Oxygen Cells for Dive Applications: Sourcing, Performance, Safety and Reliability

Results of a 6 Year Study

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APPROVALS	
ME________________________________ Hardware Architect	____________________________ Date
SM________________________________ Software Architect	____________________________ Date
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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	12th Feb 2007	Added 2006 and 2007 batch retest data.
C0 to C4	29th Mar 2007	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

Table of Contents

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. 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**
Sensor Model	**DK-32**	**PSR-11-39-MD**	**PSR-11-39-MDR**	**R10, R17D, R22D, R22-2BUD**
Dimensions	**Within limits defined**	**Within limits defined**	**Within limits defined**	**Within limits defined**
Median Output in air	**5mV**	**11.9mV**	**4.5mV**	**11mV**
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.**	**See report below.** **Reasonable time is being given to manufacturer to improve product and process before reporting.**
Consistency	**Excellent**	**Excellent**	**Excellent**	
Connector improvement	**Wire termination. Willing to adopt SMB.**	**Are adopting SMB in product variant.**	**Are adopting SMB.**	
Sensor Life	**All operated beyond 5 year life. No damage from tests.**	**Preliminary: all operating, unless destroyed by tests.**	**Preliminary: all operating, unless destroyed by tests**	
Error in temperature compensation	**Miswired inside sensor**	**0.72 mV/60C**	**NA**	
Linearity Error (PPO2 from 0.21 to 1.0)	**-2%**	**-2.26%**	**NA as it uses external compensation**	

O2 materials compatibility	**All pass**	**All pass**	**All pass**	
Hydrophobic membrane	**Present**	**Present**	**Present**	
Response time	**20s rise, 25s fall**	**6s rise / 8s fall**	**6s rise / 8s fall**	
Temperature range tested.	**20C to 90C**	**20C to 90C**	**20C to 90C**	
Stability with time	**No drift**	**No drift**	**No drift**	
Shock	**Passes**	**Original samples failed test. Manufacturer addressed this by design improvements. Improved sensors pass.**	**Same improvement as PSR-11-39-MD**	
He susceptibility	**Pass**	**Pass**	**Pass**	
Fast Decompression	**Pass**	**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.**	
Short-term CO2 susceptibility	**No effect**	**200uV offset**	**190uV offset**	
Application test	**Works but slow response**	**Excellent. No failures**	**Excellent. No failures.**	
Life test	**All still working after 5 years. Non-accelerated.**	**Passed accelerated test**	**Passed accelerated test**	
Electrolyte Loss (Stimulated fault)	**Increase in output voltage, reduction in impedance**	**Increase in output voltage, reduction in impedance**	**Increase in output voltage, reduction in impedance**	

Storage test	**All pass 5 year test. Non-accelerated.**	**Passed accelerated test**	**Passed accelerated test**	
Offgassing	**No offgassing**	**No offgassing**	**No offgassing**	
Marking	**Willing to mark date in large print**	**Willing to mark date in large print**	**Willing to mark date in large print**	
Cost	**2 x A, reducing to A**	**A**	**A**	
Overall Suitability (Lowest mark)	**1**	**4**	**4**	
Weakest Area	**Slow response**	**Shock resilience**	**Shock resilience**	

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.

Special Note on Teledyne R22-2BUD2, R22-D, R17-D and R22-A Sensors These were tested extensively, but found to be unsuitable for diving applications. The test results have been supplied to the manufacturer and are being used as the basis for product improvements. For this reason, other than noting that Teledyne sensors were found to be unsuitable on multiple grounds, no data on Teledyne sensors is being published at this time.

It was concluded that the Analytical Industries PSR-11-33 and PSR-11-39 sensors are suitable for rebreather applications, particularly the PSR-11-39-MDR as it has a suitable connector and can only fail low. 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 (MD with an SMB socket), is the most suitable sensor. **AI 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 and in 2007, 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 six year 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.

4 APPLICABLE STANDARDS

EN14143:2003

EN61508 (as a component in SIL 4 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
RIB:	Rigid hull Inflatable Boat

6 REQUIREMENT SPECIFICATION

The sensor must meet the following requirements:

- Linear within 3% over PPO2 range from 0.1 to 2.0, and within 3% 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
- Hydrophobic front membrane
- Consistent performance from sensor to sensor
- Resistance to shock in a dive environment, such as by transport on an RIB, measured using 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 100% humidity, condensing
- Should not be damaged by short term immersion in salt water
- Operating temperature range 4°C to 55°C, and no damage at up to 90°C. This requirement is due to warm exhaust from scrubber, when pre-breathed after storage in a tropical environment.
- Storage temperature range -30°C to +90°C. Note that EN14143:2003 requires -30C to +70°C but there are plausible circumstances where the temperature can rise about +90°C, 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.
- 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 labelled with the date of manufacture.

7 TYPES OF O2 SENSOR

There are six 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. These are too immature for use in rebreathers at the date of the trial.
3. Spectrographic. Gas spectroscopic and chromascopic analysers are large with high power consumption and unsuitable for use in a rebreather.
4. Heated zirconia. These are the least accurate of the available methods and not suitable for dive applications.
5. UHP Pico Ion, used by Analytical Industries for low O2 levels

6. 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.
7. Laser absorption. These suffer spectral spreading with depth and in noble gases, as well as being power hungry.

This study focuses on galvanic cells.

8 SOURCES OF GALVANIC O2 CELLS

1. Alphamed
2. Ametek
3. **Analytical Industries (USA(**
4. Analox
5. Atom
6. BCI
7. BMD
8. BCI
9. BMD
10. Bertucci
11. BIO MS
12. BioMed
13. Bio-Tek
14. Biotest
15. Bird
16. BMD
17. Burke & Burke
18. Caradyne
19. Catalyst Res. (See MSA)
20. Ceramatec (See Maxtec)
21. Cheiron
22. CIG Healthcare
23. City Technologies
24. CR
25. Criticare Systems
26. Critikon
27. Dameca
28. Datascope
29. Datex Ohmeda (GE)
30. Diversified Diag.
31. DP Medical
32. Drager
33. Drager (North America)
34. Emerson
35. Engstrom (Datex)
36. EnviteC
37. F. Stephan
38. Fresenius
39. Hamilton
40. Henleys
41. Hewlett Packard
42. Heyer

43. Hill-Rom AS
44. HP
45. Hudson RCI / Ventronics
46. Imed
47. Infrasonics
48. Inmed
49. International Tech
50. **Insovt (Russia)**
51. **IT/Wismar (Germany)**
52. Ivac
53. Libra
54. Lifecare
55. Marquette/ Hellige/ GE
56. **Maxtec (USA)**
57. Medigas
58. Megamed
59. MSA
60. Newport Medical
61. Nivaco
62. Norco Med
63. Novametrics
64. Ohmeda (Datex)
65. Omni (See IT/Wismar)
66. Oxyquip
67. Oxitron
68. Pacifitech
69. Patient Tech
70. PPG
71. PPG Hellige
72. Prolab
73. Puritan Bennet
74. Respironics
75. Schoch
76. Sechrist
77. Sensor Tech
78. Shock
79. Siemens
80. Spacelabs
81. Sun Medical
82. Taema (France)
83. **Teledyne (USA)**
84. Toptronics
85. Ventronics (See Hudson)
86. Vickers
87. VTI
88. Wardray Premise

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

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 then brand label them.

Of these companies, only three appear suitable for dive applications: Teledyne, Insovt and Analytical Industries. This assessment is based on reports of the reliability of the vendor’s product, and 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. Teledyne R22-2BUD
5. Teledyne R22-D
6. Teledyne R22-A
7. Teledyne R17-D
8. 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 obtained and examined: use of that sensor would have to rely heavily on NEDU testing due to the available time. Also late into the study were the PSR 11-39 sensors, which had been adapted by Analytical Industries specially for diving. These sensors were tested thoroughly, except that the life and storage test is still ongoing.

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.

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.

lauer.pdf. 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.

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.

9.3 Failure Modes Common to all Galvanic O2 cells

1. 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.

   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.

2. Mechanical shock causing loss of electrolyte. Mechanical shock will reduce the output from the cell, but loss of electrolyte can cause the output to rise. This effect is measured in the tests reported herein.

3. Used sensors fail permanently due to a combination of factors:

   a. Exhaustion of the anode surface: this 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".

   b. A temperature drift, 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.

4. Sensors can fail temporarily if water is allowed to fall or condense onto the face of the sensor. This results in a dramatic increase in the response time from the sensor and the sensor reading a much lower PPO2 than is the reality. This can be avoided by good design: 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 toward the scrubber is ideal.

5. Failure of the temperature compensation circuit. This can cause three 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 be as high as 100V. 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. 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.

9.4 Failure Modes Arising from Design or Manufacturing Defects

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

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 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. 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.
7. 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.
8. 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.

10 ROHS COMPLIANCE

All goods imported into, exported from, or manufactured in Europe after 6th July 2006 must be RoHS compliant, unless the goods have an exemption. Very few exemptions are being issued.

Galvanic cells are not RoHS compliant: they depend on a lead electrode. A temporary exemption is being issued for these cells, as medical equipment. It is highly desirable to replace them by RoHS compliant sensors, such as Sol Gel, but from a practical viewpoint, this is unlikely to be before the year 2011.

The rebreather and PPO2 monitor must be sold separately from the sensors due to this RoHS compliance issue.

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11 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.

11.1 General Instrumentation

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

1. Test chamber 200msw rated, fitted with gas circulation control.
2. Test chamber 1400msw rated, fitted with any DL Compact Breathing Machine.
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. 10K and 100K external load resistors, 3 off.
7. Air, He and O2 supply to 141 bar.
8. Test fixture to heat the 1400msw test chamber to 90C.
9. Test fixture to cool the 1400msw test chamber to -4C.
10. Twelve samples of each of the sensor models to be tested, unless otherwise stated.
11. Data capture and sensors as detailed in the following subsections.

11.2 Temperature sensor

Technical data:

1. Type: National Semi LM35DZ
2. Nominal temperature range: -55..+150 °C
3. Accuracy: ±1.5°C
4. NonLinearity: ±0.5°C
5. Sensor gain: +9.8..10.2 mV/ °C
6. Self-heating: 0.08 °C in still air
7. Supply voltage: 4..30 V
8. Impedance on output: 0.1Ω for 1 mA load

11.3 Humidity sensor

Technical data:

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

11.4 Pressure sensors

11.4.1 Low pressure sensor

Technical data:

1. Type: Druck LPM9381
2. Nominal pressure range: 0 .. 200 mbar
3. Overpressure: 4 bar
4. Supply voltage: 10..30 V
5. Output signal: 0..5V
6. Zero adjustment: ≤ ±15%FS
7. Repeatability: ±0.1%FS
8. Response time: 10 msec
9. Permissible load: > 5 kΩ
10. Operating temperature range: -40 ..+100 °C
11. Thermal sensitivity shift: ≤ ±0.01%FS/K
12. Sensor is differential. For absolute readings, one port is sealed and calibrated to local ambient pressure as reported for that time by a nearby national weather station.

11.4.2 High pressure sensor

Technical data:

1. Type: ME 705
2. Nominal pressure range: 0..400 bar
3. Overpressure: 600 bar
4. Supply voltage: 5 V
5. Output signal: 0.5..4.5V
6. Accuracy of offset: ≤ ±1%FS max., ≤ ±0.5%FS typ.
7. Permissible load: > 10 kΩ
8. Max. current: < 4 mA
9. Linearity: ≤ ±0.2...1.5%FS typ.
10. Hysteresis, repeatability: ≤ ±0.3%FS typ.
11. Operating temperature range: -25 .. +125 °C
12. Thermal sensitivity shift: ≤ ±0.04%FS/K

11.5 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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12 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.

The silicon itself generally has 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 100V or more. 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%.

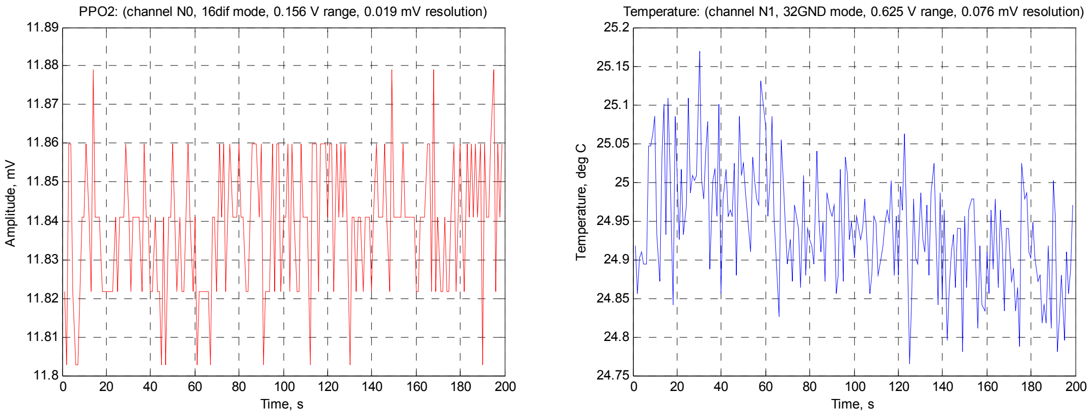


Fig 12-1: Original data.

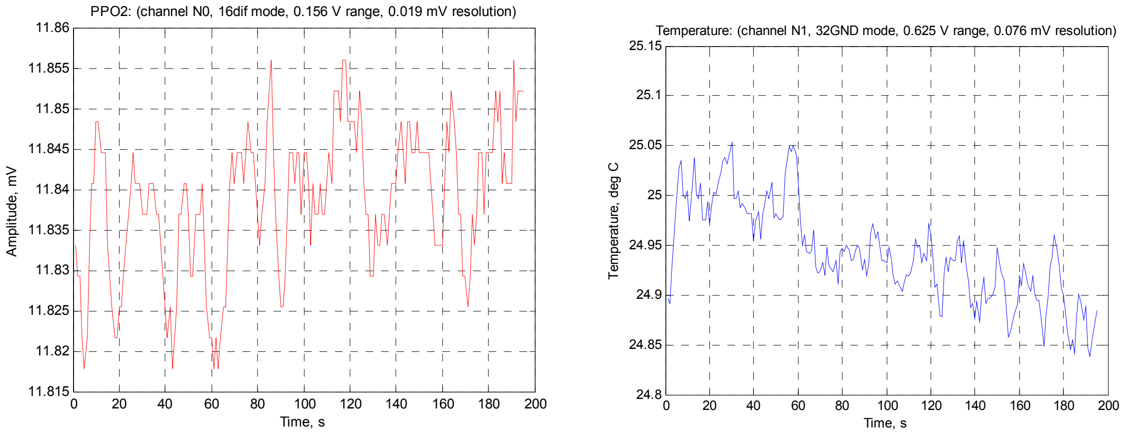


Fig 12-2: Original data filtered by moving average with window size of 5.

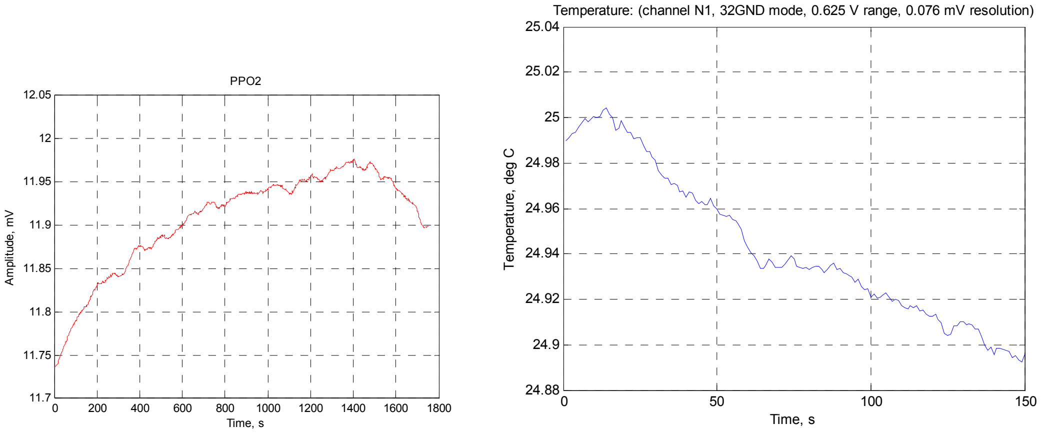


Fig 12-3: Original data filtered by moving average with window size of 50.

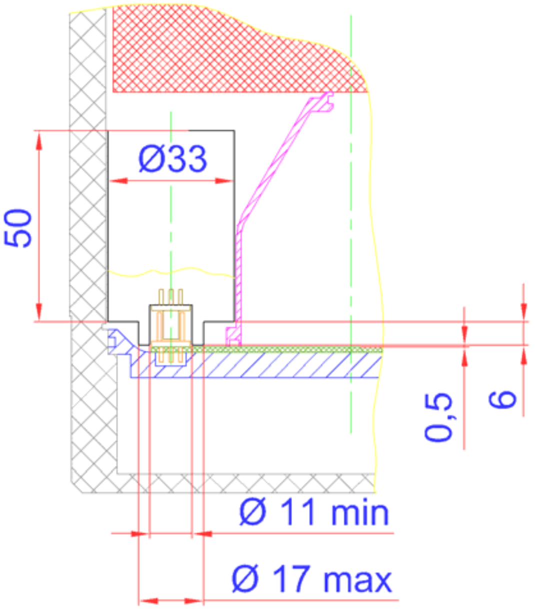
13 TEST SCHEDULE

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.

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

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 RIB.	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.

		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 (1400msw). 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 1400msw, 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

		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 RIB 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.

		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.	

13.1 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.

13.2 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[1] 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, a senior member of Deep Life staff 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?”. The Deep Life staff member 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. All vendors accepted the issues with the Molex connector and were happy to supply the sensors in an SMB socket, except possibly Teledyne. A distributor of Teledyne disclosed an exclusivity agreement with one customer on this connector to keep other companies out of the market, despite it being Deep Life staff who originated this requirement.

13.3 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.

13.4 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 RIB (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 RIB 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 RIB sides).

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

13.5 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

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[1] 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.

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 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.

13.6 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.

13.7 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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14 R17-D, R22-A & R22-2BUD TEST RESULTS

Chapter removed for publication to allow a reasonable period for manufacturer to develop and introduce product improvements. Data and results have been forwarded to the manufacturer.

These sensors were found to be unsuitable for diving applications.

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15 INSOVT ДК-32 SENSORS

Company is Insovt. We tested DK-32(ДК-32) sensor.

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 to withstand 200bar. 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 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: as the sensor is unsuitable, 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.

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.

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

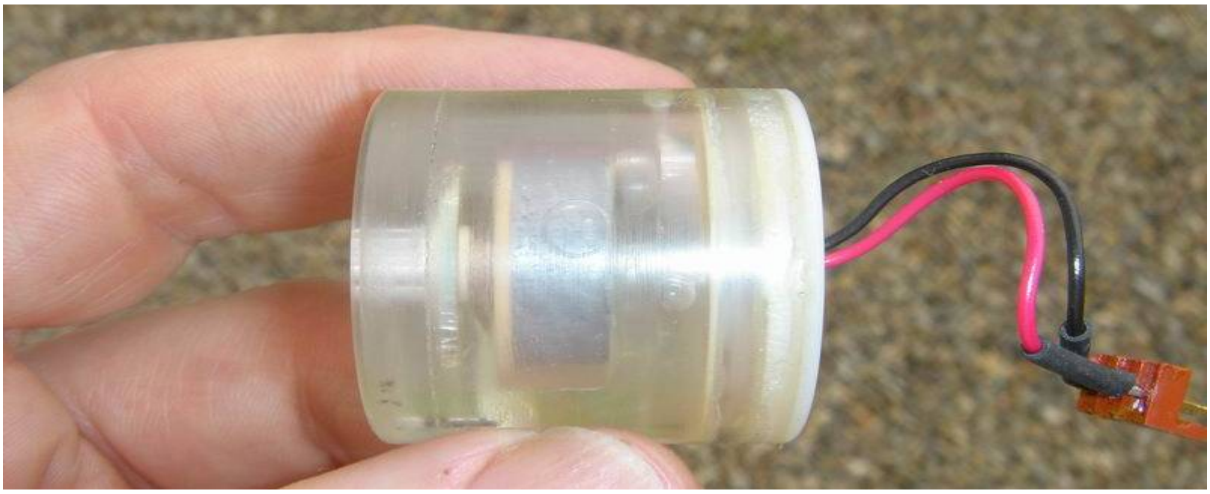


Fig 15.1-3: Insovt DK-32 showing KOH solution fill: bubble can be seen behind anode and also in second compartment. This shows the two part potting process to avoid contaminants affecting the cell. Note the thick material in front of the cell to prevent depressurisation forcing electrolyte out.

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

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.

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 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.

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).

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 9.3 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 AND MDR

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 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.

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.

18.2 Test 1: Dimensions

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

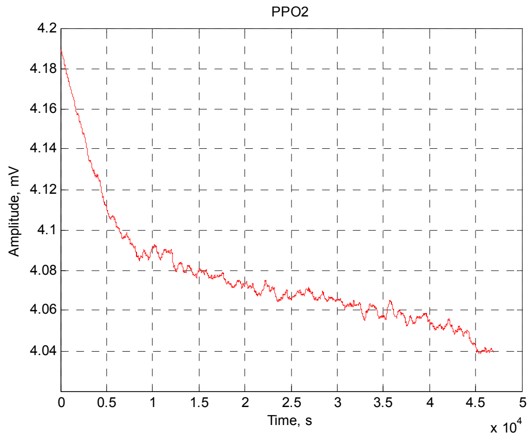
18.3 Test 2: Materials compatibility

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.

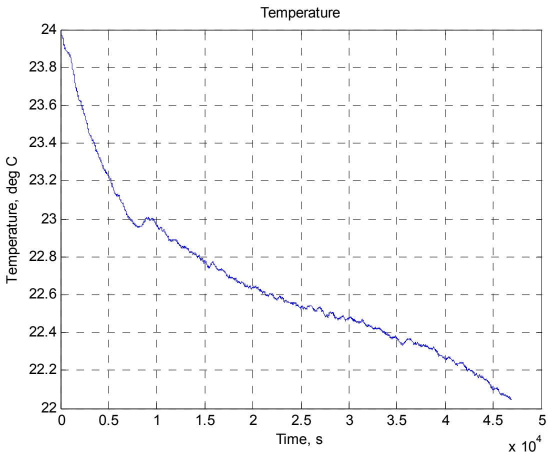
18.4 Test 3. Hydrophobic membrane

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.

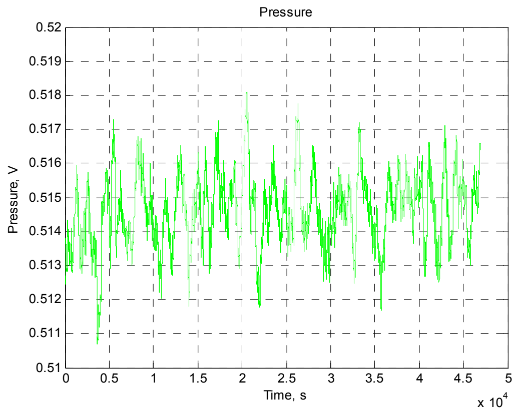
Step 2: Measure sensor voltage, and record temperature.



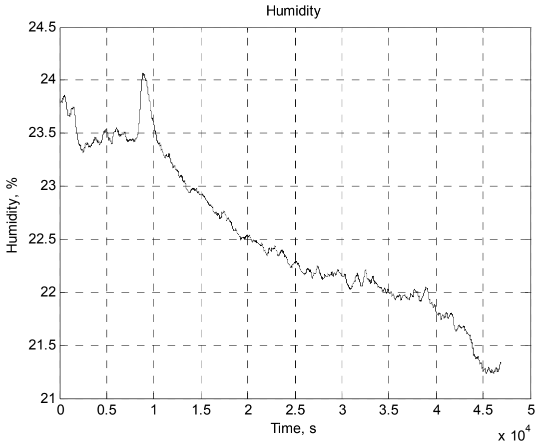
PPO2 mean = 4.08 mV



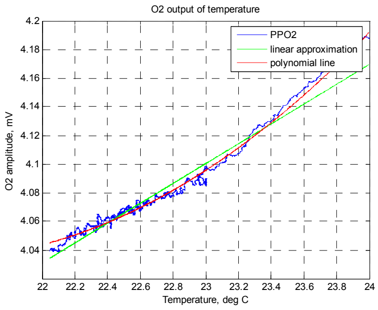
Temperature mean = 22.67 C



Pressure mean = 0.5146 V

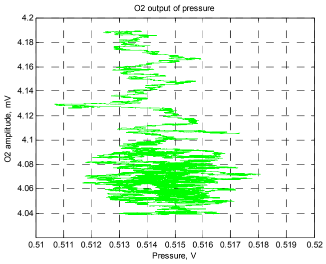


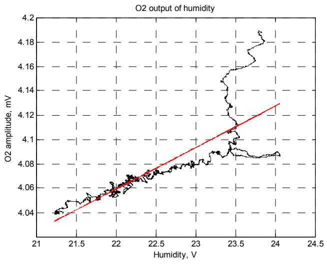
Humidity mean = 22.53%



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.

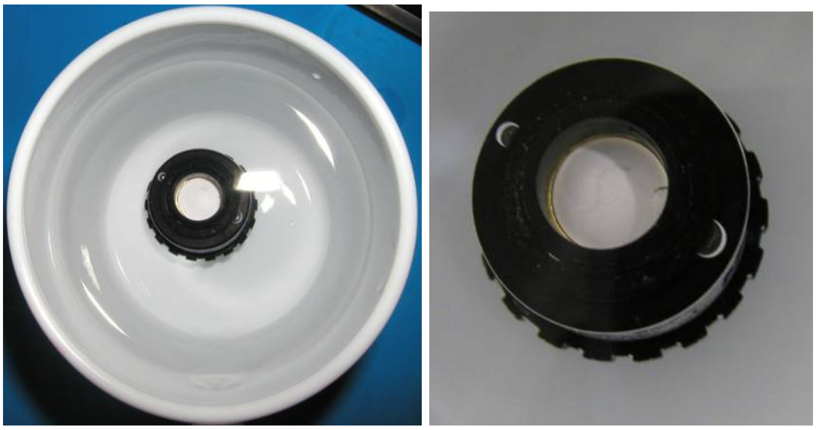
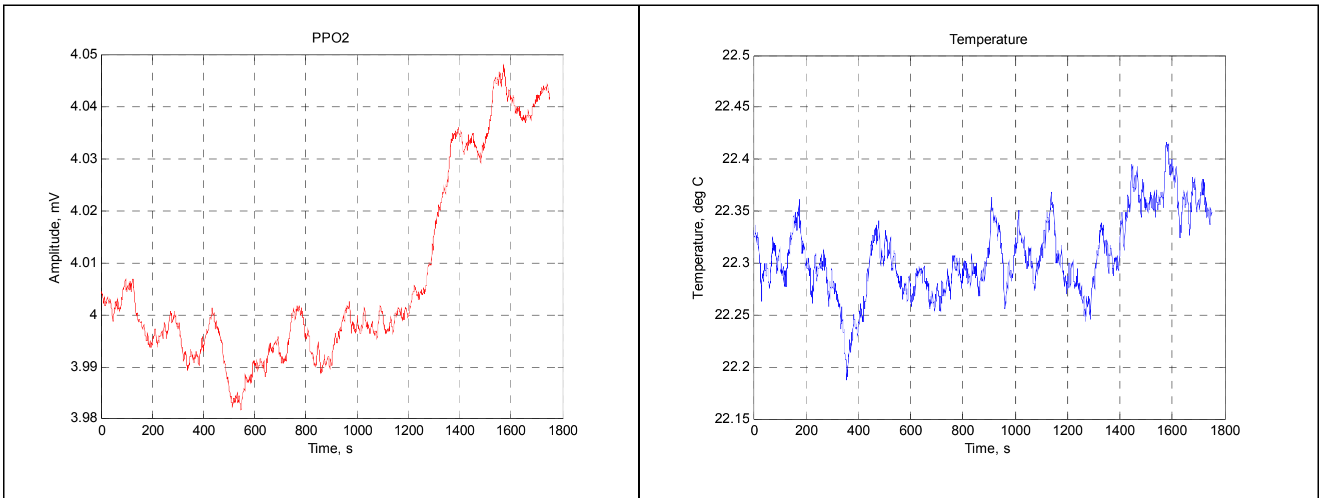


Fig 18.4-2: Sensor in water.

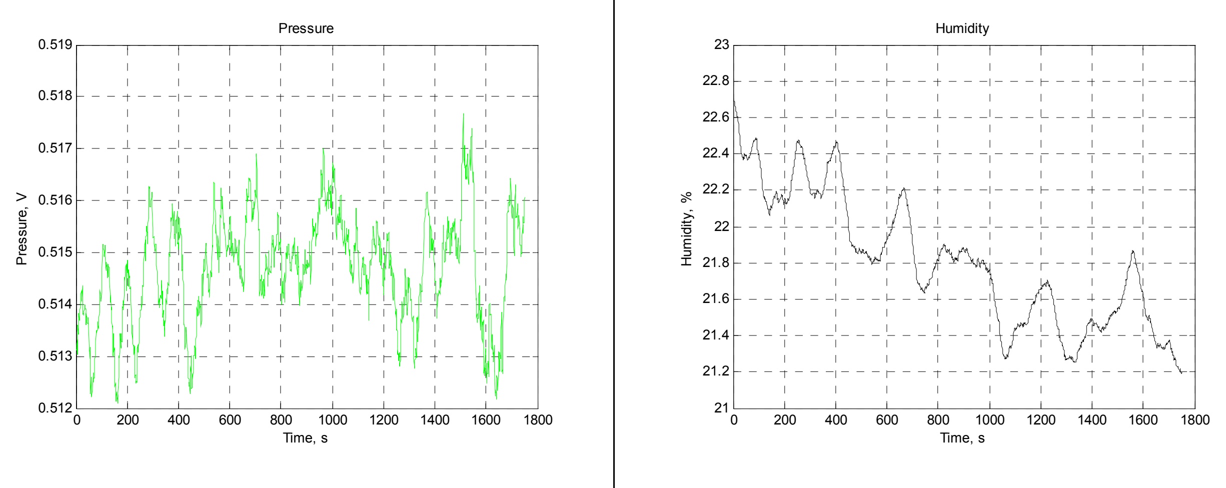
Step 4: Visual inspection using magnifier for water held on the sensor face. There was none visible.

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%

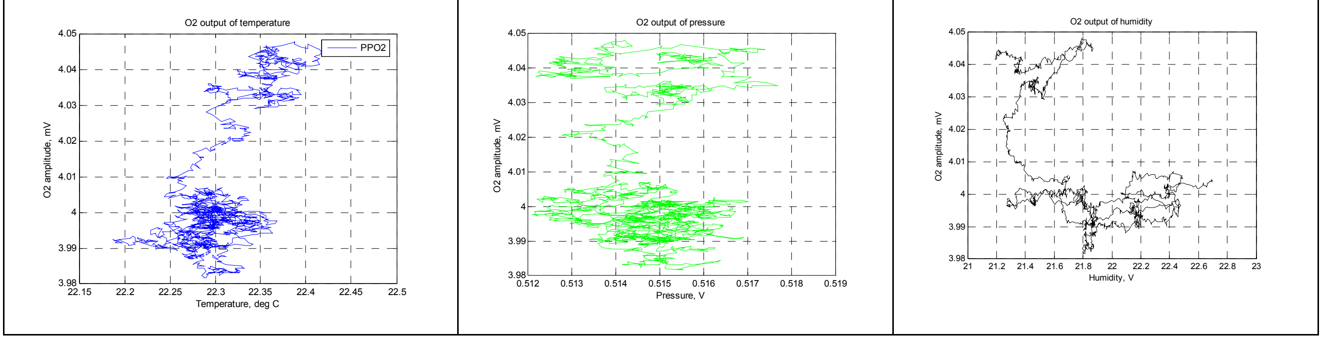


Fig 18.4-3: Sensor after immersion in water (filter: 50). The sensor output change is 1.7%. The ideal figure is under 1%, but after review, the result was acceptable.

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.

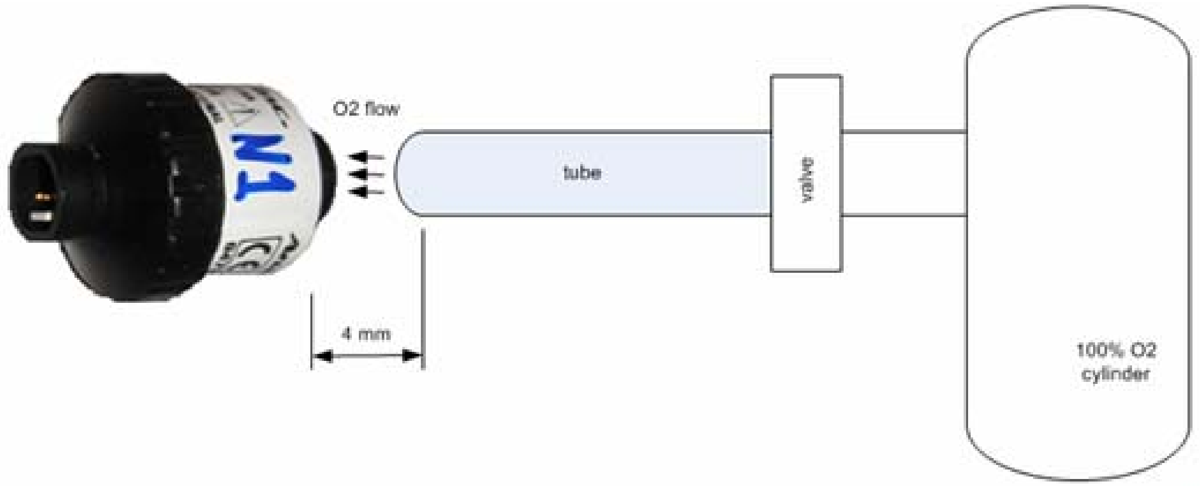


Fig 18.5-1: Test structure for sensor response test.

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

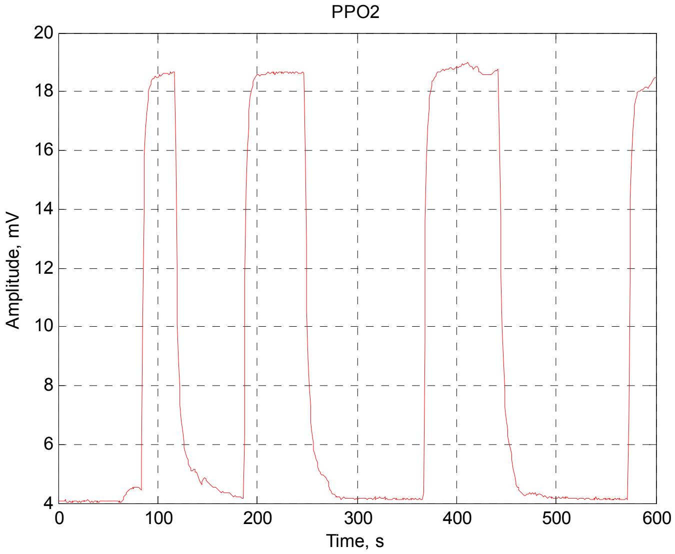


Fig 18.5-2: Output from sensor with pulsed O2 flow.

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.

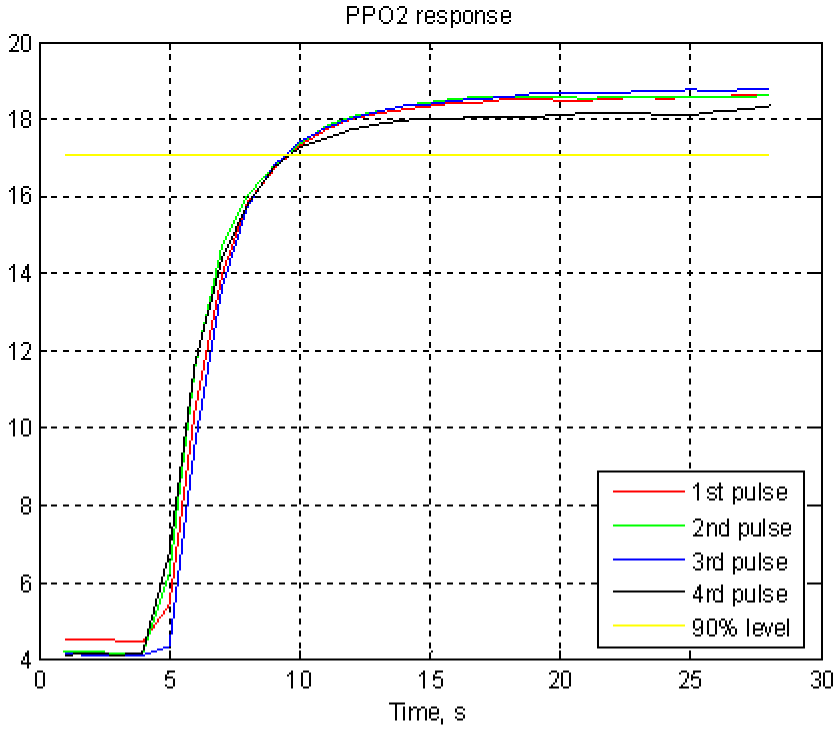


Fig 18.5-3: PPO2 time response. 90% level is 17.07 mV: (18.5-4.2)*0.9+4.2. Rise response is 6 s. The sensor output is about 18.5 mV when the sensor is in 100% O2.

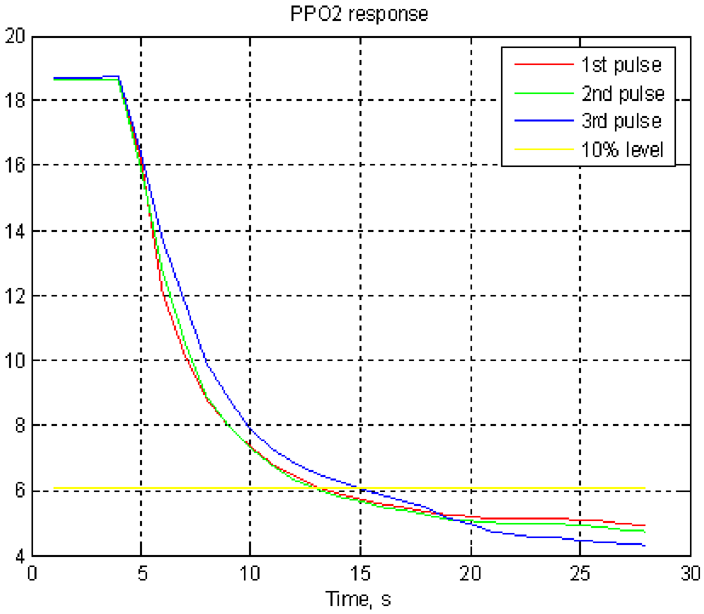


Fig 18.5-4: PPO2 time response. 10% level is 6.1 mV: (18.7-4.7)*0.1+4.7. Fall response is 10s. There is some retained O2 in the measurement fixture, so this figure equates to a fall response time of 6s.

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.

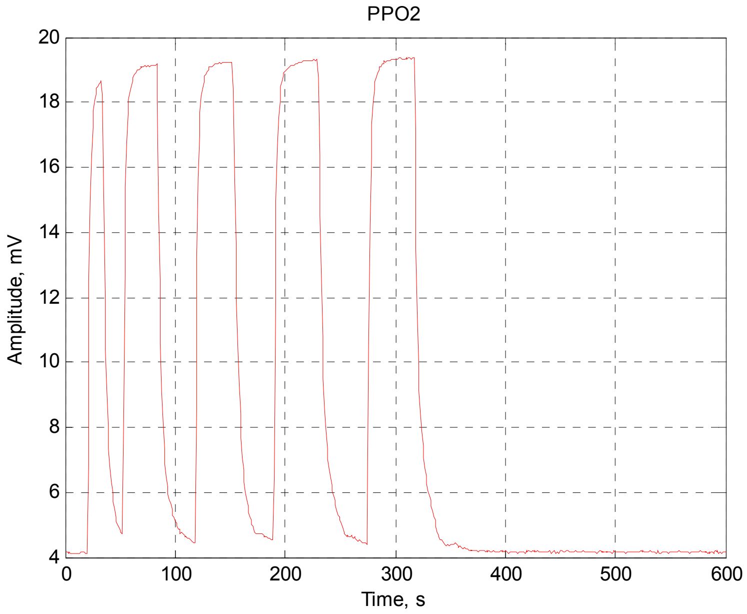


Fig 18.5-5: PPO2 of CO2 pulse flow.

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.

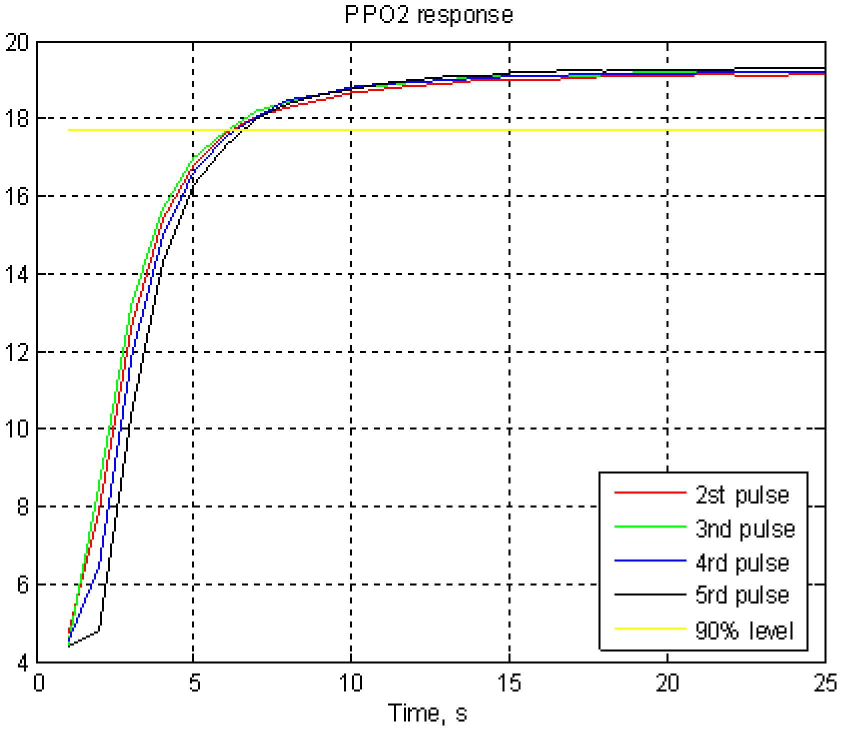


Fig 18.5-6. PPO2 time response. 90% level is 17.75 mV: (19.2.5-4.7)*0.9+4.7. Rise response is 6s.

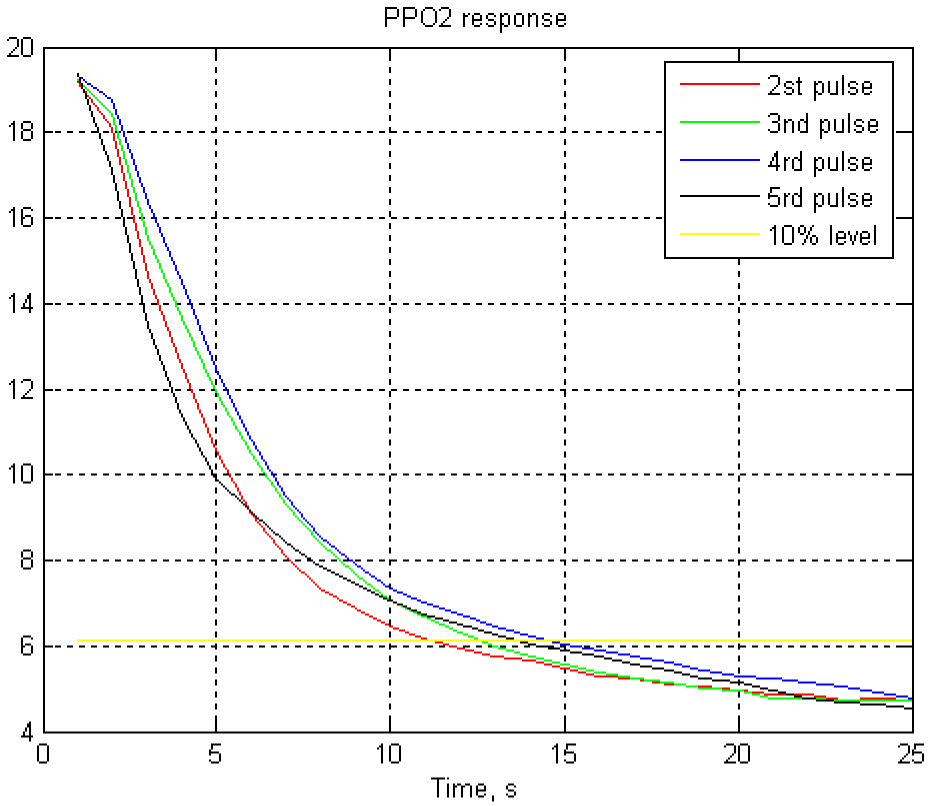


Fig 18.5-7: PPO2 time response. 10% level is 6.15 mV: (19.2-4.7)*0.1+4.7. Fall response is 13s, which equates to an actual response of under 10s due to the O2 retained in the cavity around the sensor face and in the tube.

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.

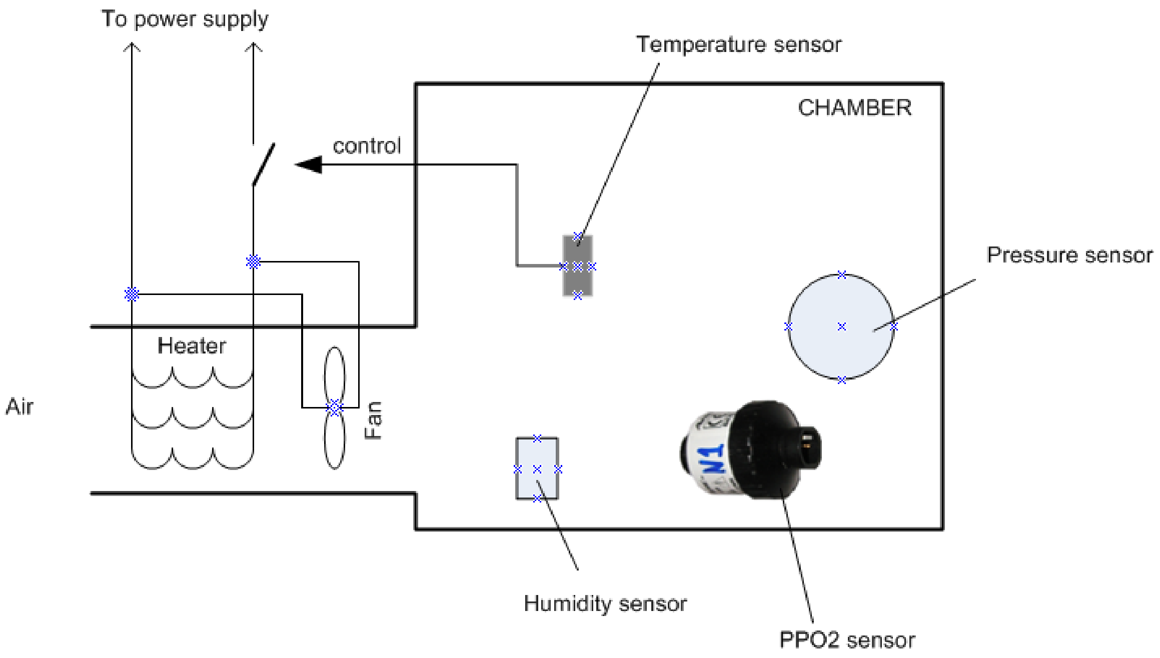
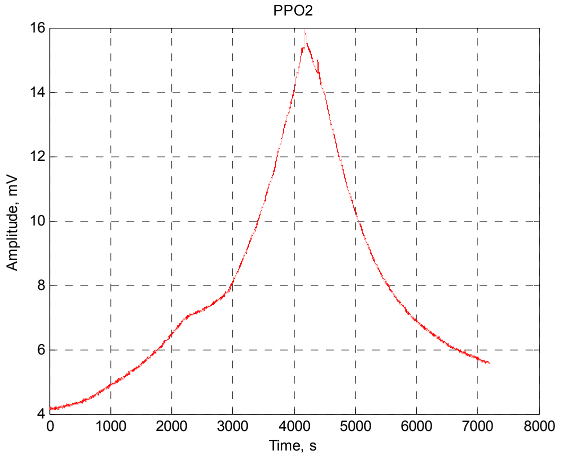
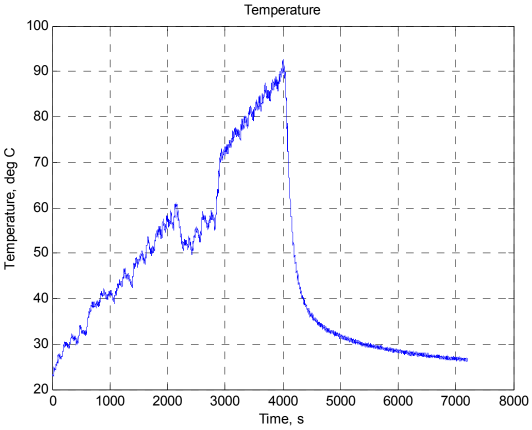


Fig 18.6-1. Test fixture for Test 5a

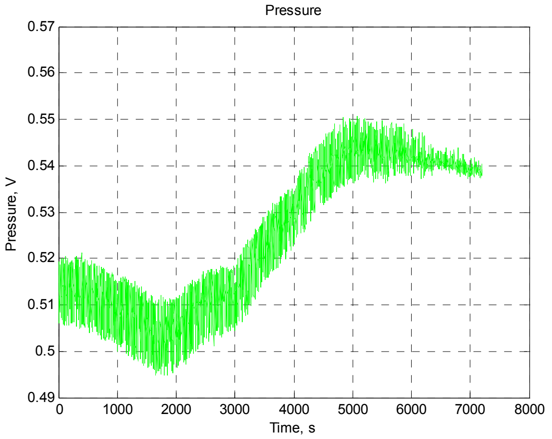
Up/down temperature.



Peak is at 4175s.



Peak is at 4002s.



Peak is at 5074s.

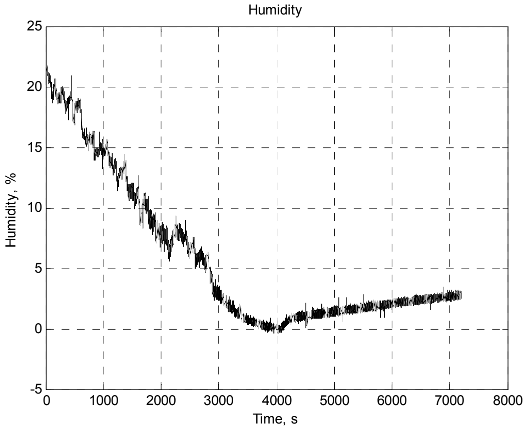


Fig 18.6-2. Maximum output from sensor is reached 173 s after the temperature starts to fall from 90 deg at 4002s. The probable reason for the delay in reaching the maximum of the oxygen sensor output is the temperature capacitance of the sensor and the temperature resistance between the sensor and environment.

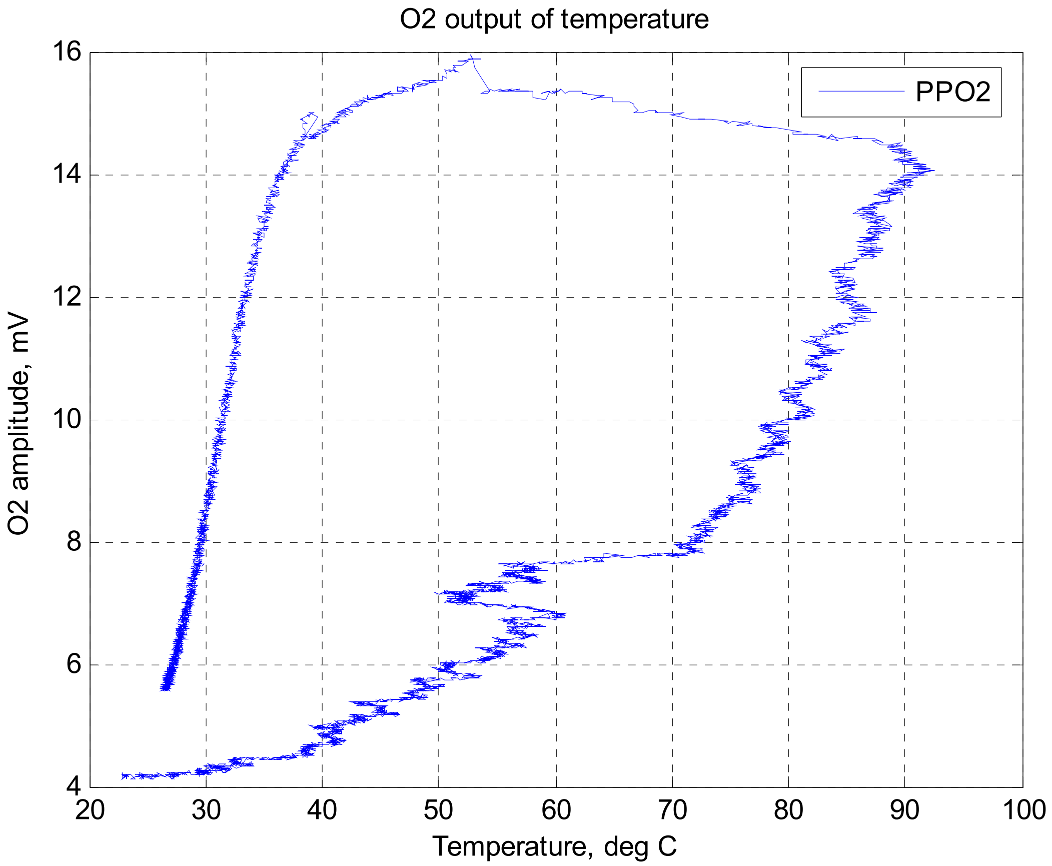
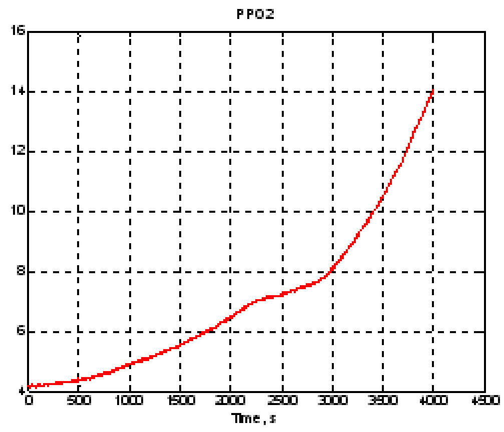
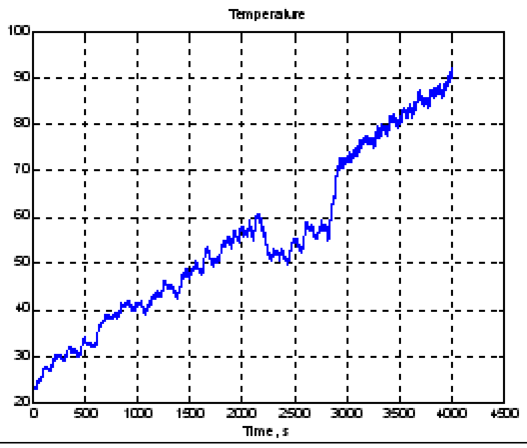


Fig 18.6-3. Output of cell as a function of temperature (PPO2 label is of apparent PPO2 voltage, PPO2 was constant during the test).

Step 4: Raise temperature for 4002 seconds.





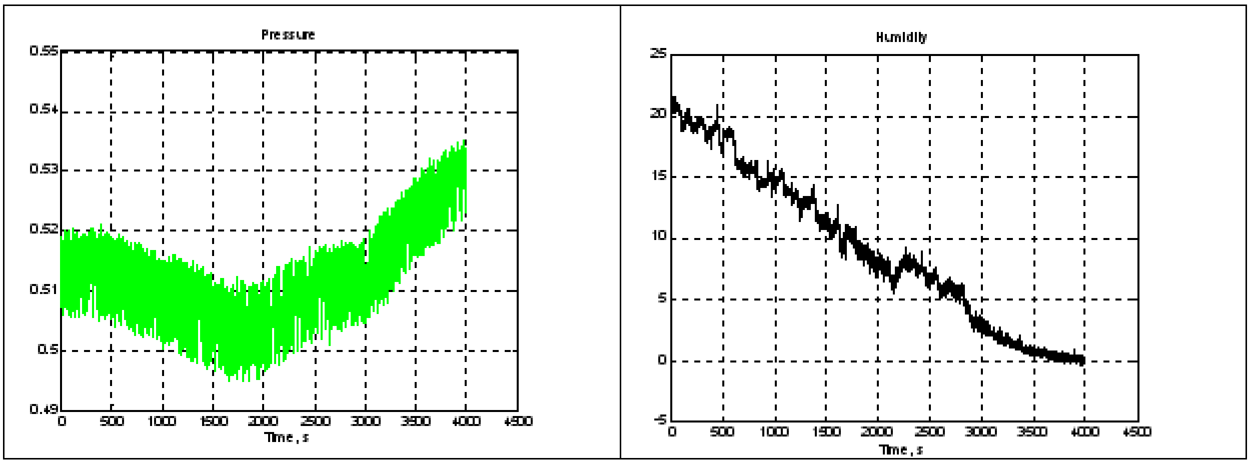


Fig 18.6-4. Effect of temperature, pressure and humidity.

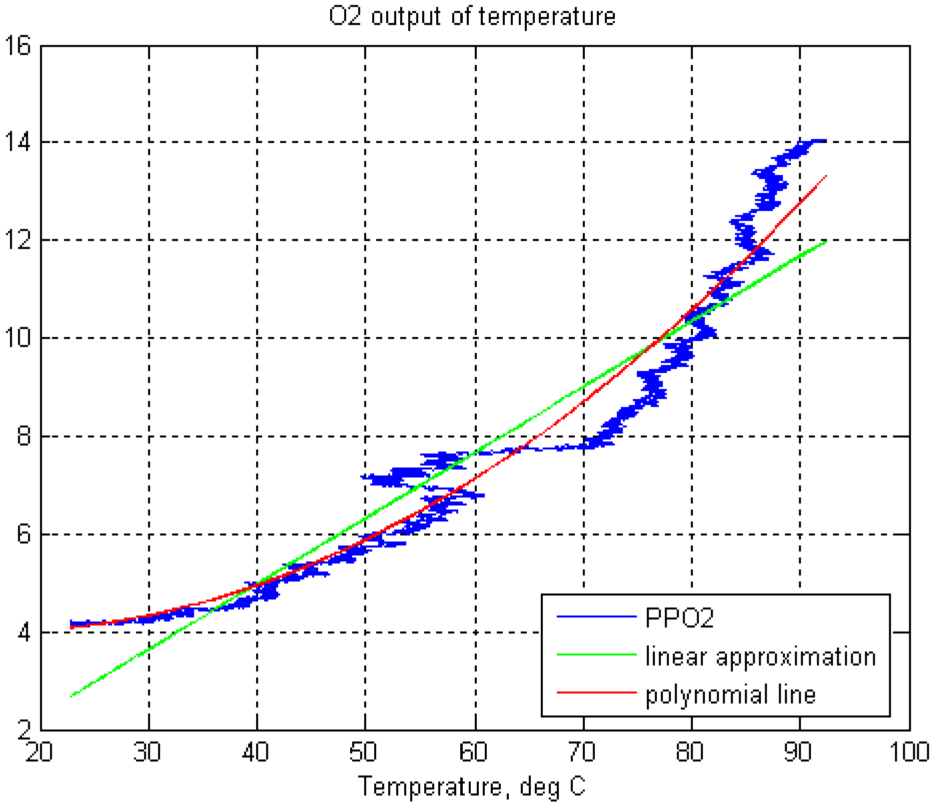


Fig 18.6-5. Cell output in mV as a function of temperature during the positive temperature ramp. Label of PPO2 is apparent PPO2 voltage, that is the actual cell output: PPO2 itself was constant during the test. The linear approximation of the temperature dependence of the cell is PPO2 = 0.1341*t - 0.3835, 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.

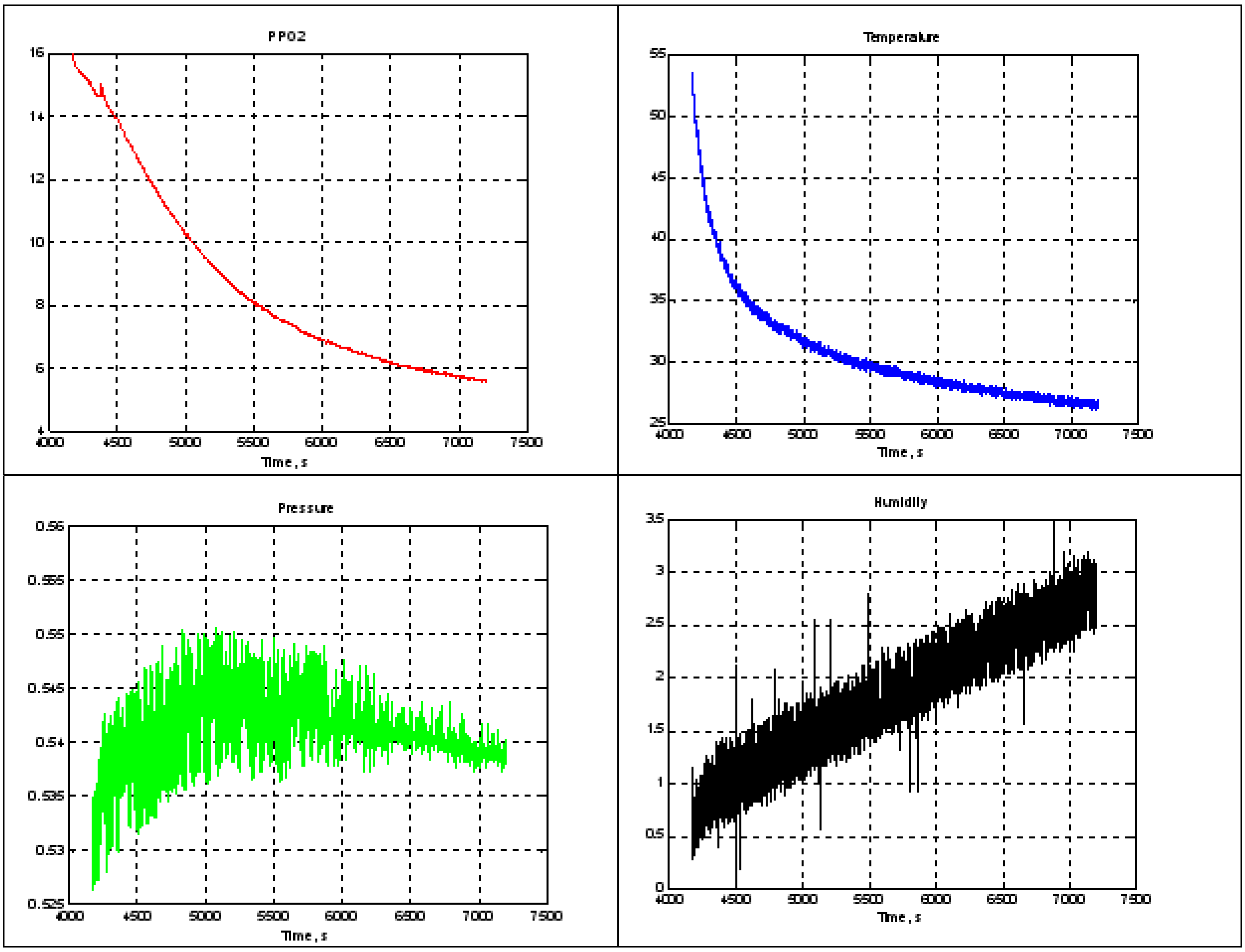


Fig 18.6-6. Apparent PPO2 while the sensor is cooling. All conditions are otherwise the same as for the previous test.

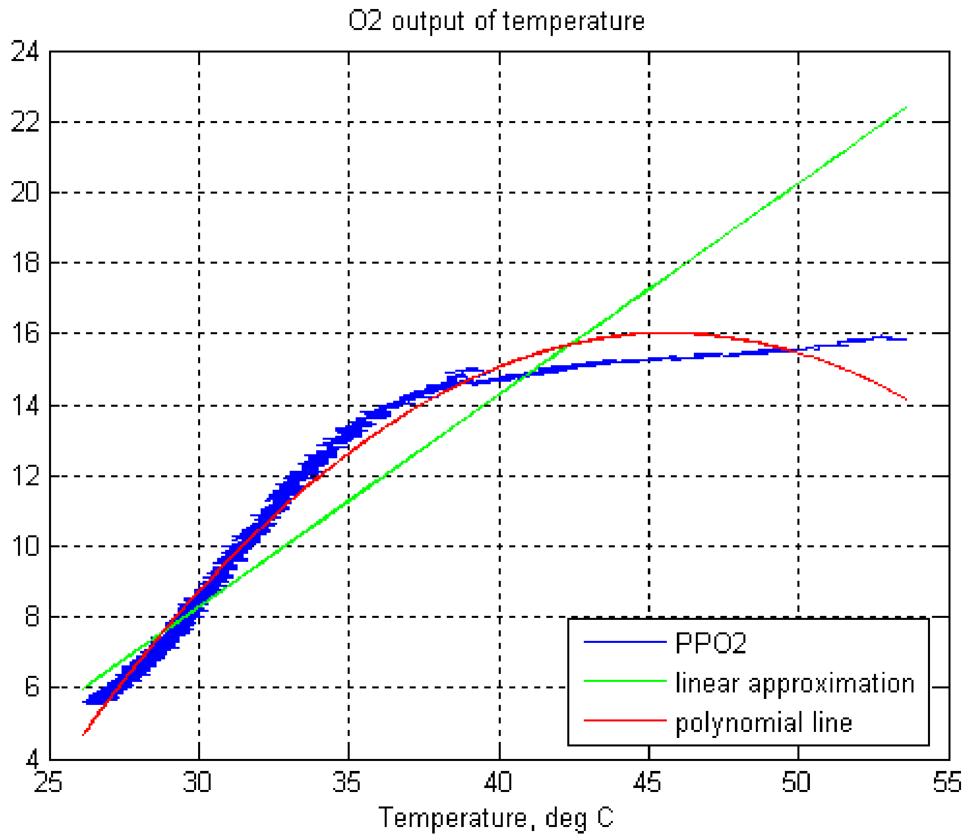


Fig 18.6-7. Cell output in mV as a function of temperature during the cooling phase. The label of PPO2 is apparent PPO2 voltage, that is the actual cell output: PPO2 itself was constant during the test. The linear approximation of the temperature dependence of the cell is PPO2 = 0.5977*t - 9.6380, second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

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 RIB.	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.

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 RIB (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 RIB 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 RIB 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.

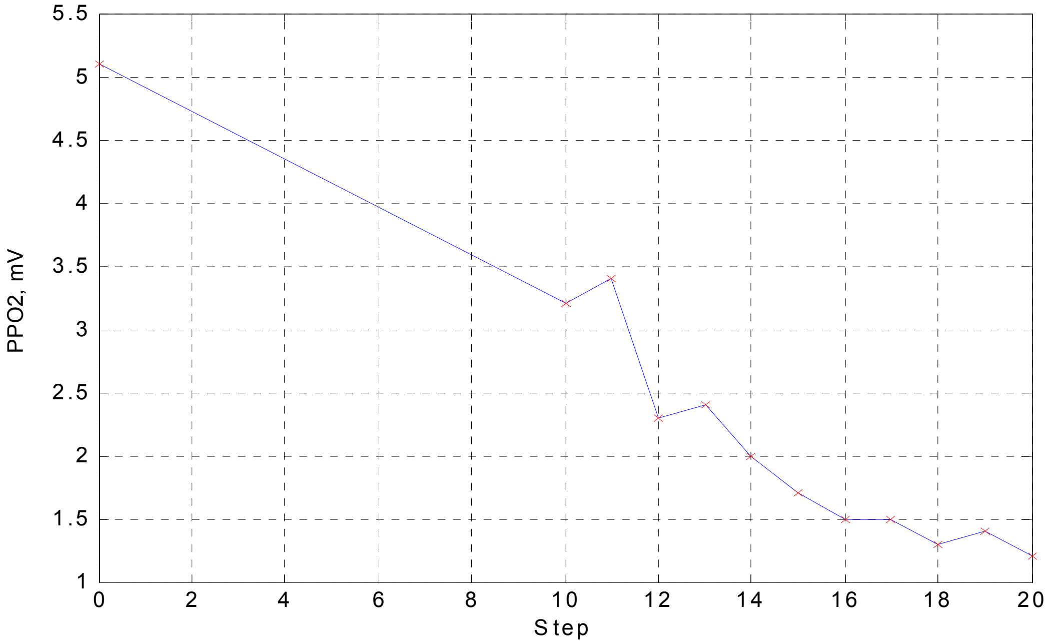


Fig 18.8-1. The apparent PPO2 voltage, i.e. the cell output. The cell output of 1.2 mV is after 20 drops onto two types of surface as specified by the test plan. Each drop decreases the initial output by about 3%. After the ninth drop, with the output at 3.2, a component became loose inside the sensor;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

18.8.1 Detailed analysis of first drop in experiment

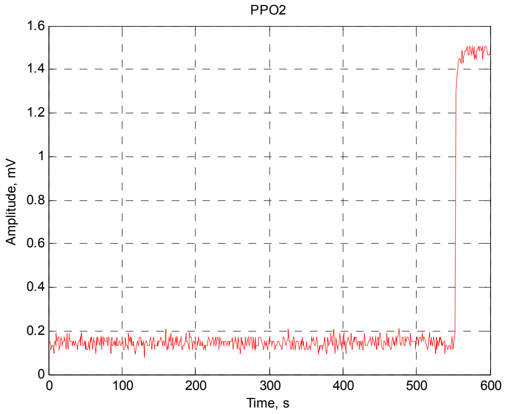


Fig 18.8.1-1. PPO2 sensor in 100% O2 flow. Before the drop test, the PPO2 in air was 4.17mV. It is less than 1.2 mV after the drop test. After the drop test, the PPO2 sensor does not respond to a pulse of 100% O2 flow (the two drops in humidity are noted to confirm the timing of the O2 pulse, from 40-100s 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.

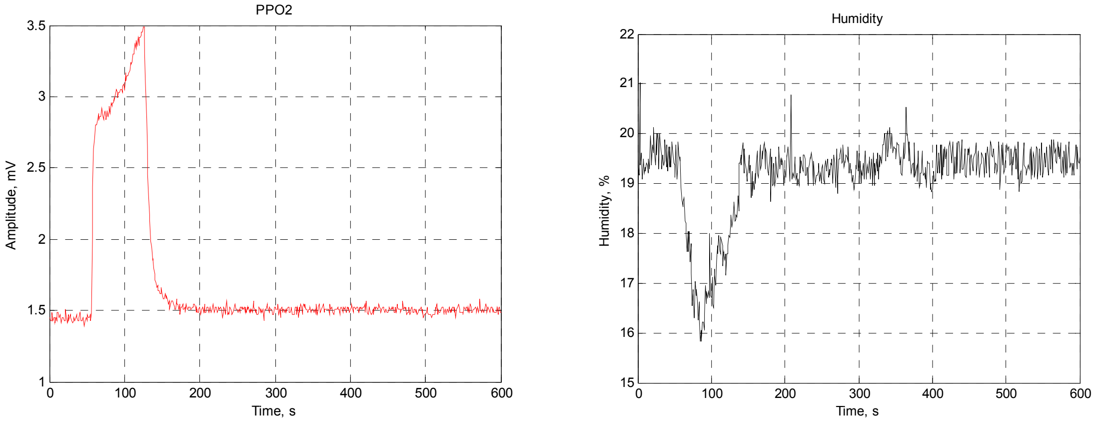


Fig 18.8.1-2. PPO2 sensor in 100% O2 flow. Drop in humidity from 60-130s shows the time of O2 flow pulse.

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	
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.

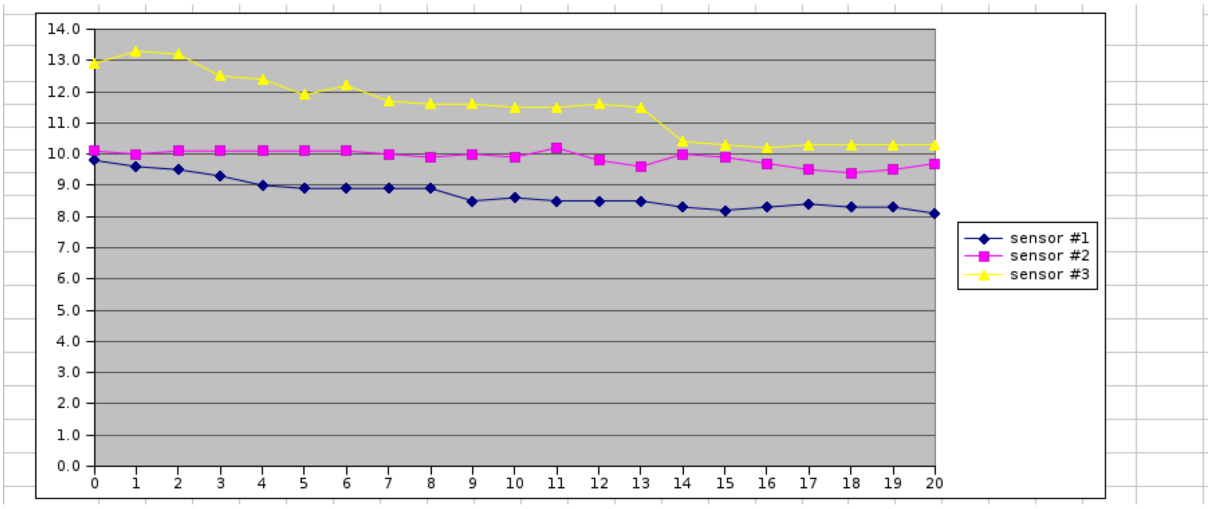


Fig 18.8.2-1: Manufacturer's results on a sample of three sensors with the mechanical improvements to improve robustness. Note the sensors show small rises, of a few percent in value, in the worst case, from 9.4mV to 9.7mV, a 3.19% change. This may be due to temperature changes or mechanical creepage.

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.

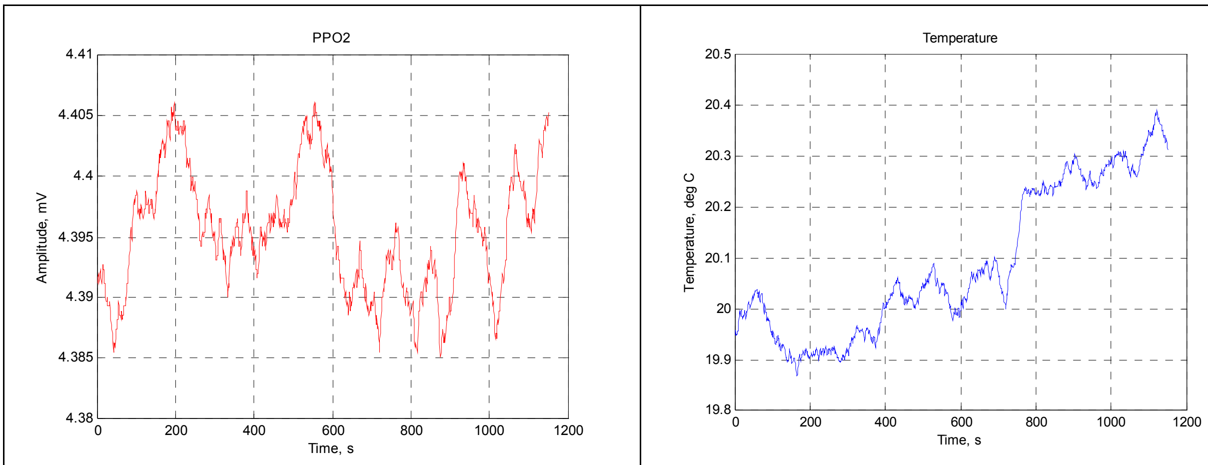
18.9 Test 7. Linearity with pressure, and susceptibility to helium

Test	Purpose	Method	Result
7. Linearity with pressure, and susceptibility to 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 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 (1400msw). 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.	Pass: operates correctly over range 4 bar to 14 bar relative to ambient.

Steps1 and 2:

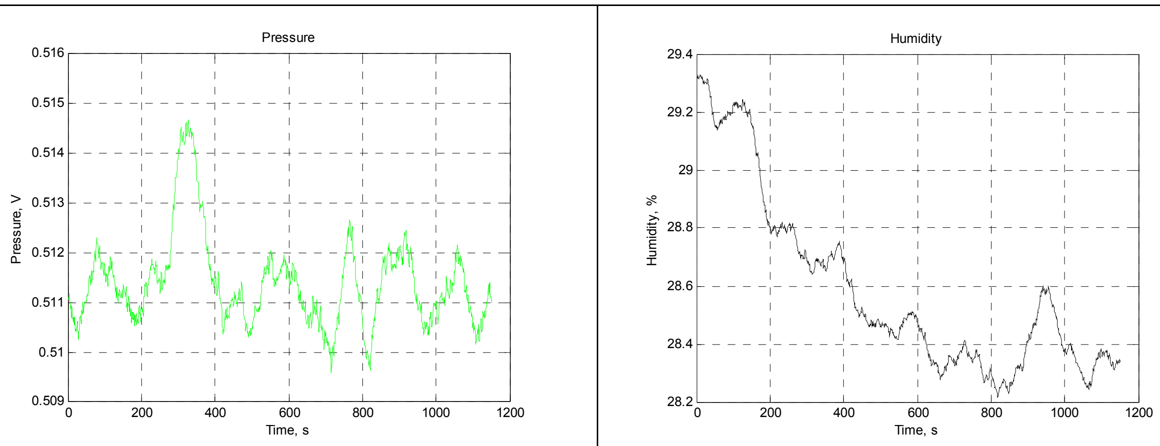
Fig 18.9-1. O2 sensor test fixture. Gauge on top of chamber is for safety only: pressure readings were taken digitally (electronically).

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



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.

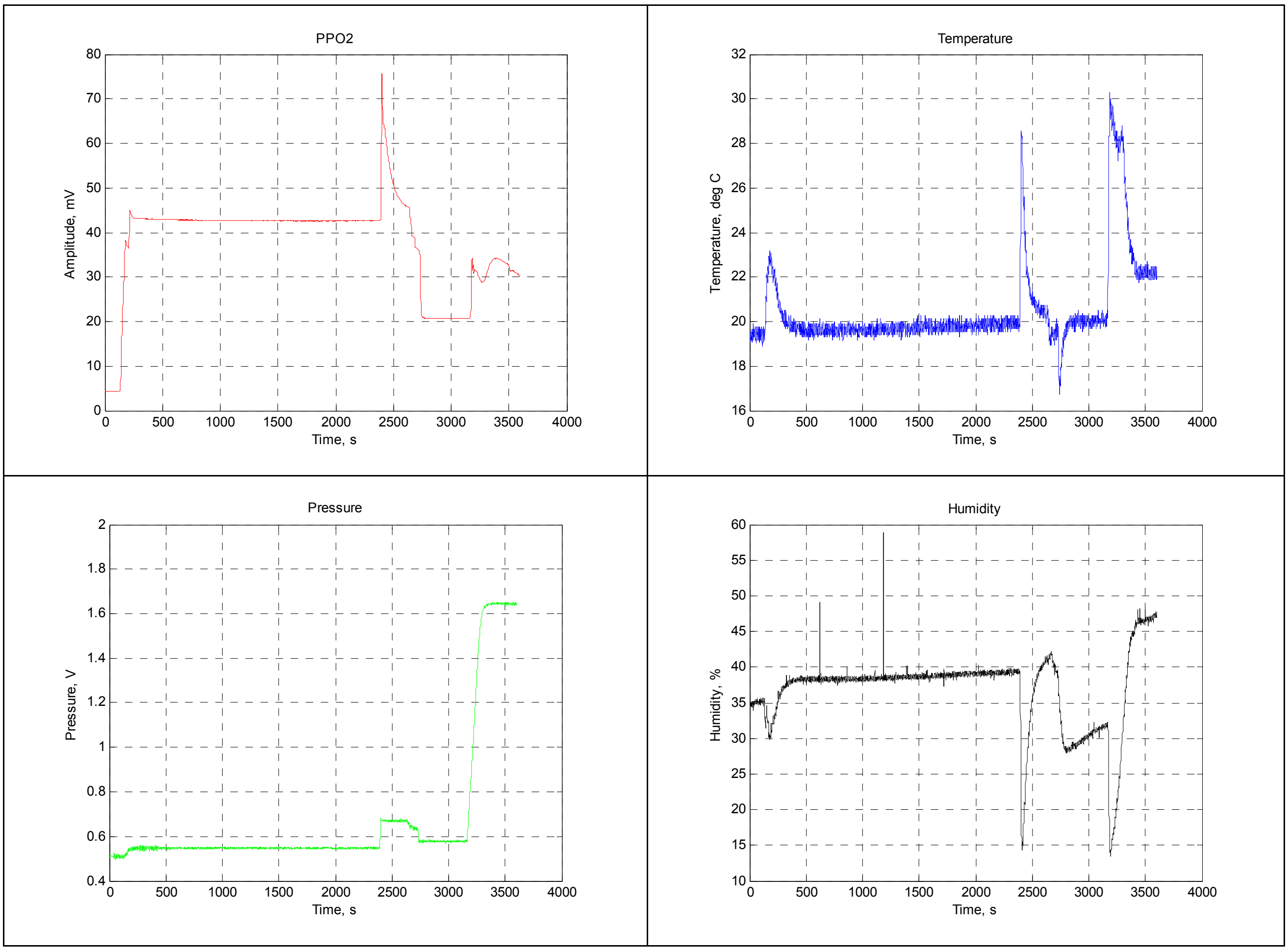


Fig 18.9-3. Sensor in O2 and then in He. Filter window is 0. These results were analysed carefully. The sensor has a lower output sensitivity when under high pressures of helium. The graphs show the raw voltage levels from the sensors, other than for humidity.

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 1400msw, 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.

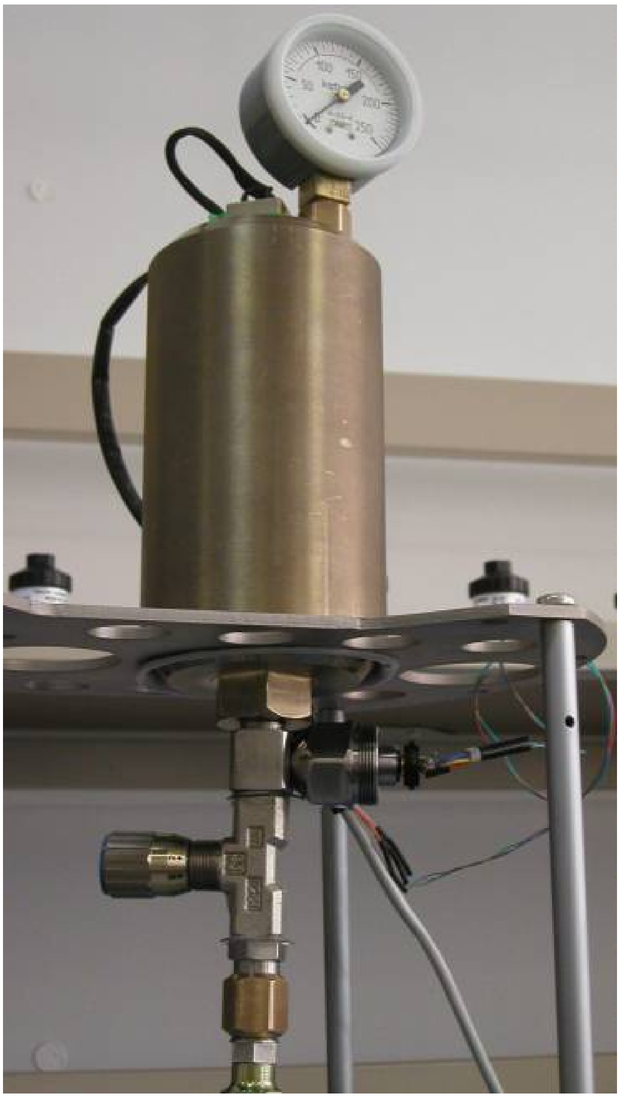
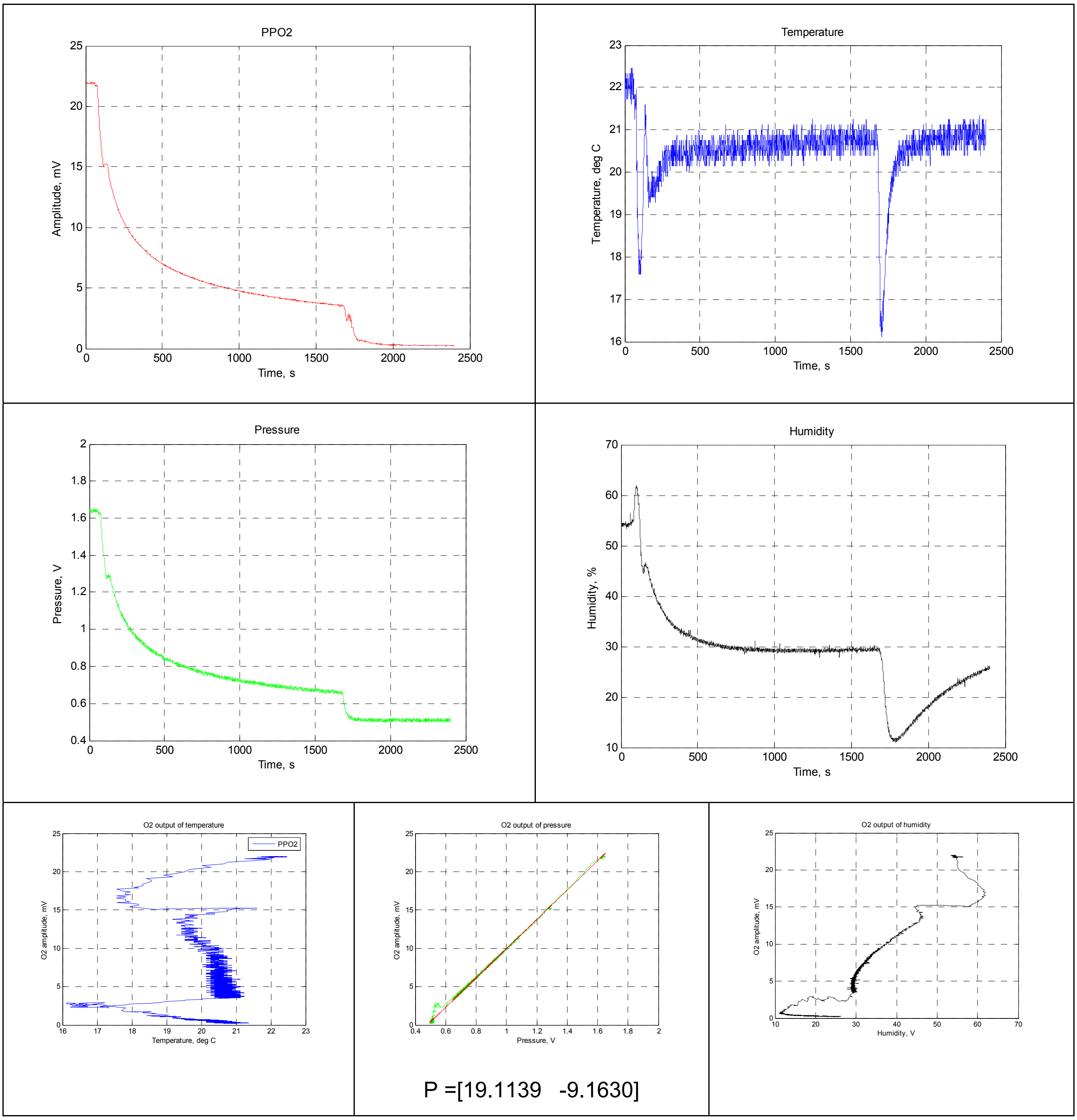


Fig 18.10-1. Test chamber showing attachment point below for pressure sensor

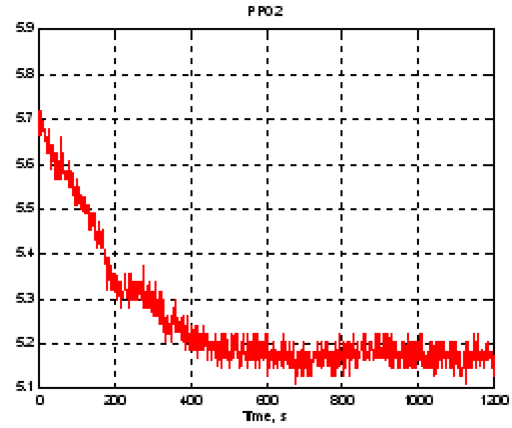
The experiment was run repeatedly due to inconsistent results in the first experiment. The first run is not recorded for this reason: results below are for the second, third and fourth runs.

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

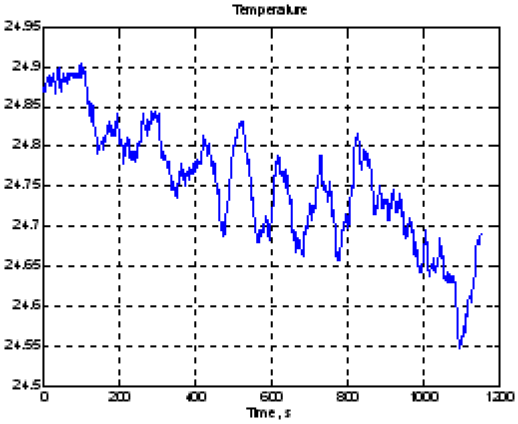


P =[19.1139 -9.1630]

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

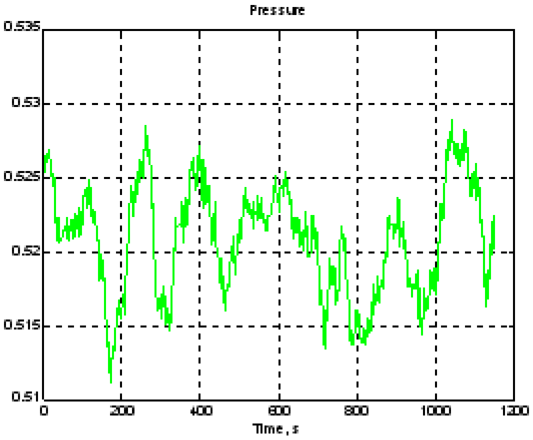


Filter window is 0



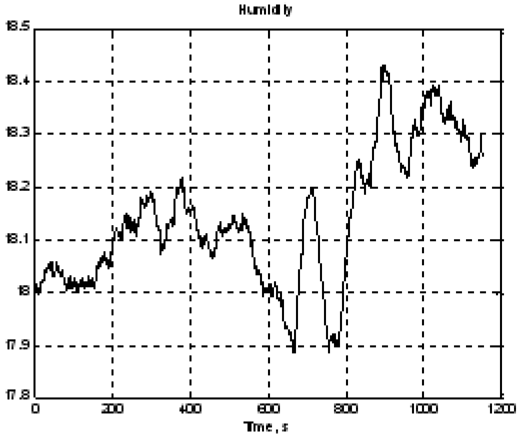
Filter window is 50

Temperature mean = 24.75 C



Filter window is 50

Pressure mean = 0.5208 V

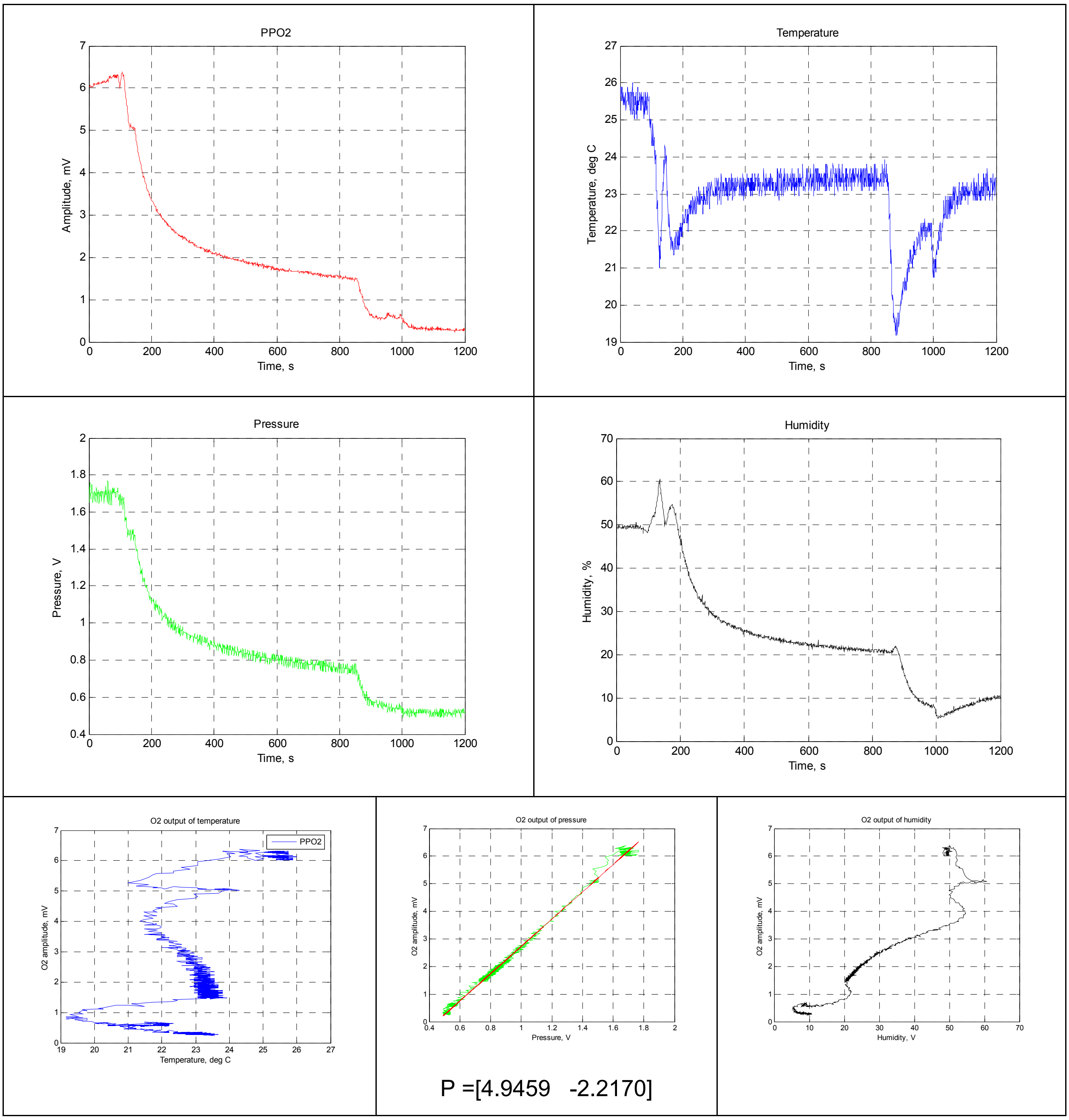


Filter window is 50

Humidity mean = 18.14%

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

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



P =[4.9459 -2.2170]

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

Step 4 and repeat of 2: Experiment run 3.

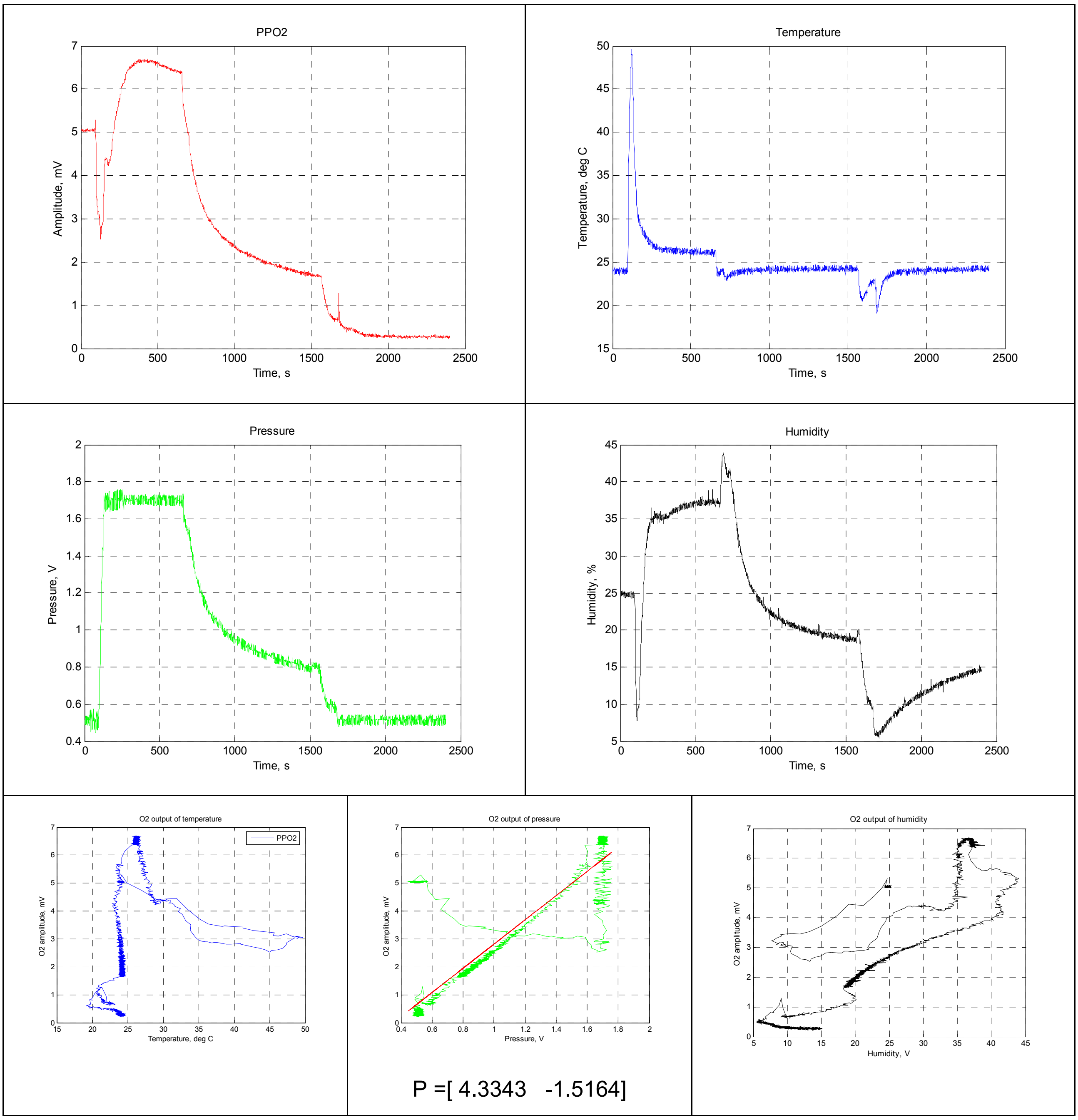
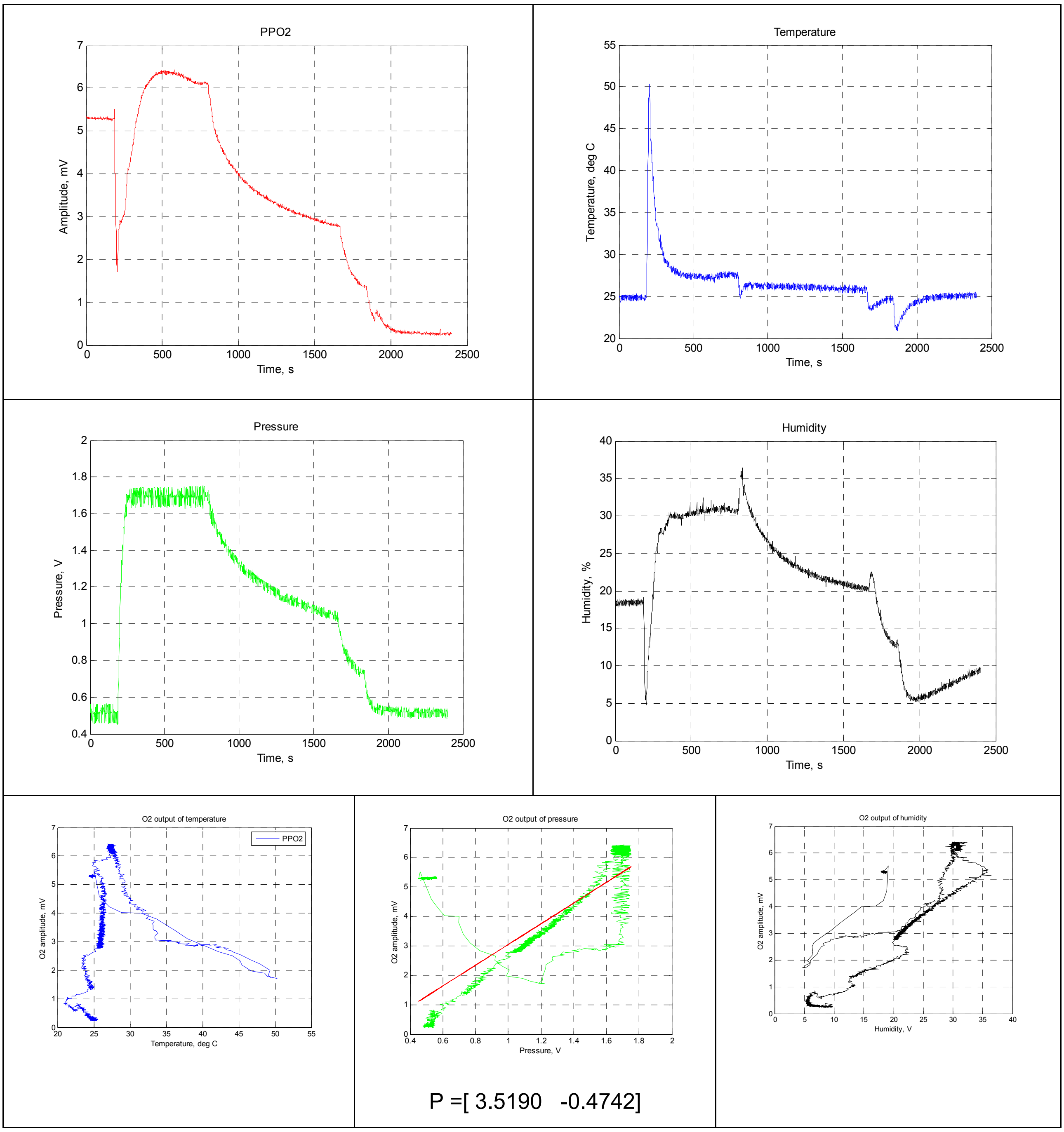


Fig 18.10-5. Rise and fall pressure.

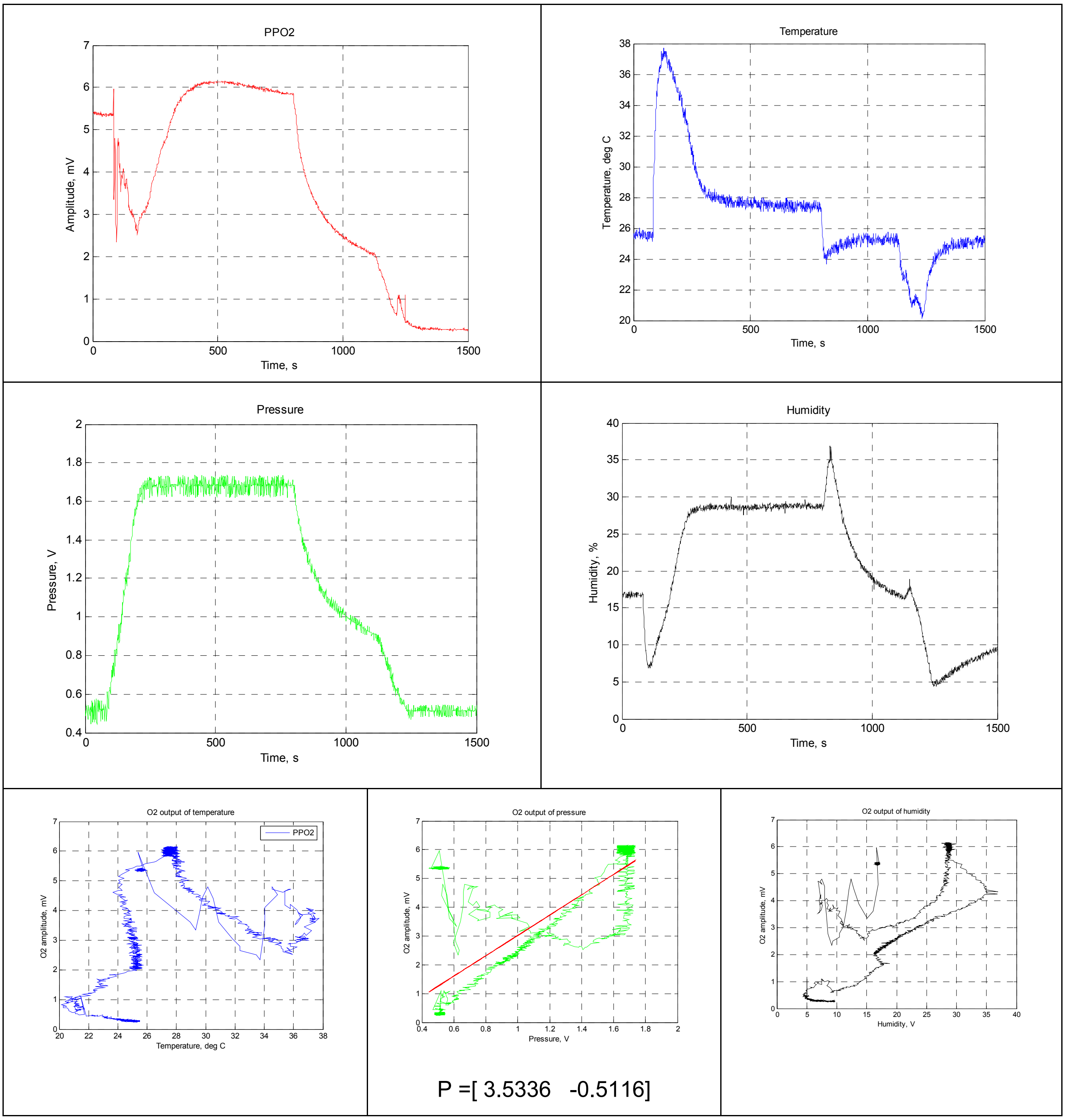
Steps 4 and 2: Experiment run 4.



P =[3.5190   -0.4742]

Fig 18.10-6. Rise and fall pressure.

Steps 4 and 2: Experiment run 5.



P =[3.5336   -0.5116]

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

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.

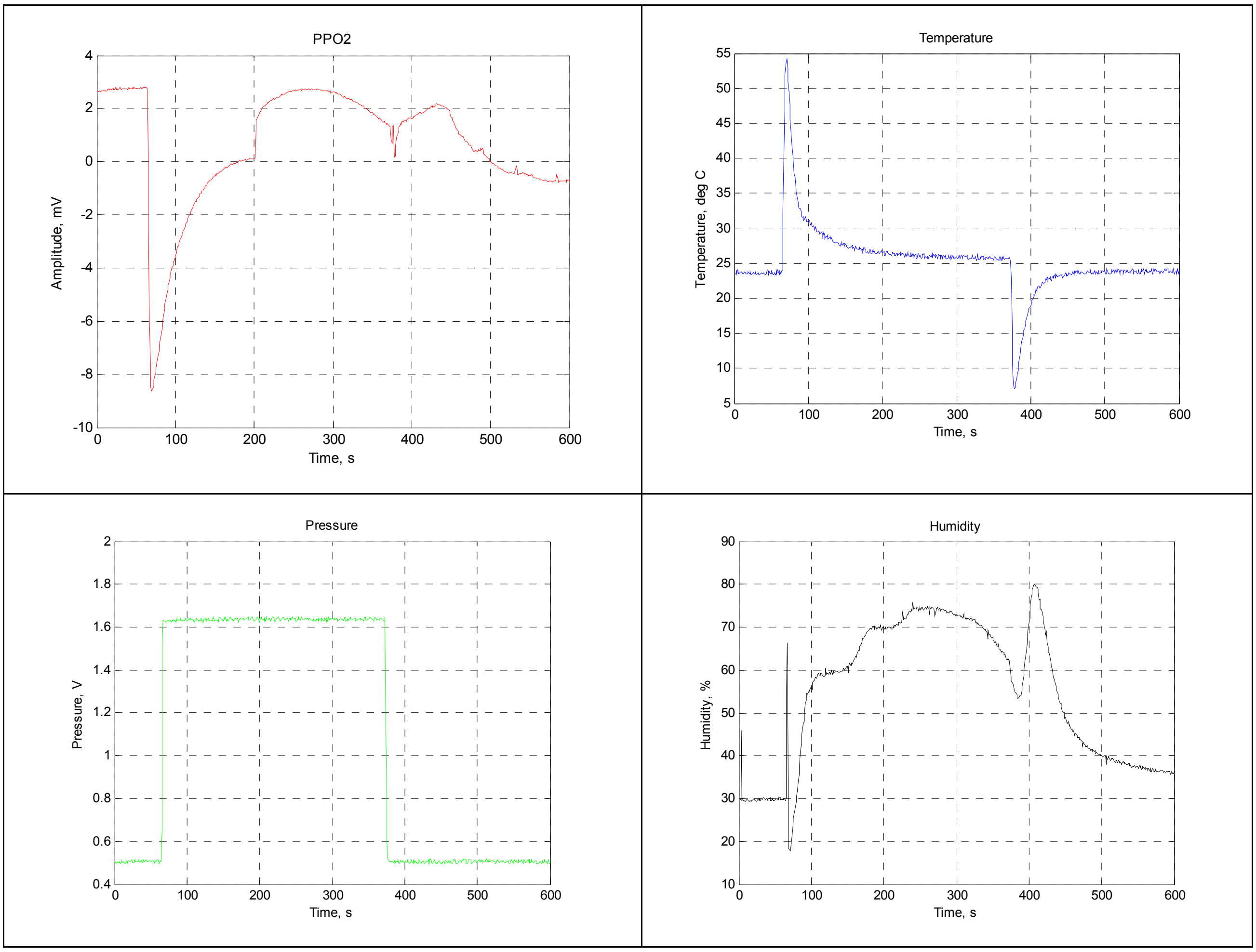


Fig 18.11-2. The test results. Pressure from 1 ATM to 130 bar in under 1 second, using He**.** No particles or liquid were thrown out from the sensor inside the chamber.

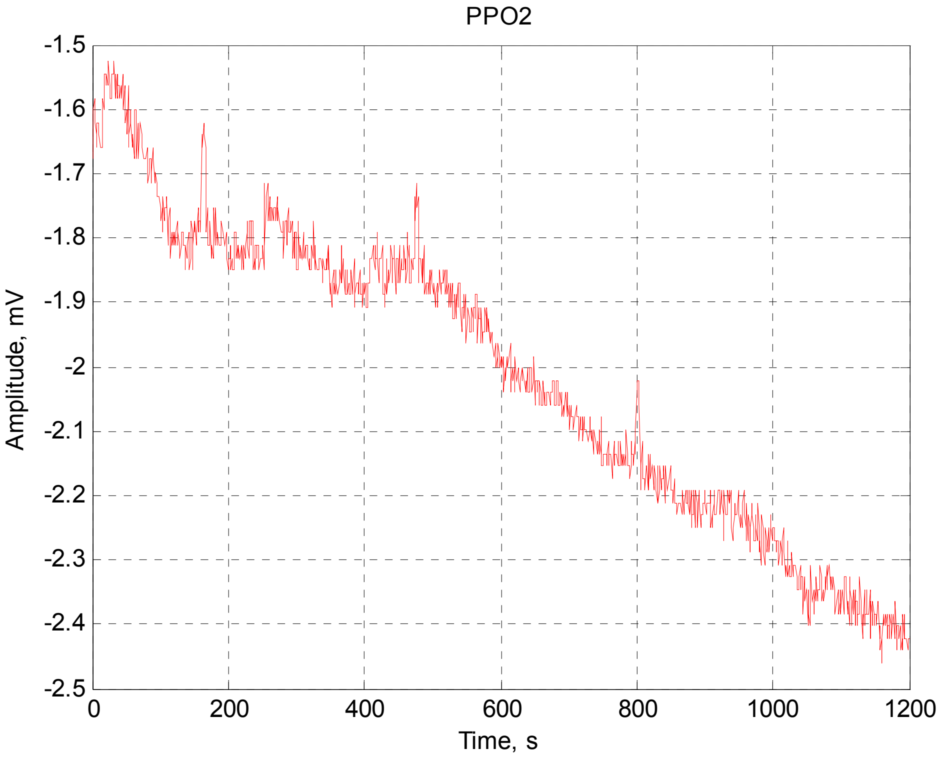


Fig 18.11-3. After the test. The sensor in atmosphere over 20 min. The filter window is 0. PPO2 mean is negative of -2.01 mV, temperature mean = 23.13 C, pressure mean = 0.5045 V, humidity mean = 24.69%. Note the sensor output polarity is reversed.

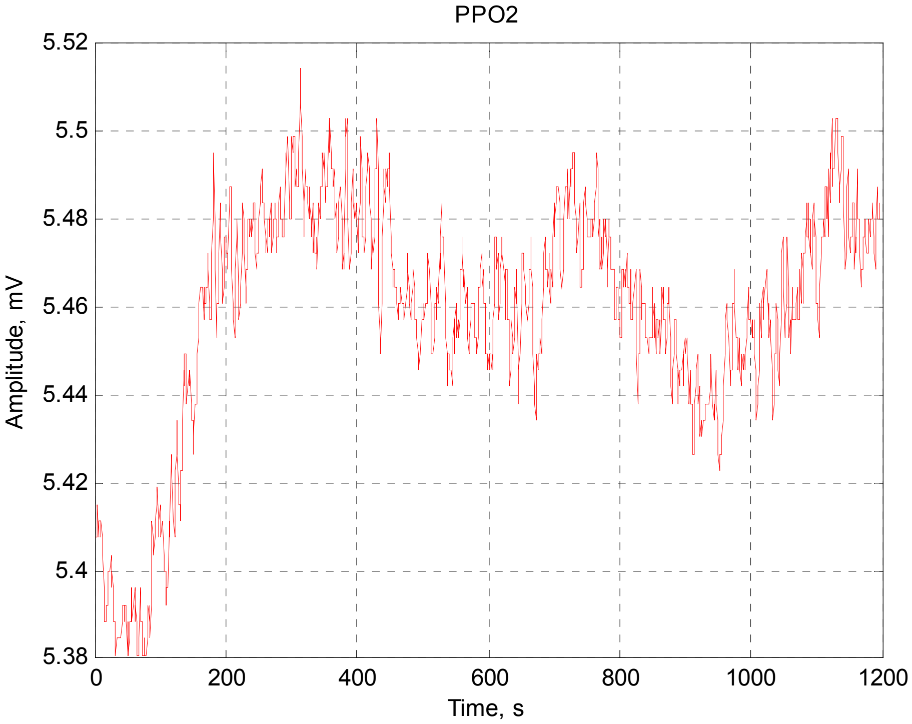


Fig 18.11-4. Two days later. The positive output of the sensor is restored.

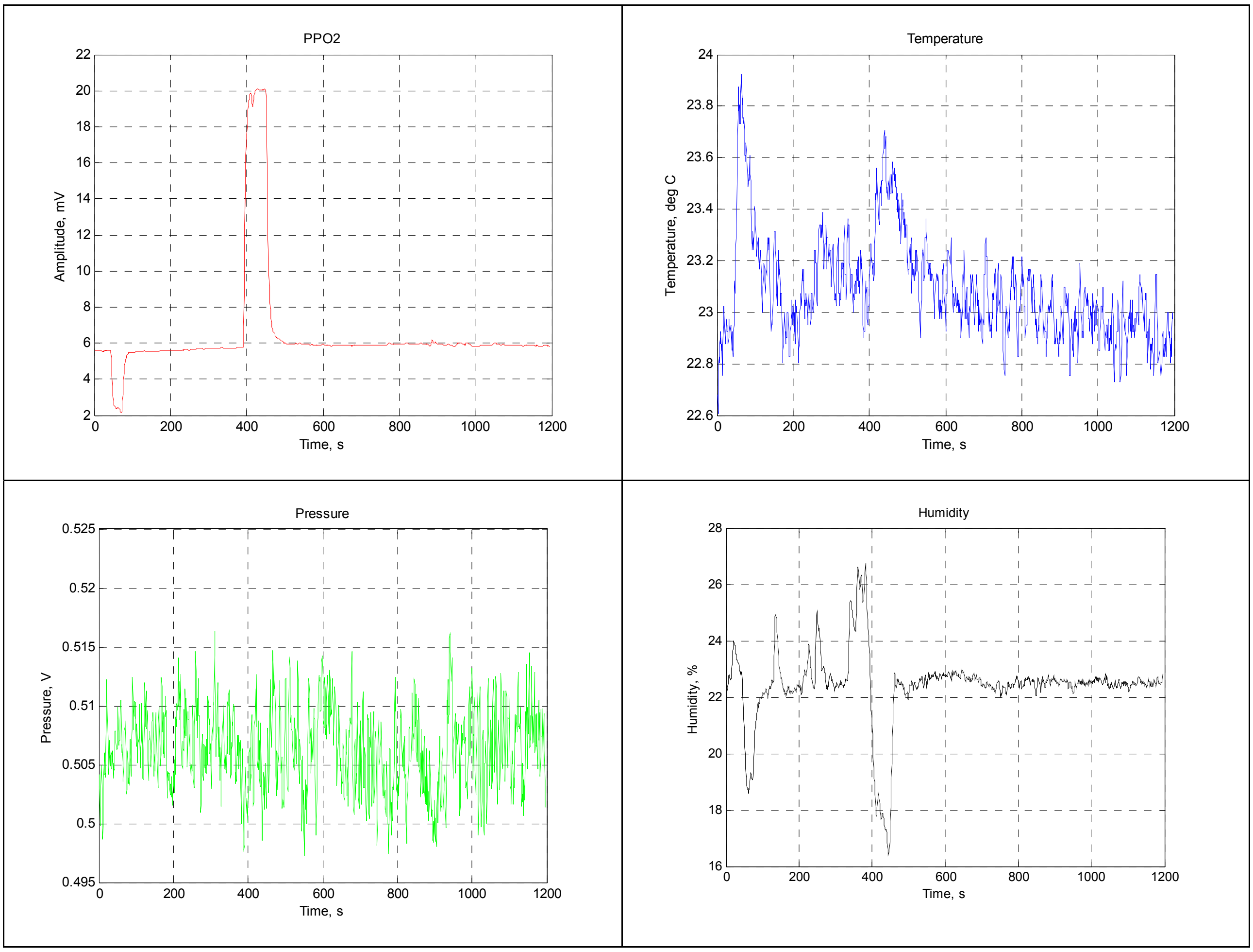


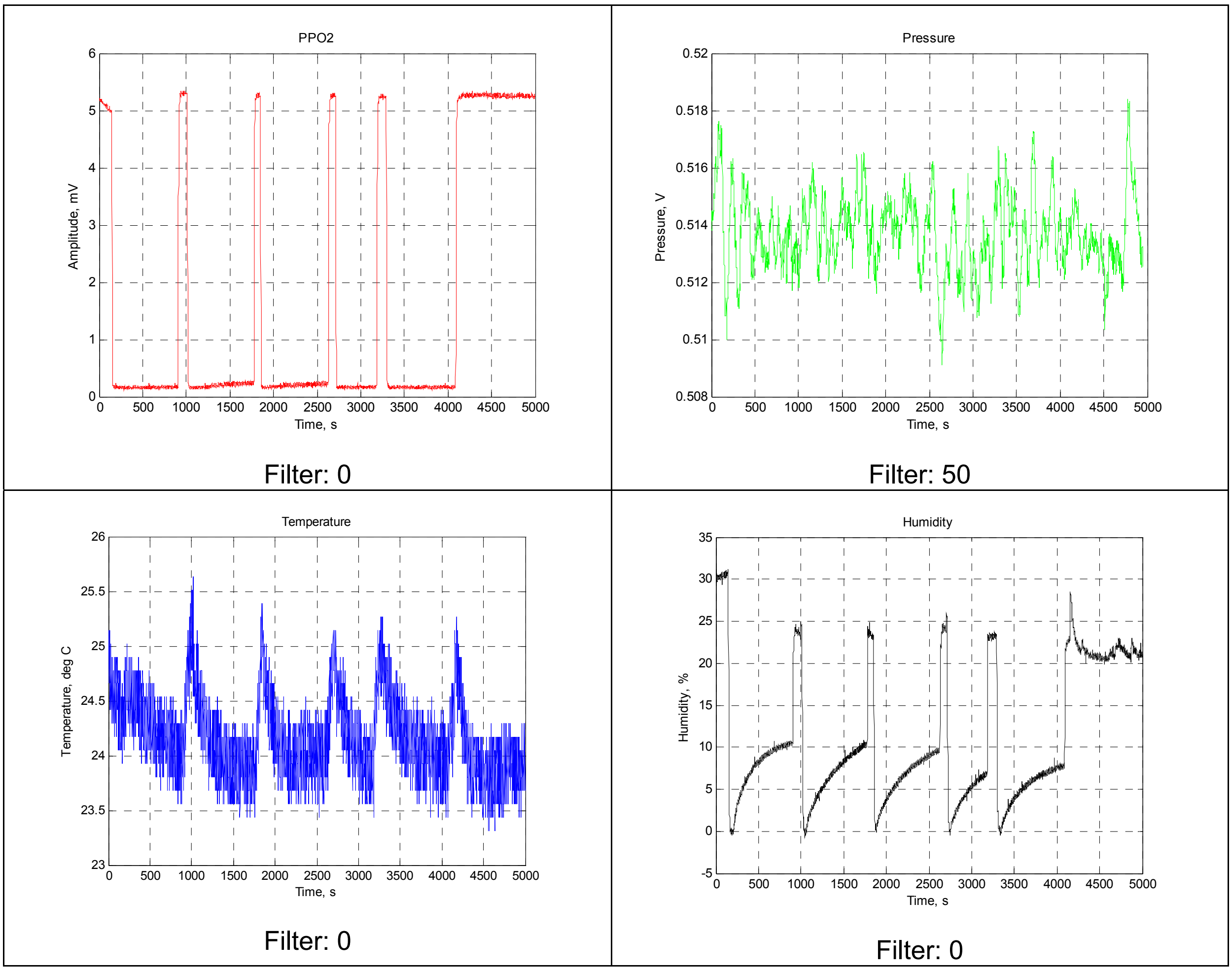
Fig 18.11-5. Check of the sensor gain after restoration of the output signal. First the sensor is placed in a CO2 flow, then in 100% O2 flow. The output of the sensor in CO2 increases from 0.19 mV (see test 10) to 2.1 mV. The output of the sensor in 100% O2 increases from 18.5 mV (see test 4) to 20.4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

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.	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 remains in air for the remainder of this test. 8. 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 chamber with CO2 feed.



Filter: 0

Filter: 50

Filter: 0

Filter: 0

Fig 18.12-2. Sensor when five pulses of pure CO2 are applied. Note there is a small offset to the sensor reading in a CO2 environment. This may be due to imperfect flushing of the bag.

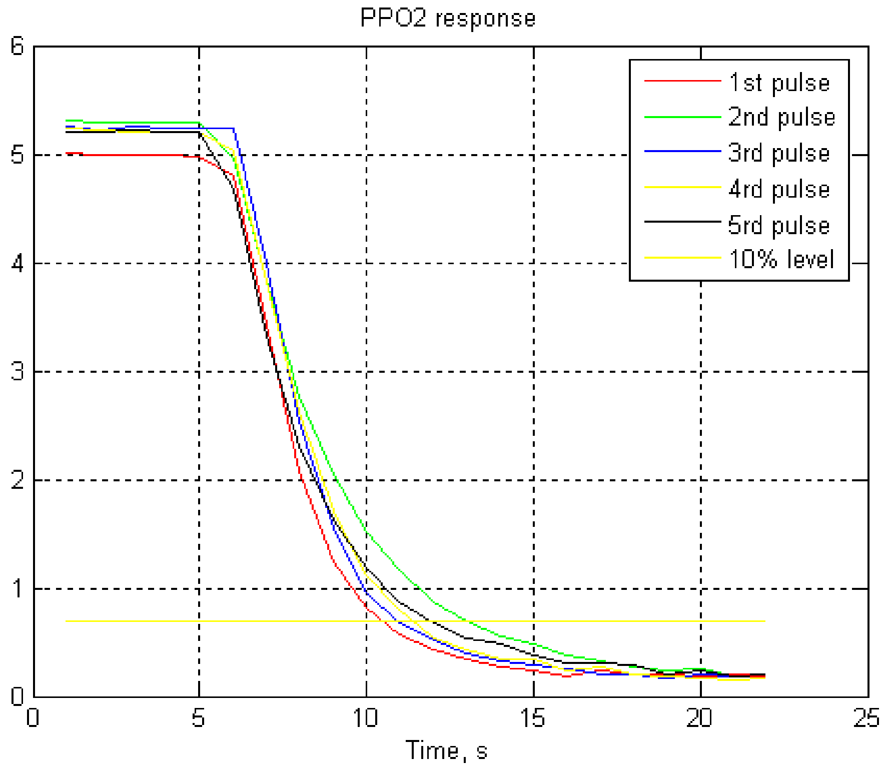


Fig 18.12-3 Sensor response at onset of CO2 pulse. 10% level = 0.696 mV, ((5.25-0.19)*0.1+0.19). Time of response is 7s.

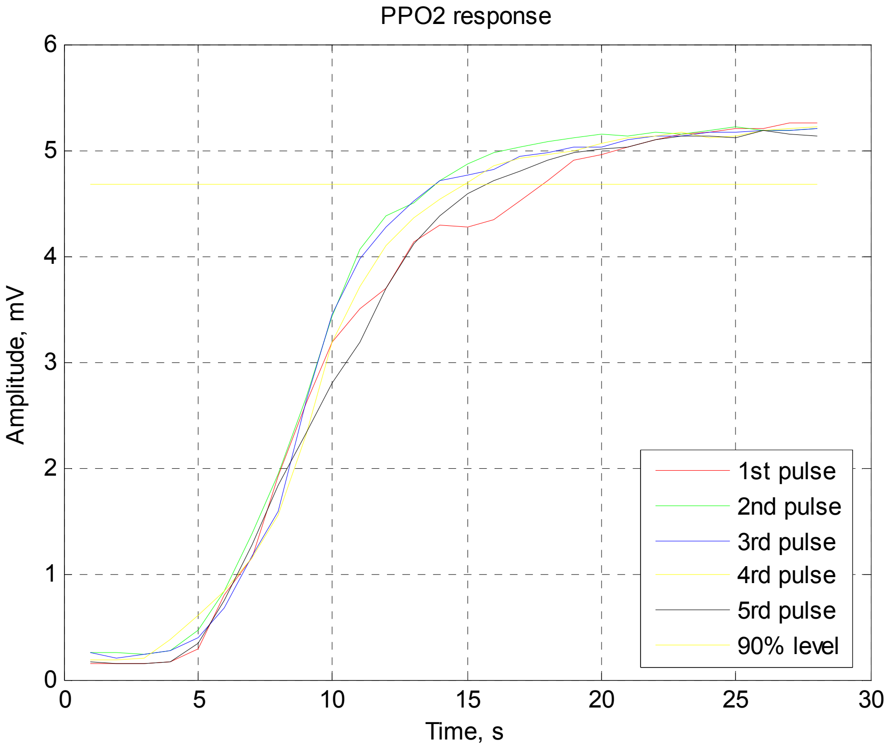
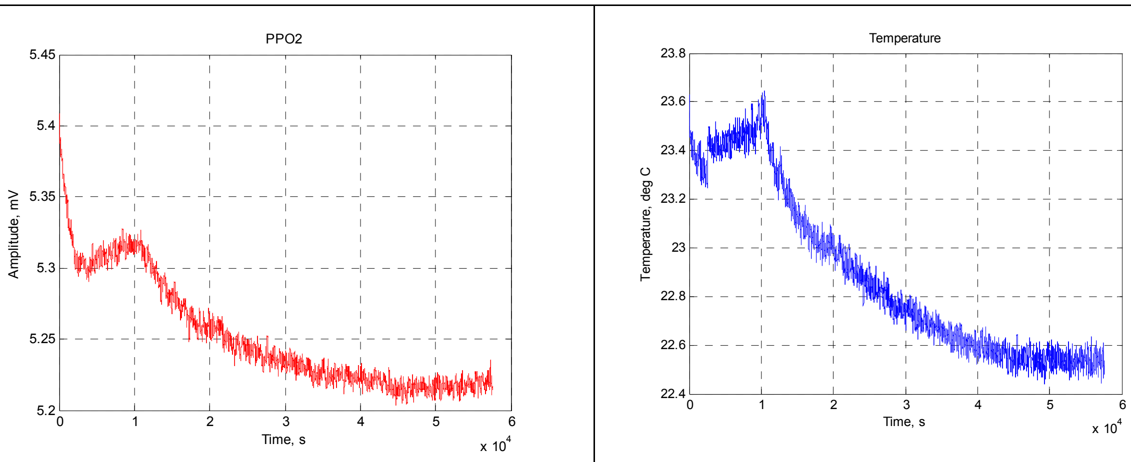


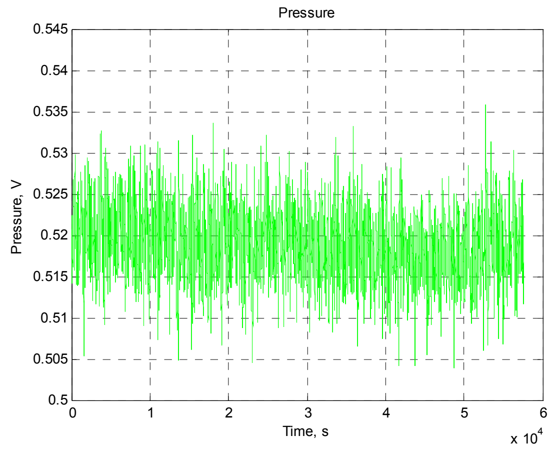
Fig 18.12-4. Sensor response when returned from CO2 to air. 10% level = 4.673 mV, ((5.17-0.2)*0.9+0.2). Time of response is 12s.

Step 8: 1st day.

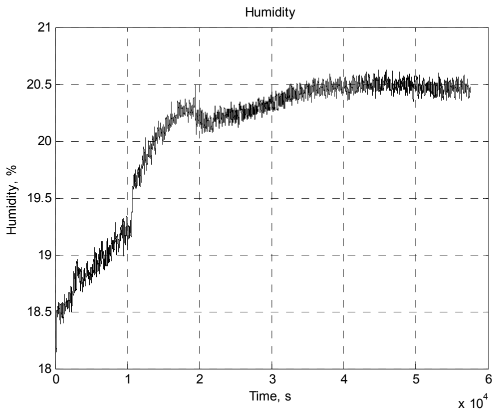


PPO2 mean = 5.25 mV

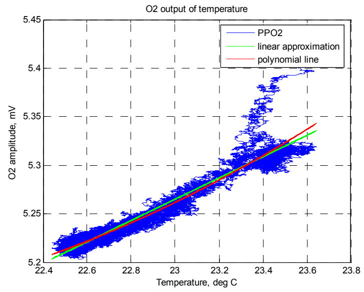
Temperature mean = 22.89 C



Pressure mean = 0.5191 V

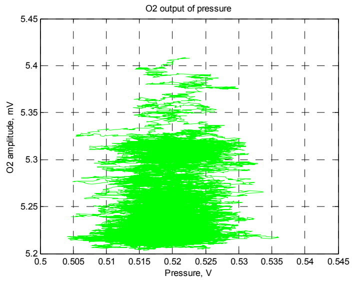


Humidity mean = 20.06%



P 1st order = [0.1096 2.7448]

P 2nd order = [0.0255 -1.0617 16.2056]



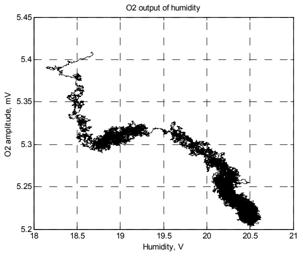
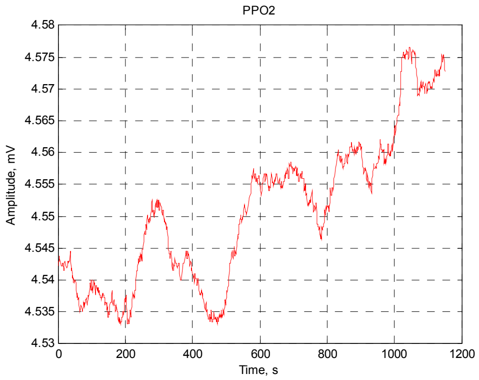
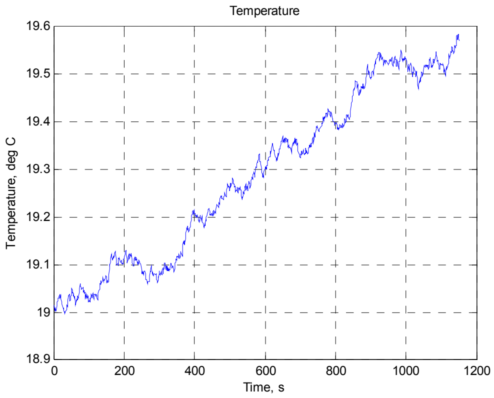


Fig 18.12-5. Sensor response on 1st day after CO2 experiment. Filter window: 50.

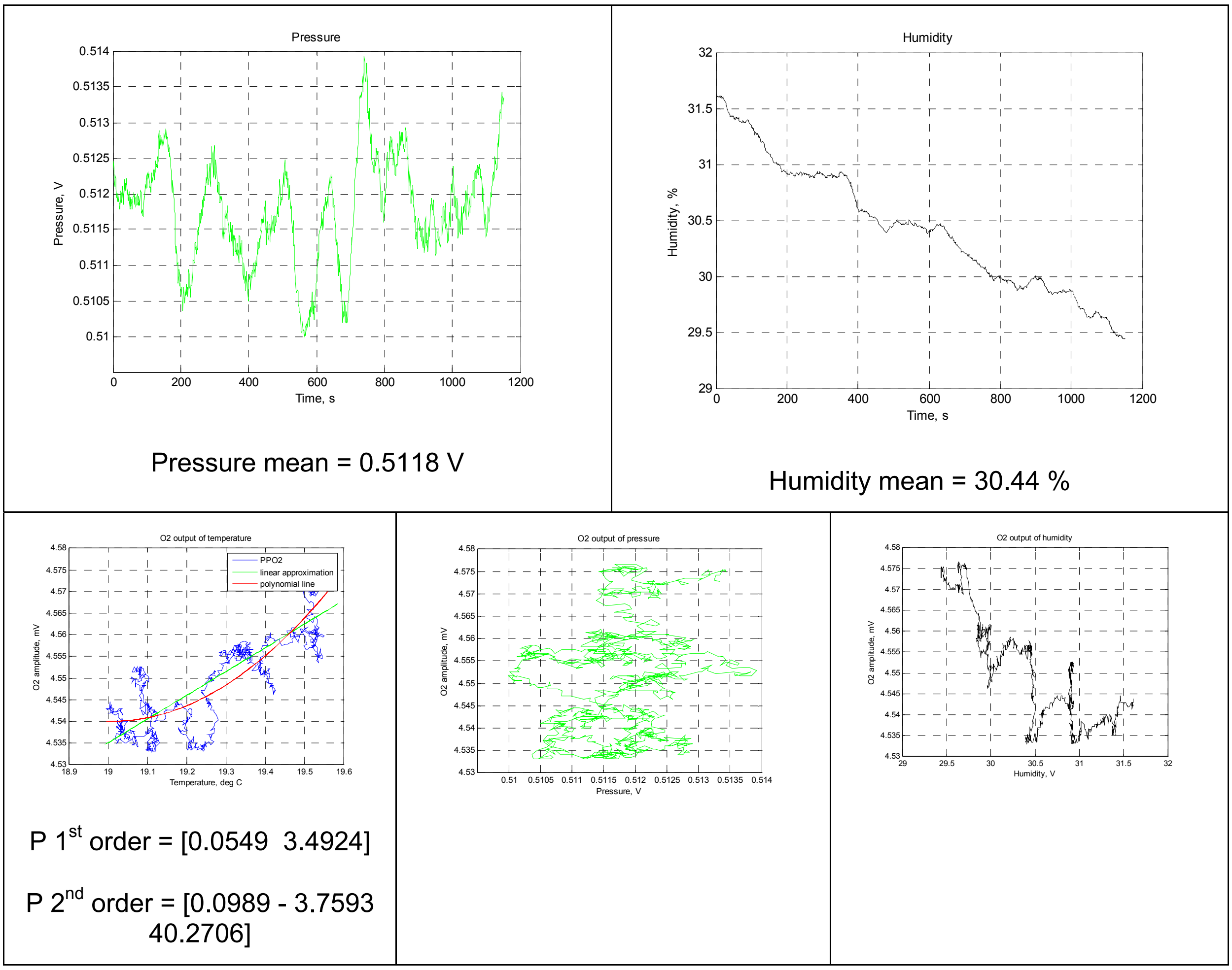
Step 8: 2nd day.



PPO2 mean = 4.55 mV



Temperature mean = 19.29 C



Pressure mean = 0.5118 V

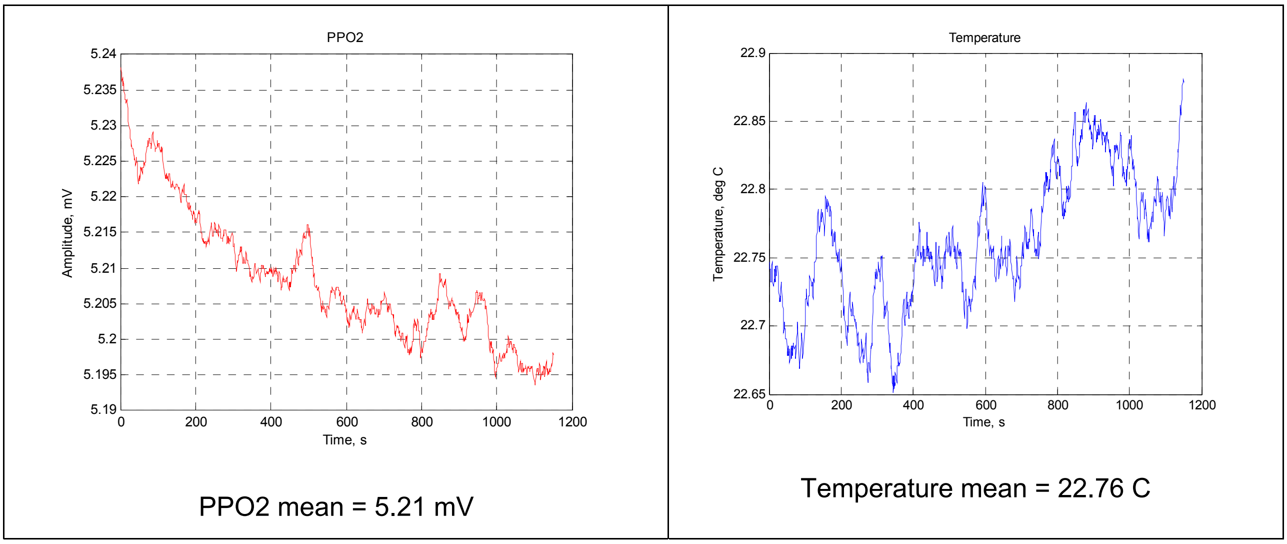
Humidity mean = 30.44 %

P 1st order = [0.0549 3.4924]

P 2nd order = [0.0989 - 3.7593 40.2706]

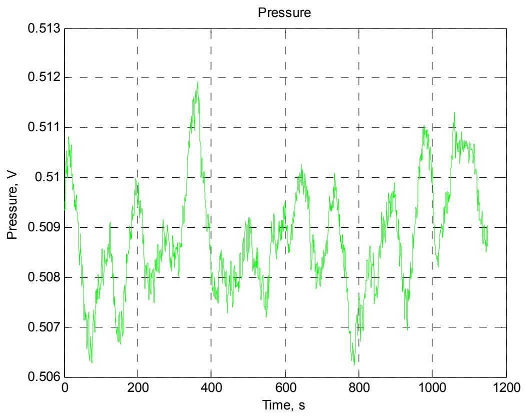
Fig 18.12-6. Sensor response on 2nd day after CO2 experiment. Filter window: 50.

Step 8: 3rd day.

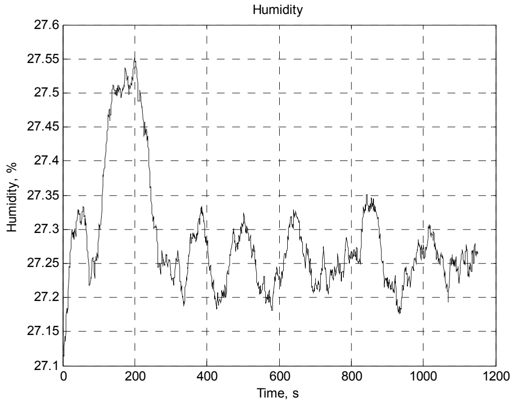


PPO2 mean = 5.21 mV

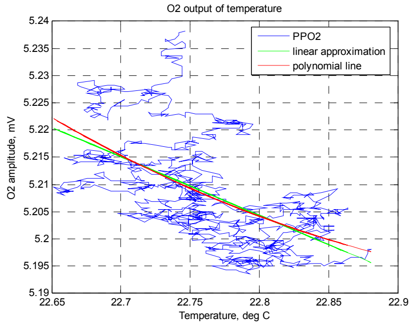
Temperature mean = 22.76 C



Pressure mean = 0.5088 V

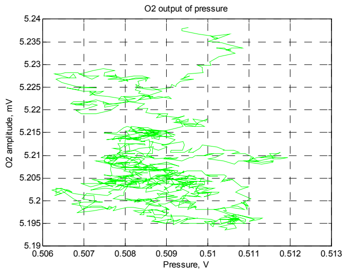


Humidity mean = 27.28%



P 1st order = [-0.1076   7.6579]

P 2nd order = [0.1764   -8.1361 99.0309]



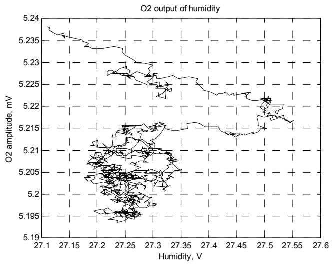
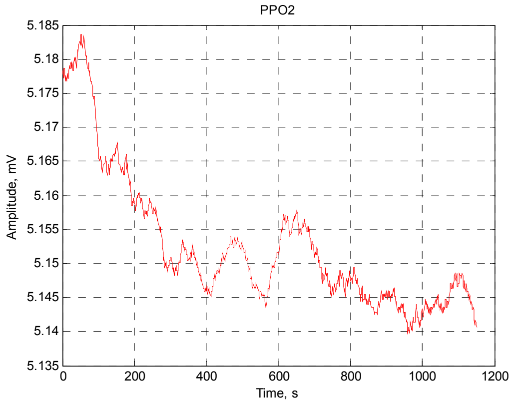
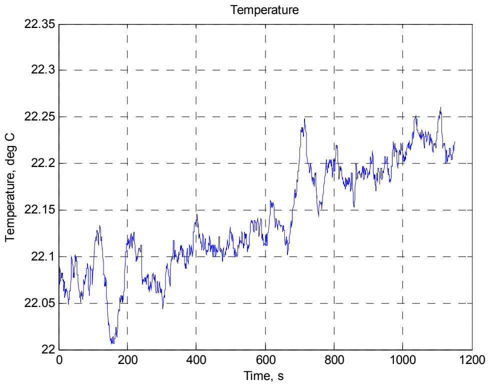


Fig 18.12-7. Sensor after 3rd day after CO2 experiment. Filter window: 50.

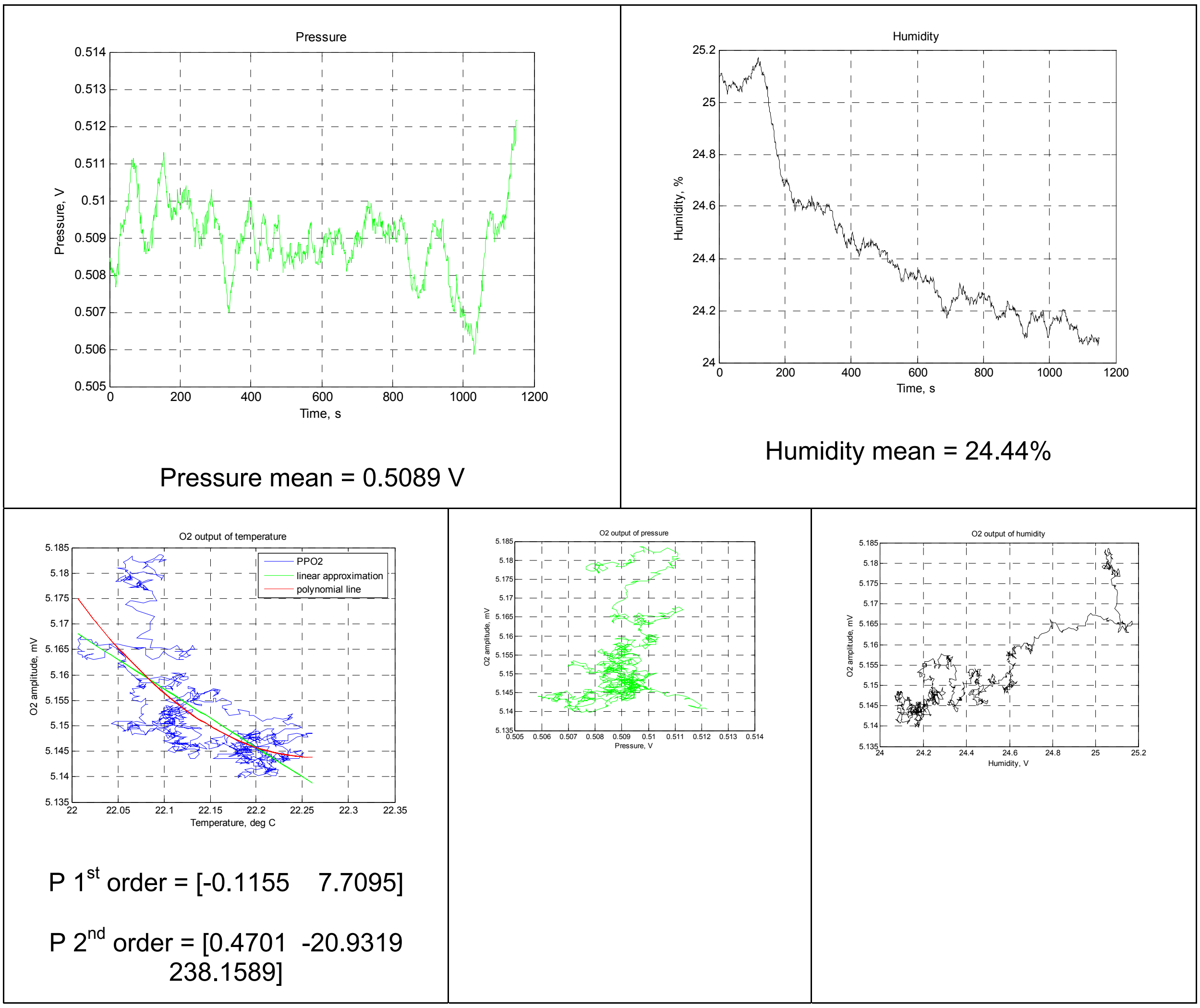
Step 8: 4th day.



PPO2 mean = 5.15 mV



Temperature mean = 22.14 C



Pressure mean = 0.5089 V

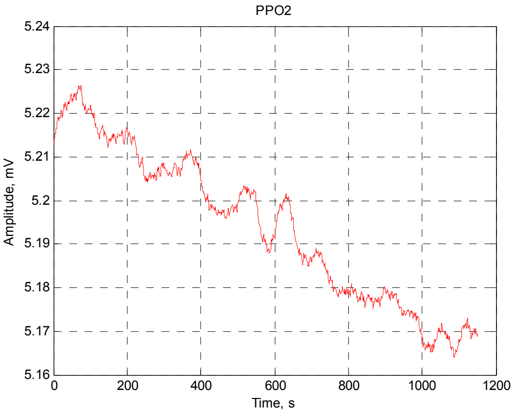
Humidity mean = 24.44%

P 1st order = [-0.1155 7.7095]

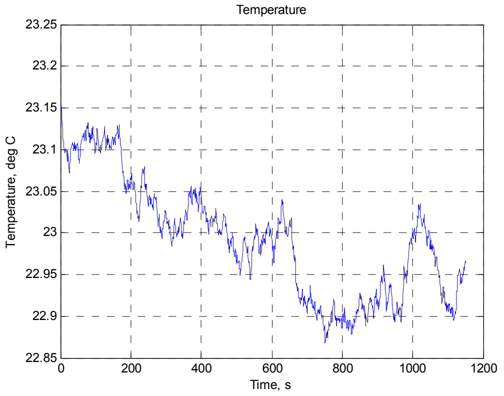
P 2nd order = [0.4701 -20.9319 238.1589]

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

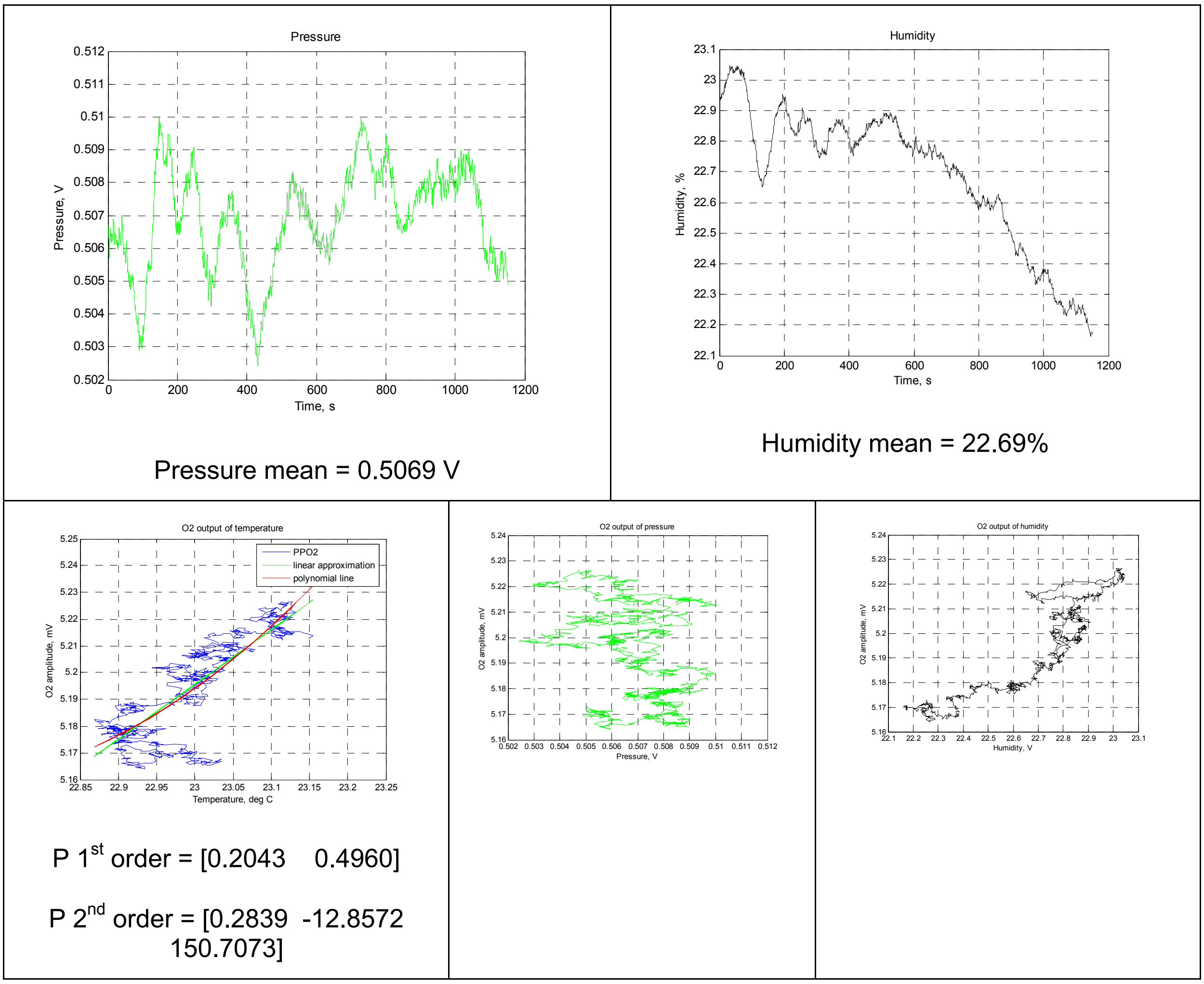
Step 8: 5th day.



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.

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 RIB 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.

The test will be repeated in a further 6 months.

18.14Test 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.

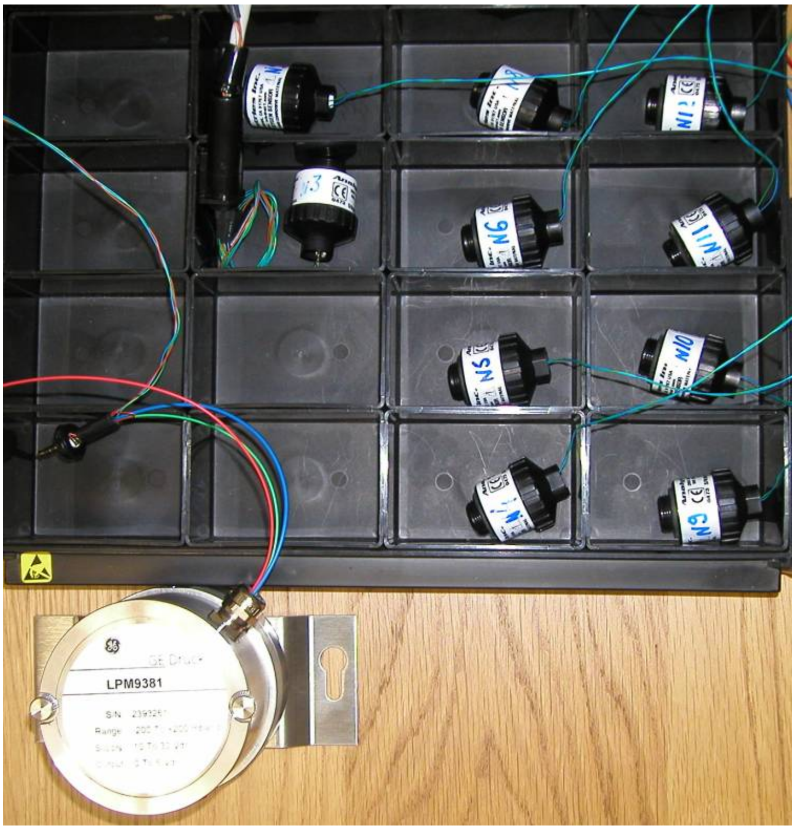
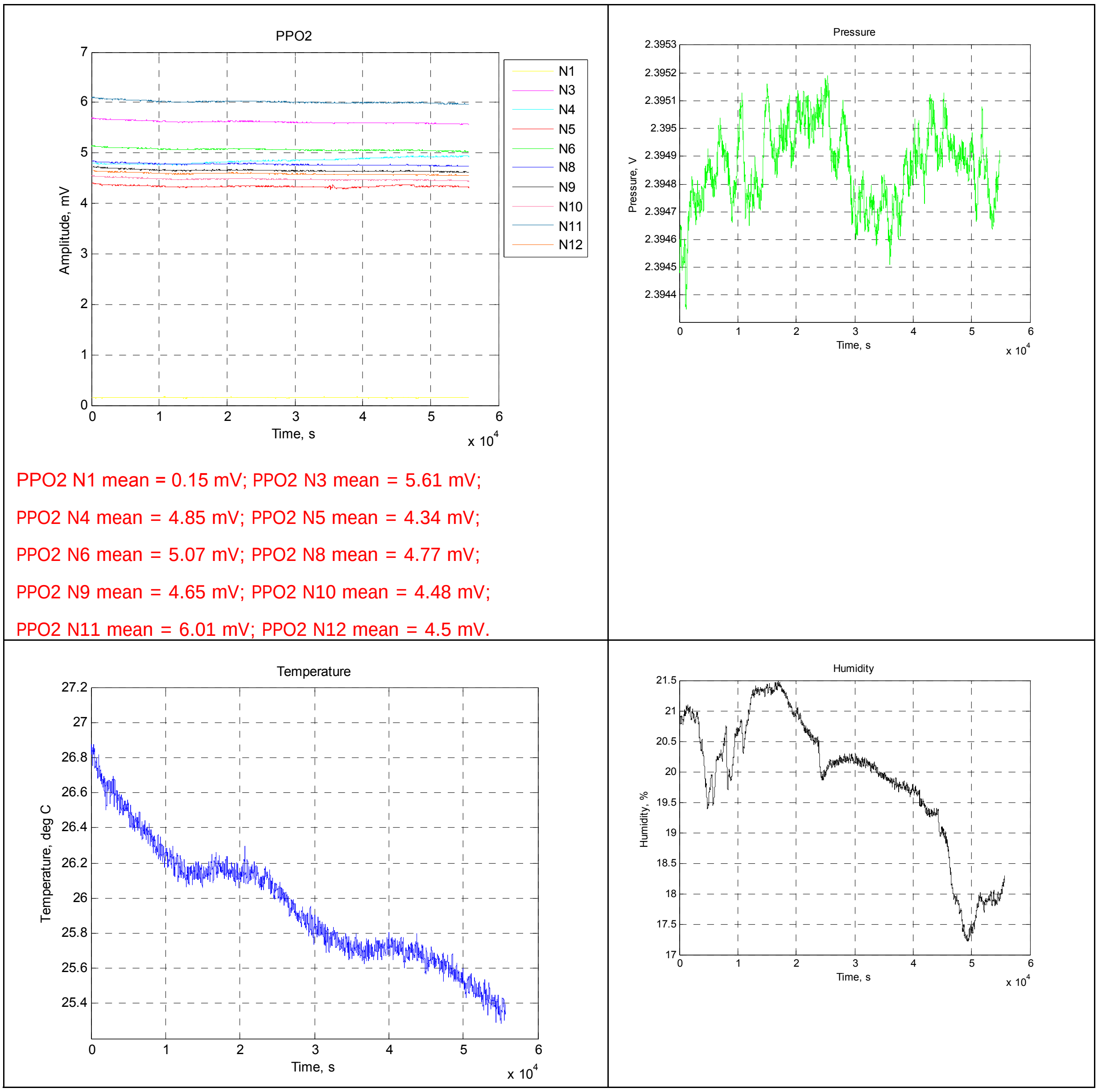


Fig 18.14-1. MDR sensors tested in air. Druck pressure sensor shown below tray. Temperature sensor is on left of tray.



PPO2 N1 mean = 0.15 mV; PPO2 N3 mean = 5.61 mV;

PPO2 N4 mean = 4.85 mV; PPO2 N5 mean = 4.34 mV;

PPO2 N6 mean = 5.07 mV; PPO2 N8 mean = 4.77 mV;

PPO2 N9 mean = 4.65 mV; PPO2 N10 mean = 4.48 mV;

PPO2 N11 mean = 6.01 mV; PPO2 N12 mean = 4.5 mV.

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.

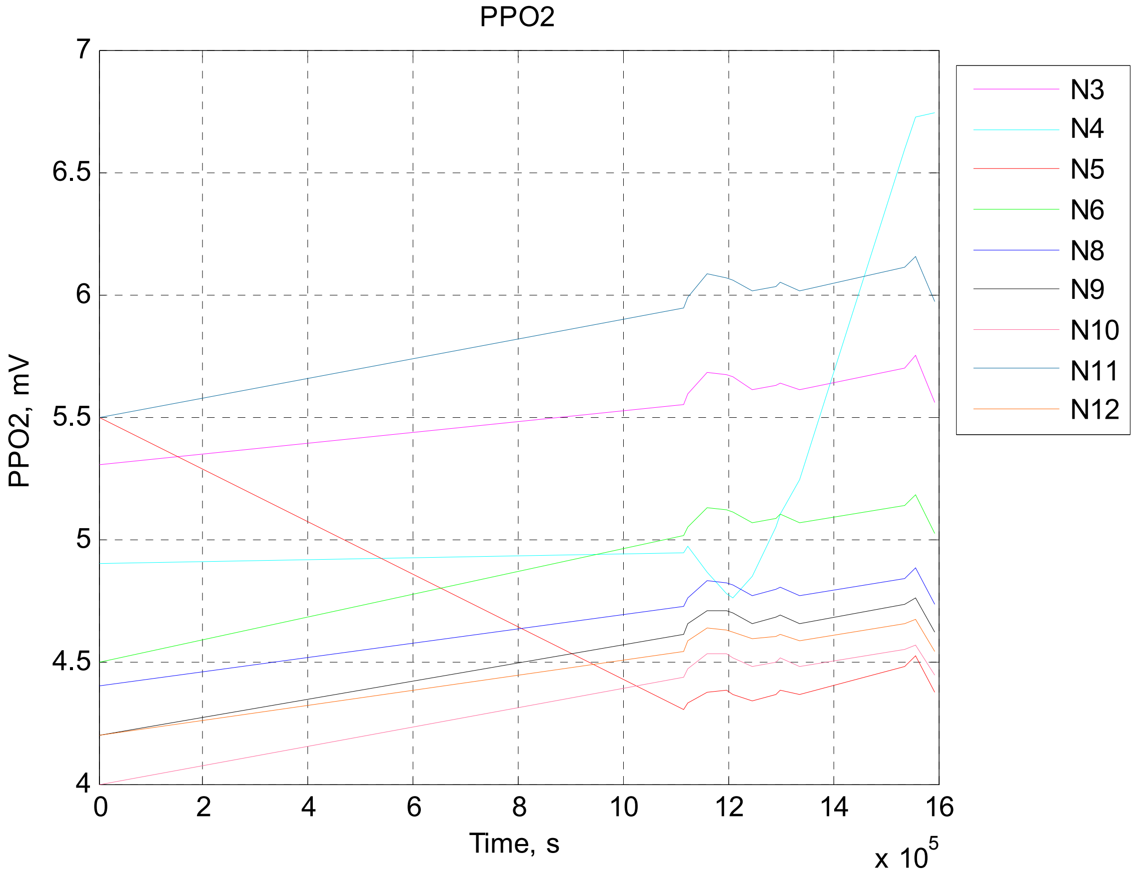


Fig 18.14-3. PPO2 averages of time during 18 days. Lines are used to connect the average points. The output of sensor 1 of 0.15 mV is not shown. Note the scale is seconds to 10^5. The general drift is due to changes in temperature and pressure: the sensors themselves are not drifting, except for those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

Date, Start	Date, finish	Temperature	Pressure	Humidity	PPO2 sensor									
					N1	N3	N4	N5	N6	N8	N9	N10	N11	N12

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.

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

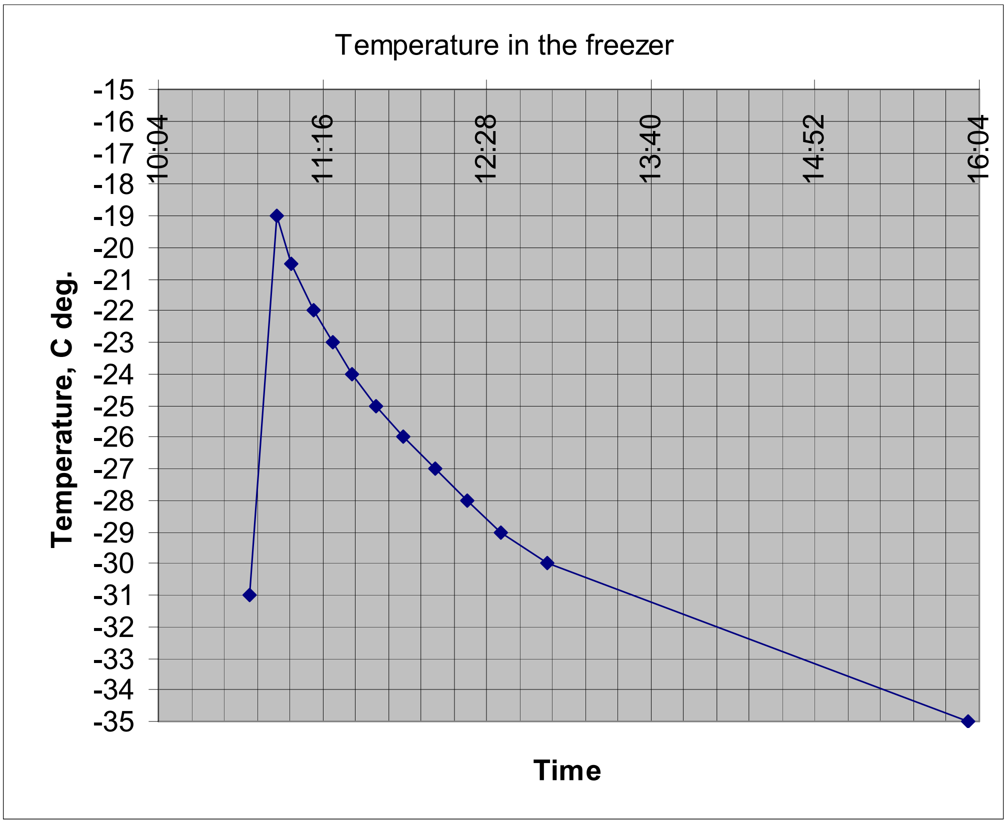


Fig 18.16-3. Temperature after putting the units into the freezer. Total time of the test was 5 hours 15 minutes including 2hours and 15 minutes for getting below -30 C.

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.

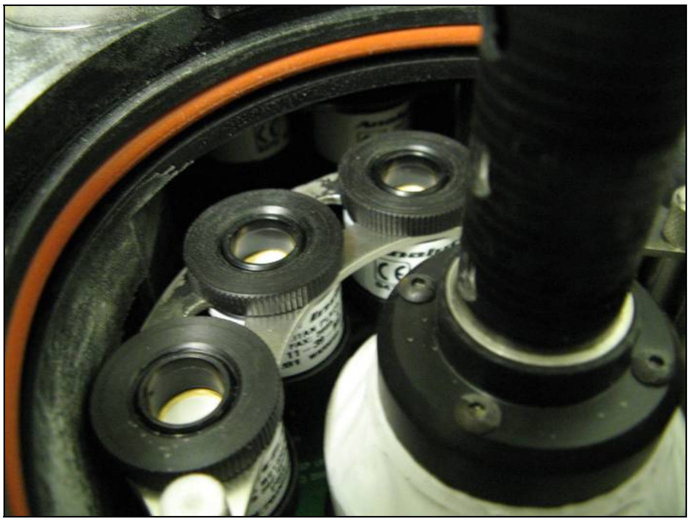
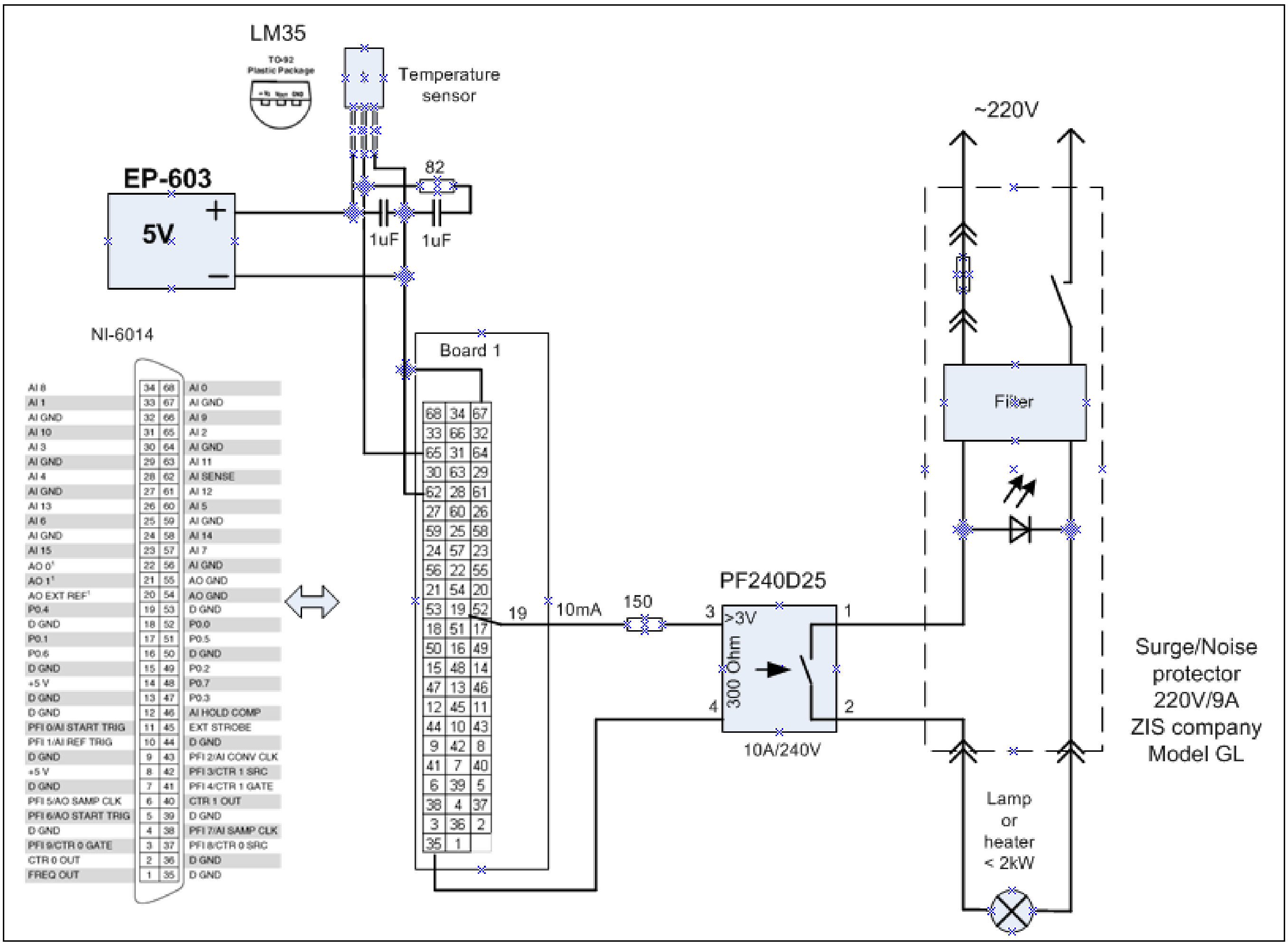


Fig 18.16-7. PPO2 cells after the cold test.

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.



AI 8	34	68	AI 0
AI 1	33	67	AI GND
AI GND	32	66	AI 9
AI 10	31	65	AI 2
AI 3	30	64	AI GND
AI GND	29	63	AI 11
AI 4	28	62	AI SENSE
AI GND	27	61	AI 12
AI 13	26	60	AI 5
AI 6	25	59	AI GND
AI GND	24	58	AI 14
AI 15	23	57	AI 7
AO 0[1]	22	56	AI GND
AO 1[1]	21	55	AO GND
AO EXT REF[1]	20	54	AO GND
P0.4	19	53	D GND
D GND	18	52	P0.0
P0.1	17	51	P0.5
P0.6	16	50	D GND
D GND	15	49	P0.2
+5 V	14	48	P0.7
D GND	13	47	P0.3
D GND	12	46	AI HOLD COMP
PFI 0/AI START TRIG	11	45	EXT STROBE
PFI 1/AI REF TRIG	10	44	D GND
D GND	9	43	PFI 2/AI CONV CLK
+5 V	8	42	PFI 3/CTR 1 SRC
D GND	7	41	PFI 4/CTR 1 GATE
PFI 5/AO SAMP CLK	6	40	CTR 1 OUT
PFI 6/AO START TRIG	5	39	D GND
D GND	4	38	PFI 7/AI SAMP CLK
PFI 9/CTR 0 GATE	3	37	PFI 8/CTR 0 SRC
CTR 0 OUT	2	36	D GND
FREQ OUT	1	35	D GND

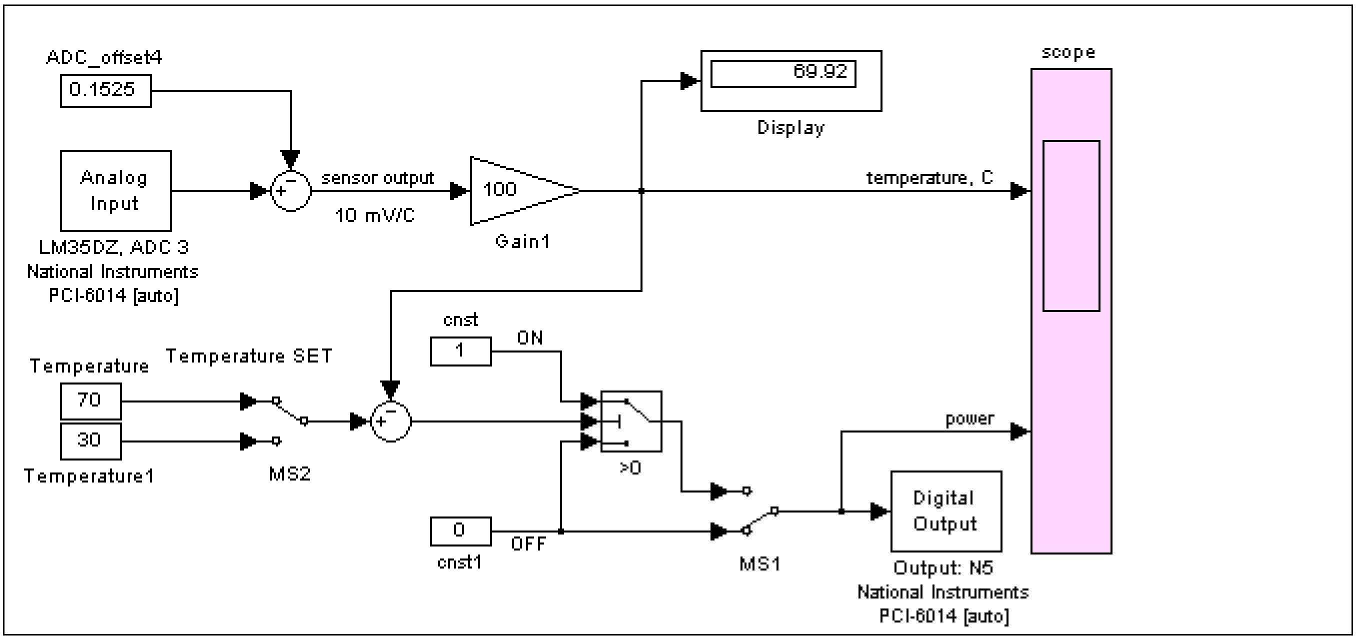


Fig 18.16-8. Structure of the temperature control system for the hot soak test.

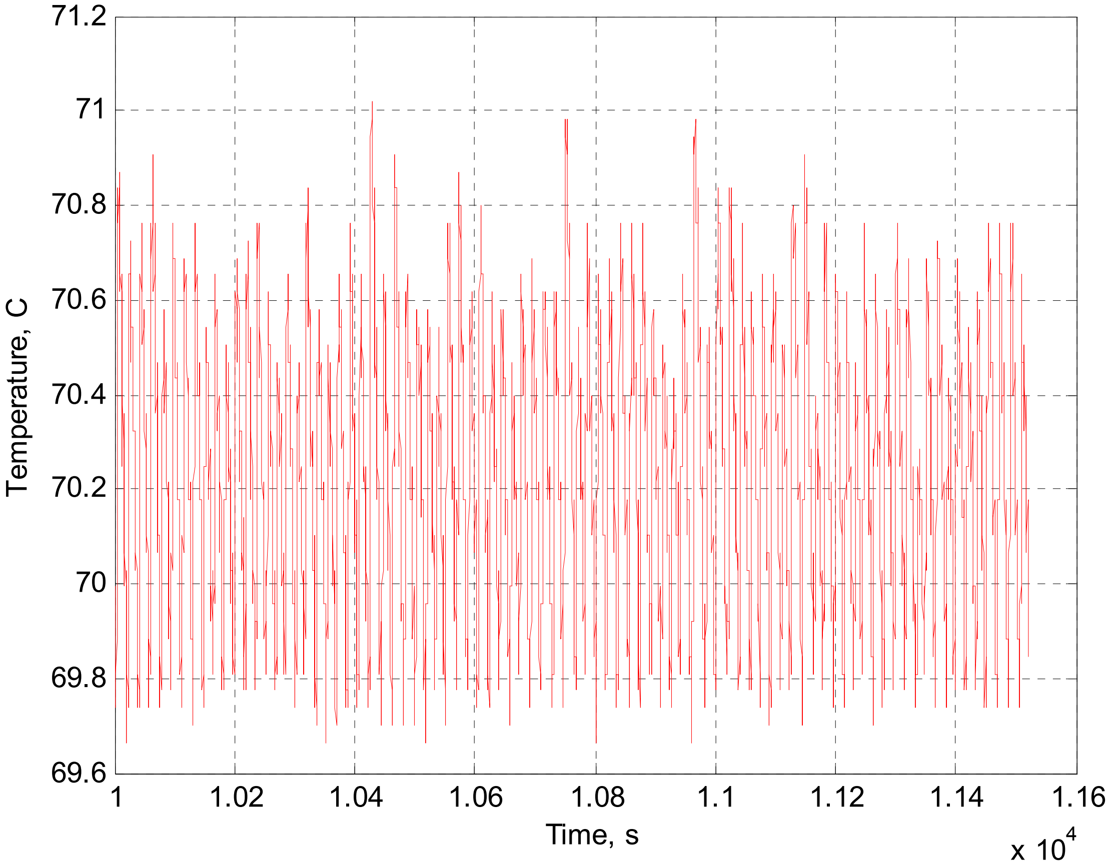


Fig 18.16-9. The temperature during the 3 hour hot soak test.

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

Table 2. 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%

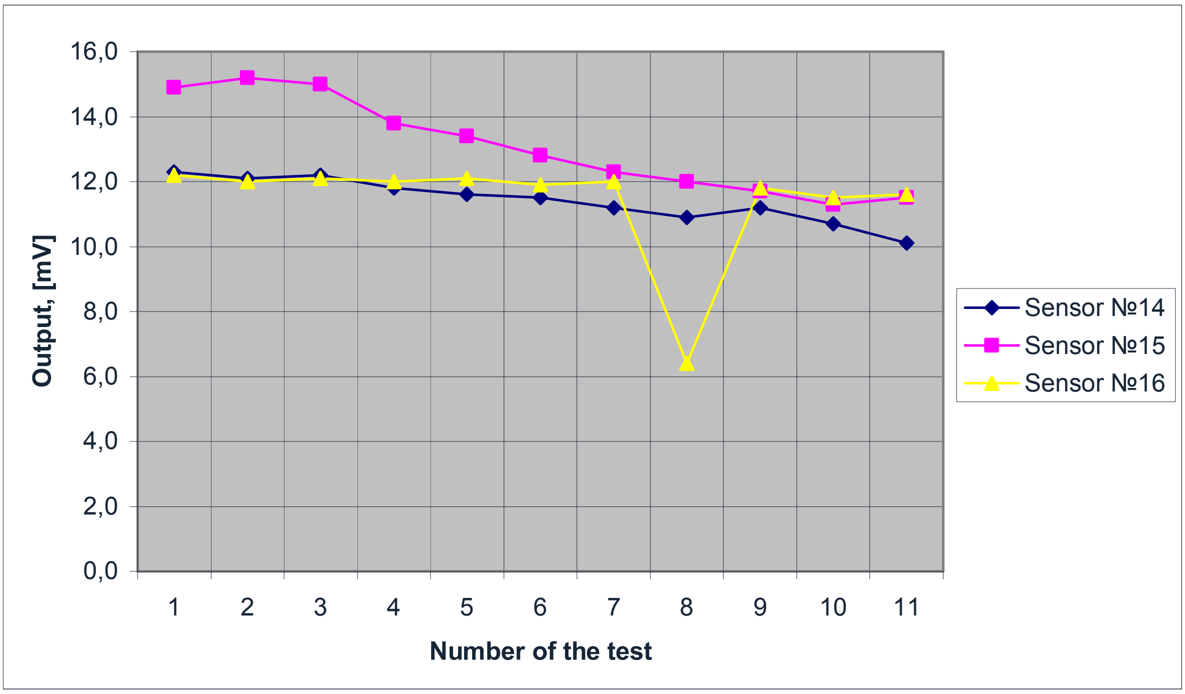


Fig 18.18-1: PPO2 sensor output at 1.5m drop tests.

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%

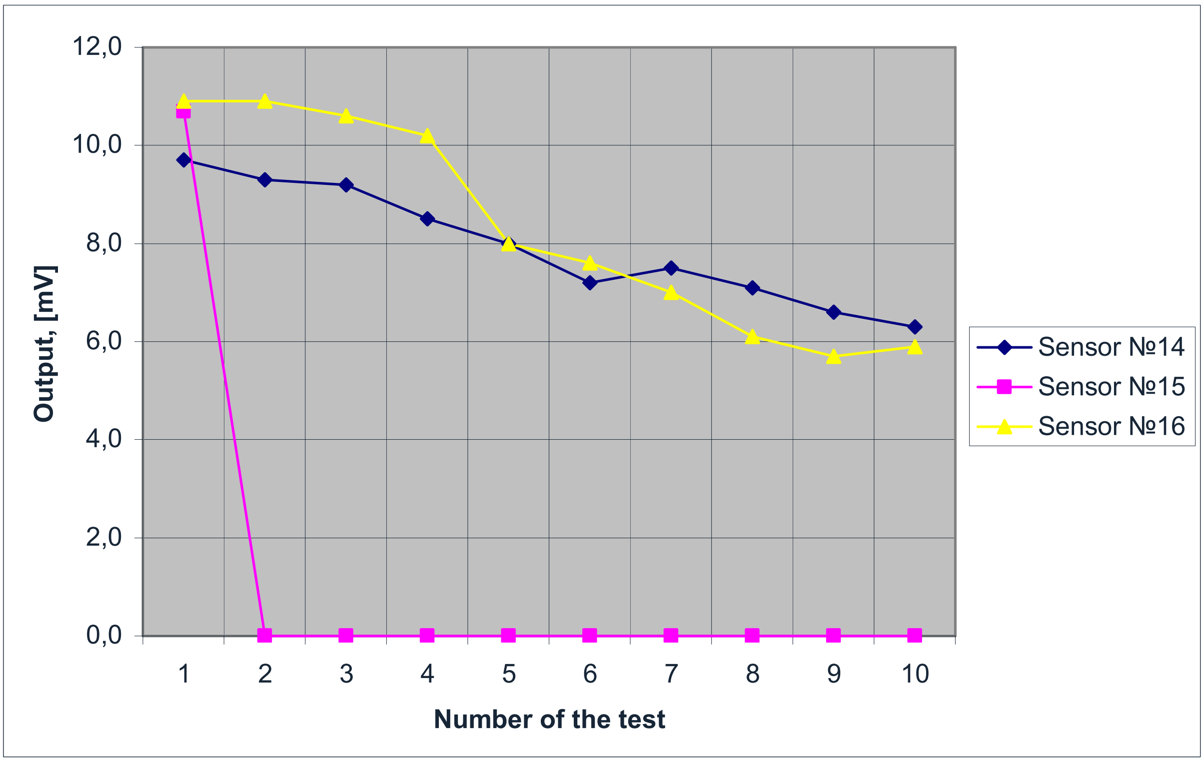


Fig 18.18-2: PPO2 sensor output with 3m drop tests.

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

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.

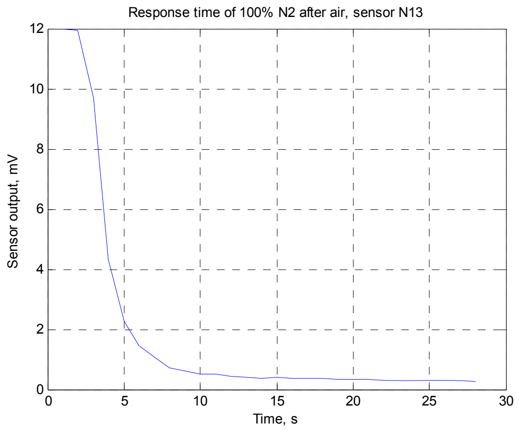
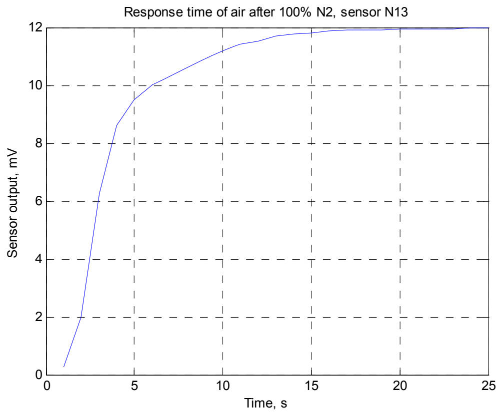
Sensors 14 and 16 both have a 'knocking' noise when shaken after the 3m drop test. Sensor 16 has no visible damage, unlike sensor 14, which has a small dent near the connector hole (Fig 18.18-4).

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

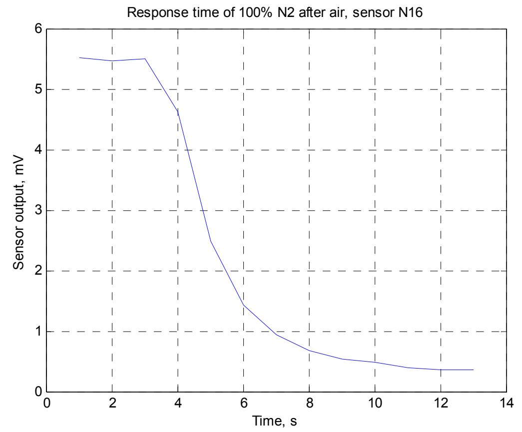
18.18 Response time after environmental tests

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)

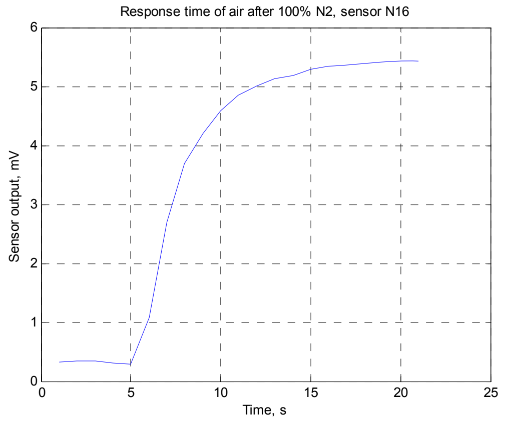
 from air into 100%N2	 from 100%N2 into air Response is 9 s

Response is 7 s



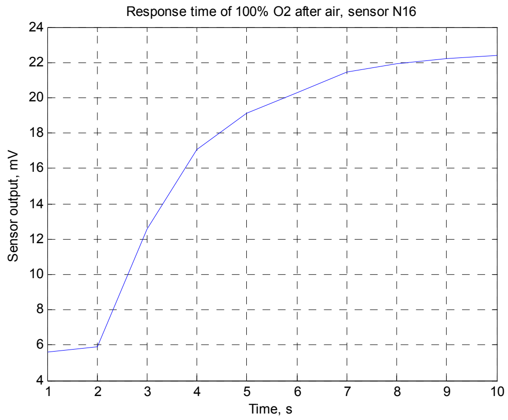
from air into 100%N2

Response is 6 s



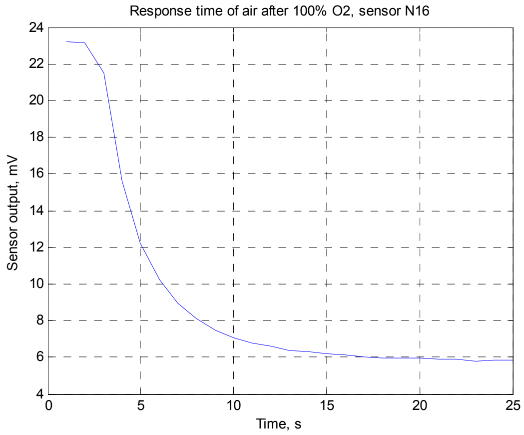
from 100%N2 into air

Response is 9 s



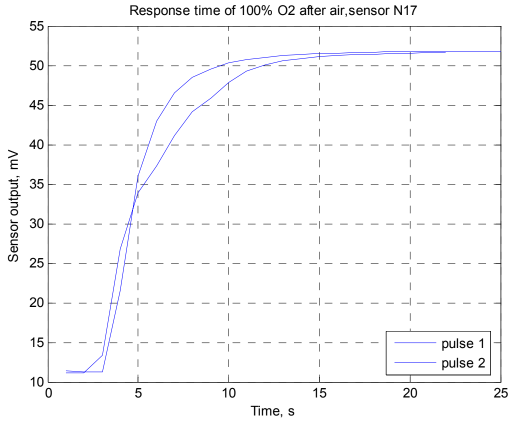
from air into 100%O2

Response time is 6 s



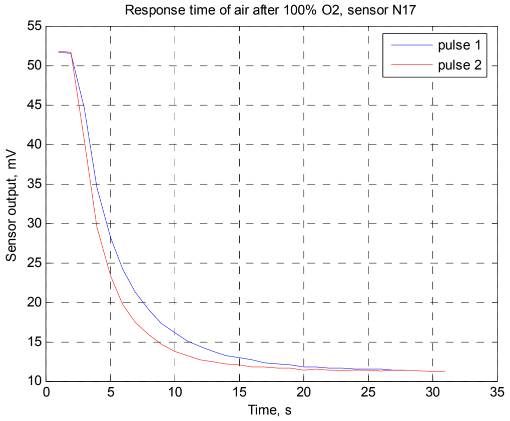
from 100%O2 into air

Response time is 9 s



from air into 100%O2

Response time is 7 s



from 100%O2 into air

Response time is 9 s

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

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 passed -30C and +70C storage tests and 1.5m and 3m drop tests. Sensor output before the test was 6.4mV. During the test the pH was measured with Litmus paper: it should be a pH of 12 to 14.

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 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.

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.

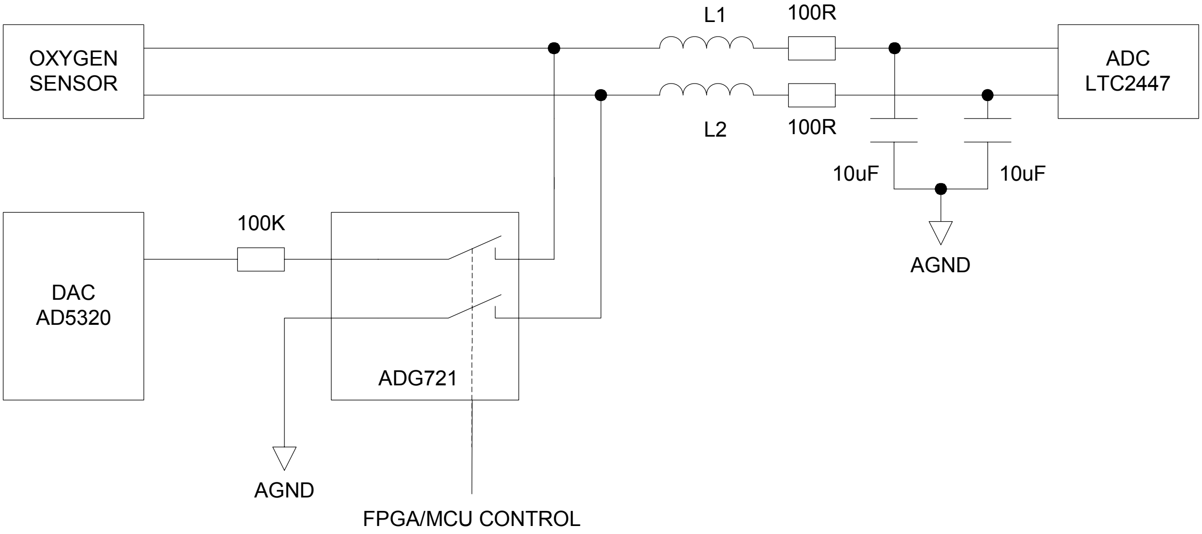


Fig 18.21-1: DAC circuit used to screen O2 sensors in all safety critical applications designed by Deep Life Ltd.

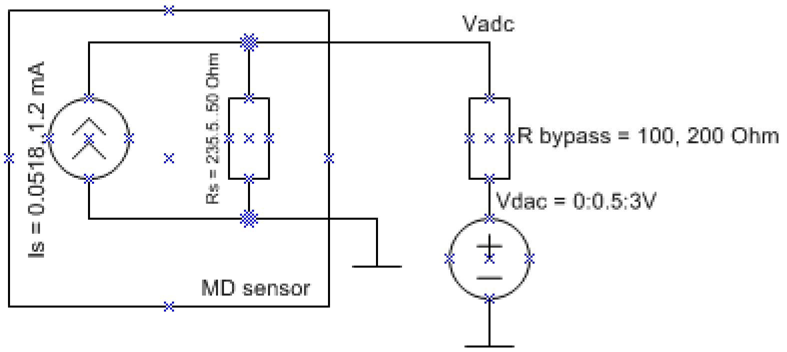


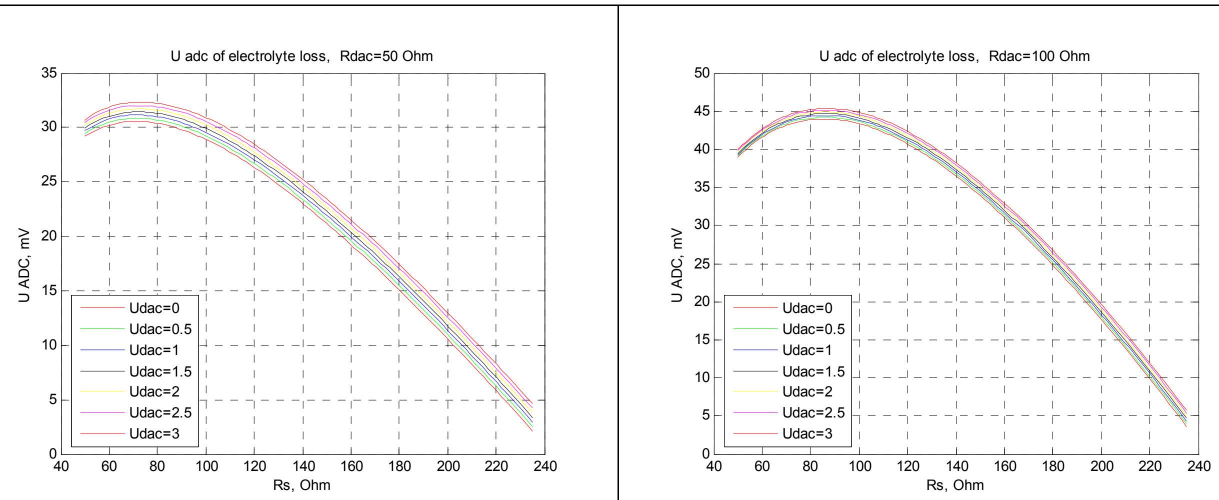
Fig 18.21-2: Sensor impedance test circuit.

Table 3. 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	

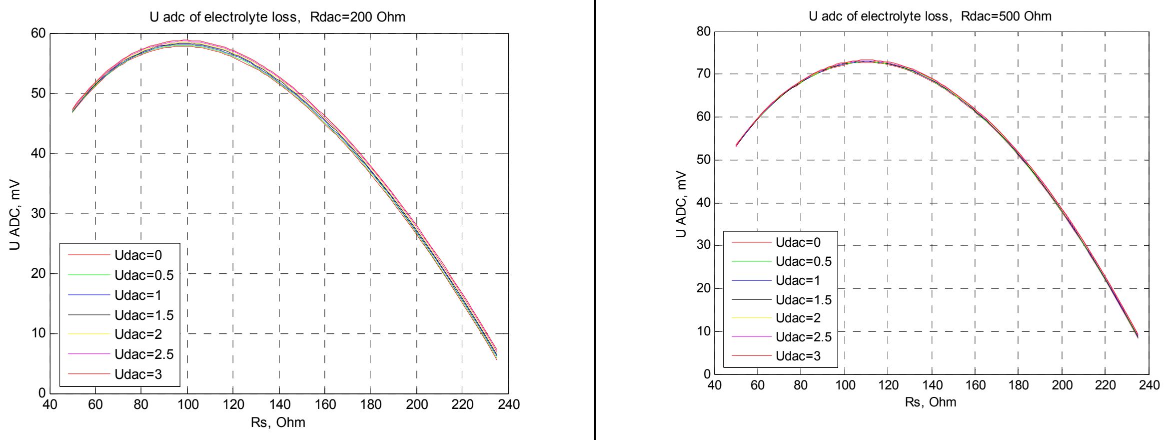
Table 4. Sensor test and calculated parameters

	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



R bypass = 50 Ohm

R bypass = 100 Ohm



R bypass = 200 Ohm

R bypass = 500 Ohm

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

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.

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.

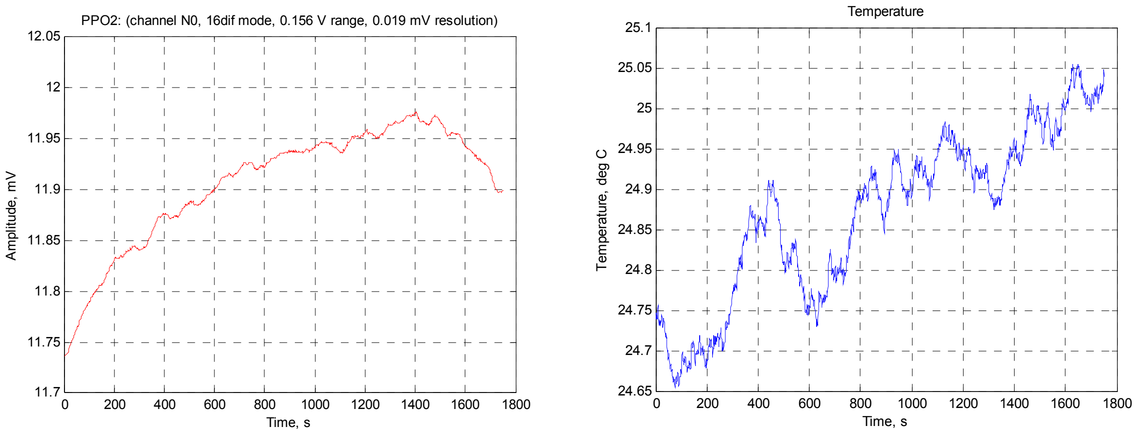


Fig 19.4-2. Cell output and temperature after water bath. Filter window is 50. PPO2 mean = 11.90 mV. Temperature mean = 24.87 °C. Output change is 0.34% (less than1%).

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.

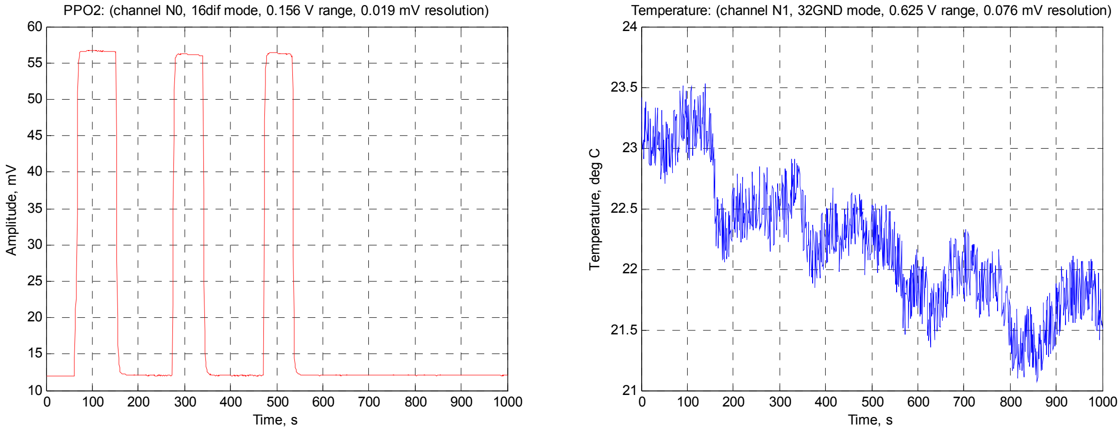


Fig 19.5-1. Step 2. Filter window = 0.

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

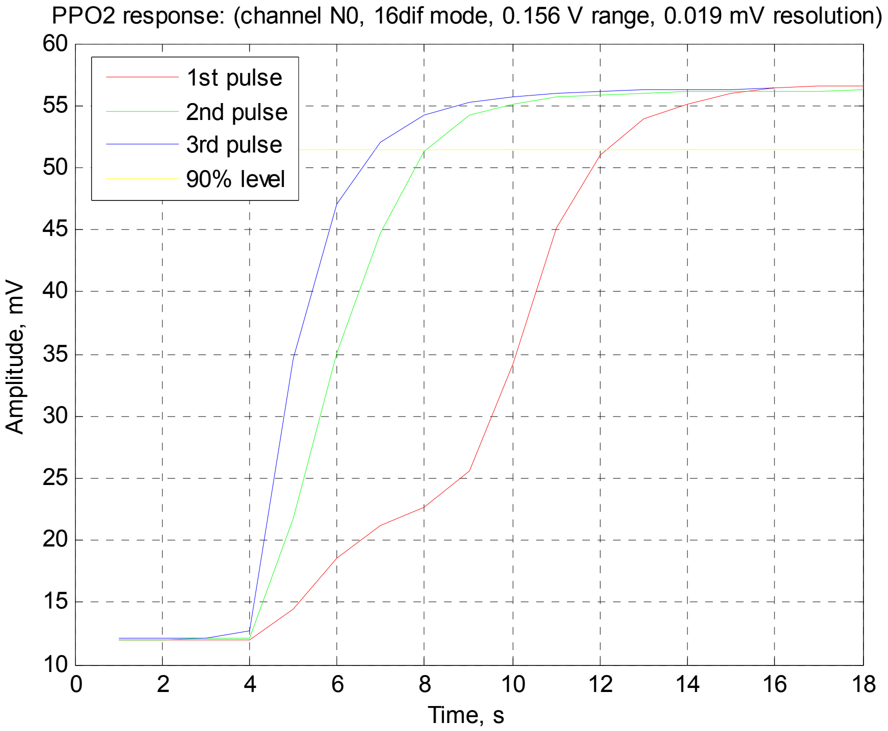


Fig 19.5-2. It seems that the less steep start of the red plot is due to a slow O2 flow. Rise time response is otherwise 4 to 6 seconds. The sensor output is 57 mV when the sensor is in 100% O2.

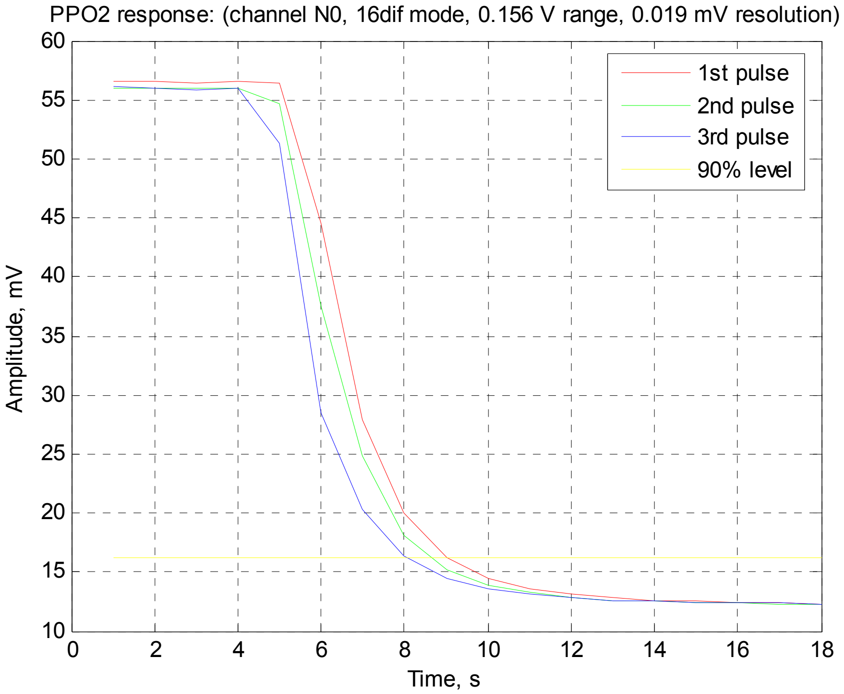
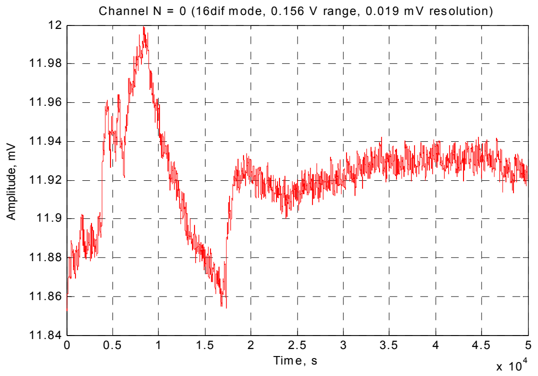


Fig 19.5-3. Fall response is 5 s (less than 10 s).

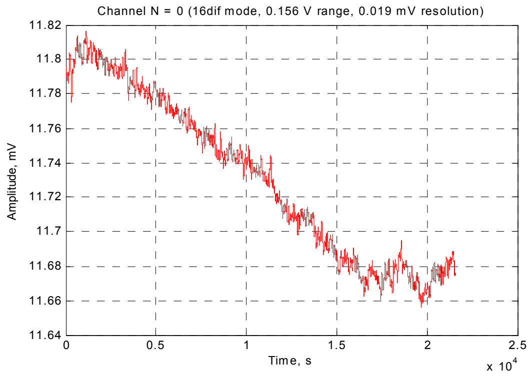
19.6 Test 5b Stability

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

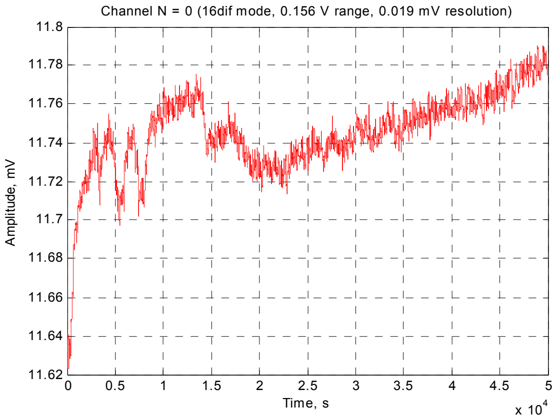
Steps 2 and 3, Sensor 2: Measure the output voltage with a 10K load. Record atmospheric pressure, temperature and humidity.



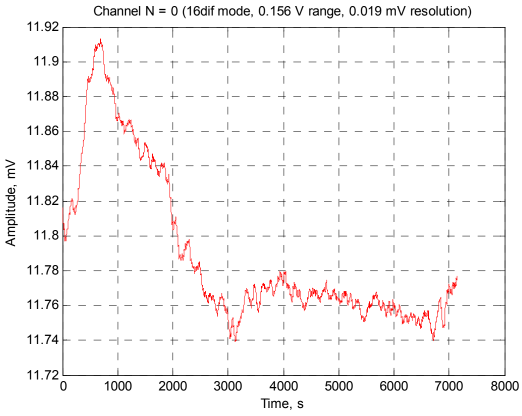
PPO2 mean = 11.92 mV



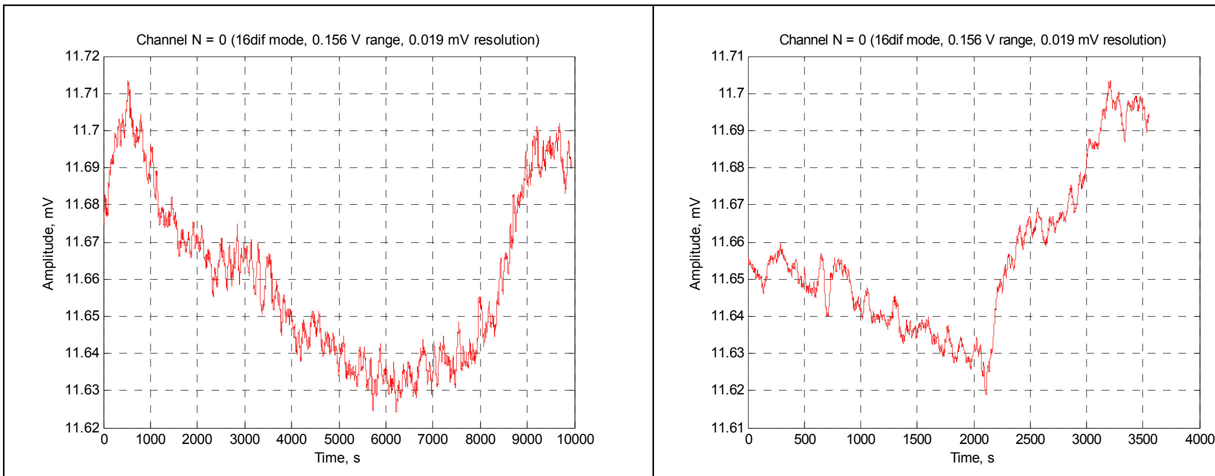
PPO2 mean = 11.73 mV



PPO2 mean = 11.74 mV

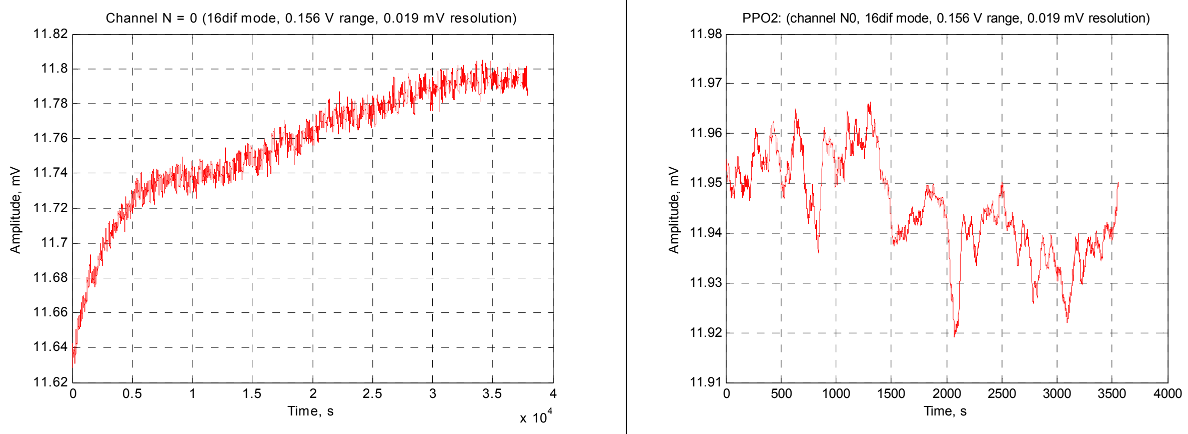


PPO2 mean = 11.79 mV



PPO2 mean = 11.66 mV

PPO2 mean = 11.66 mV

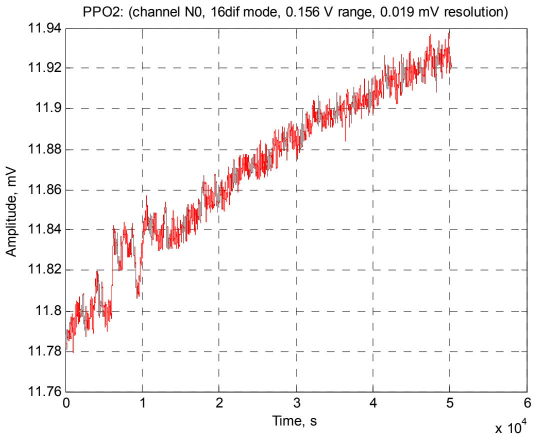


PPO2 mean = 11.76 mV

PPO2 mean = 11.95 mV

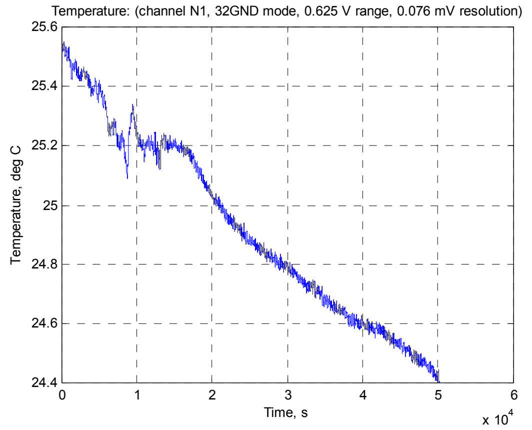
Fig 19.6-1. Stability of the two sample MD sensors under laboratory conditions, exploring dependency on small scale changes in pressure and humidity. The method of waiting until there is sufficient change in other parameters to allow the correlation between each parameter change and the cell output to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

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

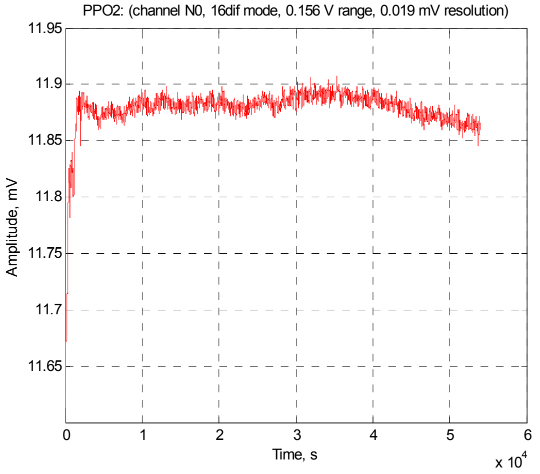


PPO2 mean = 11.87 mV

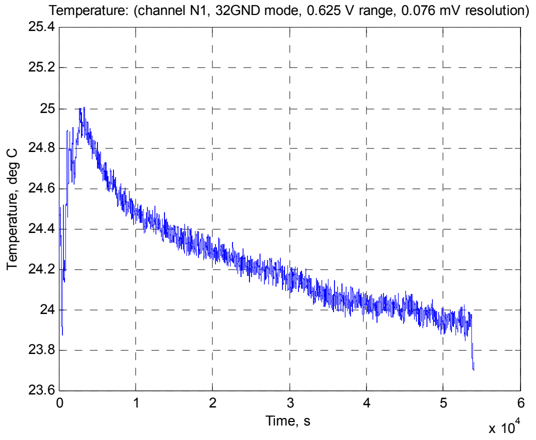
-0.14 mV/K



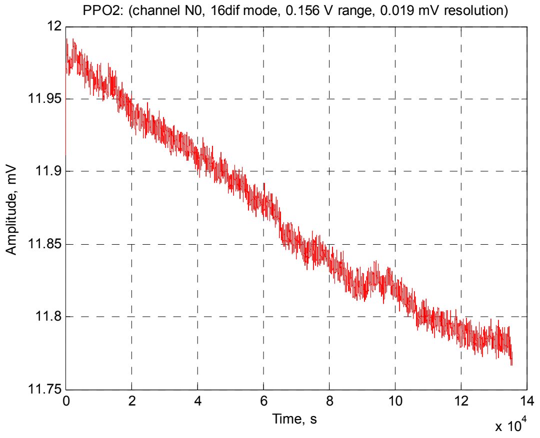
Temperature mean = 24.92 C



PPO2 mean = 11.88 mV

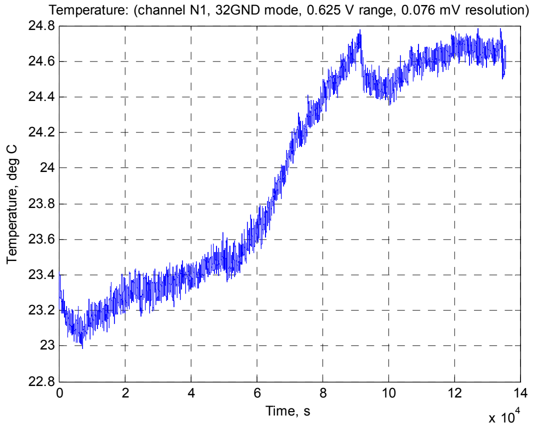


Temperature mean = 24.25 C

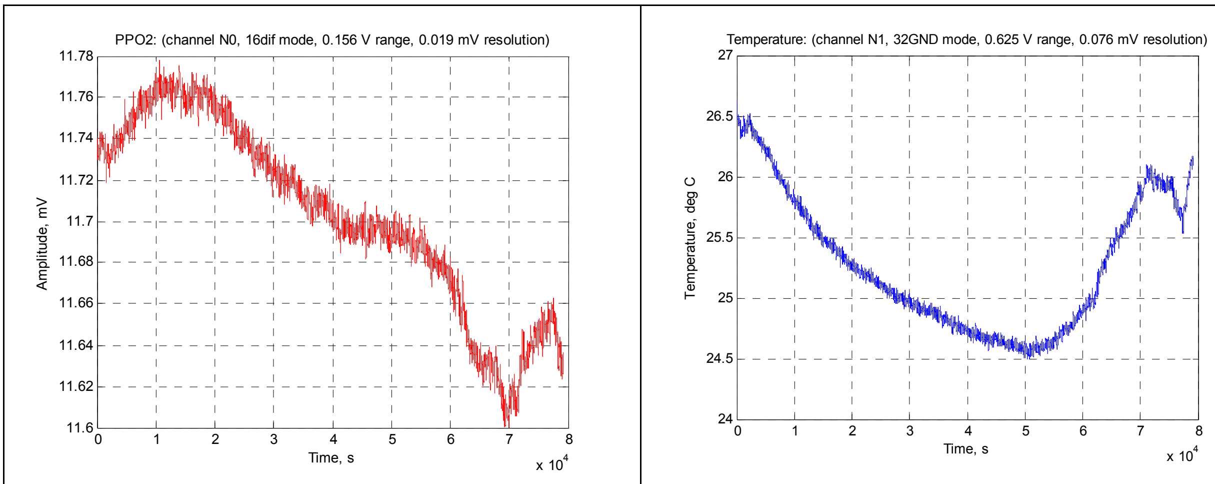


PPO2 mean = 11.87 mV

+0.12 mV/K



Temperature mean = 23.95 C



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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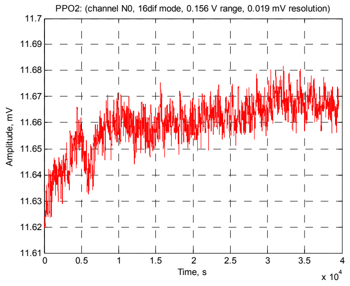
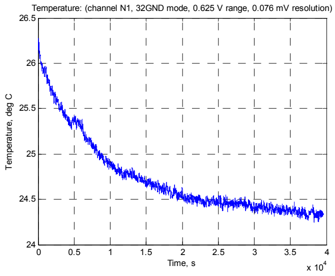
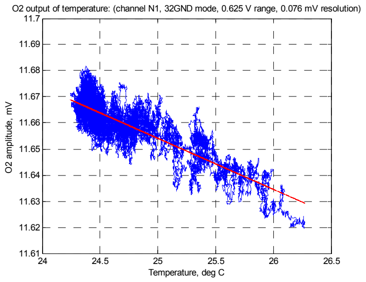


PPO2 mean = 11.66 mV

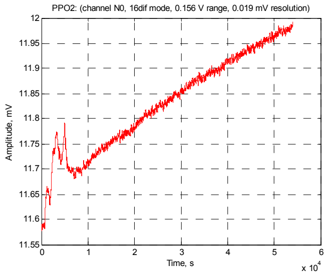


Mean = 24.73 C

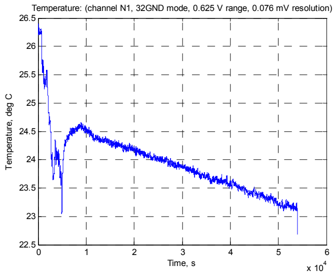


p = [-0.019545 12.143]

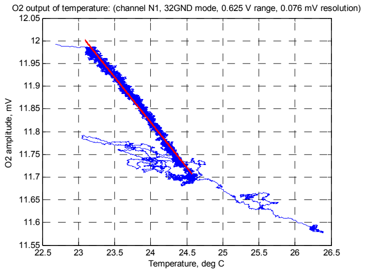
ΔPPO2=-0.019545mV/ΔC



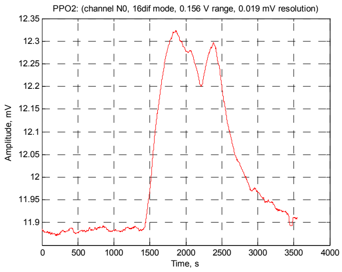
PPO2 mean = 11.83 mV



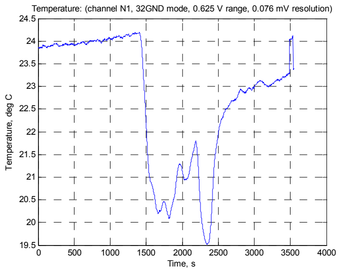
Mean = 23.95 C



p = [-0.1990 16.5972]

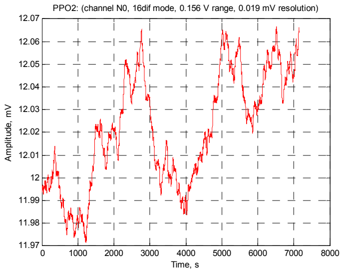


PPO2 mean = 12.01 mV

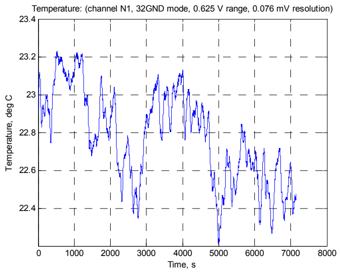


Mean = 22.76 C

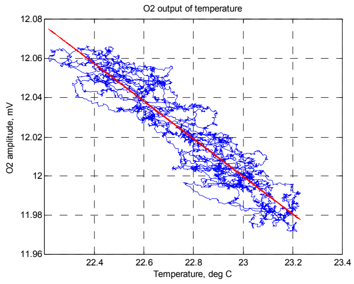
← O2 sensor inversely tracks the temperature change



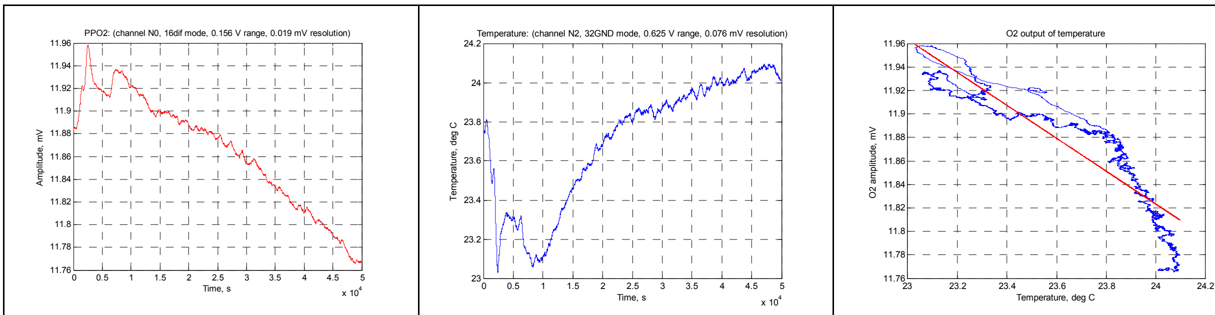
PPO2 mean = 12.02 mV



Mean = 22.78 C



p = [-0.0961 14.2090]



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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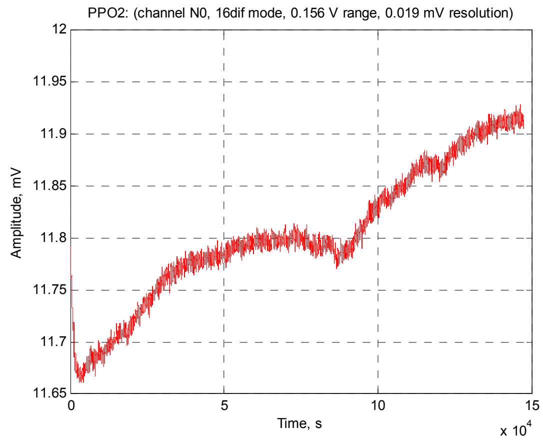
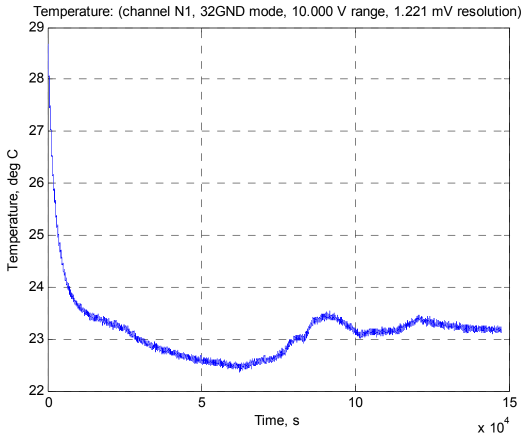
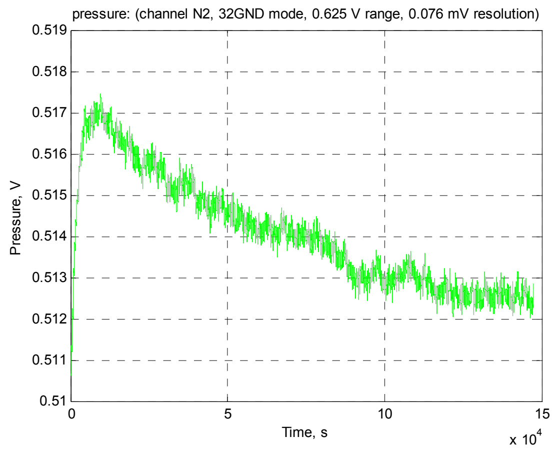


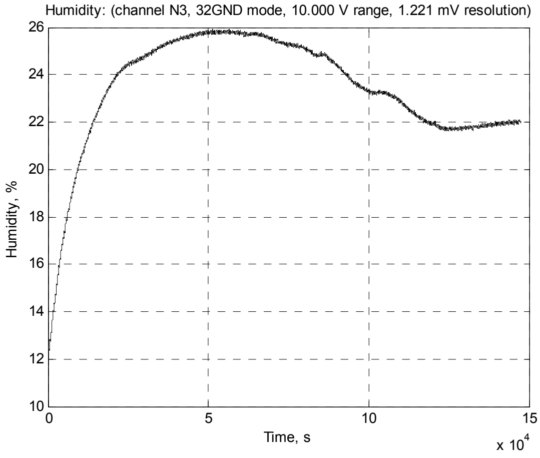
PPO2 mean = 11.8 mV



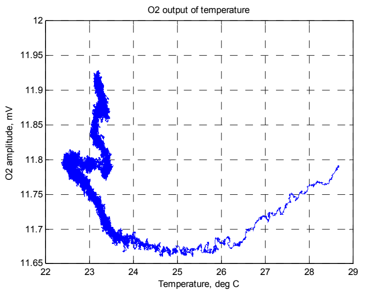
Temperature mean = 23.16 C

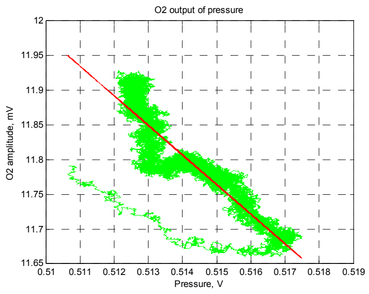


Pressure mean = 0.51 V



Humidity = 23.39%





p = [-42.6914 33.7502]

-0.43 mV/bar

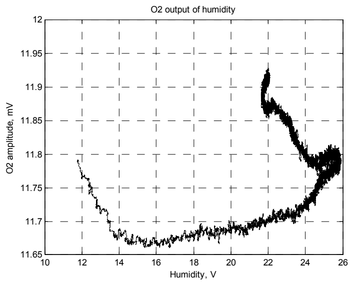
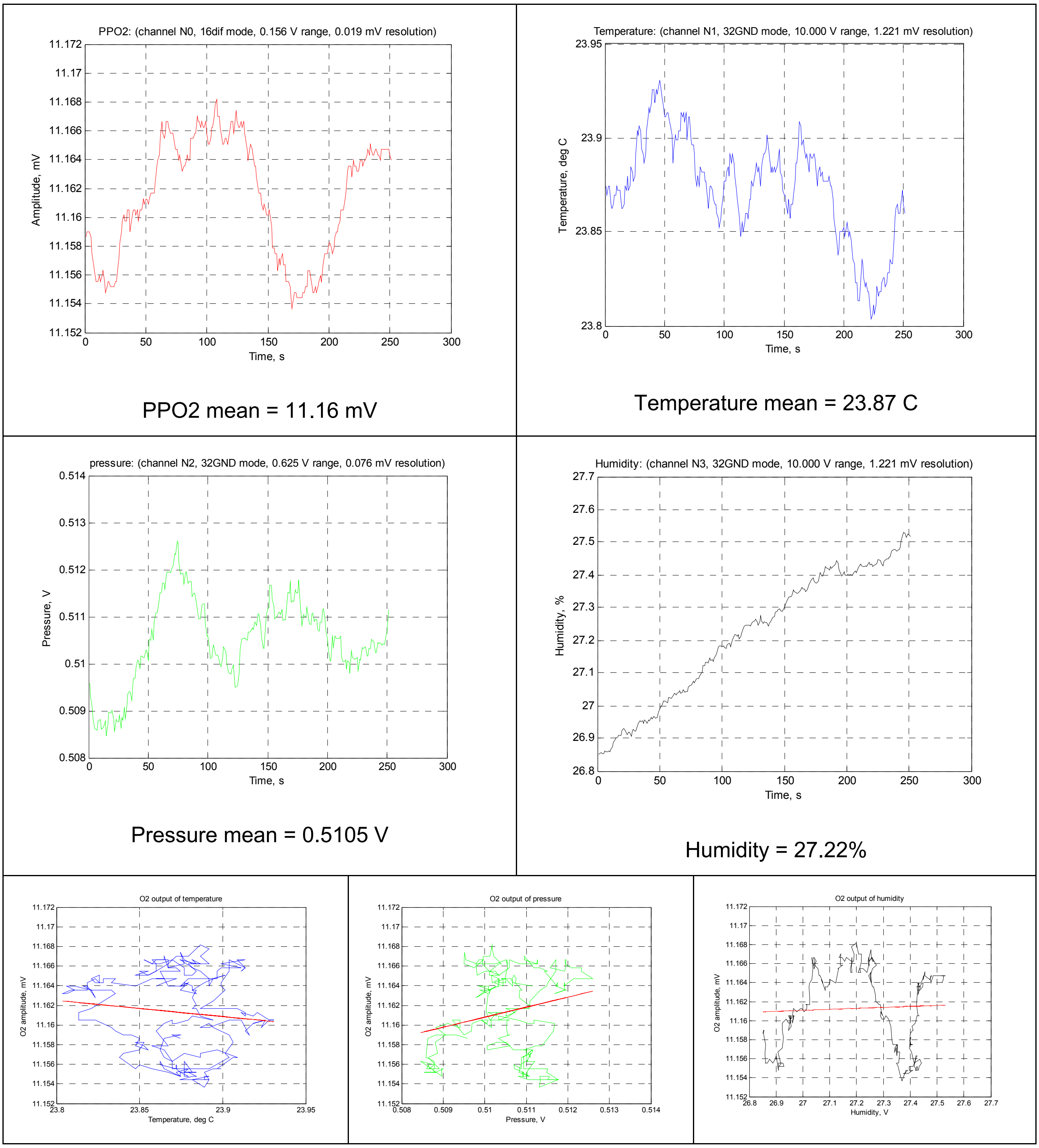


Fig 19.6-4. Sensor stability. When the temperature and humidity are constant, the oxygen sensor output is inversely proportional to the pressure as a linear function of -0.43 mV/bar.



PPO2 mean = 11.16 mV

Temperature mean = 23.87 C

Pressure mean = 0.5105 V

Humidity = 27.22%

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.

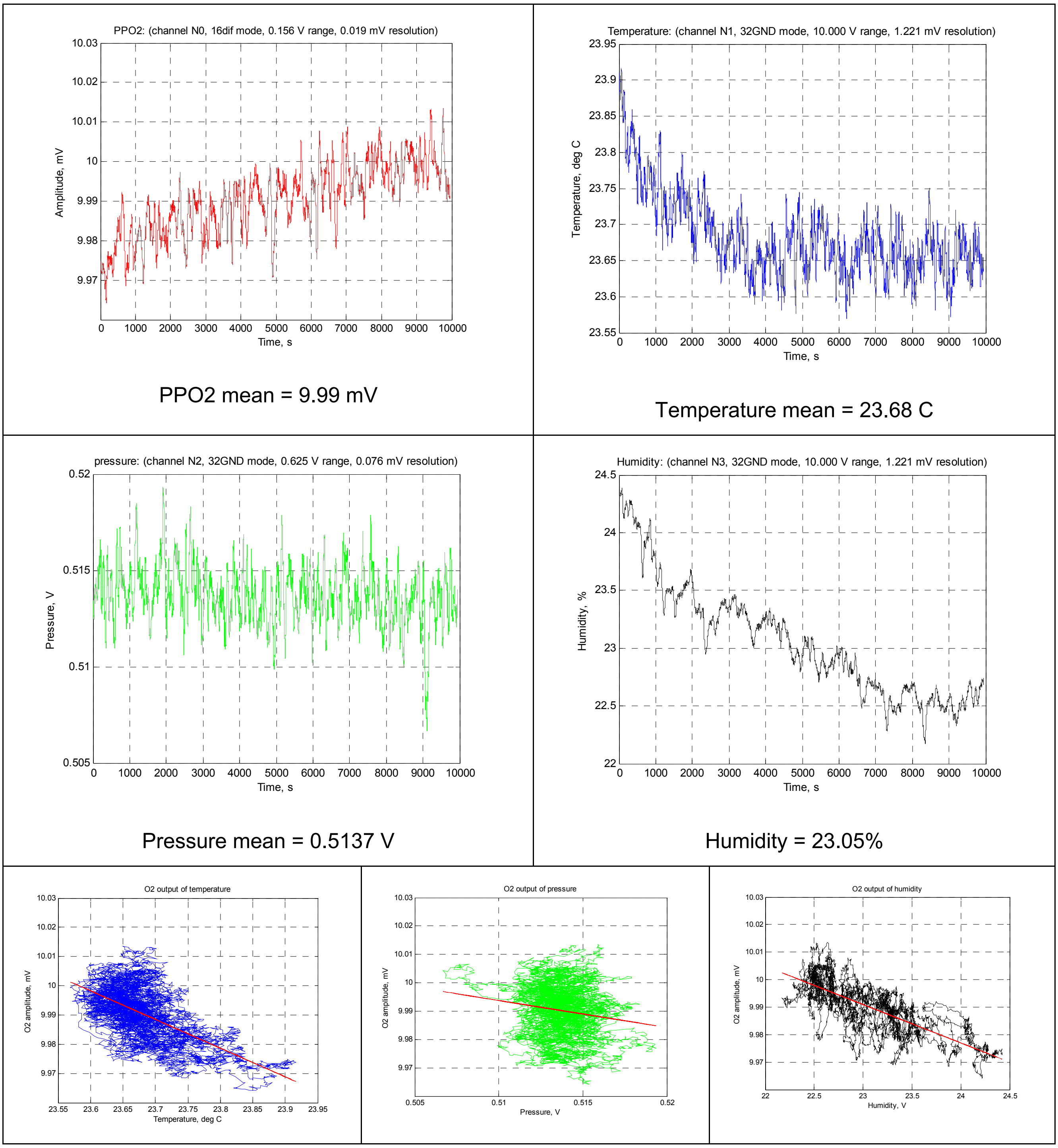
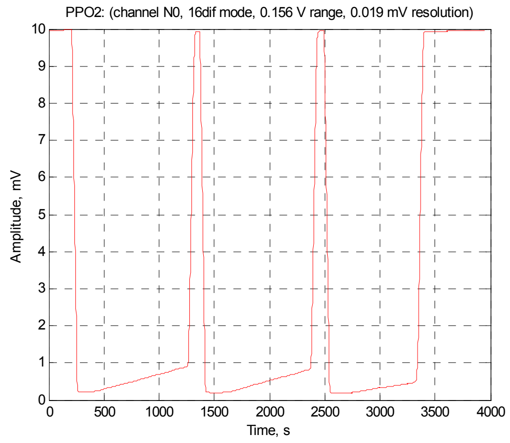


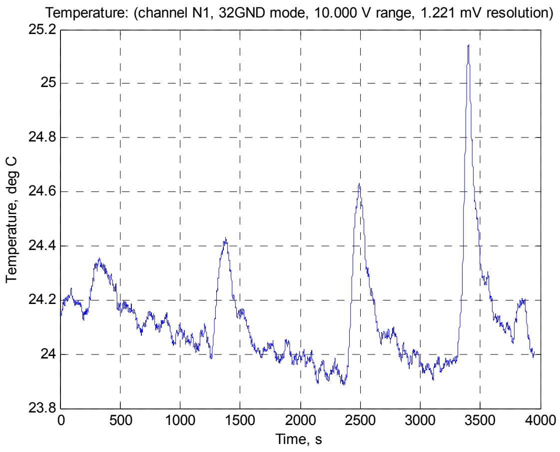
Fig 19.6-6. When the pressure is constant, the PPO2 sensor output inversely depends on temperature.

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

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





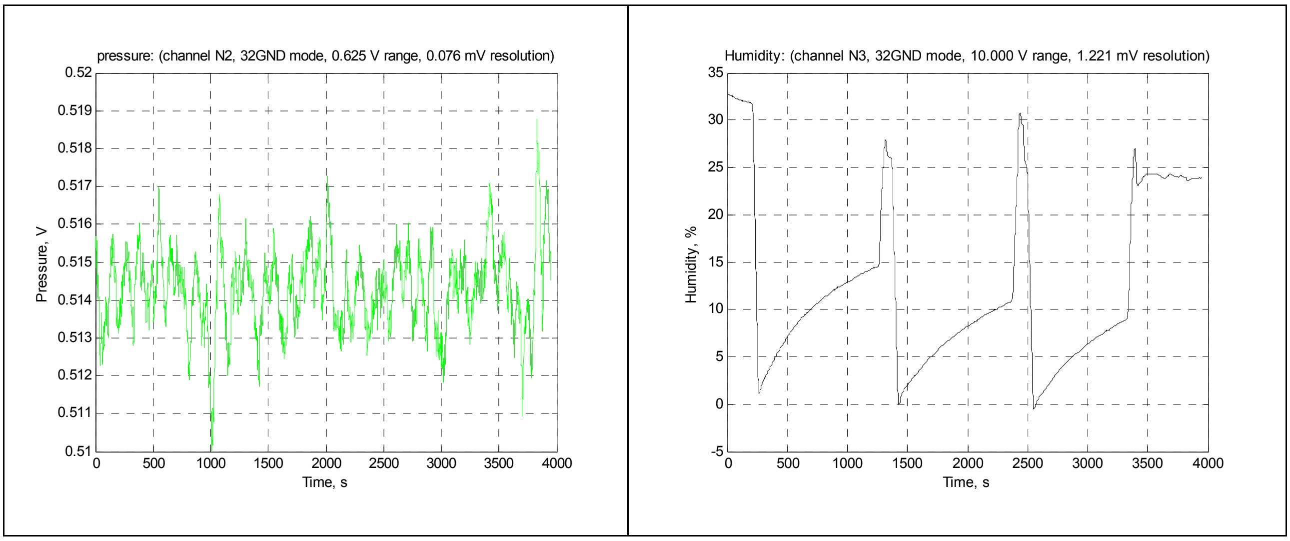


Fig 19.7-1. The offset (minimum reading) from the oxygen sensor in dry CO2 is 0.2 mV.

19.8 Conclusions of test of PSR 11-33-MD and MDR sensors

Both sensor types pass all tests. These are the first sensor tested by the review team ever to have done so.

The following conclusions are made:

1. The MD and MDR sensors are not damaged by exposure to CO2 for short periods.
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 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 place in 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 both MD and MDR 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.
9. The response time of the MDR sensor on a step increase of O2 from 21% to 100% is 6 to 7 seconds.
10. 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).

11. 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.
12. 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.
13. 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).
14. 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.
15. 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.
16. 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.
17. 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 RIBs, 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.
18. 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.

20 FAULT TOLERANCE AND PPO2 MEASUREMENT

The O2 cells are used in a predictive PPO2 control loop. This section considers just the PPO2 measurement: in predictive control the PPO2 sensor is monitored using calibrated O2 injection orifices and a model of the rebreather. Use of predictive control allows a simplified method to be applied to combining the results of multiple O2 cells (sensor fusion).

The most common method of combining multiple O2 cells is to use voting logic. This typically takes the average of the two closest PPO2 cells and rejects the others. This method gives a very poor overall reliability figure when most failure modes are in the same direction (failing with a low output).

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

$$ppO2(real) = M = \frac{P1 * ppO2(1) + P2 * ppO2(2) + P3 * ppO2(3) + P4 * ppO2(4) + P(pr) * ppO2(pr)}{P1 + P2 + P3 + P4 + P(pr)}$$

where:

Pn = probability of sensor n nonfault working during diving time,

P(pr) = probability of nonfault prediction during diving time,

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.

Of the O2 sensor failure modes listed in this report, only three 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.

The probability of the first two cases is very low, 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-MDR. 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.

In this case, 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 diving time,

Td –diving time,

MTBF –mean time between failures for PPO2 sensor,

P(pr) – probability of nonfault prediction during diving time

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 4 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 time,

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.

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.

21 MTBF

A very large batch of sensors is needed to determine the MTBF. The batch size of this study was sufficient only to audit the results published by the manufacturer. Based on the batch size and the results, the following conclusions are drawn:

1. The MTBF data from Insovt is substantiated by this study in regard to both operating life and storage life.
2. The MTBF data from Analytical Industries is substantiated at a preliminary level by this study in regard to both operating life and storage life. This conclusion is still preliminary: two more years are need to verify this in a non-accelerated environment for the latest models of the sensors tested.
3. The MTBF data from Teledyne is not substantiated by this study. The MTBF is probably a quarter of that claimed by Teledyne, based on the sample batches, with a disproportionate number of units failing early in their life. This problem of early failure was not observed, nor does it seem to be reported on the internet, for sensors from the two other vendors whose products were considered in detail in this study.

22 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.

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.