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

Results of a 6 Year Study

DOCUMENT NUMBER: [Filename]	O2_Cell_Study_070213.doc
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DATE ORIGINATED:	**20th May 2000, updates to Feb 07**
REVISION:	**B DRAFT**

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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.

This document was prepared using OpenOffice: before issue the enumeration and format to be corrected using MS Word.

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1 Executive Summary

O2 sensors 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 of 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.

Sensor Model	PSR-11-39-MD	PSR-11-39-MDR	R22- 2BUD, R22-D, R17D, R22-A	DK-32
Manufacturer	Analytical Industries	Analytical Industries	Teledyne	Insovt
Dimensions	Within limits defined	Within limits defined	Within limits defined	Within limits defined
Median Output in air	11.9mV	4.5mV	11mV	5mV
Quality	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.	Wide statistical spread in samples even in the same batch. None met datasheet. Very dangerous failure mode witnessed in 2006 R22-A that is hard to explain if sensor had been properly factory tested.	Extremely narrow statistic spread. Adequate QA but error in internal circuit identified: resolved.
Consistency	Excellent	Excellent	Very inconsistent within a batch. None met datasheet.	Excellent
Connector improvement	Are adopting SMB in product variant	Are adopting SMB	Teledyne rep refused to supply in SMB at 5K pce single drop purchase due to to their arrangements to prevent competition. Units required for testing had to be procured by alternative routes.	Wire termination. Willing to adopt SMB
Sensor Life	Preliminary: all operating, unless destroyed by tests.	Preliminary: all operating, unless destroyed by tests	Many early failures. None achieved stated life.	All operated beyond 5 year life. No damage from tests.
Error in Temperature compensation	0.72 mV/60C	NA	0.3mV/60C to 1.5mV/C in 2006 sensors. Much improved compared to older samples.	Miswired inside sensor

Linearity Error (PPO2 from 0.21 to 1.0)	**-2.26%**	**NA as it uses external compensation**	**Wide variation. -15% and -20% in 2006 sensor, also seen in earlier batches.**	**-2%**
O2 materials compatibility	**All pass**	**All pass**	**Electrolyte contaminated with organics during manufacture, causing drift and early failure. KOH leaked. KOH on external surfaces is a health hazard to operators.**	**All pass**
Hydrophobic membrane	**Present**	**Present**	**Present, except for -A sample**	**Present**
Response time	**6s rise / 8s fall**	**6s rise / 8s fall**	**Best case was 4s rise, 7s fall in R17 but R22-2BUD and R22-A varied excessively. The worst case was a R22-A purchased in 2006 to check for any circuit improvements in the R22 series over the period of this study; the sensor had a 50s response time, 5x worse than datasheet!**	**20s rise, 25s fall**
Temperature range tested.	**20C to 90C**	**20C to 90C**	**20C to 90C**	**20C to 90C**
Stability with time	**No drift**	**No drift**	**Large drift due to organic contamination of electrolyte. This is a result of poor manufacturing procedures and design issues. Requires frequent calibration checks as a result. Contaminated sensors display early failure.**	**No drift**
Shock	**Original samples failed test. Manufacturer addressed this by design improvements. Improved sensors pass**	**Same improvements as PSR-11-39-MR**	**Rear membrane tears, leaking KOH onto PCB.**	**Passes**
He susceptibility	**Pass**	**Pass**	**Pass**	**Pass**
Fast Decompression	**Pass but changes observed**	**Pass but changes observed**	**Pass but KOH leaks**	**Pass**
Chamber Lockout (Torpedo test)	**Reversed polarity. 2 days to recover**	**Reversed polarity. 2 days to recover**	**Output reduced 20%. 1 day to recover**	**Pass**

Short-term CO2 susceptibility	**200uV offset**	**190uV offset**	**500uV offset**	**No affect**
Application test	**Excellent. No failures**	**Excellent. No failures.**	**100% failed, leaking electrolyte onto pcb**	**Works but slow response**
Life test	**Passed accelerated test**	**Passed accelerated test**	**All failed well before stated operating life. Non-accelerated.**	**All still working after 5 years. Non-accelerated.**
Storage test	**Passed accelerated test**	**Passed accelerated test**	**All failed by ½ stated storage life. Non-accelerated.**	**All pass 5 year test. Non-accelerated.**
Offgassing	**No offgasing**	**No offgasing**	**Leaked KOH**	**No offgasing**
Marking	**Willing to mark date in large print**	**Willing to mark date in large print**	**Restrictive market practices. Unwilling to change anything.**	**Willing to mark date in large print**
Cost	**A**	**A**	**3.2 x A even in 5000 unit batches**	**2 x A, reducing to A**
Overall Suitability (Lowest mark)	**4**	**4**	**0**	**1**
Cause	**Shock resiliance**	**Shock resiliance**	**QA and multiple performance issues**	**Slow response**

Smaller batches were 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 comparable to its Teledyne R10D equivalent other than the PSR sensor having a higher level of quality control. This confirms a result reported by NEDU comparing the NM sensor with the R10D, finding the NM had a statistical spread half that of the Teledyne sensor.
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).

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-MDS (MD with an SMB socket), is the most suitable sensor.

It was concluded that the Teledyne sensors are not suitable for rebreather applications due to poor quality control and a series of design errors, causing unpredictable failure rates and modes. None achieved either the stated shelf life or operational life, and at the end of their life, leaked KOH, an extremely caustic solution that is a safety hazard for operators. Sensor response varied widely, the worst being a 2006 sensor which from new had a response time ten times worse than the median, and five times worse than the data sheet specification: this is a particularly dangerous failure mode that seems to be unique to Teledyne. Changes in output of up to 20% were observed after exposure to high O2 environments. There are widespread internet reports of similar quality issues. Compounding the technical defects in the Teledyne sensors are some questionable market practices: when a batch of 5K pce was attempted to be procured from Teledyne's UK distributor, they accidentally copied DL an intracompany email disclosing that Teledyne have a restrictive market practice with APD. Teledyne 's rep then declined to supply the sensor with SMB sockets and the sensors required had to be obtained through another route. Teledyne operates through representatives and dealers who showed very little interest in improving any product based on test results, and generally difficult to work with: the opposite to all the other companies.

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 was 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 sensors 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 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 manufacture 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 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 1% over range of 0.21 to 1.4
- Maximum size is 50mm high and 33mm wide, except for within 6mm of the socket, 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
- Resistant to shock in a dive environment, such as by transport on a 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 with the vendor to install an SMB for production quantities.
- Maximum response time to 90% of final value of under 10 seconds, measured by moving a sensor from a pure O2 at 1ATM to air at 1ATM at room temperature (Requirement added May 06).
- Integral temperature compensation providing temperature equalization to within 3% over the whole operating temperature range.
- Operable in 100% humidity, condensing
- Not damaged by short term immersion in salt water
- Operating temperature range 4°C to 55°C, and no damage at up to 90C. This requirement iis due to warm exhaust from scrubber, when pre-breathed after storage in a tropical environment.
- Storage temperature range -5°C to 90°C
- Should not damaged by chamber lockout processes.
- Output should not change in the presence of helium or nitrogen mixes, subject to PPO2 being constant
- Should not 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 which includes a batch number and clearly labeled 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 spectoscopic 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.

This study focuses on galvanic cells.

8 Sources of Galvanic O2 Cells

Galvanic O2 Sensors 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

Eighty-eight (88) companies brand or claim to manufacture galvanic O2 sensors. These are listed in Table 1 below. The reality is there are around 6 actually manufacturing their own sensors, the remainder relabel the sensor.

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

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

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.

The screening 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 year 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 Instruments specially for diving. These sensors were tested thoroughly, except that the life and storage test of those 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.

r22d.pdf (http://www.btinternet.com/~madmole/DiverMole/r22d.pdf) Specifications of R22D cell

diving.pdf http://www.btinternet.com/~madmole/DiverMole/diving.pdf Teledyne Diving Sensors Availability Sheet

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

sensormsds.pdf. http://www.btinternet.com/~madmole/DiverMole/sensormsds.pdf Oxygen Sensor Material Safety Data Sheet

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 between different O2 sensors

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 tradeoff is response time versus sensor life: this is determined by the thickness of the Zitex hydrophobic membrane at the sensor face. There are also fundamental distinctions also 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. Analytical Industries and Insovt have eliminated the rear membrane problems, which remains an issue with the Teledyne sensors.

A third area where design differences are apparent are in the method used to prevent offgassing 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 company's 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 Sensors

1. Unused sensors in storage will fail eventually due to the water carrying the KOH electrolyte evaporating eventually. 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 Insovt and AI both state a 60 month shelf life for their sensors. 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 a 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 stated service life is for use at 1 ATM pressure in air at 20C, and must be down rated for pressure and temperature. A 2:1 downrating is appropriate: this figure is based on discussions with several manufacturers.

2. 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 first an increase in the response time of the sensor, then in a 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 reading low, but a sudden temperature drop can cause a cell to read high, depending on the fault.

3. 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.

4. 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, then if those sensors still operate, the remainder are 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, all 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 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 (another weakness unique to the Teledyne sensor), 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 the cell reads low, but can cause an increase in the cell output if the pressure pushes the cathode towards the anode, or visa 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. The Teledyne sensors are particularly prone to this due to the construction depending on the rear membrane: if that membrane leaks, then Potassium Hydroxide is deposited onto circuit board, causing rapid degradation of the board, 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 the sensor may pass calibration but then 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, 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 sensors have to be sold separately 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 precisionl precision bench meter: TTi 5075
6. 10K land 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 sensors 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 the appropriate to this application, due to the SIL 4 target.

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 for the O2 sensors used by DL they 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 of using a 10K Ohm resistor, as is common in contemporary rebreather equipment.

The noise from the series resistor on the results 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 enable the noise from that resistor was assessed, was and confirm that 50 times oversampling and a moving average filter is beneficial.

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

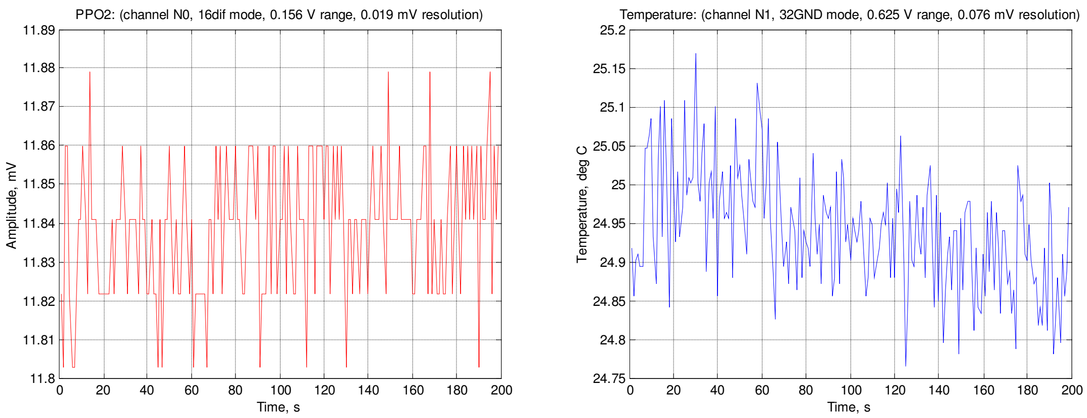


Figure 4-1. Original data.

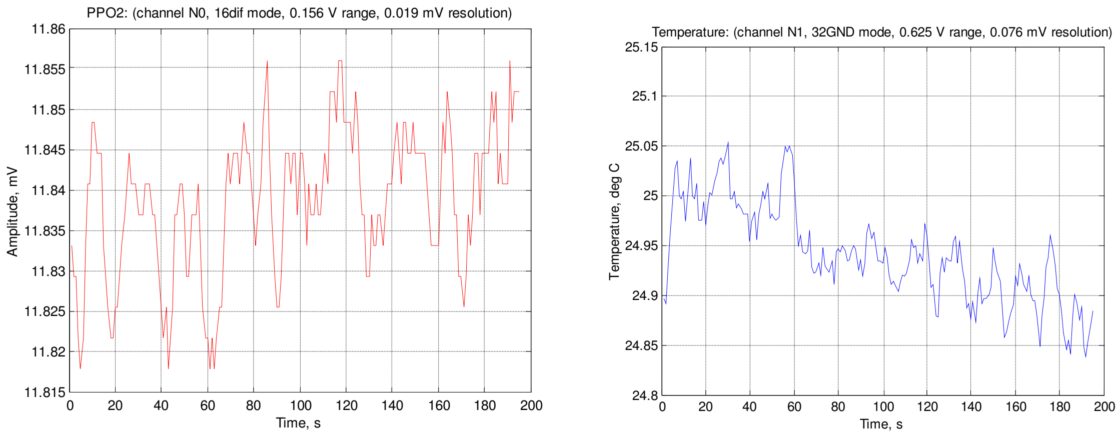


Figure 4-2. Original data filtered by moving average with window size of 5.

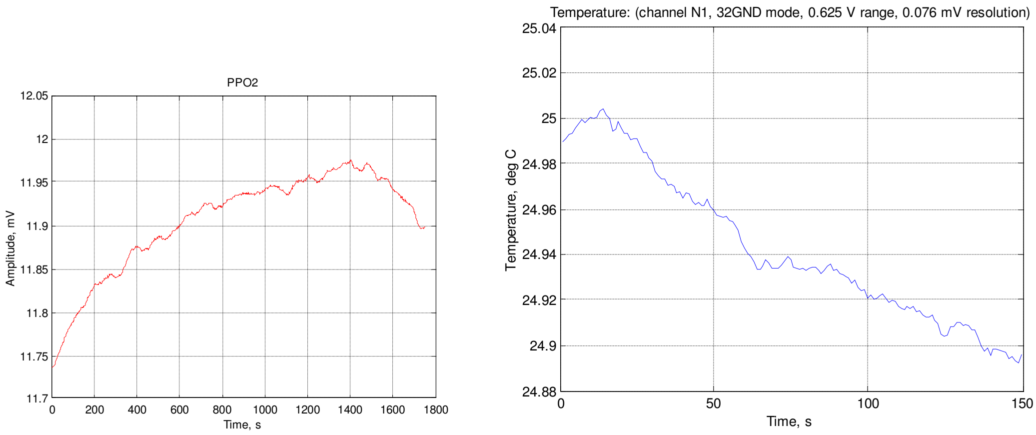


Figure 4-3. Original data filtered by moving average with window size of 50.

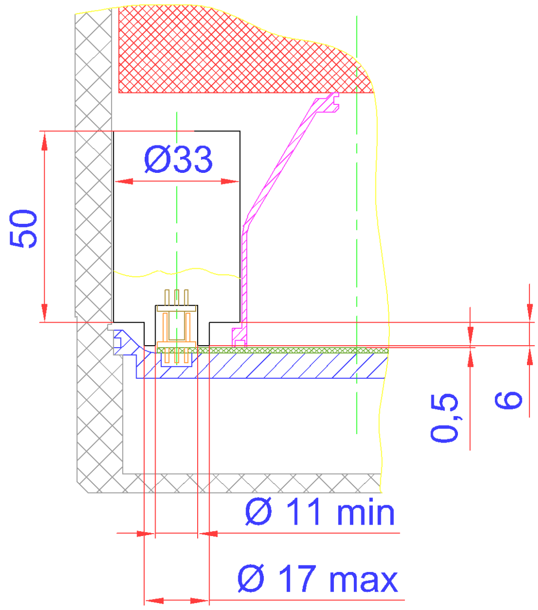
13 Test Schedule

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 described 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, document model and serial numbers of sensors, and take a photographic record. Treat all sensors as Customer Supplied Material according to QP-05. Mark the sensors 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.	• Use sensor 1. • Measure dimensions to confirm the sensor fits the space shown below, which is 33mm x 50mm + 6mm connector extension. • Check there is a means to hold the top of the sensor using a clamp, to prevent it shaking loose from the connector. • Check the active face is at the top in the drawing below (that is, the active face faces downwards in normal operation). • 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.	5. Use sensor 1. 6. 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	5. Use sensor 1. 6. Measure sensor voltage, and record temperature. 7. 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. 8. Check for any water held on the face. 9. Measure the output voltage every minute over a 30 minute period. 10. Verify that output does not change more than 1%.	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	• Use sensor 1 and allow output voltage to settle in air. • Apply a stream of oxygen to a sensor with a pressure of 30mbar +/-20mbar . Measure the readings every 100ms. • Compute response time to a 0.21 to 1.0 change, and from 1.0 to 0.21. • Verify that the response is less than 10 seconds to 90% of final value.	Reject. Discuss with manufacturer. Continue tests.
5. 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
5. Stability.	Confirm sensors are stable in air and confirm calibration	9. Use sensors 2 and 3. 10. Measure the output voltage with a 10K	Reject, but continue tests.

	interval required for their use	load, once per day, for six months. Record atmospheric pressure, temperature and humidity. 11. Correct data for temperature and pressure. 12. Confirm results are within 5% throughout the measurement period. 13. Extrapolate any trend to verify that operating life is not less than that quoted by manufacturer.	
6. Shock test Drop from 1.5m and 3m.	Test robustness. Test simulates effect of a sensor being mounted in a CCR transported by a RIB.	5. Use sensor 1 and 5 6. Photograph the sensor to be tested. 7. Measure the output voltage in air with a 10K load. 8. Drop 3m onto a hardwood surface 10 times. 9. Measure the output voltage in air after each drop. 10. The output voltage should not change more than 2% after 10 drops. 11. Drop 3m onto a wooden board laid on concrete 10 times and measure flow rates at 1ATM. 12. Photograph the external surfaces again. Repeat flow rate test (4) and note any differences. 13. Sensor then to be monitored once per day for 6 months, as per Test 4. 14. 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 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.	Must operate correctly over range 4 bar to 14 bar relative to ambient, otherwise design change.

		9. Plot linearity with Depth. 10. Do not decompress: move to Test 7	
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 vertically 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. 90. Use sensor 1. This test is the last in the sequence for sensor 1. 91. Wrap sensor in single sheet of 80gms paper. 92. 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. 93. Check inside of chamber for particles thrown out from sensor. 94. Check paper for holes and leakage.	Review
10. CO2 Susceptibility	To determine damage of 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. 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
11. Application Test	10 dives to recreational depths.	9. Use sensor 3, 8, 9, 10, 11, 12 10. Fit sensors to two PPO2 monitors: one a pure PPO2 monitor and the second to a rebreather head.	Review.

		11. Perform 10 dives with a mix of RIB and hardboard diving. 12. Measure the output voltage and record ambient pressure and temperature between each dive. 13. Store for 6 months, then take a further set of readings, and perform 10 more dives. 14. Correct the data for temperature and pressure. 15. Compare differences beween units before and after use. 16. Examine carefully for signs of corrosion or other visible deterioration.	
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.	9. Use sensors 5, 6 and 7 7. Store at room temperature in unopenned packages. 8. After 1/3rd, 2/3rd and the full storage life quoted by the manufactuer, open one sensor. 9. 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. 10. For the final sensor, after measuring the voltage, disassemble the sensor and compare with sensors 8 and 9 which should be likewise disassembled. 11. Take a photographic record of any changes. 12. Particular attention should be paid to the size of the anode and any changes in the cathode. 13. Examine the housing for possible sources of contamination. 14. Examine the PCB for corrosion.	Review.
14. Offgassing	Not tested, but if during the course of the trail the material appears to have any odour, contact manufacturer to determine	-	N/A

	composition.		

13.1 Note on Test 1: Mechanical Dimensions

The sensors were supplied with Molex connectors. These are entirely unsuitable for the application, being subject to corrosion, have poor reliability in a marine environment and 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 makes before the signal, as well as the provision of ESD protection in the sensing circuitry.

In 2000, a senior member of Deep Life staff on touring the AP Valves factory in Cornwall pointed this out to Martin Parker, their General Manager, and was asked what was 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.

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 Teledyne, who disclosed they have an exclusivity agreement with APD on this connector to keep other companies out of the market.

13.2 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 no dangerous off gassing or leakage, or permanent damage.

13.3 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 is when equipment is laid on the floor of a RIB (a Rigid hull inflatable boat), which are 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 of the peaks of the waves, falling into the trough of the following, 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).

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

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

13.5 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, and take the period stated by the manufacturer: this can be up to 5 years.

One manufactuer'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.

13.6 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 assemly 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 the result of this review.

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14 R17-D, R22-A & R22-2BUD Test Results

Teledyne are a US company whose products have the highest market penetration for rebreathers.

The R17-D, R22-A and R22-2BUD datasheets provided by Teledyne show all three sensors tol have a 6 second response time (to 90% of FSD), with a typical output voltage of 10mV in air. The D model variants have a hydrophobic membrane fitted. All three sensors appear to be designed for use at 1ATM, but an equalization port means they should operate to 20 bar subject to the pressure changes being slow. The manufacturer claims a 36 month storage life and an 18 month service life on their web site.

14.1 Sensor Sampling

Two lots of six R22-2BUD sensors of the same batch were purchased from AP Valves: now re-organised as Ambient Pressure Diving Ltd.

The formal test schedule was applied.

Three of the R22-2BUD sensors from each batch were fitted to an AP Valves Classic Inspiration, and three were stored in their original packing, unopened.

After 10 hours of normal use in an AP Valves Classic Inspiration in sea water, the unit was washed and stored for six months in an office environment. The sensors were then removed and examined.

An R17-D sensor included in the test group to determine if there is any significant difference.

At the end of this trial, new R17 and R22-A sensors were purchased, and compared to determine if any of the problems revealed during the trial had been resolved by product development within Teledyne.

14.2 Teledyne APD R22-2BUD Test Results

14.2.1 Results of the Storage and Operation Tests

The control group of unused sensors were examined after 18 months of storage, as that is half the manufacturer's claimed storage life. The sensors had been stored in their original packaing, unopened, in a laboratory. Two observations were made:

1. All the unused sensors had failed. The output of the sensor was zero. Dissection the sensor showed that the electrolyte had dried out, either fully or partially.
2. There were black areas on the cathode of the sensors. This is indicative of organic material introduced into the sensor during manufacture due to poor quality control.

The manufacture claims a 36 month storage life for the R22 sensor family. This is not substantiated by this trial.

Considerable corrosion was apparent on the circuit board inside all three sensors that had been used for 10 hours in a rebreather. This is shown in Fig 8-1 to Fig 8-3. It can be seen from these pictures that any component and any track in the R22-2BUD is liable to fail within the sensor, so the sensor failure modes must consider the failure of any component with a very high degree of environmental downrating. The component failure rate is estimated at 100 hours of use, or 12 months, with the component failing open circuit in every case. The cause of the corrosion was investigated. After detailed examination, it was found that the rear membrane had very small tears and this allowed Potassium Hydroxide (KOH) electrolyte from the cell to contaminate the board. The KOH greatly accelerates the corrosion of the pcb.

All of the sensors used for testing, that is those not in the control group, developed “Ceiling faults” where the maximum voltage that could be generated by the sensor fell, ultimately to zero.

All of the sensors used for testing showed significant drift during the course of the trial. This is believed to be caused by organic contaminants. The cathode of the exhausted cells was examined and found to be reduced in area by the action of the contaminants. The sources of the contamination is believed to of epoxy resin to seal the pin that penetrates the wall of the cell, and possibly a lack of cleanliness during the assembly process.

14.2.2 Quality Observations on the R22-2BUD

The quality control of the Teledyne sensors does not appear to be of the level required for a life critical application. The reasons for this conclusion are:

1. It was observed that only one side of the sensor pcb had a conformal coating applied, and from the brush marks, this is evidently done by hand. Quality control issues arising from this process gave rise to concern.
2. The over specification of the shelf life by the manufacture also suggests a serious lack of quality control.
3. There are widespread reports on the internet of quality problems with Teledyne sensors, due to dry joints, poor shipping practice and misassembly. One review found 60% of Teledyne R22 cells to fail within 12 months (http://www.btinternet.com/~madmole/divemole.htm). The scale of failures suggest than any quality control system that Teledyne are using, is not working.
4. The circuit board had no UL rating. Visual inspection could not identify exactly the form of FR4 used. The components appear to have been assembled and soldered manually without compliance to normal assembly guidelines on bend radii or clearance. It is understood these sensors were assembled in the USA.
5. Dissecting sensors after testing showed large black areas on the cathode. This indicates gross organic contamination. This may be skin cells from the assembly operators, or organics in the epoxy resin that seems to be used in this sensor to seal the hole where wire from the cell chamber exits.

Fig 8-1: R22-2BUD Sensor with rear plastic removed, showing considerable corrosion after 10 hours. This is due to microscopic tears in the rear membrane of the sensor allowing Potassium Hydroxide to be deposited on the pcb and its components.

Fig 8-2: R22-2BUD sensor from stored batch, showing circuit board in original condition.

Fig 8-3: Rear side of circuit board after use (S/N 410243), alongside control sensor (S/N 410245). The deposition of KOH can be seen on the membrane as a whitish film.

Fig 8-4: Unused R22-2BUD Disassembled, showing electrodes, membrane, housing, and electrolyte suffering from dehydration after storage in a air conditioned laboratory environment. Note the cathode is almost completely black: this is caused by organic contamination in the electolyte.

In testing sensors in a separate rebreather accident, it was found the R22-2BUD labels are prone to rotating if they are damp for an extended period, which makes all text unreadable. The manufacturer should be advised to use a different adhesive. The data code is unacceptable, and a custom label would have to be made showing the date clearly such as SEPT 06.

During the tests, issues were also identified in the poor temperature compensation, wide variations in response time and non-linearity.

14.2.3 Conclusions from test of R22-2BUD

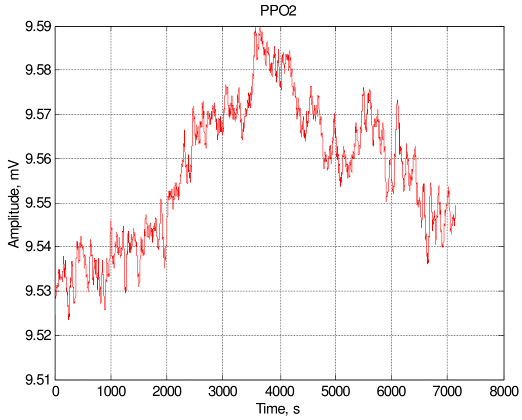
1. Very poor quality control was evident
2.
3. Temperature compensation was poor but it is noted this was improved during the period of this study. The improved results are shown below on the retest of sensors in 2006 so the reader has the most up to date information.
4.
5. Organic contamination of electrolyte was evident on all sensors that were dissected, and in the drifting output of those not dissected.
6.
7. None passed either the storage life test or the operational tests: all failed at much less than half the stated life.

14.3 Retest of Teledyne R22 Sensor in 2006

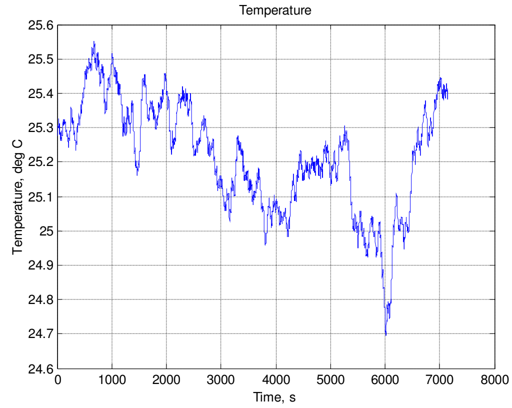
To determine if Teledyne had introduced any quality improvements during the course of the trial, in June 2006 a R-22A sensor purchased: this is the same as for the R22-2BUD except there is no hydrophobic membrane. The Serial number of this sensor was 421535. Unlike the original batch, which was purchased from the distributor without explaining any reason, Teledyne's distributor was told the purpose of the purchase was to test the sensor for suitability for diving and the result may be published.

The results from the retest are shown below, and indicate that apart from an improvement to the temperature compensation circuit, there has been no useful product improvement between 2000 and

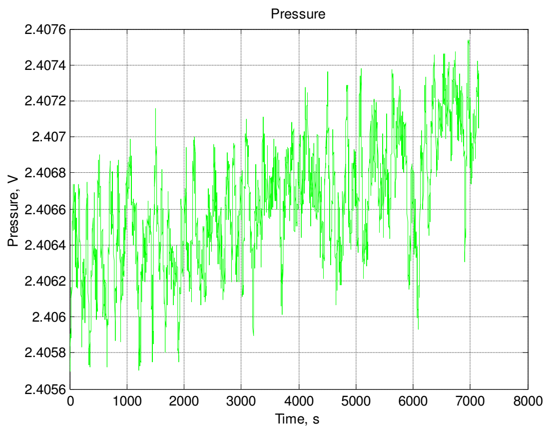
2006, at least none that improve the performance in testing. The sensor supplied did not confirm with the datasheet, and displayed a slow response, which is a particularly dangerous failure mode.



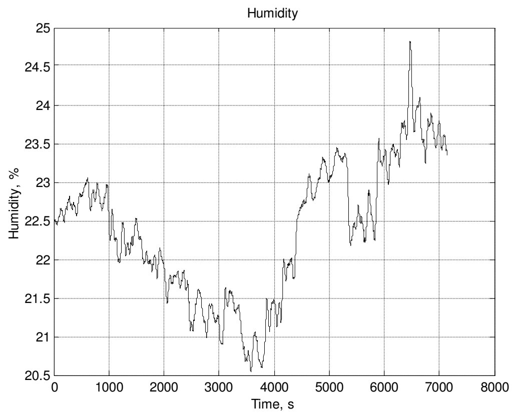
PPO2 mean = 9.56 mV



Temperature mean = 25.22 C



Diff pressure mean = 2.4066 mV



Humidity mean = 22.37%

Fig 3-5. O2 sensor output in 1 ATA.

14.3.1 Test N4. Response to pure O2

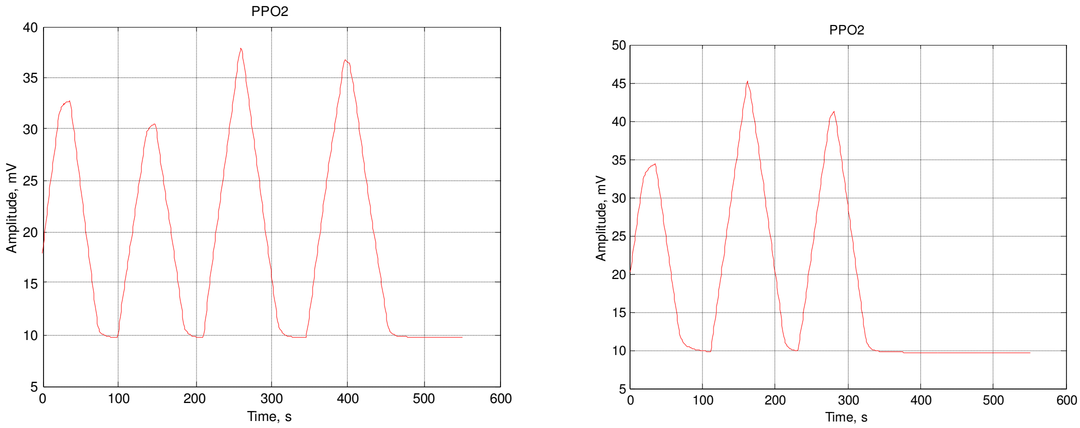


Fig 3-6. Response to O2 flow pulses is more than 50 seconds. This is similar to what was observed in the original batch of sensors, but even more pronounced. This type of failure could have lethal consequences in a rebreather if it affected several sensors in the same batch.

14.3.2 Test N10. Response to pure CO2

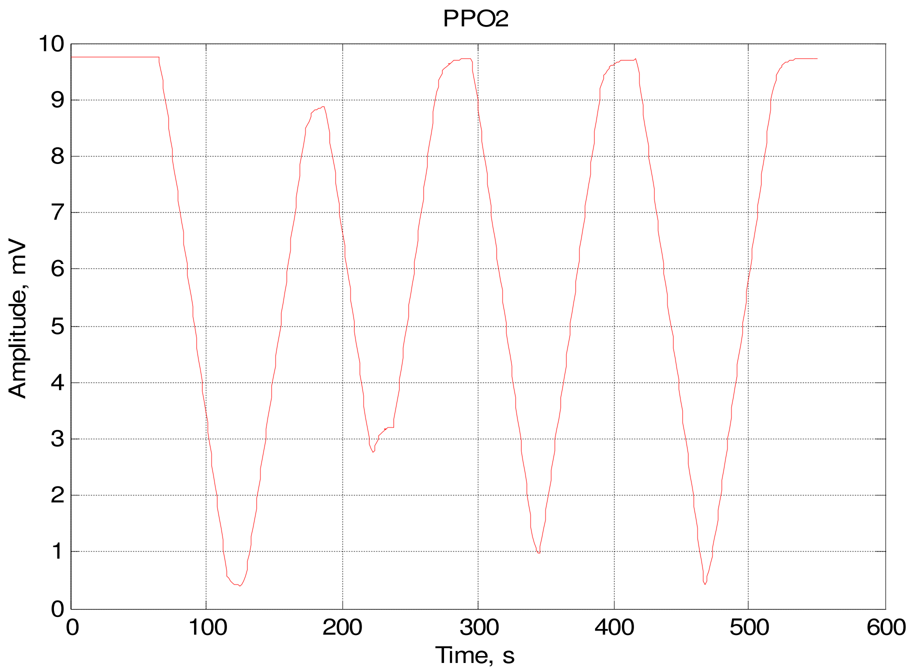


Fig 3-7. O2 output in pulse CO2 flows. Minimum is 0.4027 mV. Response is 50s, offset 500mV. This is the same as was observed for pulsed O2 flow, and again indicates Teledyne are shipping sensors with particularly hazardous failure modes, that appear to be unique to their process.

14.3.3 Test N5a. Linearity over full temperature range.

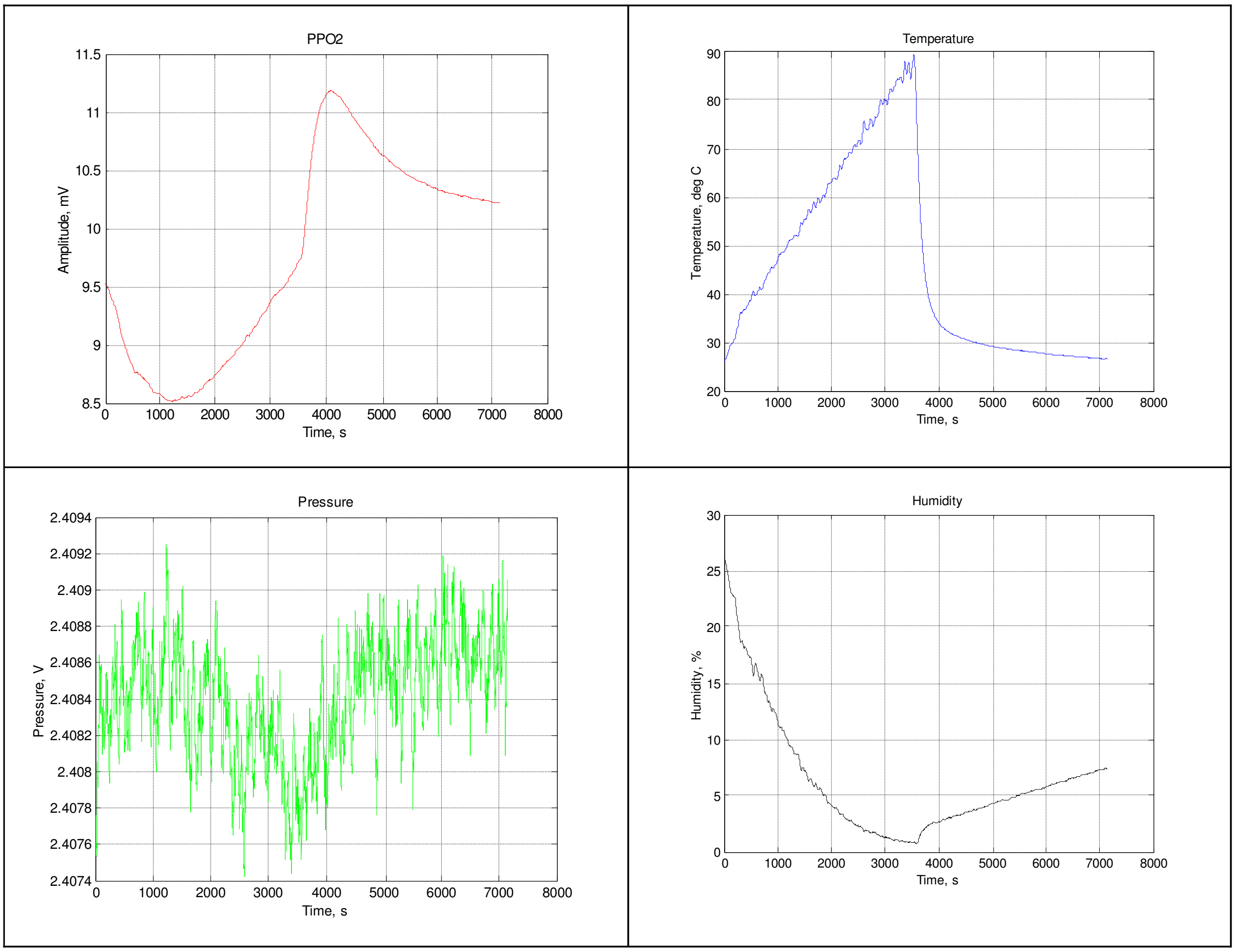
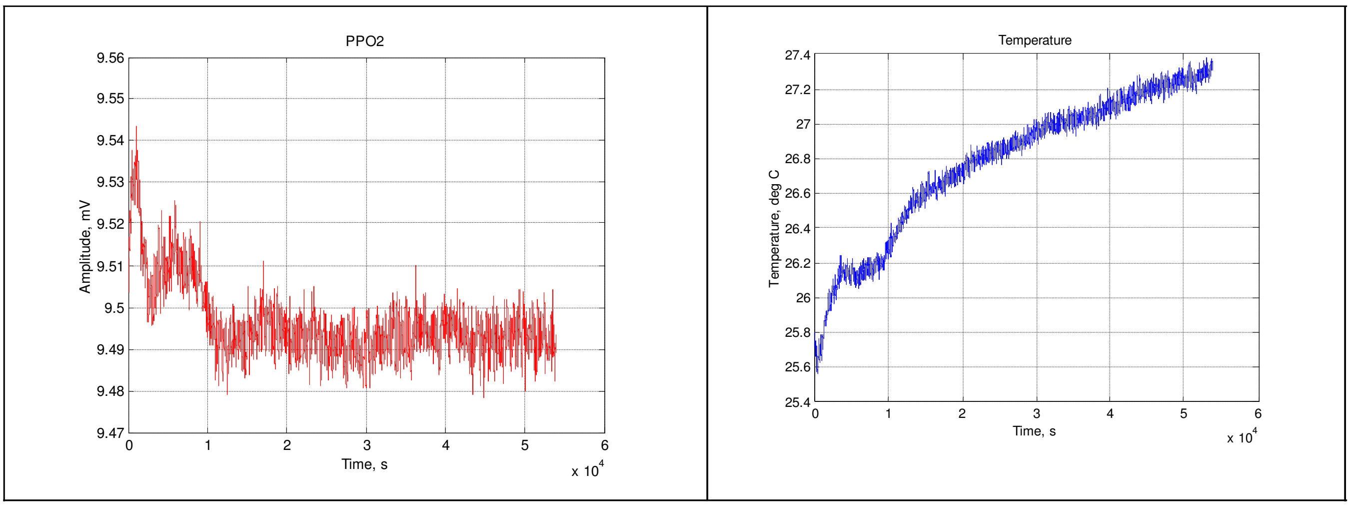
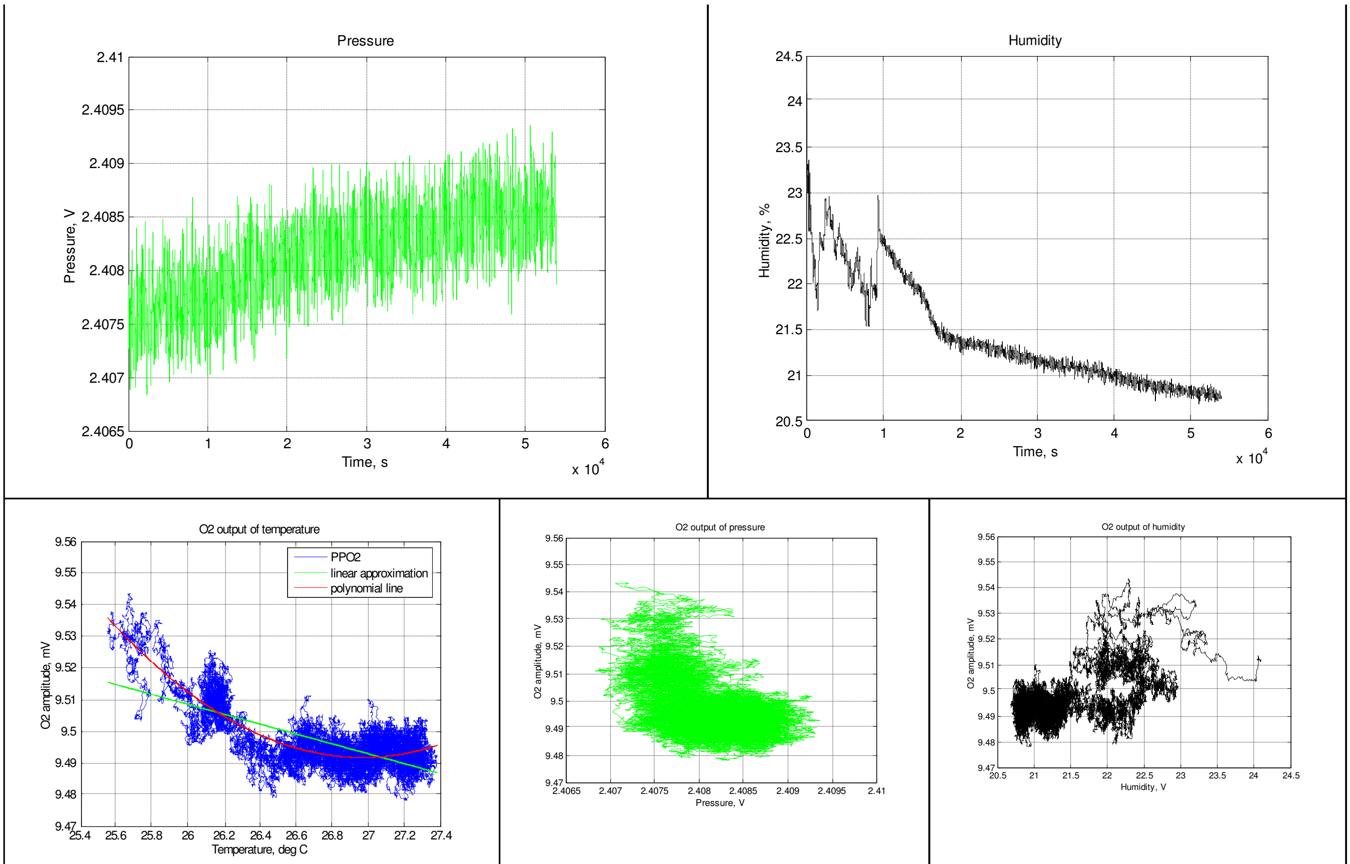


Fig 3-8. Sensor in temperature chamber. This result is much better than on units tested earlier, amounting to a difference of 1.7mV worst case over the 26C to 60C range: Teledyne have improved the design of their temperature compensation circuit since the first batch of sensors were purchased.

14.3.4 Test N5b. Stability in air





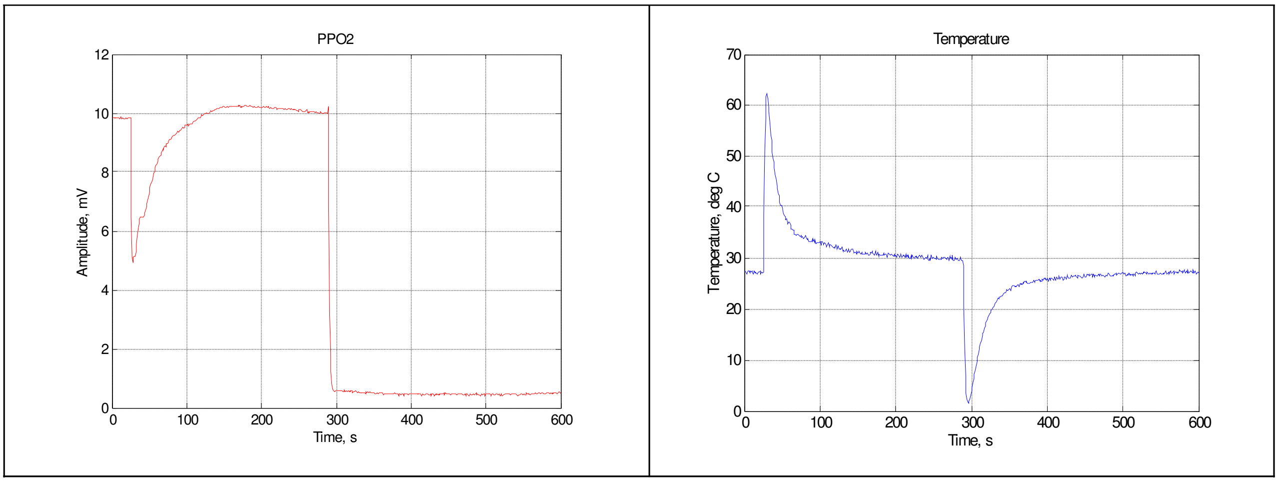
PPO2 = -0.0157t +9.9158;

PPO2 = $0.0222t^2$-1.1988t+25.6569

Fig 3-9. Example of the stable in air in 15 hours for the R22-A

14.3.5 Test N9. Chamber lockout (Torpedo) test

This was the last in the sequence of tests carried out for this sensor, as it is regarded as a destructive test.



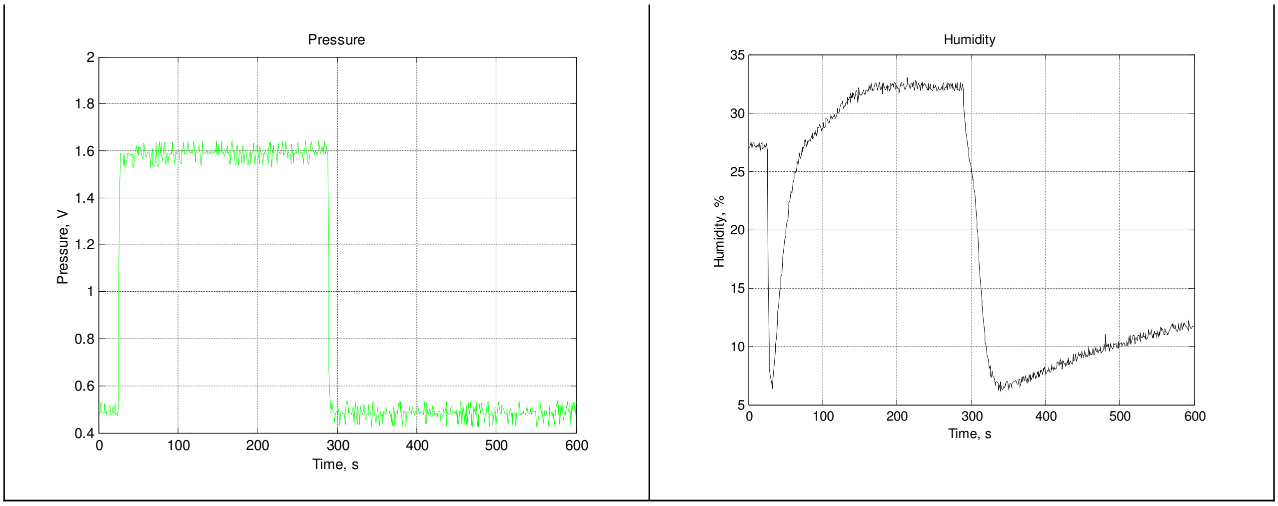


Fig 3-10. The test data. Pressure from 1 ATM to 120 bar in under 1 second, using He**.** There are no particles thrown out from sensor inside of chamber.

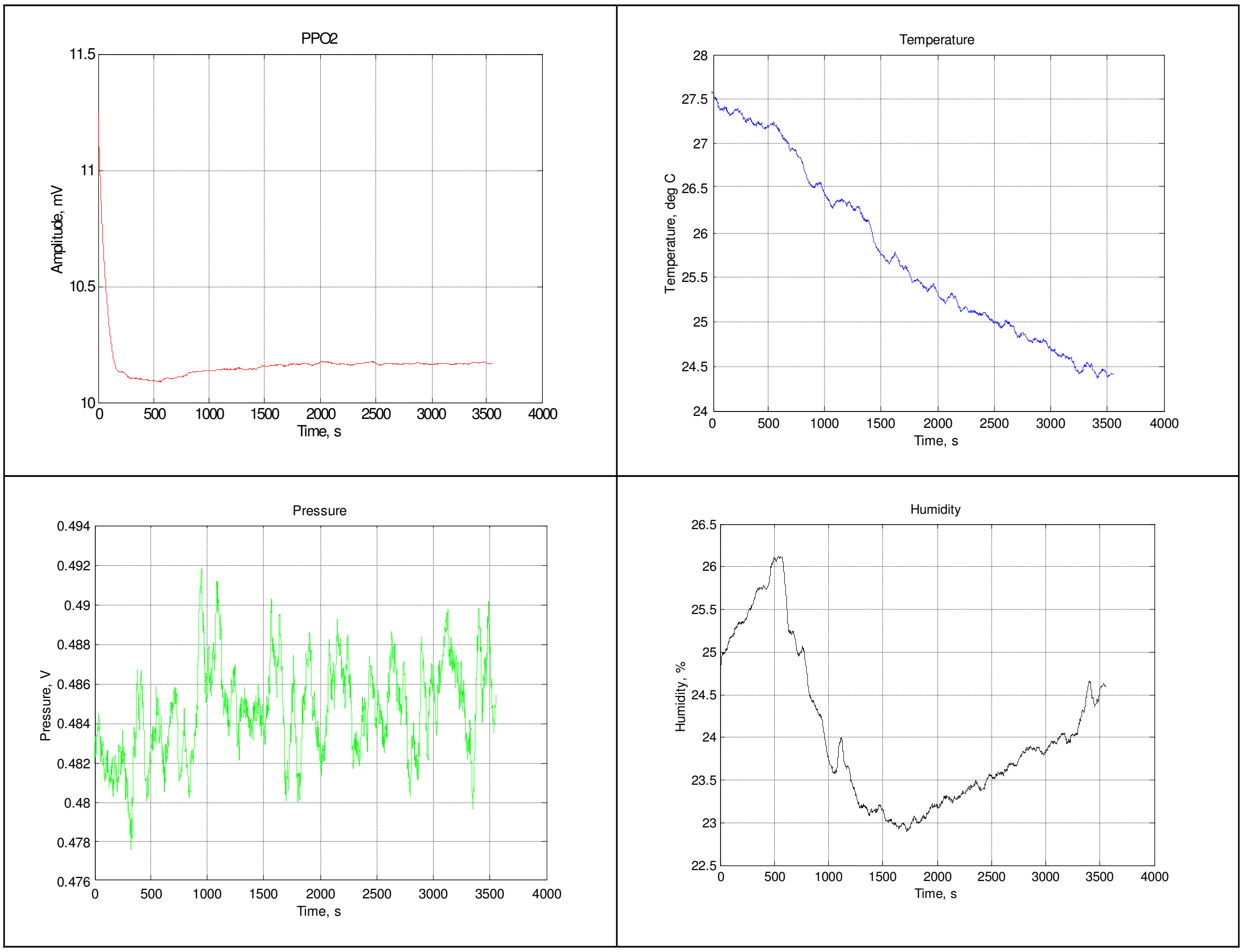


Fig 3-11. After the Chamber lockout (Torpedo) test. Sensor at 1 atm in air over one hour. Note output falls by 20%. The sensor recovers a day later.

14.3.6 Shock Testing

A failure report from Teledyne indicated that over the past 5 years, the shock resistance was reduced by changing from a CNC machined housing to an injection moulded housing. For this reason the shock tests were not repeated with the new sensors.

FAILURE ANAYLYSIS REPORT

RMA #44213

Zhenhe Sun
10-06-2006

INTRODUCTION:

The purpose of this failure analysis was to determine the premature failure of R22D oxygen sensor, S/N 660549, 660551, and 700939, reported by Innerspace System Corp. under control number 900-44213. Customer reported: "*BEFORE A ROUTINE DIVE, I MADE A STANDARD LEAK TEST OF MY BREATHING LOOP WHICH I FOUND IT FAILED. AFTER HOURS OF REVIEW AND CHECKING THE REBREATHER, LEAK WAS FOUND TO BE THROUGH THE SENSORS THEMSELVES. ONE WAS COMPLETEDLY LEAKING FLUID, THE OTHER HAD A VERY SMALL LEAK. I THEN PUT NEW SENSORS IN THE MACHINE AND LEAK CHECKED AND IT PASSED.*"

PROCEDURE:

Sensors were first visual inspected for any damage or sign of electrolyte leaks. Then, the mV output was measured. After measurements, sensors were disassembled. The cell body, sensing membrane sealing, and the expansion sealing, liquid electrolyte inside cell were examined.

RESULTS:

Sensor, 660551:

External visual examination did not reveal any defect. The mV output in air was 10.4mV, which is still within spec.

However, when label was removed. Liquid electrolyte was seen under the sleeve. After remove the clamp ring, Zitex porous membrane, etc, it was revealed that the front end of cell body had several cracks. There is a big gas bubble inside the cell that indicated electrolyte lost from the cracks.

The evidence list above showed this sensor failed due to the electrolyte leaks caused by cell body cracking.

Sensor, 660549:

Visual examination did not see any defect. The mV output in air was 2.2mV and unstable, which is out spec.

Reference: R22MAS Failure Analysis Report 1

Fig 12: Page 1 of Teledyne report on sensor failure in rebreather due to shock

TELEDYNE
INSTRUMENTS
Analytical Instruments
A Teledyne Technologies Company

When the clear protection label removed, it was revealed that the word printed on the label was damaged indicated an electrolyte leaking. Further, analysis showed that front cell body cracking lead to the leaking of electrolyte.

Sensor, 700739:

Visual examination did not reveal any defect. The output of this sensor was 10.3mV, which is within spec.

Further analysis did not find any defect on this sensor. The sensing membrane seal, expansion membrane seal and cell body were all in good condition.

CONCLUSION:

All three sensors were made with molded high density polyethylene cell bodies which are more likely developing body cracks (See attached forensic failure analysis report by Plastic Failure Labs, Inc as attached).

The cause of the failure of 660551 and 660549 is cell body cracking.

RECOMMENDATION (or CORRECTIVE ACTION if any):

(1) Replace all three sensors under warranty.
(2) Use the machined high density polyethylene cell body that successfully used for many years instead of injection molded high density polyethylene cell body for R22D to reduce the body cracking.

Fig 13: Page 2 of Teledyne failure report, highlighting change to moulding

14.3.7 Conclusions from 2006 Retest of R22-A

1. The retest used an R22-D instead of an R22-A, as the former were out of stock in Teledyne's UK distributor, and long lead times were quoted for the R22-D. The distributor confirmed the only difference is the lack of the hydrophobic membrane and board coating.
2. The output of the tested R-22A sensor, serial_number: 421535, is 9.5 mV in atmospheric conditions. This is lower than observed for the R22-2BUD sensors, but given their wide statistical spread, does not appear to be exceptional. It is within the data sheet specification for the sensor.
3. The sensitivity of the sensor to temperature is low. It is 0.3 mV/60 deg.
4. The R-22A sensor passes the Chamber lockout (torpedo) test successfully, though the failure mode is of some concern.
5. The shock test was not repeated, as Teledyne report a problem with the mouldings.
6. The response time of 50 seconds is much more than that stated in the datasheet. This is a dangerous failure mode, that is hard to explain if the sensor had been tested properly by the

factory. It appears the quality control problems within Teledyne still exist. This view is supported by numerous statements by users buying Teledyne R22D and R22-2BUD sensors in 2006 on RBW forum.

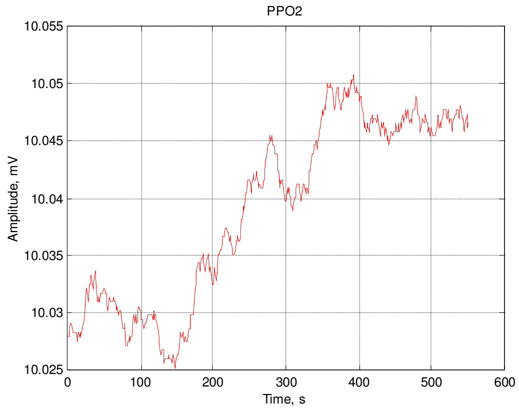
7. A batch of at least five R22-D sensors should be procured and retested after 9 months to determine if Teledyne are addressing any of these issues. This action was carried out: see further test results herein.

14.4 Retest of Teledyne R17-D Sensor in 2006

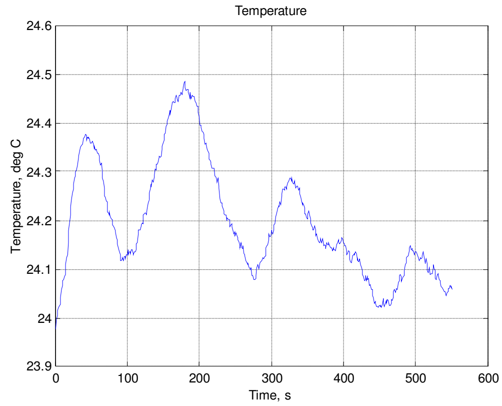
In 2006, a R-17D sensor was purchased directly from Teledyne's UK distributor, Serial_number: 655949 for the purpose of further checking if any product improvements had been introduced during the period of this trial.

R17-D sensors had been procured earlier and apart from the connector appeared to be the same as the R22-D. The R17-D sensor purchased in 2006 was similarly examined and found to be essentially the same construction as the R22-2BUD. The only difference observed was the connector and this was confirmed by the UK distributor with respect to the R22-D. Reference is made to the R22-D, because APD claim the R22-2BUD is the same as the R22-D except that it has been tested to PPO2 levels of at least 1.6.

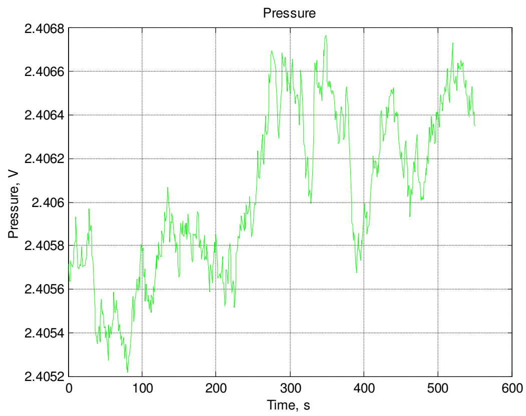
14.4.1 Response in Air



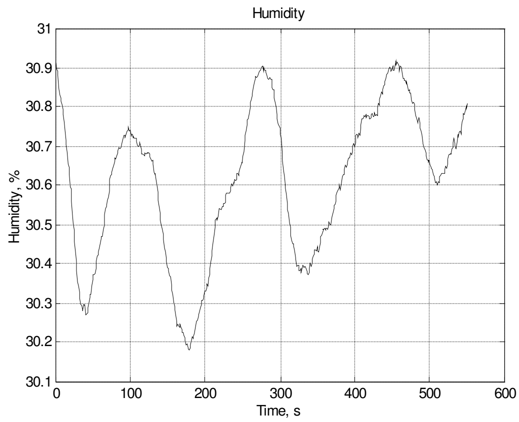
PPO2 mean = 10.04 mV



Temperature mean = 24.2 C



Diff pressure mean = 2.406 mV



Humidity mean = 30.61%

Fig 3-14. R17-D O2 sensor output in 1 ATA.

14.4.2 Test N4. Response to pure O2

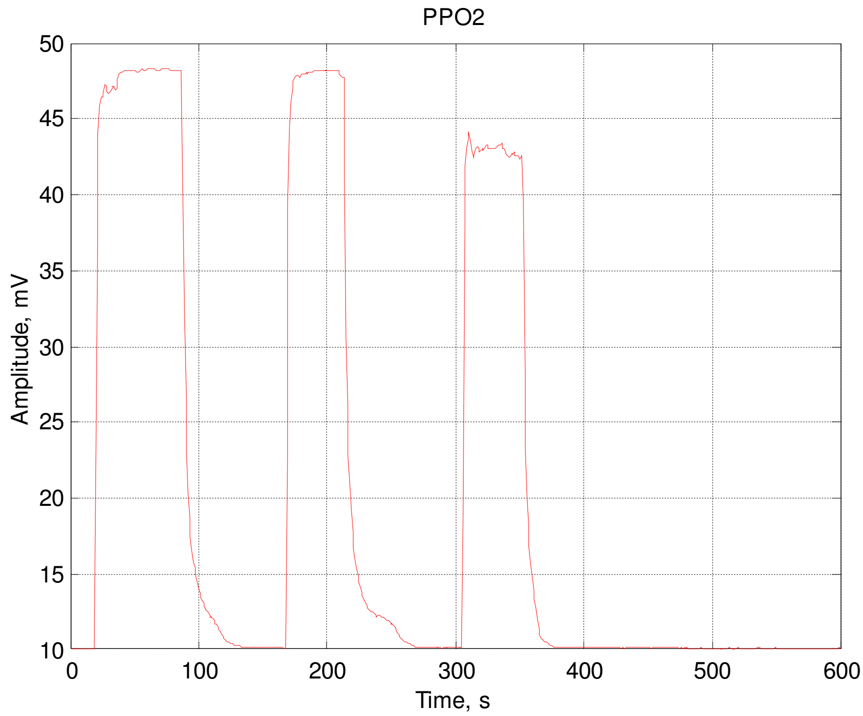


Fig 3-15. Response to O2 flow pulses.

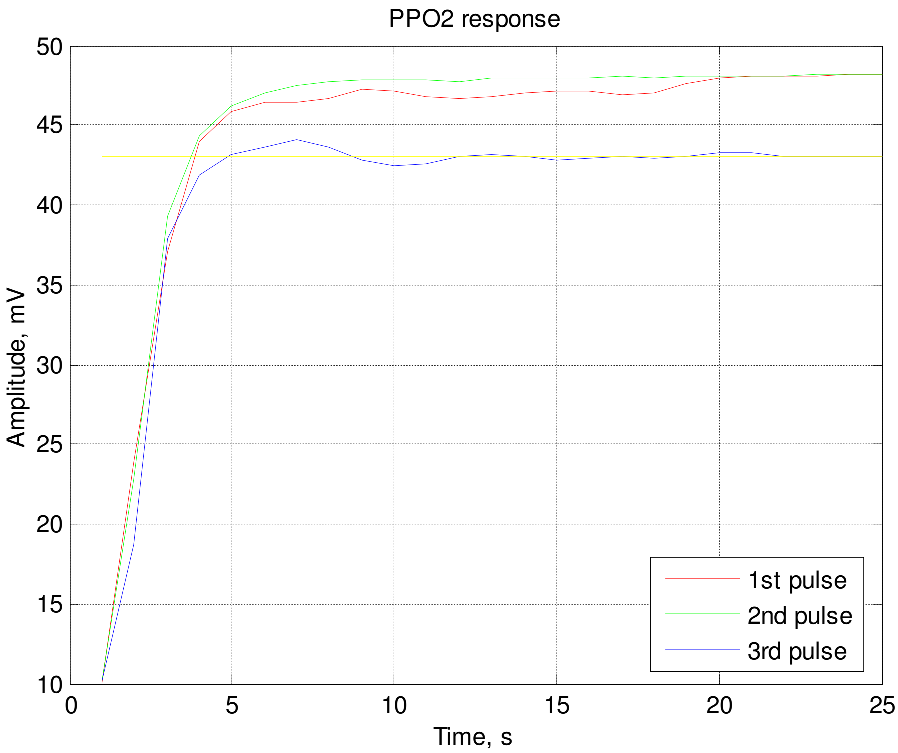


Fig 3-16. PPO2 time response in O2. 90% level is 40.47 mV: (47-10.049)*0.9+10.049. Rise response is 4 s. The sensor output is about 47 mV when the sensor is in 100% O2.

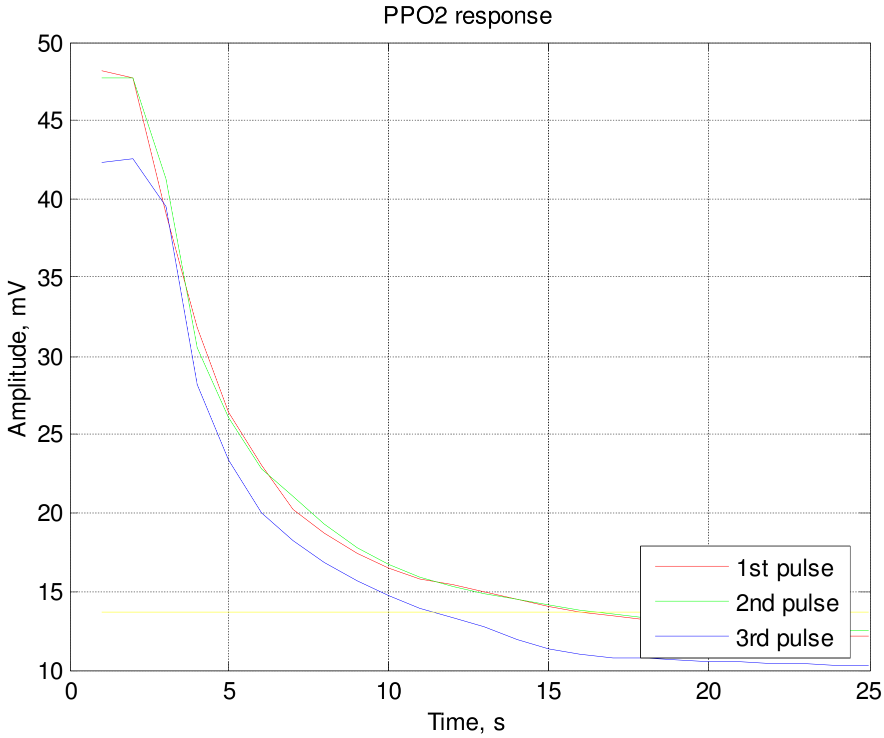


Fig 3-17. PPO2 time response in air. 10% level is 13.74 mV: (47-10.049)*0.1+10.049. Fall down response is 12 s.

14.4.3 Test N10. Effect of CO2 environment

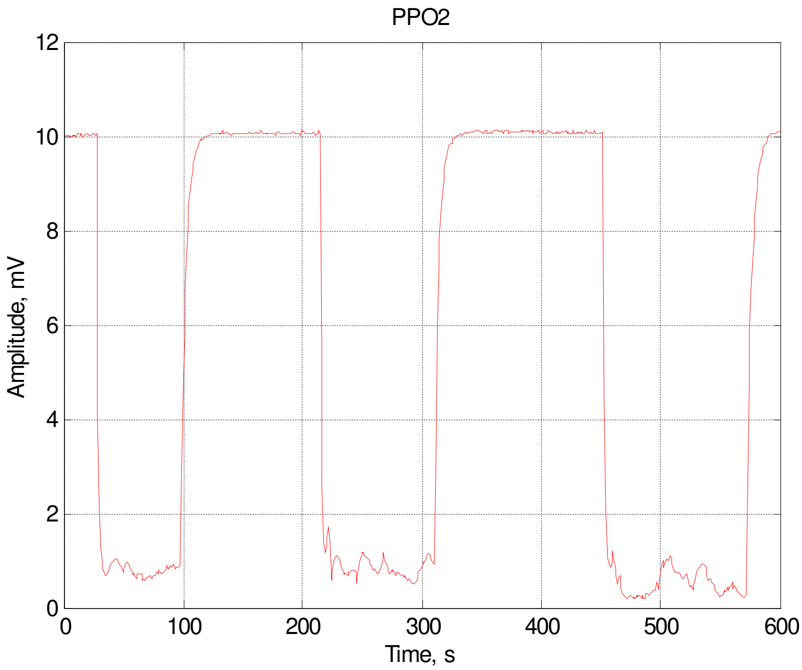


Fig 3-18. PPO2 output in pulsed CO2 flow. Minimum is about 0.3 mV, general offset is 0.8mV.

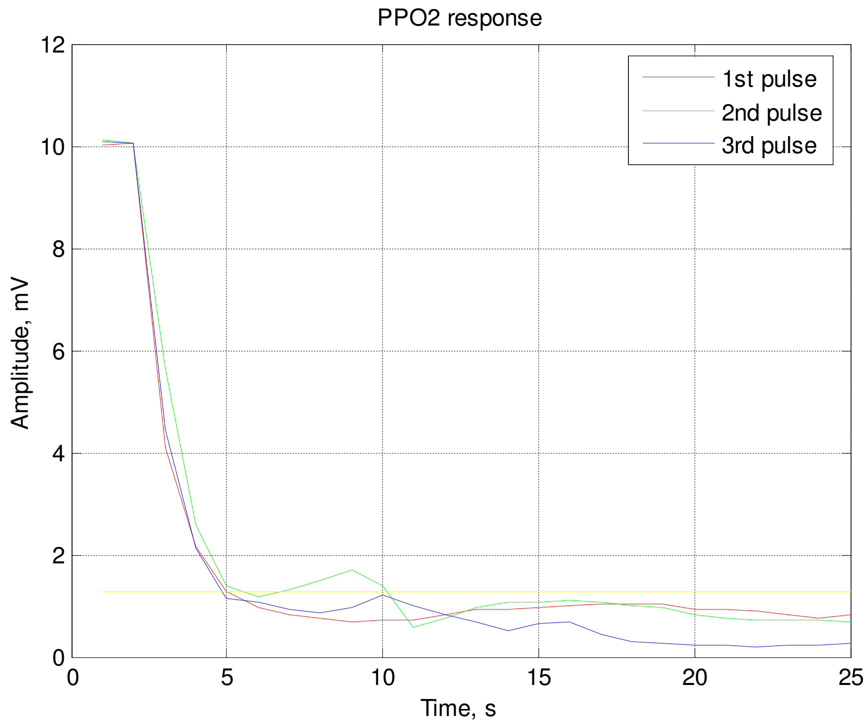


Fig 3-19. PPO2 time response in CO2. 90% level is 1.275 mV: (10.05-0.3)*0.1+0.3. Fall down response is 3 s. The sensor output is from 0.3 mV to 0.8mV when the sensor is in 100% CO2.

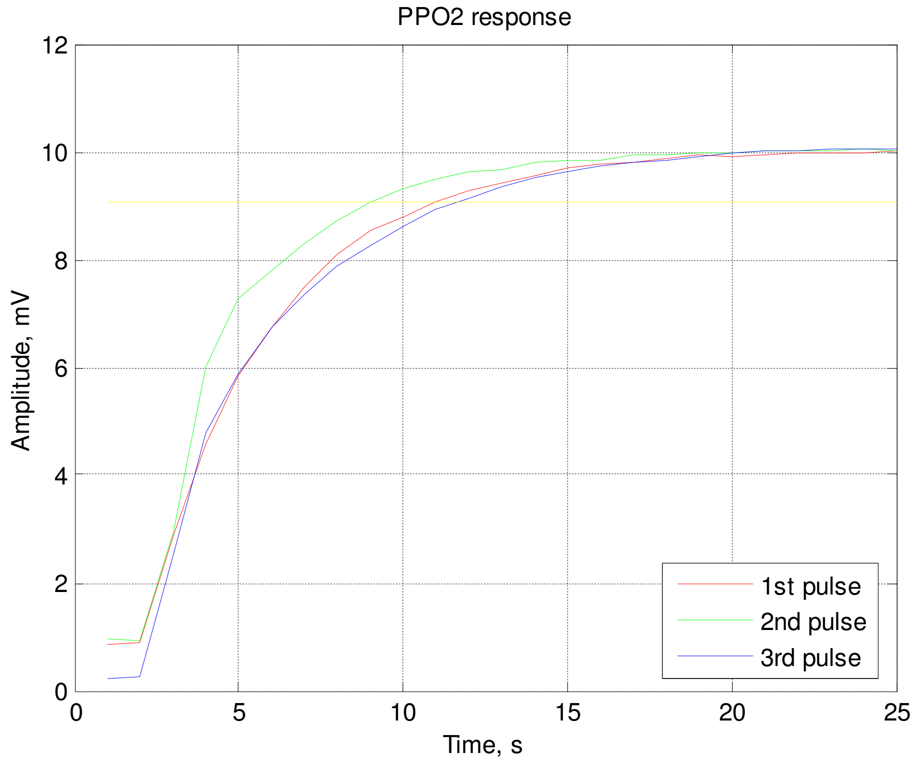


Fig 3-20. PPO2 time response in air. 10% level is 9.075 mV: (10.05-0.3)*0.9+10.05. Rise response down response is 10 s.

14.4.4 Test N5a. Linearity over full temperature range

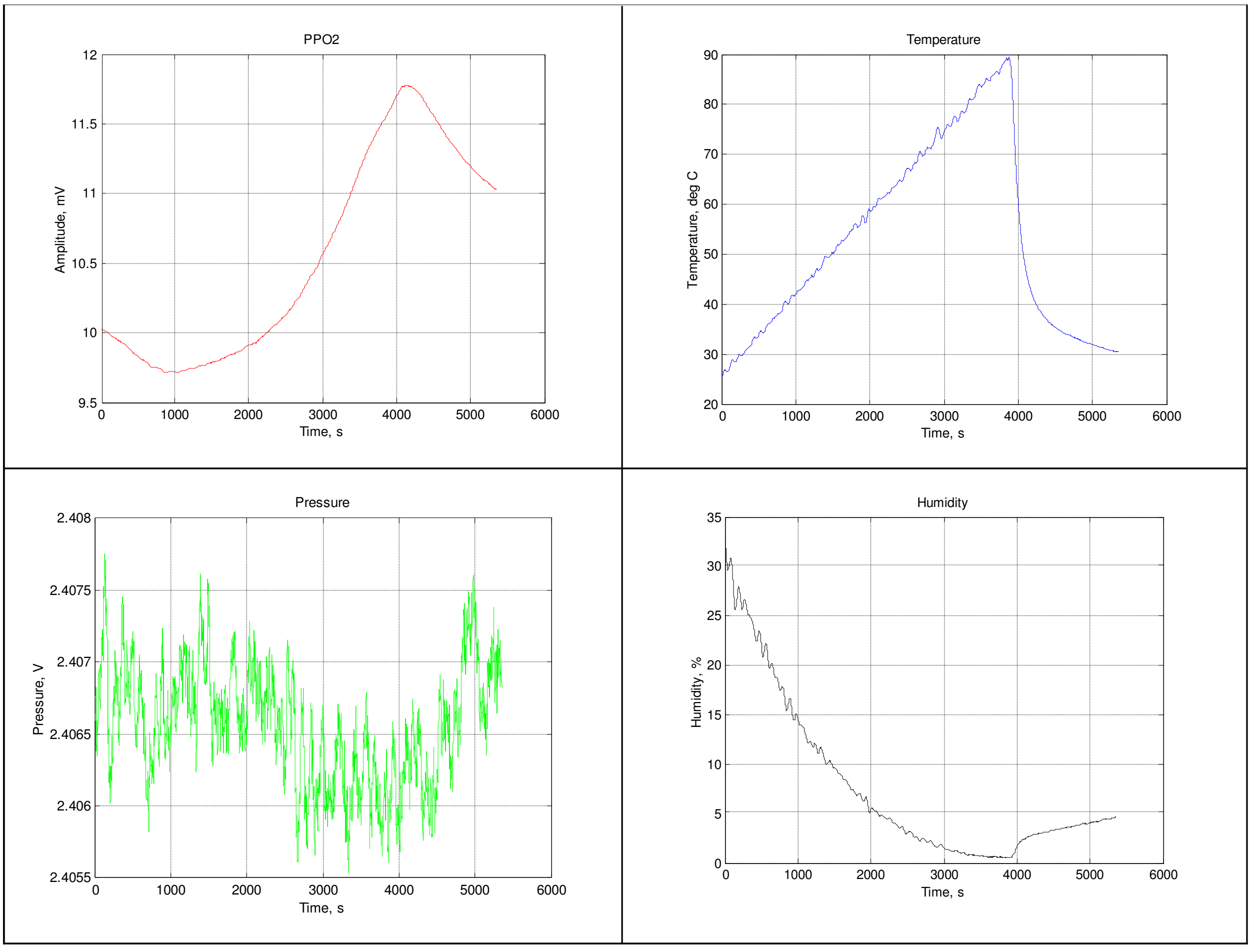


Fig 3-21. Sensor in temperature chamber

Review of the results from Test N4a, reported above, resulted in a request for further data. This second N4a test using a pulsed O2 stream was carried out just after the test N7 (high PPO2) when the sensor output is about 8 mV. Note the sensor had an output of 10 mV before test N7.

The results of the repeat N4a test are shown below.

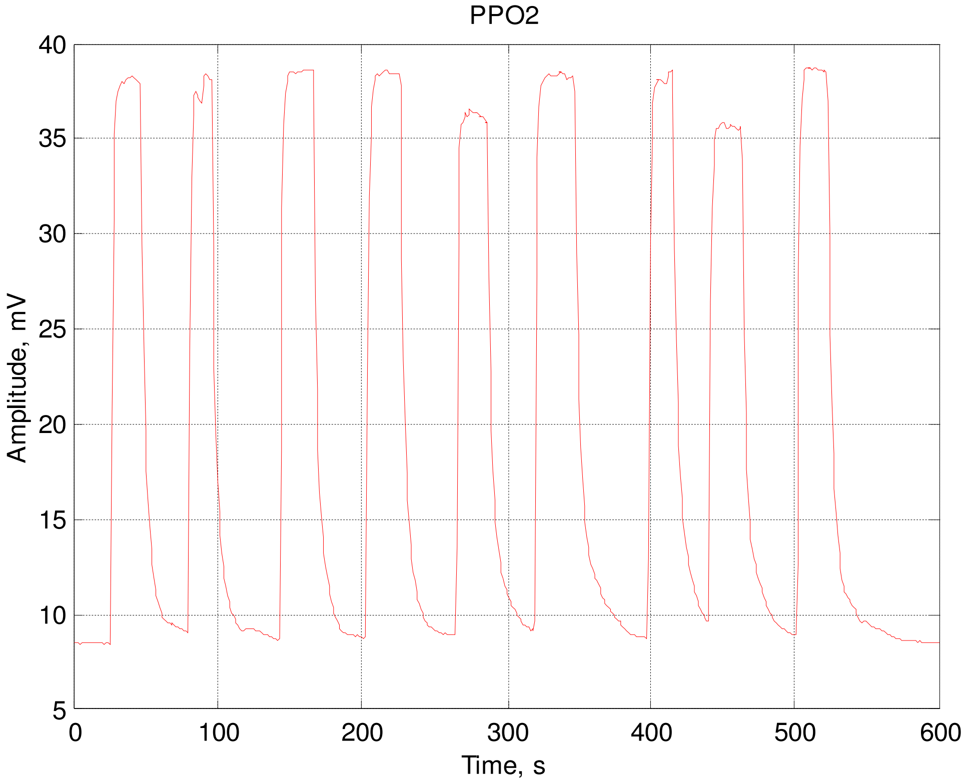
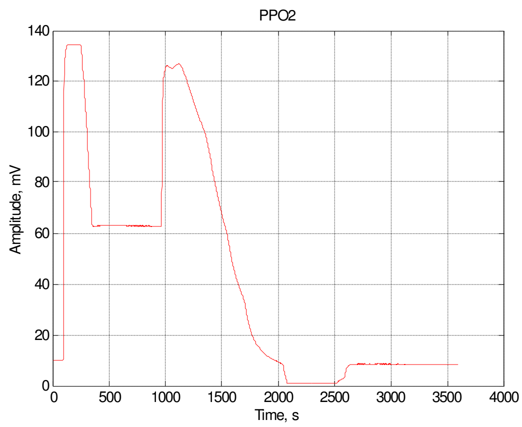
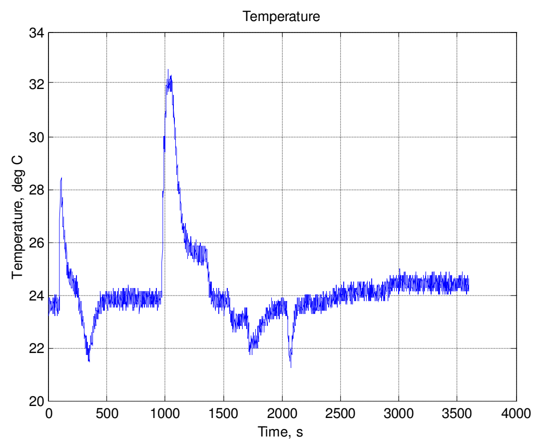


Fig 3-22. Response to O2 pulses. Pulse amplitude depends on the O2 flow rate and position of the tube end supplying O2.

14.4.5 Test N7. Operation across full PPO2 and pressure ranges





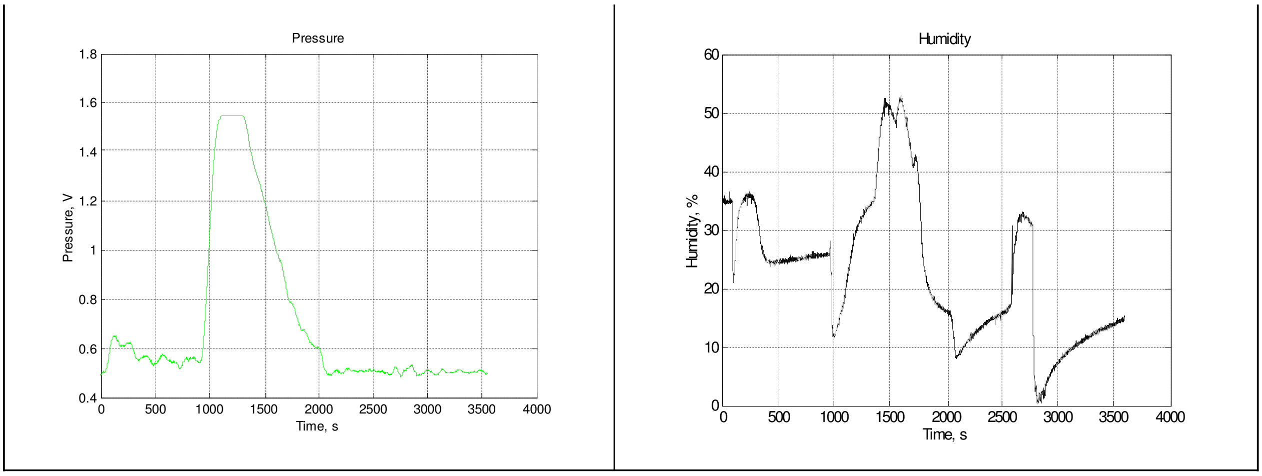


Fig 3-23. At first air pressure is increased up to 13.3 bar (123 msw, PPO2 of 134mV), which is considered the maximum sports diving depth. After a short soak period, the pressure is then dropped gradually down to PPO2 of 1.26 ATA or 62.4 mV. After allowing the pressure to settle for 10 minutes pure helium is added to the chamber to increase the pressure to 120 bar (twice the maximum planned operating depth for commercial dive operations).

14.4.6 Test N9. Chamber Lockout (Torpedo) test

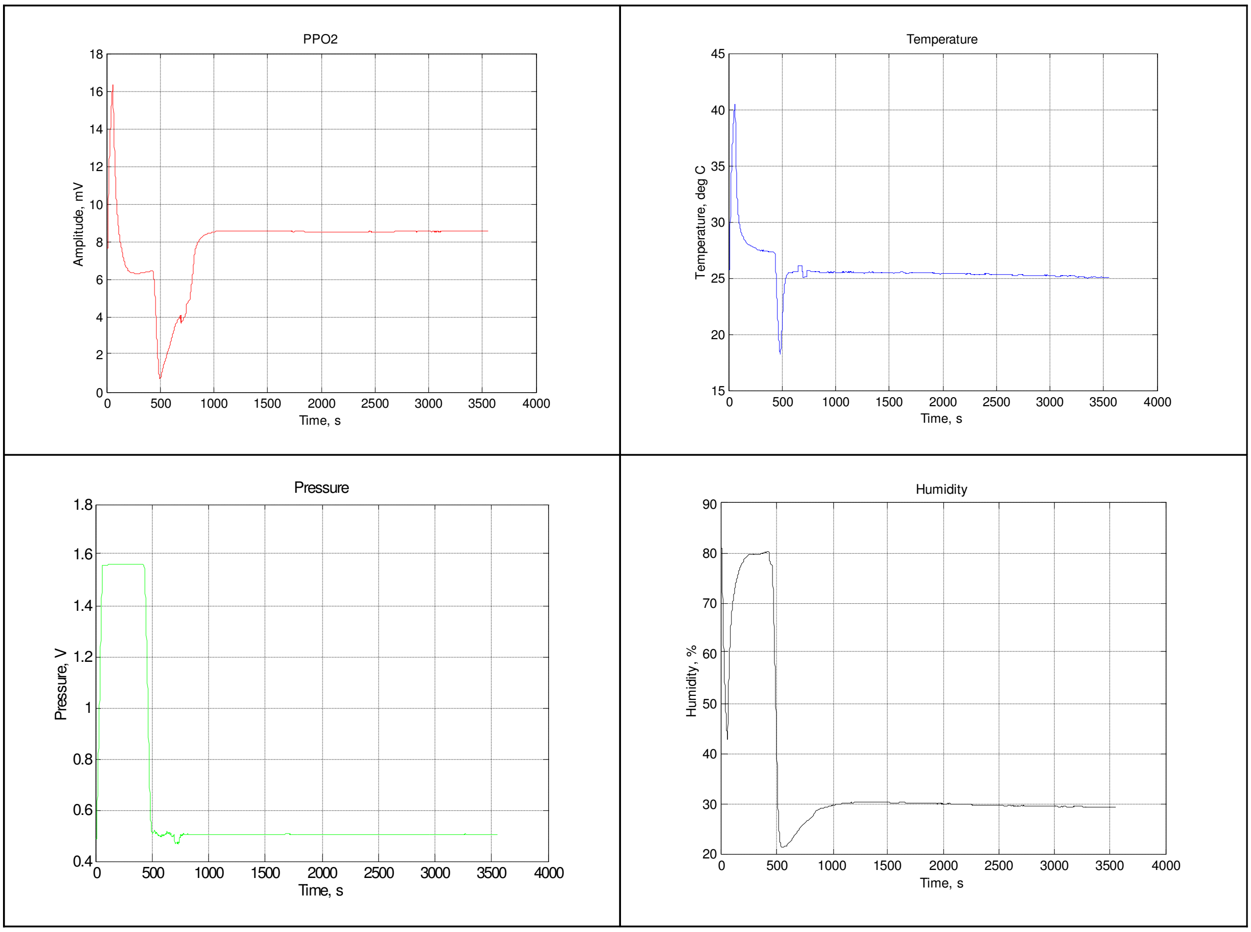


Fig 3-24. The test data. Pressure from 1 ATM to 115 bar in under 1 second, using He**.** There are no particles thrown out from sensor inside of chamber.

14.4.7 Conclusions from 2006 Retest of R17-D

- The output of R-17DA, serial_number: 655949, was 10.05 mV in atmospheric conditions, 40.5 mV in 100% O2 under 1 ATA, 0.3 mV in 1ATA where O2 is close to zero. This is a non-linearity of 15%.
- The sensitivity of the sensor to temperature is 1.5 mV/60 deg.
- The rising response time was 4 and 3 seconds in 100% O2 and CO2 flow respectively. The falling response time of 12 and 10 seconds when the corresponding flow is off: the off response is 7s and 9s after correction for residual O2.
- The amplitude of the response to O2 flow depends on the flow rate and the tube position.
- The sensor output amplitude is decreased from t0 mV in air to 8 mV during Test N7 with high PPO2, with a pressure soak of one hour. This is a 20% change.
- An anomaly was observed during N7 where the sensor displayed an increase in its output up to 125 mV during decompression. The possible reason of it is the fast rise in temperature.
- The R-17D sensor passes the Chamber lockout (Torpedo test) successfully.

14.5 Retest of Batch of R22-D in 2007

A batch of five R22-D sensors were procured in February 2007 and tested to determine whether Teledyne had addressed any of the design deficiencies identified. The sensors were procured from a Teledyne distributor with high turnover, as Teledyne was not co-operating with the trial. In fairness to Teledyne, Deep Life had not escalated this issue to the highest level because a major UK distributor disclosed that Teledyne had an anti-competition understanding with APD: the distributor copied DL on an internal email on this topic, accidentally, and discussion with that distributor concluded that Teledyne was not interested in carrying out changes or safety improvements for batches as small as 5000 sensors supplied in a single drop – the order size Deep Life offered to place.

Sensors currently under retest.

14.6 Conclusions for Teledyne cells in safety critical applications

The review team concluded that the Teledyne sensors should **not be recommended** for safety critical applications due to:

1. Serious quality issues: there is repeated evidence that Teledyne's quality control system is either not in operation or is ineffective.
2. The failure rates witnessed during the trial: the failure rate is far in excess of that predicted by Teledyne.
3. The Teledyne sensors tested displayed a range of dangerous failure modes, with leaking KOH and slow response. The former poses a health and safety hazard to the operator, and the latter has a unacceptable probability of lethal consequences for the diver (rated using QP-22). These failure modes arise from design and from production processes, and do not seem to be present in sensors from other companies that were tested.
4. During the trial it became apparent that Teledyne or their distributors have anti-competitive measures agreed with AP Diving. The legality of these are questionable, but their very existence reveals a less than tidy business ethic within Teledyne affecting the ability of Teledyne to supply the safest product for dive 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 second for the batch. The sensor is rated to produce 5mV in air, and measured at 4.999mV. It has a hydrophobic membrane fitted,

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 Fig 9-25 to Fig 9-29 show the Insovt DK-32 and the arrangements used for sea trials of the sensor.

Fig 9-25: 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 9-26: Side view of Insovt DK-32 after testing, showing the hard wired temperature compensation circuit potted into housing. Unfortunately it was functioning in reverse, causing a 2%/C change due to a circuit error.

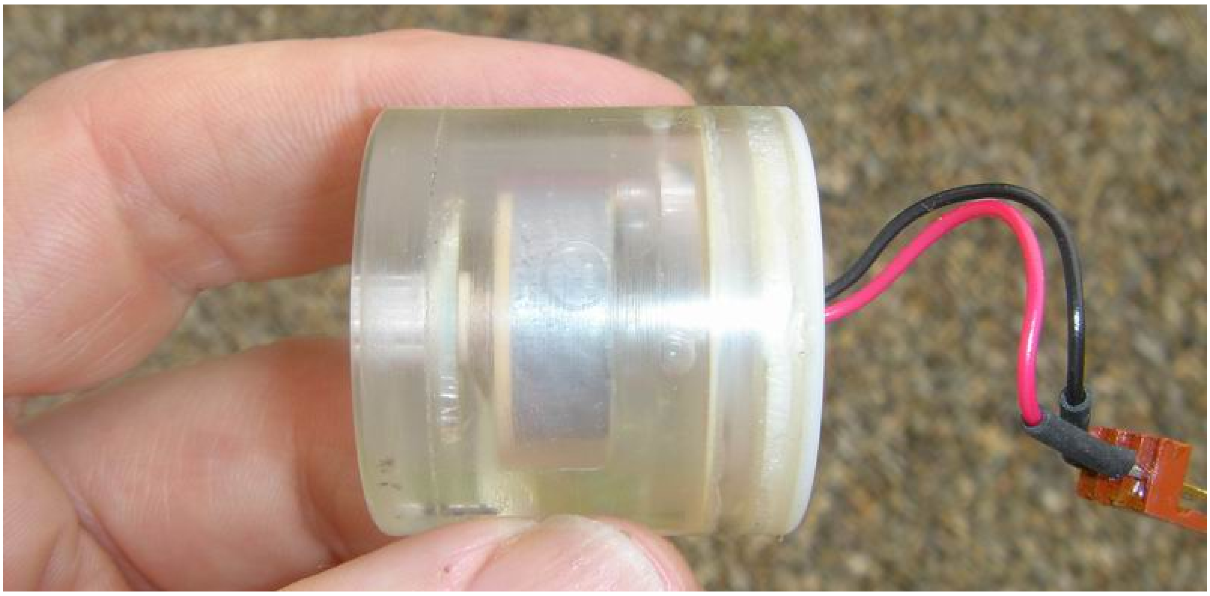


Fig 9-27: Insovt DK-32 showing KOH solution fill: bubble can be seen behind anode and also in second compartment. This shows the two part potting process to avoid contaminants affecting the cell. Note the thick material in front of the cell to prevent depressurisation forcing electrolyte out of the cell.

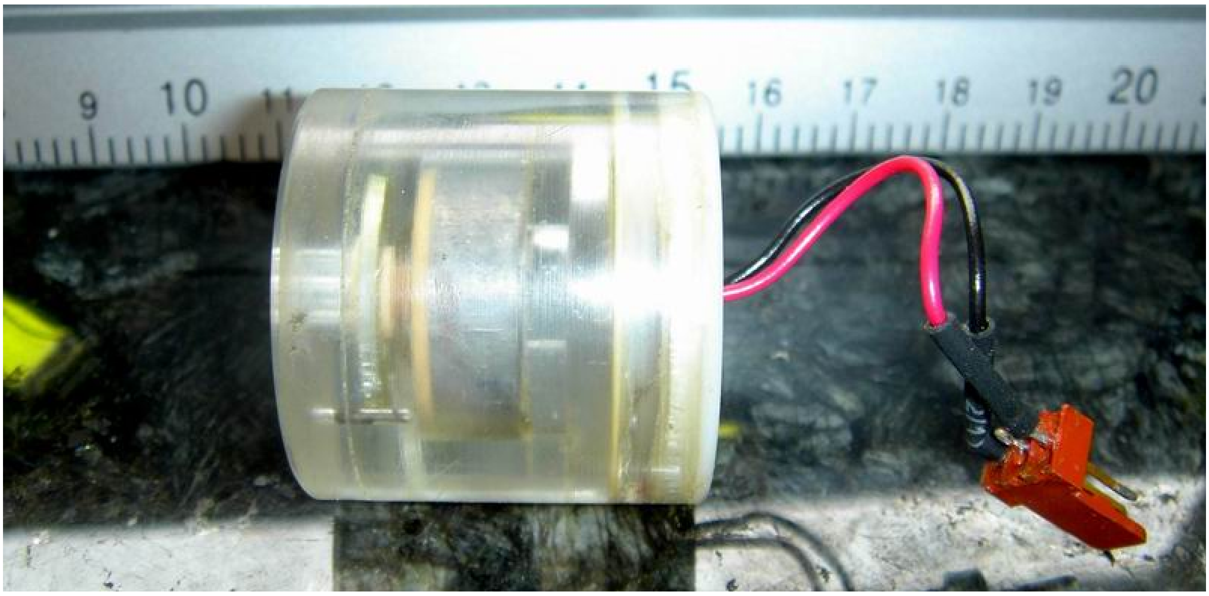


Fig 9-28: Insovt DK-32 with rule and angle showing the thick hydrophobic membrane in front of the cell

Fig 9-29: Test Rig using an improved AP Valves Inspiration Classic to test the Insovt DK.32s on dives. An ExtendAir scrubber was fitted, the batteries replaced by rechargeable lithium ion cells and the failure point at the top of the lid have been 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 sensor was trialed, 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, which 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 failure mode 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.

It was 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, as is required for commercial use, 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 responding slower than 10s (to 90% of final value).

16 Analytical Industries PSR-11-33-NM

SECTION REMOVED TO ENABLE TELEDYNE TO COMMENT WITHOUT DISCLOSING AI CONFIDENTIAL INFORMATION.

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 MD is a plug replacement for the Teledyne BUD2 and R22D.

The 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 equiped version of the MD in due course, but the samples tested had the Molex connector. The Molex connector presents a safety hazard for this application because it is corrodes, is not a reliable contact and it discharges static into the sensing electronics: it allows the signal to connect before ground.
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

SECTION REMOVED TO ENABLE TELEDYNE TO COMMENT WITHOUT DISCLOSING AI CONFIDENTIAL INFORMATION.

18.1 Sensor data

SECTION REMOVED TO ENABLE TELEDYNE TO COMMENT WITHOUT DISCLOSING AI CONFIDENTIAL INFORMATION.

Fig 5-30. Part of the test batch of MDR sensors.

18.2 Test 1: Dimensions

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

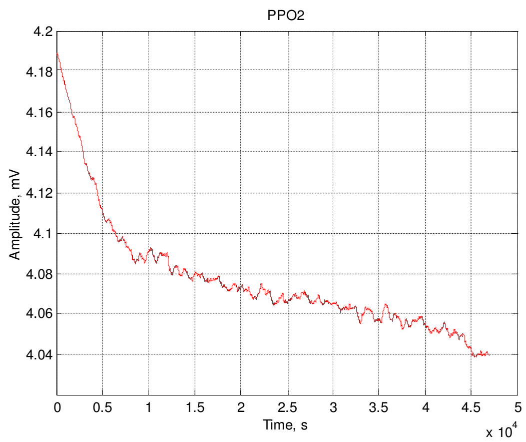
18.3 Test 2: Materials compatibility

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.

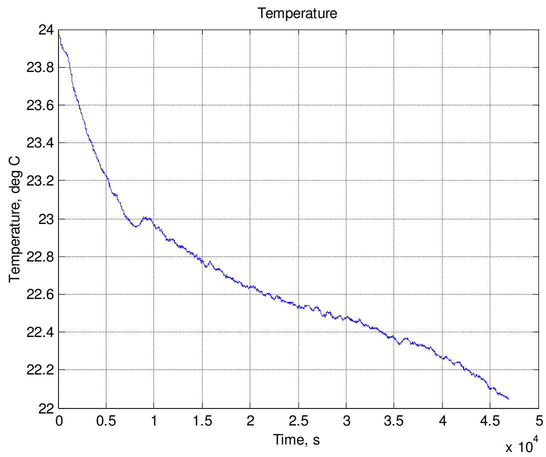
18.4 Test 3. Hydrophobic membrane

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.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%.	The sensor output change is 1.7%. Accept as a pass.

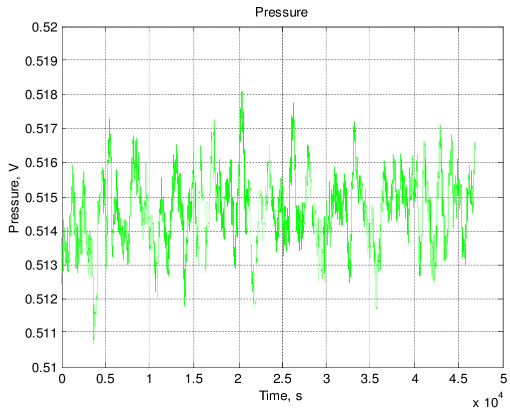
Step 2: Measure sensor voltage, and record temperature.



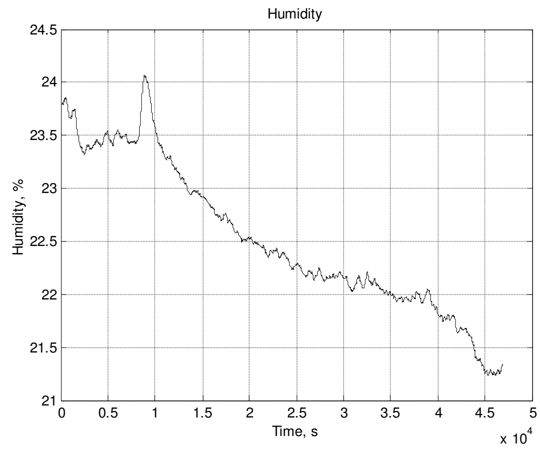
PPO2 mean = 4.08 mV



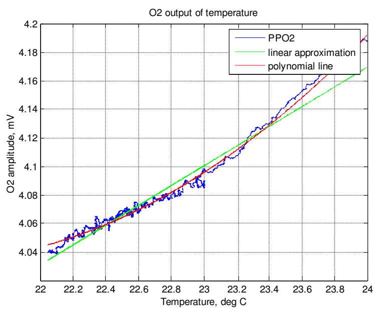
Temperature mean = 22.67 C



Pressure mean = 0.5146 V

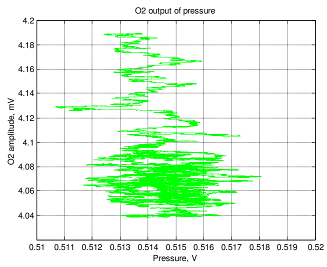


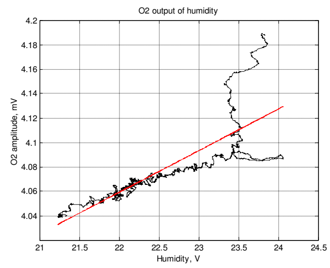
Humidity mean = 22.53%



p = [0.0693 2.5065]

0.07mV/K





p

= [0.0341 3.3097]

Fig 5-31. 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.

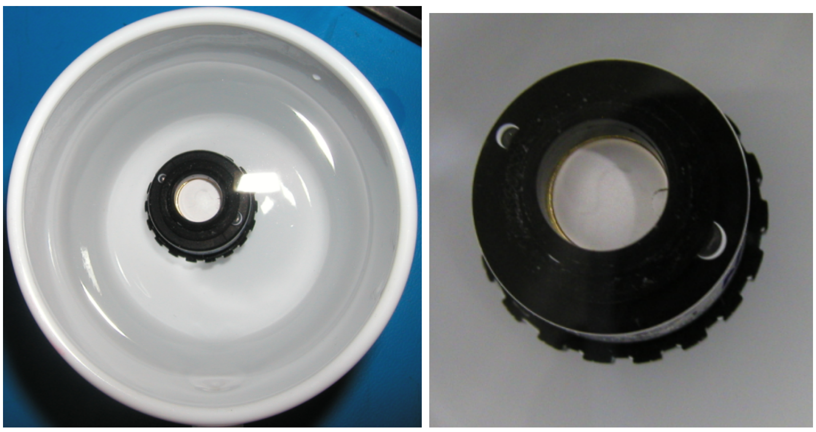


Fig 5-32. Sensor in water.

Step 4: Check for water held on the sensor face. There was none visible.

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

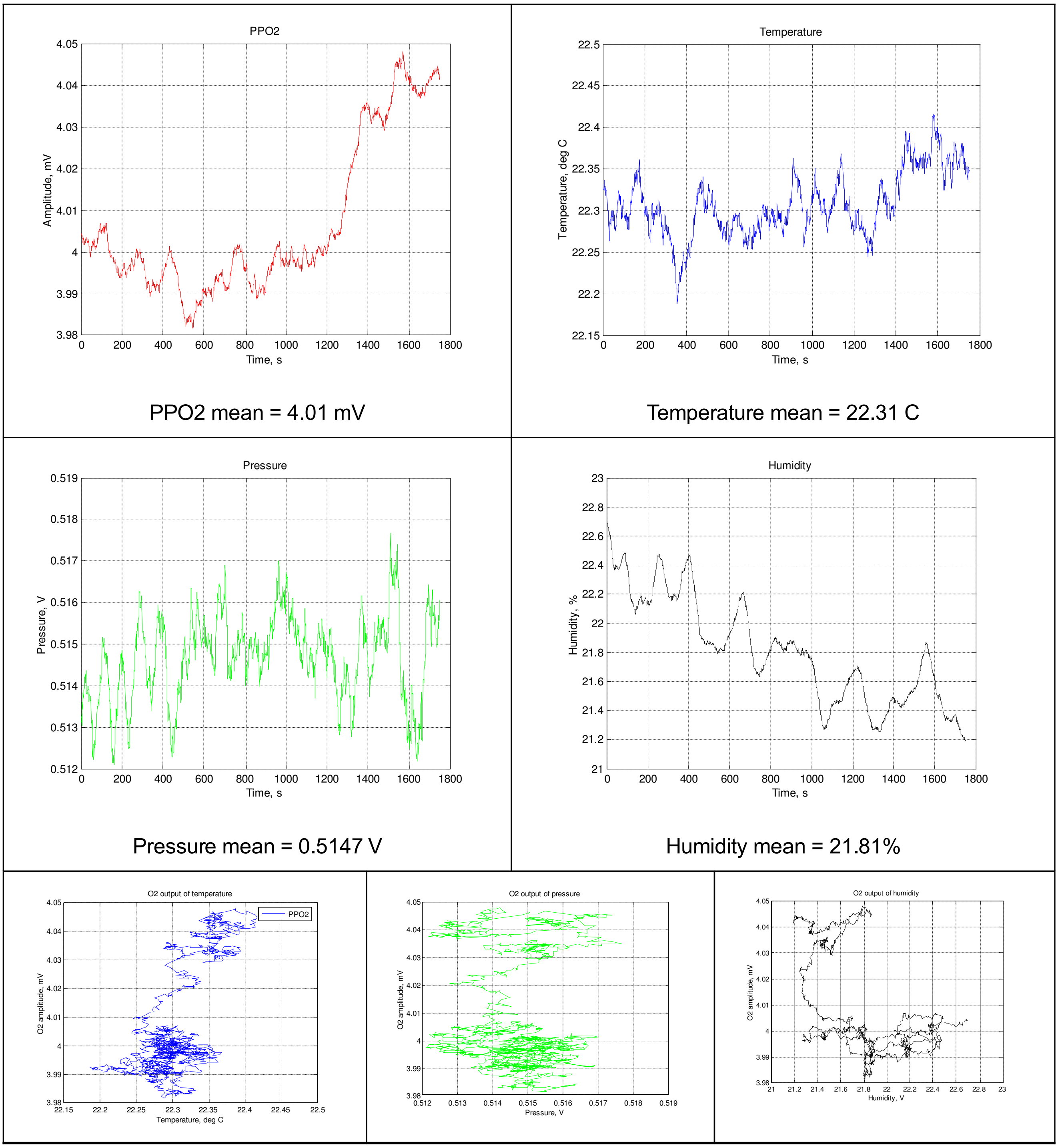


Fig 5-33. Sensor after immersion in water (filter: 50). The sensor output change is 1.7%. The ideal figure is under 1%, but after review, the result was acceptable.

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.

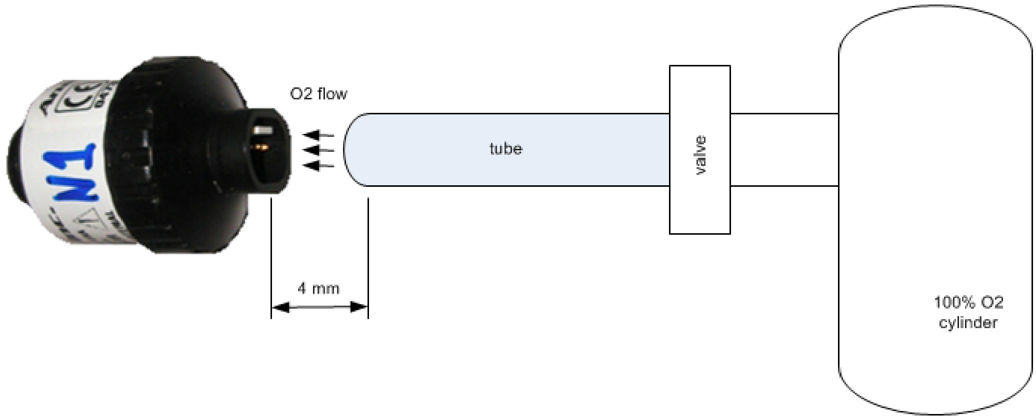


Fig 5-34. Test structure.

Step 2: Sensor 3. Experiment 1. Apply a stream of oxygen to a sensor with a pressure of 30mbar +/-20mbar. Measure the readings every 100ms.

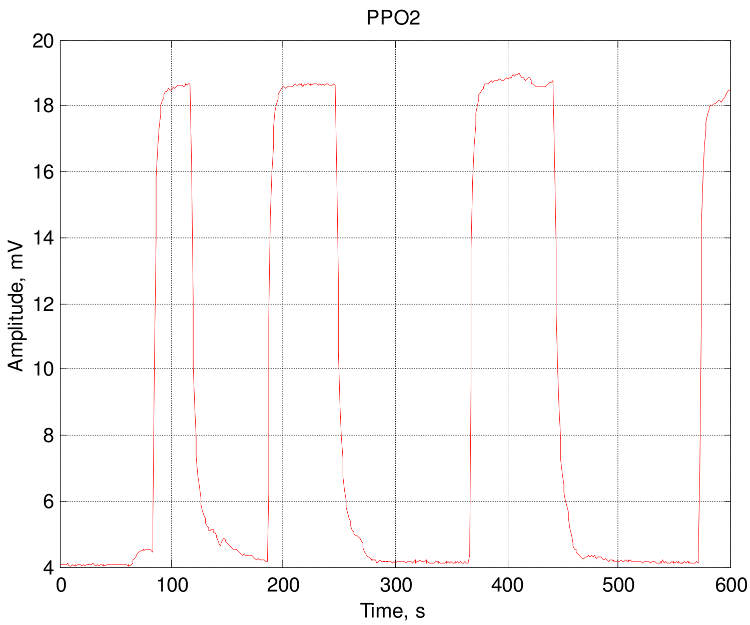


Fig 5-35. **Output from sensor with pulsed O2 flow.**

Step 3 & 4: Sensor 3. Experiment 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.

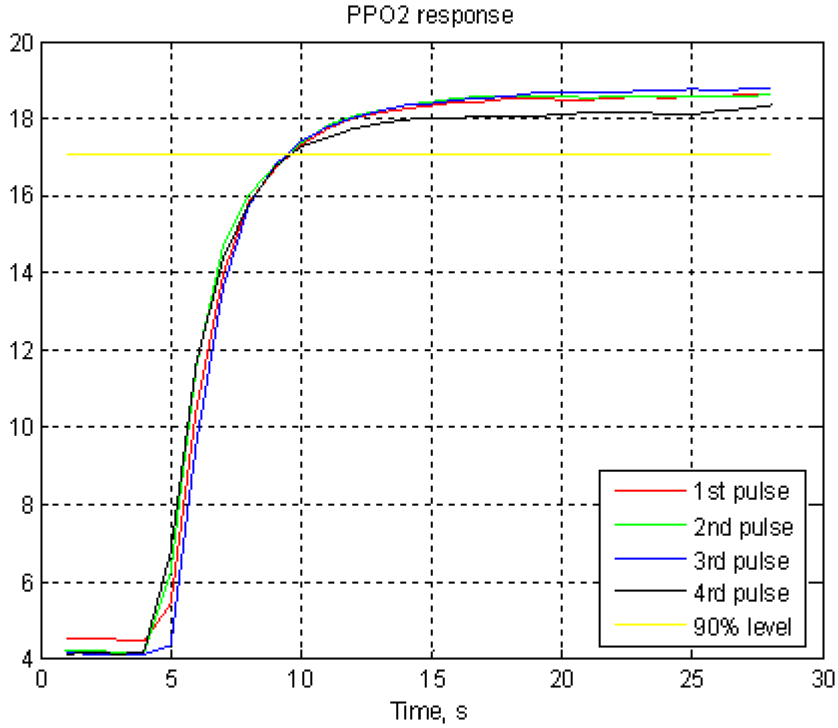


Fig 5-36. PPO2 time response. 90% level is 17.07 mV: (18.5-4.2)*0.9+4.2. Rise response is 6 s. The sensor output is about 18.5 mV when the sensor is in 100% O2.

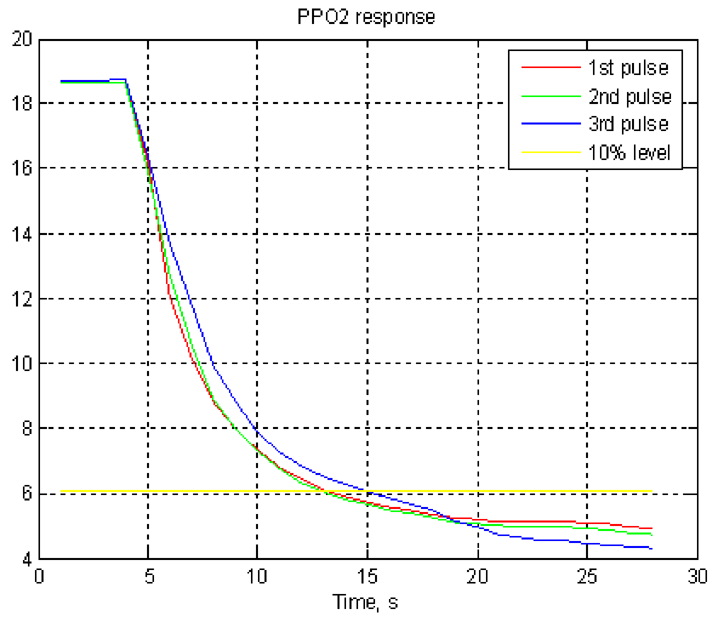


Fig 5-37. PPO2 time response. 10% level is 6.1 mV: (18.7-4.7)*0.1+4.7. Fall response is 10s. There is some retained O2 in the measurement fixture, so this figure equates to a fall response time of 6s.

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

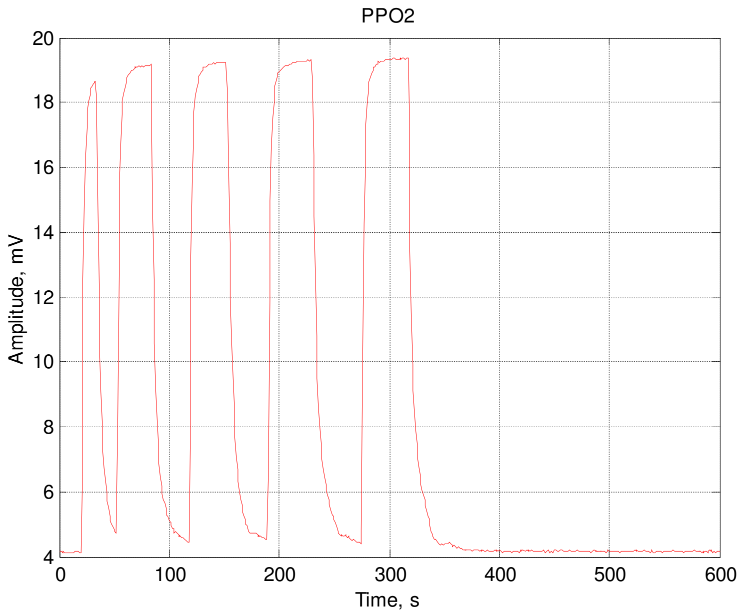


Fig 5-38. PPO2 of CO2 pulse flow.

Step 3 & 4: Sensor 3. Experiment 2. 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.

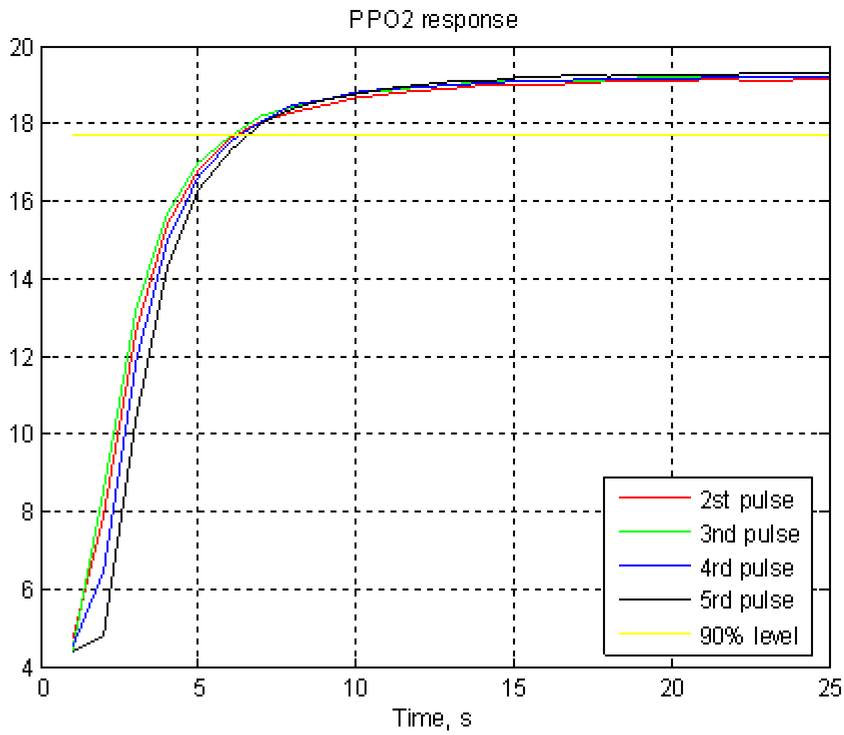


Fig 5-39. PPO2 time response. 90% level is 17.75 mV: (19.2.5-4.7)*0.9+4.7. Rise response is 6s.

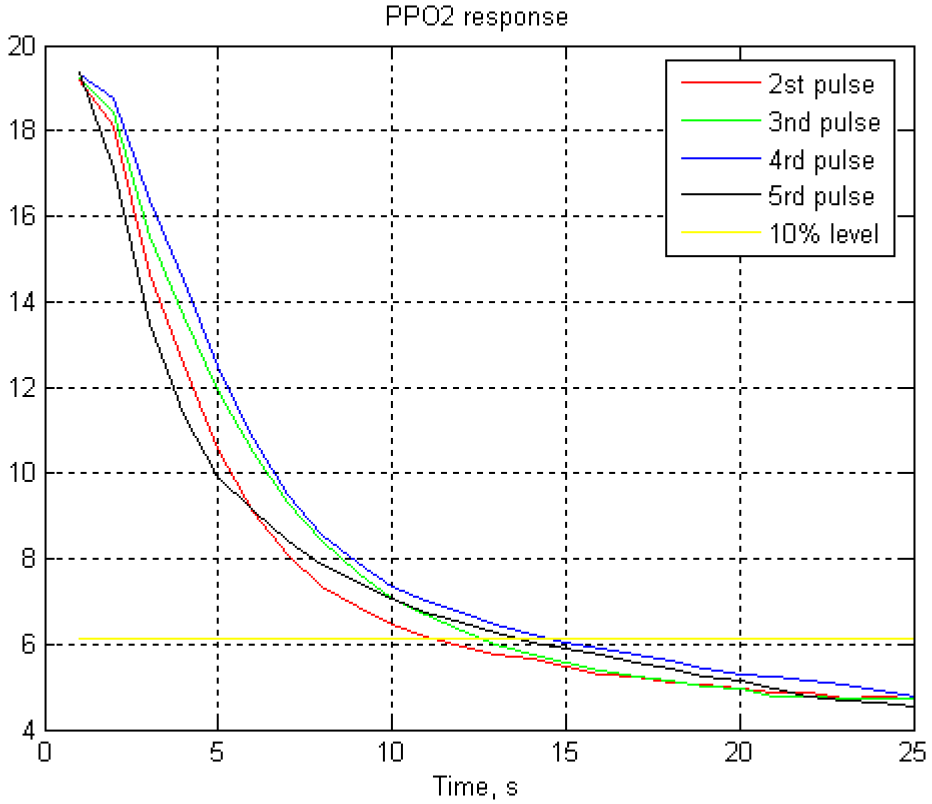


Fig 5-40. PPO2 time response. 10% level is 6.15 mV: (19.2-4.7)*0.1+4.7. Fall response is 13s, which equates to an actual response of under 10s due to the O2 retained in the cavity around the sensor face and in the tube.

18.6 Test 5a. Temperature range.

Test	Purpose	Method	Result
5a. Temperature range.	To verify linearity over full temperature range.	4. Use sensor 1 5. Place in the 300mm dia compression chamber immersed in saline, with the DL Compact Breathing Machine. 6. Cool chamber to -4C for 3 hours, then run breathing machine at 4x2.5l strokes per minute to mix the gas, record temperature, humidity. 7. Heat the chamber at 1C per minute to 90C. 8. Record temperature, pressure, humidity and measured PPO2 throughout test. 9. 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.

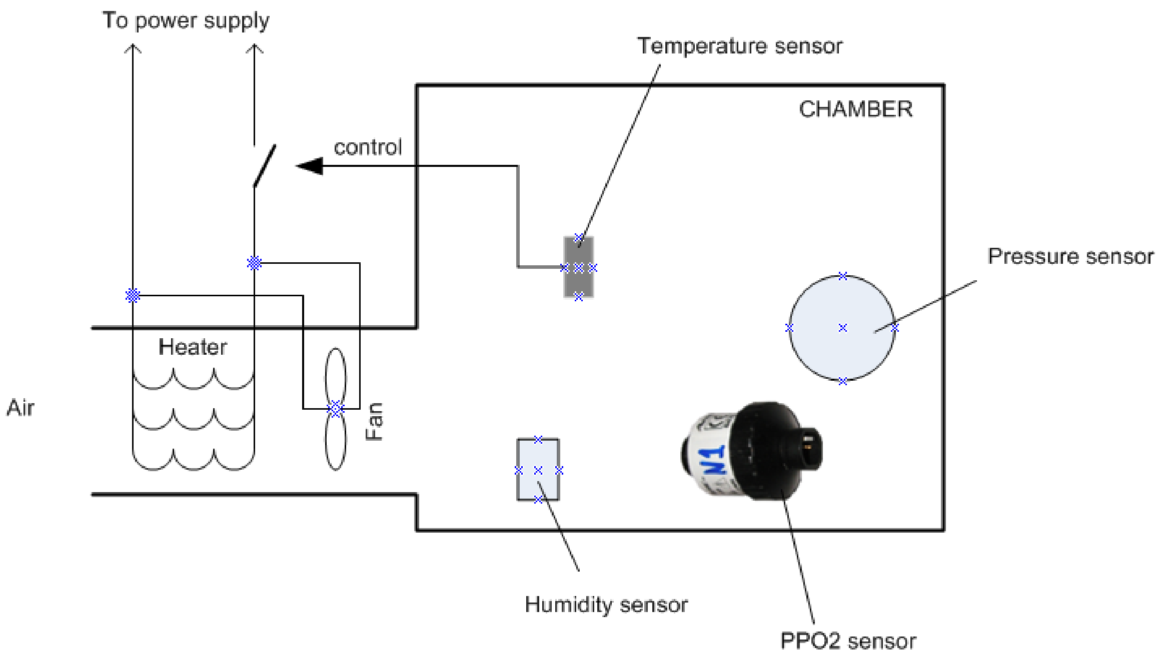


Fig 5-41. Test fixture for Test 5

SECTION REMOVED TO ENABLE TELEDYNE TO COMMENT WITHOUT DISCLOSING AI CONFIDENTIAL INFORMATION.

19 PSR 11-39-MD TEST RESULTS

SECTION REMOVED TO ENABLE TELEDYNE TO COMMENT WITHOUT DISCLOSING AI CONFIDENTIAL INFORMATION.

20 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 non-accelerated environment for the latest models of the sensors tested.
3. The MTBF data from Teledyne is not substantiated by this study and cannot be relied upon. The MTBF is probably a quarter of that claimed by Teledyne, based on the sample batches, with a disproportiate number of units failing early in their life. The failure modes that occurred were not observed, nor do seem to be report in the internet, for sensors from the two other vendors whose products considered in detail in this study.