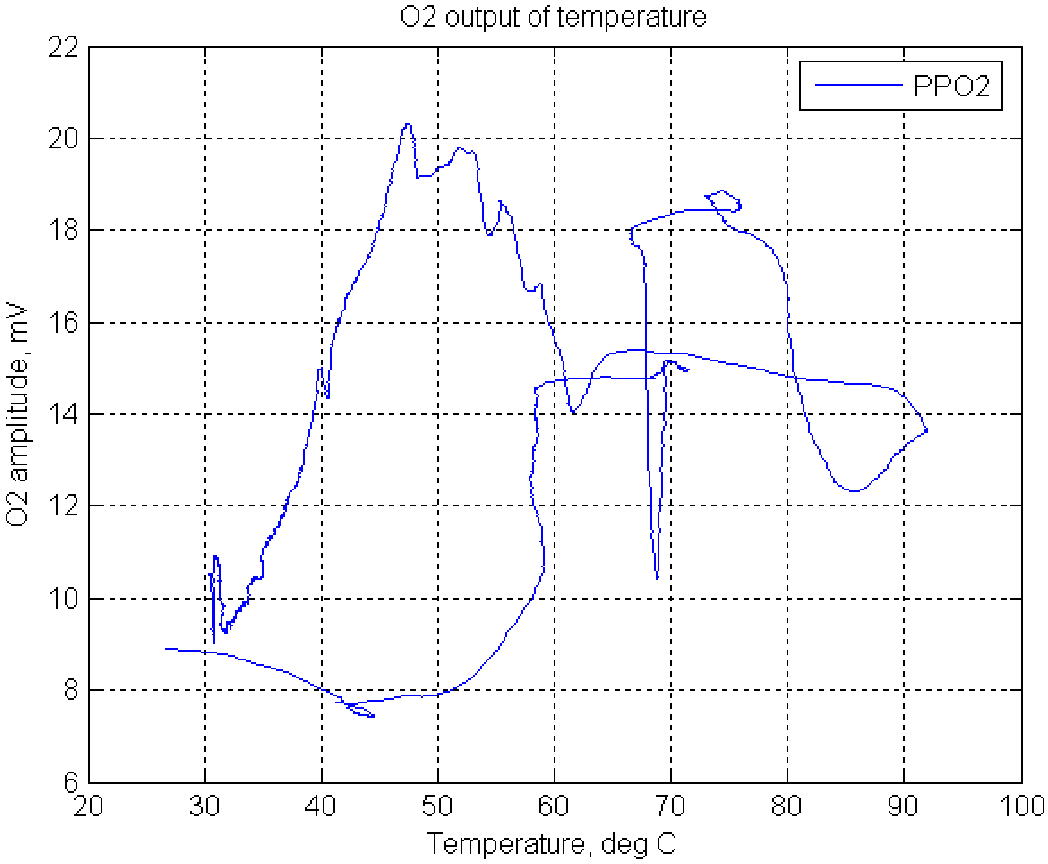

Figure 20.5-Output of cell as a function of temperature (PPO2 label is of apparent PPO2 voltage, PPO2 was constant during the test). This is a complex relationship: temperature compensation is far outside the specification.

This was a huge error in the output of the sensor as function of temperature. The recommendation remains that the sensor should be supplied without temperature compensation for safety critical applications, and the designer should compensate digitally (using a filter to model the sensor thermal response).

The sensor 8 became degraded (1.2 mV output) next day after temperature test: exposure to high temperatures destroyed the sensor.

The temperature test showed that temperature compensation was an approximately linear relationship to 43.66C and temperature sensitivity was -0.103736mV/K. When the sensor temperature is more than 43.66C temperature coefficient sign changes from negative to positive.

20.6 Test 5b. Cell Stability.

Test	Purpose	Method	Result
5b. Stability.	Confirm sensors are stable in air and confirm calibration interval required for their use	1.Use sensors 4,5 and 6. 2.Measure the output voltage with a 10K load. Record atmospheric temperature and humidity. 3.Correct data for temperature . 4.Confirm results are within 5% throughout the	Pass

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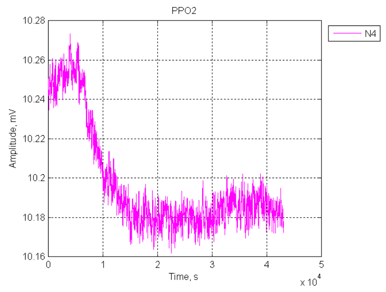
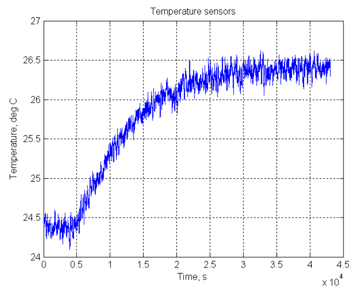
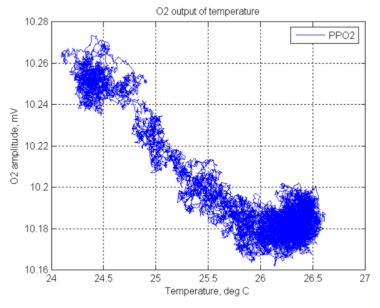
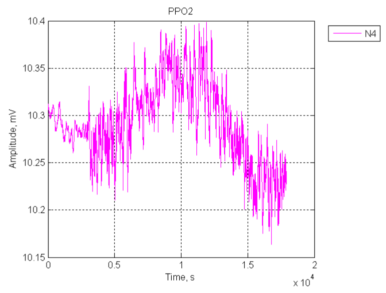
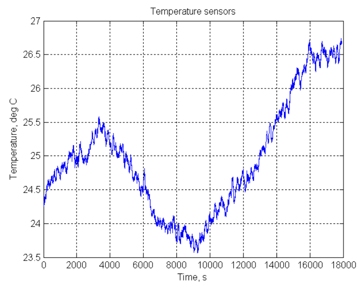
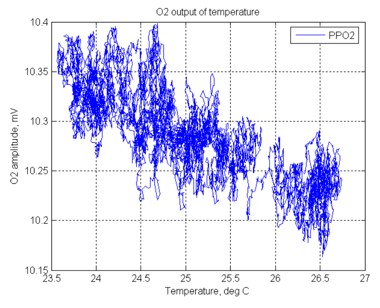
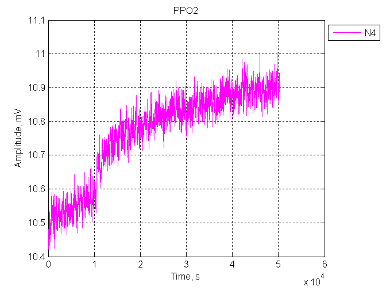
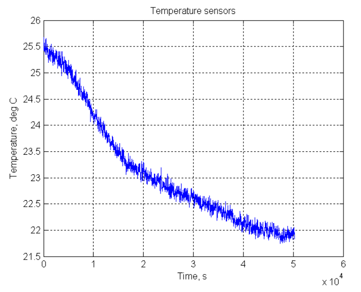
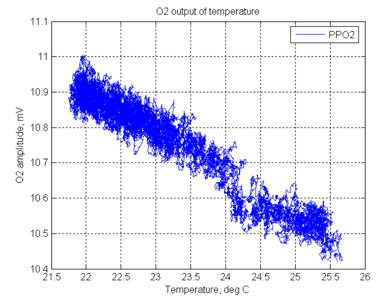
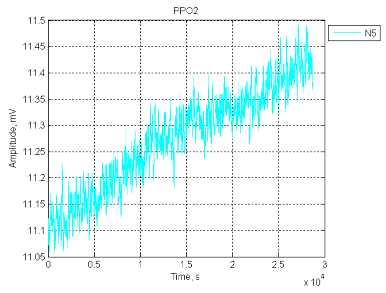
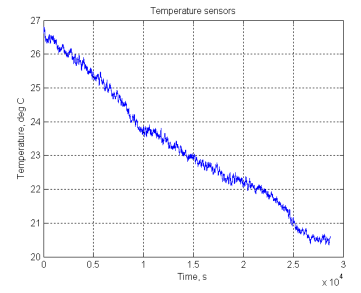
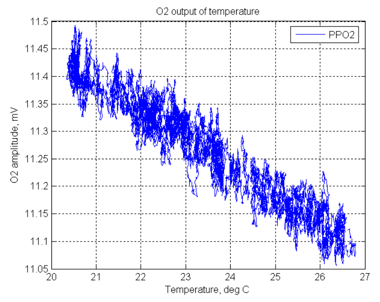
		measurement period. 5.Extrapolate any trend to verify that operating life is not less than that quoted by manufacturer.	

Steps 2 and 3, Sensor 4,5 and 6: Measure and compensate for changes in temperature and pressure.

 PPO2 mean = 10.2 mV	 Mean = 25.81 C	 dPPO2/dT =-0.0442026mV/K
 PPO2 mean = 10.29 mV	 Mean = 24.95 C	 dPPO2/dT =-0.0740075mV/K
 PPO2 mean = 10.77 mV	 Mean = 23.13 C	 dPPO2/dT =-0.1481302mV/K
		

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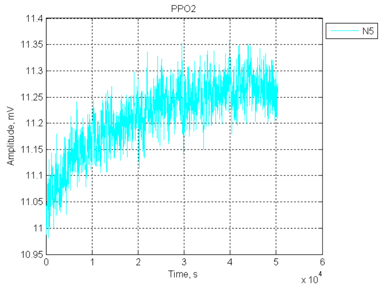
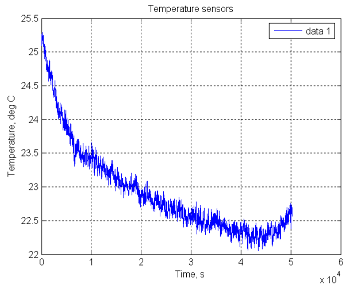
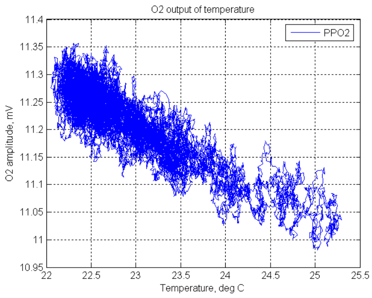
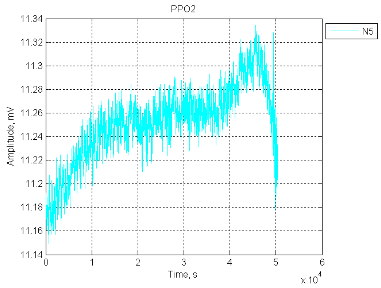
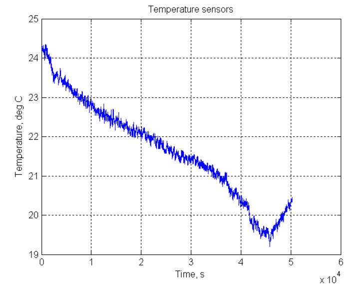
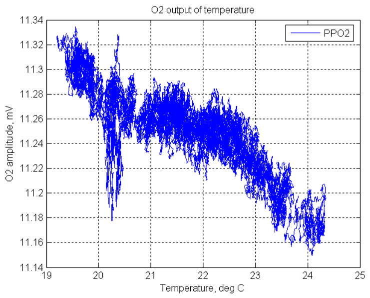
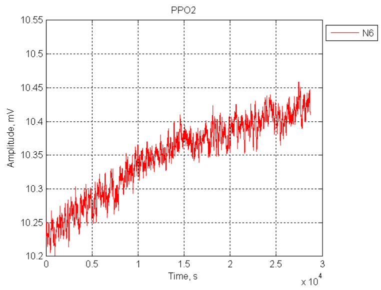
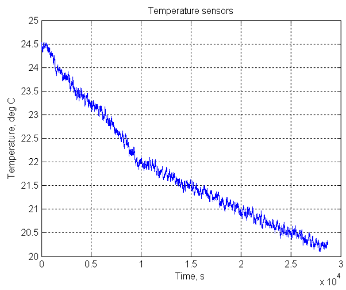
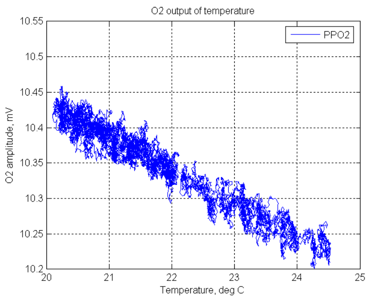
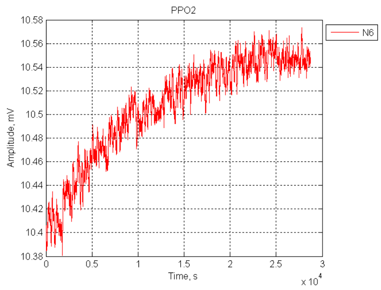
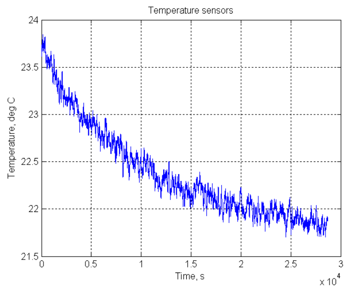
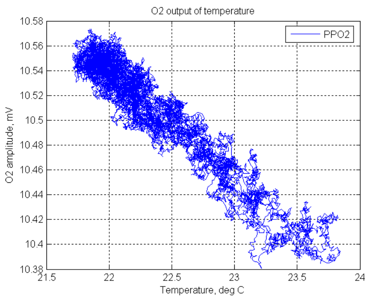
PPO2 mean = 11.28 mV	Mean = 23.27C	dPPO2/dT =-0.0676584mV/K
		
PPO2 mean = 11.21 mV	Mean = 22.93 C	dPPO2/dT =-0.1156384mV/K
		
PPO2 mean = 11.25 mV	Mean = 21.67 C	dPPO2/dT =-0.0359293mV/K
		
PPO2 mean = 10.35 mV	Mean = 21.81C	dPPO2/dT =-0.05809072mV/K
		
PPO2 mean = 10.51 mV	Mean = 22.38C	dPPO2/dT =-0.090042mV/K

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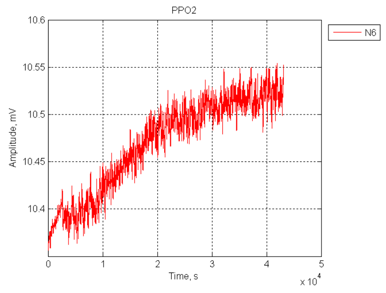
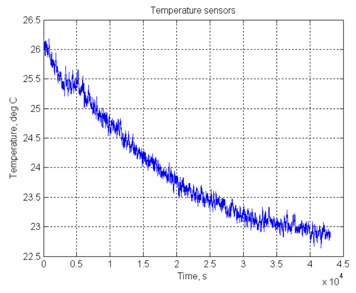
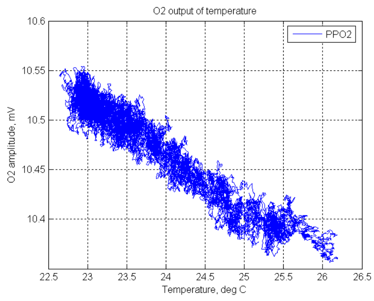


PPO2 mean = 10.47 mV



Mean = 23.94C



dPPO2/dT=-0.0557122mV/K

Fig 19.6-3. Dependency on the rate of change of temperature.

As a function of temperature, the sensitivity is within the range -0.036 to -0.148 mV/K. It is also a function of the rate of change of temperature: the faster the temperature change, the lower the PPO2 sensitivity. The lower end of the range, -0.036 mV/K, is reached when the rate of temperature change is 0.36K/hour. The upper end of the range, -0.148 mV/K, is reached when the rate of temperature change is 0.252K/hour.

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20.7 Test 6. Shock test.

Test	Purpose	Method	Result
6. Shock test Drop from 1.5m and 3m.	Test robustness. Test simulates effect of a sensor being mounted in a CCR transported by an RHIB.	1.Use sensor 1,2 and 3. 2.Photograph the sensor to be tested. 3.Measure the output voltage in air. 4.Drop 1.5/3m onto a hardwood surface 10 times. 5.Measure the output voltage in air after each drop. 6.The output voltage should not change more than 10% after 10 drops. 7.Drop 1.5/3m onto a wooden board laid on concrete 10 times and measure flow rates at 1ATM. 8.Sensor then to be monitored for two weeks on a minute by minute basis to detect any changes relative to a reference group.	Design change

Teledyne R22D batch F7 sensors were received from Teledyne incorporating a design change intended to improve the mechanical robustness of the product. These sensors are shown below.

Sample 1

Sample 2

Sample 3

Figure 20.7-Teledyne R22D batch F7 sensors used for drop tests

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Table 20.7-1: 1.5m drop test with F7 sensors

Drop №	before the tests	1	2	3	4	5	6	7	8	9	10	mV drop	% drop
Sample 1 output	9.9	9.9	10.0	9.9	9.9	9.7	9.6	10.0	9.9	9.9	10.3	0.4	4%
Sample 2 output	11.1	11.1	11.1	10.4	10.7	10.8	10.4	10.2	10.2	10.2	11.0	0.1	1%
Sample 3 output	11.1	11.4	11.6	11.3	10.9	10.6	11.3	11.6	11.5	11.2	11.2	0.1	1%

Drop tests from a height of 1.5m did not indicate any significant change in sensor output. A slight knocking sound when the sensor was shaken lightly was noticed after the first drop for Sample 3, after the fifth drop for Sample 2 and after the tenth drop for Sample 1 (the corresponding cells are marked in light blue in Table 20.7-1)

Table 20.7-2: 3m drop test with F7 sensors

Drop №	before the tests	1	2	3	4	5	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	mV drop	% drop
Sample 1	10.2	10.1	10.2	10.0	9.6	9.8	**9.6**	**9.6**	**10.4**	**10.1**	**10.5**	**10.5**	**10.6**	**12.1**	**11.1**	**11.0**	0.8	8%
Sample 2	10.9	11.6	11.2	10.8	11.2	11.2	**12.5**	**12.6**	**12.3**	**12.1**	**12.4**	**13.7**	**11.2**	**16.4**	**19.8**	**19.9**	9.0	83%
Sample 3	11.3	11.2	11.1	11.3	11.5	11.1	**10.5**	**12.2**	**12.0**	**12.0**	**12.1**	**12.0**	**11.7**	**11.3**	**11.4**	**11.3**	0.0	0%

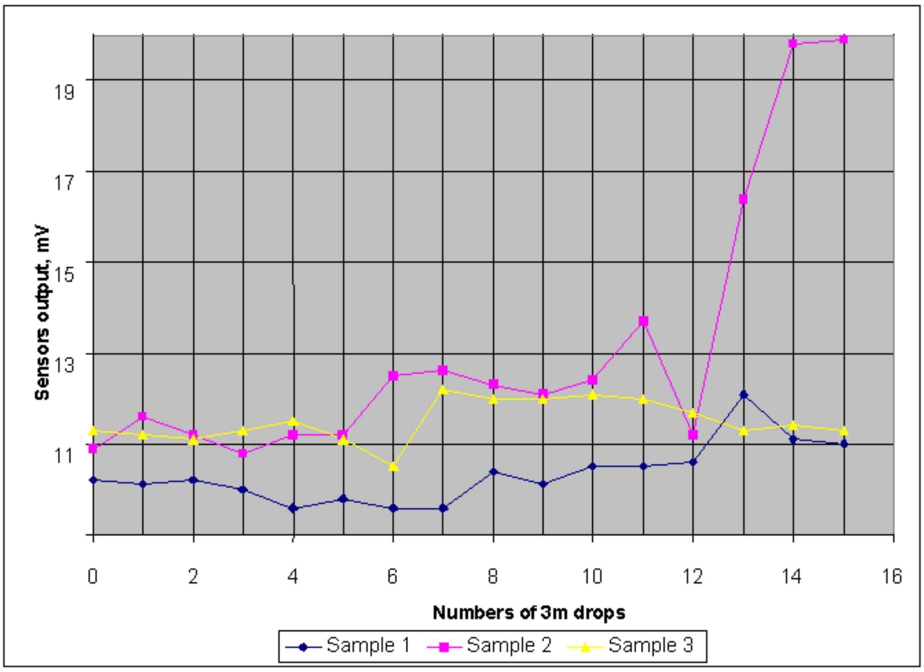

Figure 20.7-F7 sensor output during 3m drop tests.

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Three of the Batch F7 sensors were dropped 5 times on to a hardwood surface from a height of 3m. During these drops, the output signals displayed variations caused by accidental behaviour due to noise. The wooden board was then laid on a thick metal plate and the test was continued (see the bold font results in Table 20.7-2

After the sixth drop, a 'hammering' noise was heard from Sample 1 when it was held by its connector side and shaken. After the tenth drop, loud ‘knocking’ sounds were heard from Sample 2 when it was shaken. Small signs of electrolyte were also noticed on the body of the Sample 2 (Figure 20.7-). After the drop test, the sensor was laid on a slope and small amount of electrolyte dripped out (Figure 20.7-1). The hydrogen ion exponent (pH) of the electrolyte drops was about 14.

The sensor outputs were more influenced by the 3m hard drops on to the wooden board when it had the metal plate below it than without the metal plate. The output of Sample 2 changed by about 83% and there was electrolyte leakage. After two days, its output stabilized at 20mV with some noise variations.

The output of Sample 3 had a small peak increase of 1.7mV and then showed a decreasing tendency. After two days its output was 10mV, with some noise variations.

The output of Sample 1 showed an increasing tendency. The change in its output was about 8%. After two days its output was 12mV, with some noise variations.

Figure 20.7-Electrolyte drops marked in red on the body of Sample 2

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Figure 20.7-1 Electrolyte drops from Sample 2 after shaking over paper. Litmus indicator shows pH 14 when moistened with the drops. Electrolyte continued to leak after the tests, and 2 months later the sensor appeared to be dry. Equipment user manuals should warn users of the caustic risk from oxygen sensors.

The F7 batch of R22 sensors from Teledyne are significantly more robust than earlier batch B7(20.7.1), but a subsequent 6-month Life test showed degradation of every sensor, which took part in shock test: See Section (20.9).

20.7.1 Comparison with Hard Drop tests from 1.5m and 3m with a sensor from batch B7

A Teledyne type R22D OXYGEN SENSOR with Serial_number: 855166 was used for this test: the date code was B7, so it was manufactured in February 2007.

Table 20.7-3: 1.5m drop test with B7 sensor onto a wooden block

Drop №	before the tests	1	2	3	4	5	6	7	8	9	10	mV drop	% drop
Sensor SN:855166 output	12.2	11.5	7.7	7.6	7.9	7.3	6.8	8.5	8.1	15.5	53.3	41.1	337

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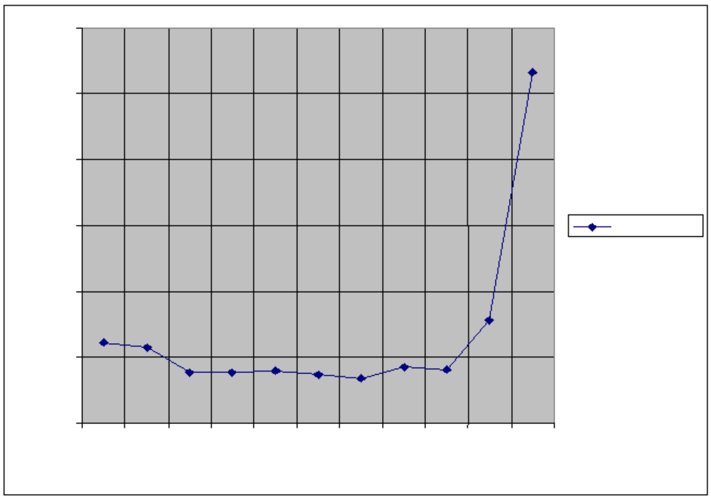

Figure 20.7- B7 sensor output during 1.5m drop tests.

During the 1.5m drops, an initial decrease in the output signal was registered. After the 7th drop the signal began to increase. After the 10th drop the output signal was the same as for situations when there was a 100% O2 flow on the sensor or when the sensor electrolyte was leaking. During the pause between the 1.5m and 3m tests, the signal decreased slowly and dropped to 41.1mV before the 3m drop test began.

It is concluded that the sensor failed on the tenth of the eleven 1.5m drops, and deteriorated immediately with the 3m drops.

Table 20.7-4: 3m drop test with B7 sensor

Drop №	before the test	1	2	3	4	5	6	7	8	9	10	mV drop	% drop
Sensor SN:855166 output	41.1	8.0	8.2	7.7	6.9	6.6	10.5	5.0	4.1	6.8	6.4	34.7	84

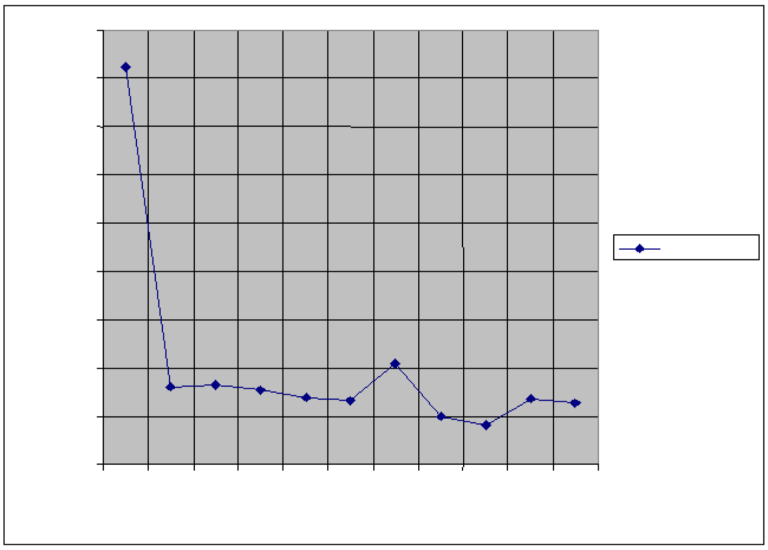

Figure 20.7-2 B7 sensor output during 3m drop tests.

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After the third 3m drop, a knocking noise was noticed when the sensor was shaken. After the sixth 3m drop, small drops of electrolyte were noticed on the sensor's membrane (Figure 20.7-3). After the eighth 3m drop, a small dent was noticed near the sensor connector (Figure 20.7-4).

Figure 20.7-3 Electrolyte drops on the sensor membrane

Figure 20.7-4 There is a small dent near the connector port of the sensor, but no other visibly apparent damage.

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20.7.1.1 Retest for 3m drops using a fresh sensor from the same batch

Sensor Serial number 855165, with date code B7, was tested without having suffered any previous 1.5m drops.

Table 20.7-5: 3m drop test with replacement B7 sensor

Drop №	before the test	1	2	3	4	5	6	7	8	9	10	mV drop	% drop
Sensor SN:855165 output	10.2	9.5	8.9	7.5	7.6	8.6	7.6	7.2	7.8	7.2	7.1	3.1	31%

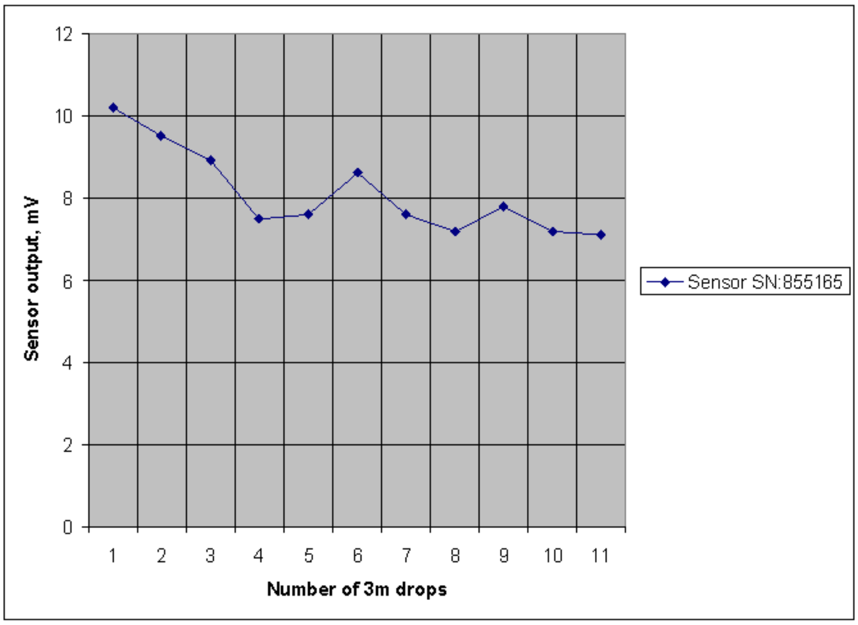

Figure 20.7-5 Fresh B7 sensor output during 3m drop tests. These results indicate damage from the first drop, and then further damage on subsequent drops.

During the 3m drops on to a hardwood board with a thick metal plate beneath, an initial decrease in the output signal was registered. The total decrease was 3.1mV or 31% of the initial value. There was no audible noise when the sensor was shaken, indicating there is nothing loose inside the sensor.

The comparison of the B7 and F7 sensors indicates the F7 sensor is improved in terms of the shock tolerance, however, the sensors fail gradually over a 6 month period. This should be picked up by pre-dive checks, so will be considered as a pass of this test.

20.8 Test 11. Application Test

Cells from the F7 batch that had not had any shock testing were removed from the life test, and fitted to rebreather using a basic three cell PPO2 monitor. A series of dives were carried out using good dive practices (ascent rates, PPO2 levels). The cells were fitted to the inhale counterlung, facing downwards.

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The cell holder fits a Deep Life P-Port (36mm ID), and is wired to 3 independent panel meters (Independent rechargeable batteries, completely independent electronics, but in the same housing).

During one of the dives the cells showed 0.7 atm during ascent, when PPO2 would be expected to be falling. Immediately after the dive, the cell holder was removed and exposed to air. Some condensation was seen on the cell faces: the well around the membrane seems to trap water. After exposure to air for 5 minutes, all three cells were still showing between 0.3 and 0.7 atm. After 30 minutes the cells were showing 0.20 to 0.21 (i.e. the correct reading in air). The cells had been exposed to very mild flood during the dive (i.e. low ionic concentration, but water on the cell faces, which was drained during the dive). The wells around the cell faces seem to restrict the shedding of water from condensate or floods.

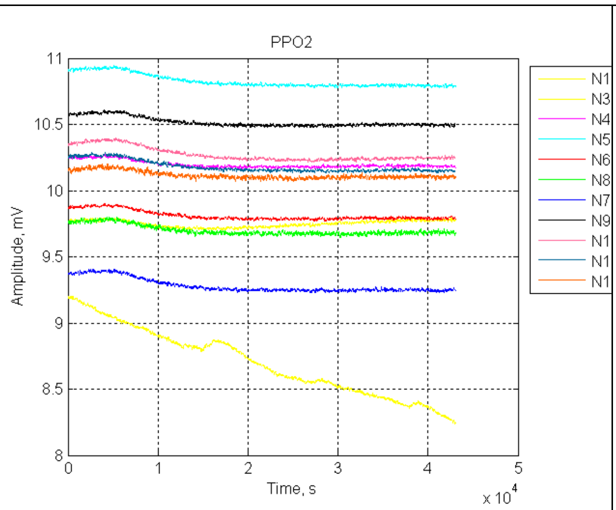
It is clear from this test that all cells that have a well around the membrane are creating an unnecessary hazard for divers, in that the well can collect and retain water. It is noted that military rebreathers from several companies use a flat face cell. It is recommended that only flat face cells, i.e. cells with the membrane on their face without any well, be used for diving.

This is a potentially fatal failure mode. The Design Authority for the equipment is obliged to avoid it by design of a suitable cell holder and by selecting suitable cells, i.e. cells without the well. The issue and its mitigation is described in more detail in Section 10.

20.9 Test 12. Life test.

Test	Purpose	Method	Result
12. Life Test	Verify the manufacturer's quoted life test	1.Record readings for all open oxygen sensors for 6 month, until 50% have failed. 2.Compare with manufacturer's stated sensor life.	Review

The fixture used for this test is an automatic test system which measures the output voltages and records atmospheric pressure, temperature and humidity. After recording the data was processed and average values were calculated for each log. The format of the data file is shown in the table below.



PPO2 N1 mean = 8.699 mV; PPO2 N3 mean = 9.749 mV;

PPO2 N4 mean = 10.2 mV; PPO2 N5 mean = 10.83 mV;

PPO2 N6 mean = 9.81 mV; PPO2 N8 mean = 9.7 mV;

PPO2 N7 mean = 9.281 mV; PPO2 N9 mean = 10.52 mV;

PPO2 N10 mean = 10.27 mV; PPO2 N11 mean = 10.18 mV.

mean pressure=1013mBar

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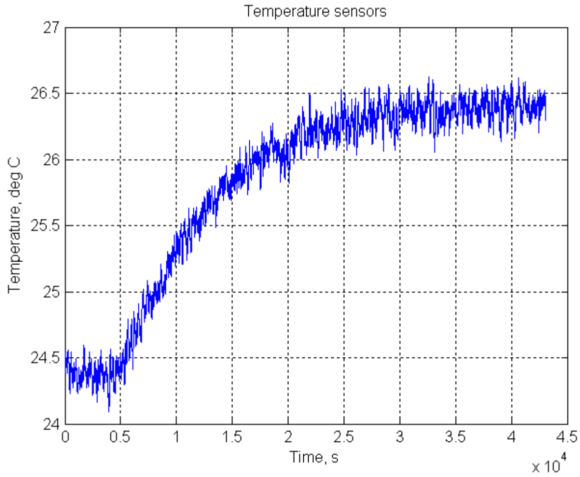
PPO2 N12 mean =10.12 mV



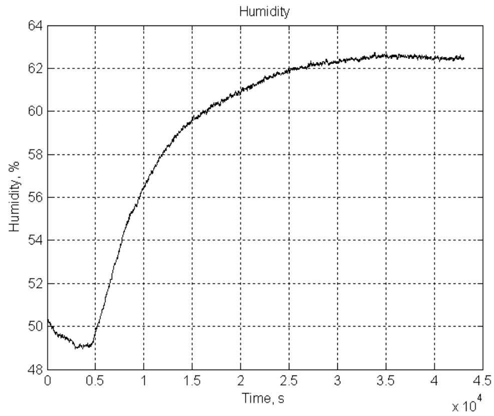
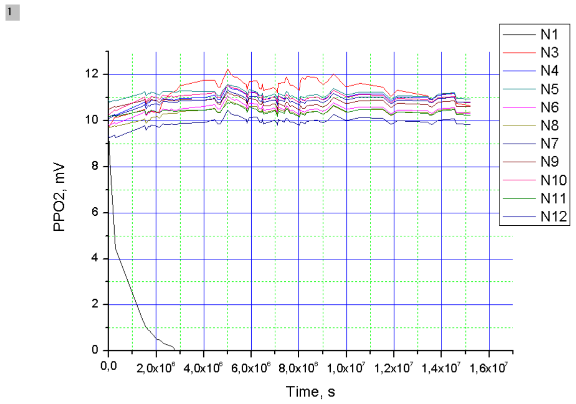
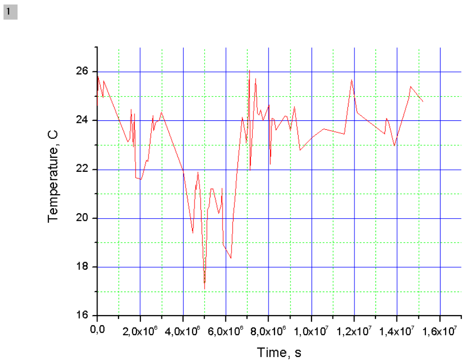
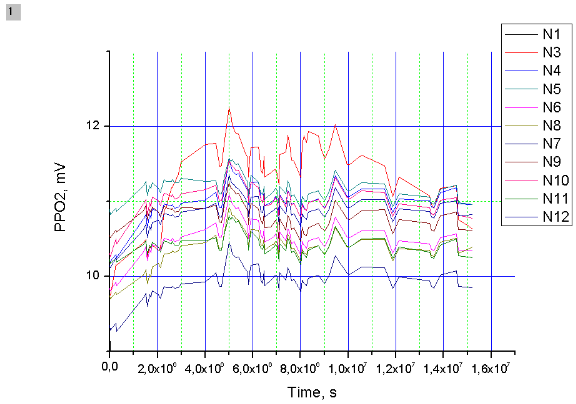


Figure 20.9-1 Example of a 12 day extract from the database that stores this data for the entire duration of the trial. Note the horizontal scale is second to the 10^4 in the extracted plots above.







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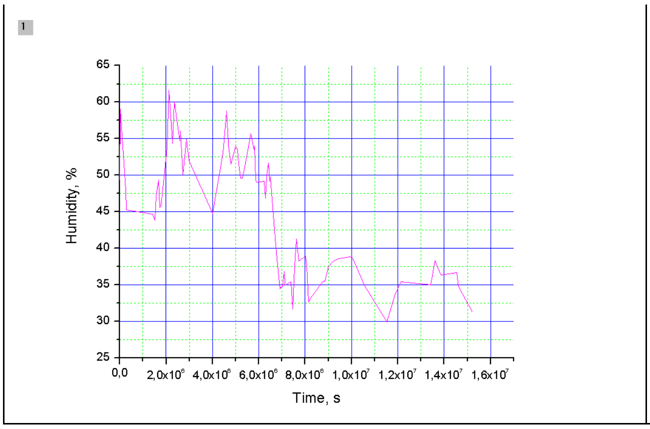

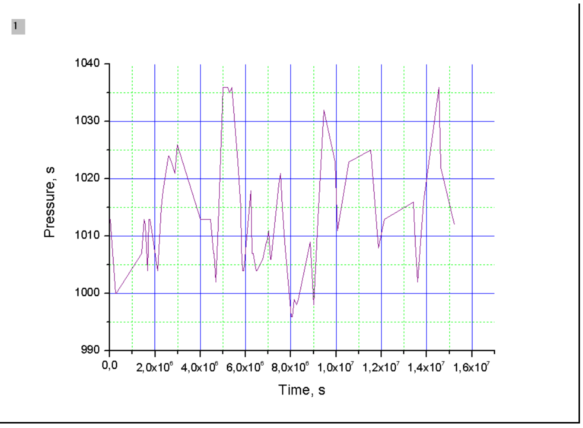

Figure 20.9- Extract from the lifetime test covering a 7 month period. Lines are used to connect the average points. Note the scale is seconds to 10^7. The general drift is due to changes in temperature and pressure: the sensors themselves are not drifting, except for those damaged by testing.

The Cell Stability test shows that the dynamics of sensors 1 and 3 are different from the other sensors in the group (Table 20.9-1). Drop test was applied to sensor 1 and 3, resulting in it being damaged. There is no significant drift of the sensors other than that due to this damage.

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Table 20.9-1. Format of the mean values database.

Date Start	Date Finish	Temperature	Pressure	Humidity	N1	N3	N4	N5	N6	N8	N7	N9	N10	N11	N12
years;months;days;hours;minutes;seconds	years;months;days;hours;minutes;seconds	C	mBar	%	mV	mV	mV	mV	mV	mV	mV	mV	mV	mV	mV
2007;8;24;11;24;23	2007;8;24;17;24;22.656	24.62	1013	49.34	9.577	9.738	10.22	10.89	9.842	9.743	9.354	10.55	10.31	10.23	10.14
2007;8;24;17;31;13	2007;8;25;5;31;13.14	25.81	1013	59.01	8.699	9.75	10.2	10.83	9.81	9.7	9.281	10.52	10.27	10.18	10.12
2007;8;27;11;5;20	2007;8;27;16;5;19.781	24.95	1000	47.84	4.86	10.16	10.29	10.91	9.93	9.79	9.38	10.62	10.5	10.24	10.25
2007;8;27;16;24;25.859	2007;8;28;4;24;25.859	25.63	1000	45.25	4.46	10.15	10.25	10.87	9.88	9.76	9.27	10.59	10.44	10.19	10.23
2007;9;10;17;19;54.562	2007;9;11;7;19;54.562	23.13	1007	44.66	1.38	10.45	10.77	11.21	10.33	10.02	9.72	10.88	10.97	10.43	10.63
2007;9;11;19;43;12.546	2007;9;12;3;43;12.546	23.27	1013	43.87	1.15	10.49	10.83	11.27	10.4	10.09	9.78	10.94	11.03	10.48	10.7
2007;9;12;17;13;0	2007;9;13;1;13;27.218	24.46	1012	47.17	1.03	10.26	10.65	11.08	10.21	9.9	9.6	10.75	10.82	10.29	10.52
2007;9;13;18;10;24	2007;9;14;8;10;24.187	22.93	1004	49.38	0.91	10.39	10.83	11.21	10.36	10.03	9.76	10.89	10.99	10.42	10.67
2007;9;14;11;56;13	2007;9;14;14;56;12.703	24.28	1013	45.6	0.86	10.38	10.78	11.18	10.32	9.99	9.73	10.85	10.93	10.38	10.62
2007;9;14;18;47;7	2007;9;15;8;47;7.281	21.67	1013	45.76	0.79	10.42	10.9	11.25	10.43	10.13	9.81	10.93	11.06	10.46	10.72
2007;9;17;18;51;2.562	2007;9;18;8;51;2.562	21.61	1006	53.8	0.5	10.35	10.86	11.18	10.39	10.18	9.76	10.86	11.01	10.39	10.75
2007;9;18;19;5;36.718	2007;9;19;3;5;36.718	21.81	1004	61.63	0.49	10.38	10.8	11.12	10.35	10.12	9.71	10.79	10.94	10.33	10.69
2007;9;20;21;29;44.5	2007;9;21;5;29;44.5	22.38	1015	54.4	0.36	10.88	10.97	11.29	10.51	10.3	9.87	10.94	11.11	10.48	10.84
2007;9;21;18;6;48.515	2007;9;22;2;6;48.515	22.34	1018	60.05	0.3	10.92	10.96	11.27	10.5	10.3	9.85	10.92	11.1	10.47	10.84
2007;9;24;14;33;30.125	2007;9;24;18;33;30.125	24.21	1024	54.7	0.22	11.19	10.94	11.27	10.48	10.32	9.85	10.89	11.07	10.44	10.81
2007;9;24;18;42;35.171	2007;9;25;2;42;35.171	23.6	1024	56	0.21	11.19	10.96	11.29	10.51	10.34	9.87	10.91	11.09	10.47	10.83
2007;9;25;17;58;47.984	2007;9;26;5;58;47.984	23.94	1023	50.09	0.14	11.25	10.91	11.25	10.47	10.32	9.84	10.86	11.04	10.42	10.79
2007;9;27;18;39;53.062	2007;9;28;6;39;53.062	24.01	1021	54.96	-0.09	11.37	10.93	11.25	10.48	10.34	9.85	10.87	11.05	10.42	10.8
2007;9;28;17;44;30.093	2007;9;29;5;44;30.093	24.35	1026	52.05	-0.1	11.53	10.98	11.31	10.53	10.41	9.9	10.92	11.1	10.48	10.86

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2007;10;10;18;35;59.281	2007;10;11;6;35;59.281	21.91	1013	44.8	-0.15	11.76	11.02	11.27	10.63	10.45	9.93	10.91	11.16	10.48	10.91
2007;10;15;18;8;17.468	2007;10;16;6;8;17.468	19.4	1013	53.02	-0.19	11.78	11.13	11.28	10.72	10.55	10.05	10.95	11.22	10.52	10.98
2007;10;17;10;46;20.14	2007;10;17;15;46;20.14	21.36	1007	57.69	-0.19	11.52	10.93	11.1	10.52	10.37	9.88	10.74	11.02	10.35	10.8
2007;10;17;18;4;36.265	2007;10;18;6;4;36.265	21.18	1007	58.79	-0.18	11.47	10.92	11.1	10.53	10.37	9.87	10.73	11.02	10.35	10.79
2007;10;18;17;53;34.359	2007;10;19;5;53;34.359	21.9	1002	54.19	-0.18	11.48	10.92	11.1	10.53	10.37	9.87	10.72	11.01	10.35	10.79
2007;10;19;15;36;22.546	2007;10;20;3;36;22.546	21.1	1012	51.53	-0.18	11.76	11.15	11.32	10.73	10.56	10.07	10.94	11.24	10.56	10.99
2007;10;22;11;19;20.187	2007;10;22;14;19;20.187	17.1	1036	54.05	-0.19	12.25	11.56	11.58	11.09	10.93	10.45	11.25	11.55	10.8	11.35
2007;10;23;10;13;41.718	2007;10;23;15;13;41.718	18.69	1036	53.44	-0.18	12.15	11.48	11.54	11.02	10.87	10.39	11.18	11.49	10.76	11.28
2007;10;23;18;57;30.406	2007;10;24;4;57;30.406	20.33	1036	51.52	-0.18	12.03	11.42	11.56	10.97	10.81	10.31	11.17	11.48	10.79	11.24
2007;10;24;17;58;13.828	2007;10;25;3;58;13.828	20.47	1036	49.58	-0.19	11.96	11.39	11.53	10.94	10.81	10.28	11.14	11.45	10.76	11.23
2007;10;25;17;33;27.703	2007;10;26;3;33;27.703	21.2	1035	49.62	-0.18	11.91	11.36	11.49	10.9	10.77	10.25	11.1	11.41	10.72	11.19
2007;10;26;18;45;55.203	2007;10;27;4;45;55.203	21.21	1036	51.21	-0.17	11.9	11.37	11.5	10.92	10.75	10.26	11.11	11.42	10.74	11.17
2007;10;29;17;26;56.343	2007;10;30;3;26;56.343	20.21	1023	55.68	-0.19	11.67	11.22	11.33	10.75	10.62	10.11	10.95	11.25	10.58	11.06
2007;10;31;11;14;49.453	2007;10;31;21;14;49.453	20.59	1015	53.55	-0.18	11.59	11.14	11.26	10.67	10.54	10.06	10.88	11.17	10.5	10.96
2007;11;1;17;51;30.343	2007;11;2;3;51;30.343	21.23	1008	54.04	-0.18	11.33	10.96	11.08	10.5	10.37	9.89	10.69	10.99	10.35	10.8
2007;11;2;9;48;23.875	2007;11;2;13;48;23.875	18.93	1004	49.38	-0.18	11.57	11.14	11.24	10.66	10.53	10.05	10.88	11.15	10.49	10.96
2007;11;2;19;43;38.859	2007;11;3;7;43;38.859	18.85	1004	49.02	-0.18	11.72	11.25	11.35	10.77	10.63	10.15	10.98	11.26	10.6	11.06
2007;11;6;13;41;13.578	2007;11;6;17;41;13.578	18.37	1018	49.19	-0.18	11.73	11.26	11.26	10.75	10.62	10.17	10.9	11.19	10.5	11.07
2007;11;7;10;39;59.437	2007;11;7;13;39;59.437	19.11	1007	46.82	-0.18	11.61	11.15	11.17	10.65	10.53	10.09	10.81	11.1	10.42	10.97
2007;11;7;16;51;45.281	2007;11;7;23;51;45.281	20.1	1007	49.91	-0.18	11.41	11.03	11.12	10.55	10.42	9.94	10.74	11.04	10.38	10.86
2007;11;8;16;54;52.515	2007;11;8;23;54;52.515	20.77	1005	51.68	-0.18	11.38	10.99	11.09	10.51	10.41	9.91	10.7	10.99	10.36	10.85
2007;11;9;9;7;41.437	2007;11;9;13;7;41.437	21.36	1004	49.19	-0.18	11.6	11.14	11.2	10.64	10.52	10.08	10.84	11.11	10.44	10.97
2007;11;9;15;30;37.156	2007;11;9;23;30;37.156	21.71	1004	49.76	-0.18	11.33	10.94	11.04	10.46	10.35	9.88	10.65	10.94	10.3	10.79
2007;11;12;17;50;28.89	2007;11;13;1;50;28.89	24.14	1006	39.32	-0.18	11.39	10.99	11.1	10.5	10.42	9.95	10.66	10.96	10.36	10.86

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2007;11;14;10;52;29.39	2007;11;14;13;52;29.39	23.44	1009	34.41	-0.17	11.43	11.04	11.15	10.54	10.44	10	10.73	11.03	10.4	10.89
2007;11;14;16;55;13.046	2007;11;15;2;55;13.046	23.1	1009	34.68	-0.17	11.43	11.07	11.18	10.57	10.47	10.02	10.75	11.05	10.43	10.91
2007;11;15;17;3;26.593	2007;11;16;3;3;26.593	23.77	1011	34.76	-0.18	11.37	11.03	11.15	10.53	10.45	10	10.72	11.02	10.4	10.9
2007;11;16;12;34;12.015	2007;11;16;17;34;12.015	26.08	1006	36.87	-0.17	11.23	10.82	10.95	10.33	10.26	9.82	10.47	10.77	10.2	10.69
2007;11;16;19;39;28.031	2007;11;17;5;39;28.031	21.97	1006	34.97	-0.19	11.63	11.09	11.2	10.59	10.51	10.05	10.77	11.08	10.44	10.94
2007;11;19;17;45;41.14	2007;11;20;3;45;41.14	25.72	1016	35.43	-0.18	11.66	10.96	11.1	10.48	10.4	9.95	10.62	10.93	10.34	10.84
2007;11;20;16;32;56.64	2007;11;21;2;32;56.64	24.3	1019	31.66	-0.18	11.89	11.15	11.28	10.64	10.57	10.12	10.82	11.14	10.51	11.02
2007;11;21;16;59;46.859	2007;11;22;2;59;46.859	24.23	1021	37.51	-0.18	11.77	11.1	11.22	10.59	10.51	10.07	10.77	11.09	10.45	10.96
2007;11;22;14;23;24.296	2007;11;23;0;23;24.296	24.45	1015	41.29	-0.18	11.55	10.96	11.07	10.44	10.37	9.94	10.63	10.95	10.32	10.82
2007;11;23;20;45;15.656	2007;11;24;6;45;15.656	24	1009	38.3	-0.18	11.54	10.98	11.09	10.47	10.38	9.96	10.65	10.98	10.34	10.84
2007;11;27;9;21;55.75	2007;11;27;13;21;55.75	24.65	996	38.92	-0.18	11.32	10.78	10.9	10.28	10.2	9.8	10.47	10.78	10.16	10.67
2007;11;27;16;45;26.937	2007;11;28;4;45;26.937	22.21	996	37.63	-0.18	11.77	10.98	11.07	10.47	10.37	9.95	10.66	10.97	10.34	10.84
2007;11;28;16;44;7.64	2007;11;29;4;44;7.64	24.1	999	32.66	-0.18	11.88	10.92	11.03	10.42	10.32	9.91	10.56	10.9	10.29	10.79
2007;11;29;16;38;14.046	2007;11;30;4;38;14.046	24.06	998	33.3	-0.18	11.79	10.88	11	10.38	10.29	9.88	10.54	10.88	10.25	10.76
2007;11;30;16;34;51.265	2007;12;1;4;34;51.265	23.62	999	33.57	-0.18	11.94	10.99	11.1	10.48	10.38	9.98	10.65	10.99	10.35	10.86
2007;12;5;16;9;50.156	2007;12;6;4;9;50.156	24.19	1007	35.42	-0.18	11.88	11.04	11.14	10.52	10.41	10.02	10.71	11.03	10.41	10.9
2007;12;6;16;33;14.671	2007;12;7;4;33;14.671	24.16	1009	35.49	-0.18	11.71	10.97	11.08	10.46	10.35	9.97	10.65	10.97	10.35	10.85
2007;12;8;14;48;24.375	2007;12;9;2;48;24.375	23.6	998	37.56	-0.18	11.57	10.92	11.02	10.4	10.3	9.91	10.61	10.91	10.29	10.79
2007;12;10;16;14;51.656	2007;12;11;4;14;51.656	24.59	1013	38.17	-0.18	11.7	11.03	11.13	10.51	10.39	10.01	10.7	11.02	10.4	10.89
2007;12;13;16;16;5.359	2007;12;14;4;16;5.359	22.78	1032	38.63	-0.18	12.03	11.34	11.42	10.79	10.65	10.28	11.02	11.32	10.67	11.19
2007;12;19;17;29;16.234	2007;12;20;5;29;16.234	23.24	1023	38.85	-0.18	11.49	11.07	11.15	10.53	10.39	10.04	10.77	11.05	10.4	10.92
2007;12;20;16;42;33.265	2007;12;21;4;42;33.265	23.34	1011	38.62	-0.18	11.49	11.07	11.14	10.52	10.39	10.03	10.76	11.04	10.39	10.92
2007;12;26;16;27;55.671	2007;12;27;4;27;55.671	23.67	1023	34.97	-0.18	11.62	11.17	11.25	10.61	10.49	10.13	10.88	11.14	10.5	11.03
2008;1;7;18;5;58.14	2008;1;8;6;5;58.14	23.45	1025	29.94	-0.18	11.48	11.17	11.24	10.61	10.49	10.12	10.89	11.12	10.51	11.03

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2008;1;11;16;15;26.593	2008;1;12;4;15;26.593	25.67	1008	33.58	-0.18	11.07	10.85	10.93	10.31	10.21	9.84	10.57	10.8	10.24	10.73
2008;1;14;19;24;11.109	2008;1;15;3;24;11.109	24.33	1013	35.41	-0.19	11.33	11.04	11.1	10.48	10.37	9.99	10.76	10.97	10.39	10.9
2008;1;29;17;29;55.984	2008;1;30;1;29;55.984	23.45	1016	35.02	-0.18	11.08	11.01	11.06	10.44	10.35	9.94	10.71	10.92	10.33	10.87
2008;1;30;16;29;55.875	2008;1;31;0;29;55.875	24.09	1009	36.3	-0.18	10.96	10.93	10.98	10.36	10.28	9.87	10.62	10.84	10.25	10.79
2008;1;31;15;57;52.453	2008;1;31;23;57;52.453	23.93	1002	38.34	-0.18	10.91	10.92	10.96	10.34	10.27	9.84	10.6	10.82	10.24	10.78
2008;2;4;17;46;12.25	2008;2;5;1;46;12.25	22.97	1016	36.34	-0.19	11.18	11.12	11.16	10.52	10.46	10.02	10.81	11.02	10.42	10.98
2008;2;12;17;22;53.109	2008;2;13;1;22;53.109	24.92	1036	36.69	-0.17	11.21	11.19	11.22	10.57	10.51	10.08	10.86	11.05	10.5	11.01
2008;2;13;13;50;33.421	2008;2;13;21;50;33.421	25.4	1022	34.78	-0.17	10.76	10.97	10.99	10.35	10.31	9.87	10.63	10.82	10.28	10.81
2008;2;20;14;10;25.078	2008;2;20;22;10;25.078	24.77	1012	31.3	-0.18	10.64	10.96	10.96	10.34	10.39	9.85	10.62	10.78	10.25	10.83
mean		**22,79**	**1013,2**	**44,52**	**0,3354**	**11,314**	**10,992**	**11,171**	**10,50**	**10,372**	**9,9386**	**10,79**	**11,02**	**10,41**	**10,85**
min		**17,1**	**996**	**29,94**	**-0,19**	**9,738**	**10,2**	**10,83**	**9,81**	**9,7**	**9,27**	**10,47**	**10,27**	**10,16**	**10,12**
max		**26,08**	**1036**	**61,63**	**9,577**	**12,25**	**11,56**	**11,58**	**11,09**	**10,93**	**10,45**	**11,25**	**11,55**	**10,8**	**11,35**
Standard deviation		**1,99**	**10,586**	**8,618**	**1,6793**	**0,5686**	**0,247**	**0,1634**	**0,231**	**0,2417**	**0,2163**	**0,170**	**0,226**	**0,143**	**0,222**

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20.10 Conclusion of test of Teledyne R22D batch F7 sensors.

1. The output of the R22D batch F7 sensor at 1 ATM is typically 10mV (20.9%O2) which is modified by temperature, pressure and other parameters examined in this report. This is within the specified range for this sensor.
2. The change in output after being placed in an artificial sea water bath is less than 0.54%.
3. The temperature test showed that temperature compensation worked up to 43.66C and temperature sensitivity was -0.103736mV/K. (If sensor temperature is more than 43.66C, the temperature coefficient sign changes from negative to positive.) The sensor became degraded (1.2 mV output) the next day after heating up to 90C.
4. The R22D batch F7 sensor is sensitive to temperature and to the derivative of the temperature. The sensitivity is in the range from –0.036 mV/K to -0.148 mV/K. The sensitivity increases the slower the change in temperature is. The sensitivity of the MDR sensor to temperature depends on gas flow rate, the temperature capacitance of the sensor and the temperature resistance between the sensor and the environment.
5. The built in temperature compensation is inadequate for rebreather applications its response to step changes in temperature, as does occur during diving: e.g. a rebreather on a hot day on a cold sea, or during flushing of the loop. The approval of this sensor for dive applications is on the basis it is supplied without temperature compensation.
6. The F7 batch of R22 sensors from Teledyne are significantly more robust than earlier batches, but every sensor which took part in the Shock test then became degraded during 6-month Life test.
7. A potentially lethal fault occurred during test dives, where the sensors became vapour locked. This should be addressed by the equipment manufacturer positioning the cells to avoid this fault, and by requesting supply of the cells without the outer housing to avoid any wells that can trap water.
8. Teledyne is approved as a supplier of O2 cells, meeting Deep Life's Procurement Specification. Those cells require significant change from the cells tested here to eliminate specific failure modes (removal of outer housing to prevent water traps, gel coating circuit board, electrical coding, SMB male socket, removal of integral temperature compensation, labelling to provide traceability and clearer identification, ink that does not come off in caustic solutions).
9. It is noted that since the start of this study, Teledyne has withdrawn from some sectors of the sports rebreather market, and the above specification is a large departure from their normal process.

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21 MTBF

MTBF normally considers only the bottom section of the bath-tub failure curve: early life failures and end of life failures are not considered. Moreover, stress induced failures are not considered. This simplification is not tenable when dealing with O2 cells because:

1. O2 cells suffer batches that are defective, resulting in early infant mortality.
2. During the bottom or "stable" period of their MTBF curve they may suffer sudden failure due to stress (mechanical shock, thermal stress, contamination),
3. The O2 cells have a very short operational life before they enter the end-of-life part of their failure curve.

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21.1 Infant Mortalities on the Bath-Tube Curve

During the period of this study, there were several reports of defective batches of oxygen sensors. The most common cause is contamination of the electrolyte. This can cause similar failures as those at the end of the sensor's life, but after a matter of weeks or months instead of years.

The most common method used to mitigate these failures is to calibrate the sensor before every dive. Given the most common failure mode is a ceiling fault, that is not sufficient. Active testing of the sensor is required to screen out sensors with the early-life faults.

21.2 MTBF during Bottom of Bath-Tube Curve

A very large batch of sensors is needed to determine a MTBF. The batch size of this study was sufficient only to audit the results published by the manufacturer, not to determine that MTBF.

An overall figure for the failure rate of oxygen sensors in the "bottom" part of their curve, based on this audit and a review of the manufacturer's data, is once in five years: that is, monitoring five sensors for a year will likely find one sensor has failed.

Given the ease in which cells are damaged by exposure to environment factors, such as shock, temperature or contaminants, there is a strong likelihood of multiple cells failing simultaneously. Quantitive data is hard to obtain, as it does depend heavily on environment factors, but a realistic estimate taken from field studies run in conjunction with this study is that once in ten years any single diver should expect to experience more than one cell failing in the same mode during a dive.

21.3 End of Bath-Tube Curve

The number of samples tested during this study is sufficient to confirm the lifespan of an oxygen cell. The lifespan depends on the manufacturer:

1. The MTBF data from Insovt is substantiated by this study in regard to both operating life and storage life.
2. The operating life of the Analytical Industries and Teledyne sensors tested, in dive applications, is 18 months except for the DL sensors which is 2 years, with failures occurring quickly after this period

The user should change the cells annually to keep within these limits, with adequate margin. This implies a maximum storage life prior to sale of 6 months.

22 FAULT TOLERANCE AND PPO2 MEASUREMENT

O2 cells are used in Deep Life designs in two different applications:

1. For PPO2 measurement and display.

2. As an element in an automatic PPO2 control system.

Automatic PPO2 control is particularly onerous application and alternative methods are necessary to monitor the operation of such a system: it would not be competent simply to rely on the integrity of the PPO2 measurements. One alternative method is predictive control where the PPO2 sensor is monitored using calibrated O2 injection orifices and a model of the rebreather. It is evident from this study that using a PPO2 measurement derived from O2 cells in a simple feedback control system with a means to inject gas depending on the PPO2, would be unsafe.

In analysing the fault tolerance of sensors the PPO2 control application, only the PPO2 measurement will be considered, but in practice, a substantial additional analysis would be needed and carried out for the control system as a whole.

To fault tolerance of a PPO2 measurement system depends on:

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1. The MTBF of the cells
2. The number of cells in the set
3. The method used to obtain a PPO2 measurement from the set of cells, i.e. the Sensor Fusion Algorithm.

All three factors must be considered together to arrive at an overall integrity assessment for the PPO2 measurement system.

It shall be assumed that the sensor fusion algorithm requires at least one working cell. In some sensor fusion algorithms more than this minimum is required, in which case the number of cells determined here would need to be multiplied by that number.

If there are four PPO2 cells and predicted PPO2, the simplest method of estimating the true PPO2 is to take the average. That is:

$$ppO\ 2(real) = M = \frac{P1 * ppO\ 2(1) + P2 * ppO\ 2(2) + P3 * ppO\ 2(3) + P4 * ppO\ 2(4) + P(pr) * ppO\ 2(pr)}{P1 + P2 + P3 + P4 + P(pr)}$$

where:

Pn = probability of sensor n non-fault working during a dive,

P(pr) = probability of nonfault prediction during a dive,

ppO2(n) = sensor n measurement result,

ppO2(pr) = prediction result,

The problem with this method is that if all the failure modes are in the same direction, such as reading low, then any combination of failure modes will tend to pull off the average in the same manner. Averaging is therefore totally unsuitable for a safety-critical PPO2 measurement system: it is considered here only to form a baseline for the minimum number of cells required.

On the topic of averaging, it is noted that the most common method of combining multiple O2 cells is to use a logic tree, described as “voting logic” but is actually subset averaging: a typically process involves takes the average of the two closest PPO2 cells and rejects the others, then checks the cells averaged are within 10% of each other. This subset averaging method gives a very poor overall reliability figure when most failure modes are in the same direction (failing with a low output): it is worse than simple averaging in fault terms**. In general, “Voting logic” is totally unsuitable for use with oxygen cells, as the risk of common mode faults is very high.**

It is suggested that the cells for rebreather applications are optimised to remove fault modes where the output increases above the correct level. The Sensor Fusion algorithm can then use the fact that almost all failures cause the sensor output to fall. Of the O2 sensor failure modes listed in this report, only four result in the sensor output voltage exceeding that of a correct sensor. These are:

1. A sudden rapid temperature drop which causes any bubbles within the electrolyte to shrink, causing a greater diffusion through the membrane than normal,
2. Storing the cells without being connected to a load in available oxygen (an excess charge will be created) and then connecting to a load.
3. Loss of electrolyte.
4. Water blockage of the front membrane.

The probability of the first two cases can be managed so as to be near zero, and can be avoided entirely by testing the sensor to ensure the load resistor is present, and by eliminating the temperature compensation within the cell: using external compensation instead as is intended with the PSR 11-39-DL. The third case can be detected by applying a load across the sensor and detecting the change in output: that is, the fault changes the output impedance of the cell. The fourth case should be mitigated by design as outlined herein.

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Under these conditions, the true PPO2 will not be less than the higher PPO2(n) measurement during diving after sensor calibration. Therefore, to measure the true PPO2, the system should take and use only the highest sensor measurement.

For the other 3 sensors, non-fault probability will be equivalent to near zero: that is the MTBF of the sensors must be adequate to reduce the non-fault probability from one of the four sensors to substantially less than 1 in 10^9.

Given these assumptions:

$$ppO2(real)=M=\frac{P\max * ppO2(\max)+P(pr)\cdot ppO2(pr)}{P\max + P(pr)}$$

Case 1. If predicted PPO2 is more then PPO2(max), the probability is:

$$P\max = P(n)=1-\frac{Td}{MTBF}$$

This depends on the sensor age. Tests reported herein suggest the operating life is just 12 months for the fast response sensors (R17, R22) and 5 years for the slow response sensor (ДК-32).

P(pr) will depend on the calculation algorithm and prediction interval. The probability of a critical PPO2 fault in this case is:

$$Pf=(1-P(pr))\cdot\left(\frac{Td}{MTBF}\right)^4$$, where

Pf – critical PPO2 fault probability during a dive,

Td –diving duration,

MTBF –mean time between failures for PPO2 sensor,

P(pr) – probability of nonfault prediction during a dive

Case 2. If predicted PPO2 is not available or predicted PPO2 less then PPO2(max)

(P(pr)=0) then use the simplest algorithm:

$$ppO2(real)=M=ppO2(\max)$$

This algorithm will overcome all PPO2 sensor faults except the case when all sensors have faults, or in the case of the three fault modes where the sensor gives a high reading. We can obtain the probability of the former case:

$$P(4f)=\left(\frac{Td}{MTBF}\right)^4$$, where

P(4f) – four sensors fault probability during a dive,

Td –diving duration

MTBF –mean time between failures for PPO2 sensor.

As a final safeguard, the output from the sensor should be screened such that PPO2(real) cannot exceed the ambient pressure in ATA. For example at 10m, the PPO2(real) cannot exceed 2.0. Any sensor that does so is faulty. The load characteristic should be tested by the electronics as a further screen both on start up and when any sensor differs in its normalised output by more than 10% from the other sensors. During the dive, the capacitance, resistance and charge transfer characteristic should be checked on a round-robin basis every minute.

If the charge transfer response is not checked during the dive then an alternative method should be used. For example, the Posedion method of using a calibration gas applied in pulses to a reference sensor, alternating between reference gas and loop gas, is an acceptable and effective method of detecting faulty sensors, when all the other mitigating factors described herein are also applied.

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The response time of the sensor should be verified during automatic pre-dive checks and any sensor with a slow response should be eliminated using this screening.

23 MATERIAL SAFETY

Each company has provided Material Safety Data Sheets for all the materials in the sensor. These were both credible – there is a problem of cursory MSDSs in circulation, but this was not an issue in this case.

The MSDS was examined for off-gassing compounds, including softeners and plasticisers. No serious issues were identified.

The KOH electrolyte is a known safety hazard if spilt and is mitigated by instructions in the user manual and by user training.

The lead anode is a known safety hazard but well contained. The cells should be returned to the equipment manufacturer after use to prevent contamination of waste with lead.

The housing material varies between manufacturers. None were ideal, but none revealed serious off-gassing problems.

24 CONCLUSIONS

This document presents the summary of an extensive study, characterising O2 cells for use in a safety-critical system.

O2 cells are a key component in PPO2 measurement. The cells have an extremely high failure rate, including common mode failures, and present a severe but not insurmountable challenge in use within life support and similar applications – there is no alternative technology presently available for measuring PPO2 in a rebreather or portable life support system.

Careful engineering of the cells, and use of specific design features, can greatly improve the reliability of the cells, and in particular improve their characteristics within a life-support system. These methods ruggedise the cell, remove many failure modes, and enable the cell to be tested in use. Moreover, the key recommendation here is to force the overwhelming majority of defects to cause a low output from the cells, thereby enabling them to be screened from service as they start to fail.

The many different recommendations are made, which have been tagged and applied in a Mantis system operated by Deep Life, to ensure that all requirements and recommendations are met in all products where O2 cells are used.

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