ANALYSIS OF ACCURACY IN SERVICE OF OPEN REVOLUTION REBREATHER HELIUM SENSORS

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Revision History

Revision	Date	Description
A1	26th July 2007	Assessment of O.R. Commercial and Military diving helium sensors
B0	11th Sept 2009	Updated with latest circuit revision (Rev D0), for models OR_Incursion, OR_Umbilical and OR_Apocalypse Type IV.

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1. PURPOSE AND SCOPE

The purpose of the assessment reported here is to determine the accuracy that can be claimed for the helium sensor system in following rebreathers developed by Deep Life Ltd:

- OR_Apocalypse Type IV iCCR
- OR_Incursion,
- OR_Umbilical.

The scope is:

1. Determine whether the apparatus meets the relevant engineering and safety requirements.
2. Determine the maximum error likely in use. This is required to comply with a European PPE Directive audit that the apparatus is undergoing.

2. REQUIREMENTS

2.1. Safety Requirement to warn of narcosis hazard

The HAZID and FMECA for the apparatus (V6 Section 18.14: Narcosis Hazard) identifies a safety requirement is that a diver should not be exposed to dangerous levels of nitrogen narcosis without warning.

2.2. Safety Requirement to warn of decompression hazard

The HAZID and FMECA for the apparatus (V6 Section 15: Decompression Computer Hazard) identifies a safety requirement that the apparatus shall protect the diver against decompression hazards. Decompression hazards are intrinsic to the environment in which the equipment is used, when used for diving below 18msw. When Heliox or Trimix Gases are used, FMECA V6 Section 15, Item 9, identifies the need to measure the actual helium content of the gas. The accuracy required is that to avoid a significant decompression risk, which appears to be around +/-10%.

2.3. Engineering Requirement to provide accurate data for CO2 sensor compensation

The HAZID and FMECA for the apparatus (V6 Section 11: Carbon Dioxide Level Failures) identifies a safety requirement that the apparatus shall protect the diver against excessive carbon dioxide hazards, and concludes a carbon dioxide sensor shall be fitted. The Deep Life carbon dioxide sensor requires a working helium sensor with +/-10% accuracy, for the purposes of helium compensation when the apparatus is used with gas mixtures other than Oxygen, Air or Nitrox.

2.4. European Legal Requirement to quantify the helium sensor error.

A non-conformance has been raised by the Notified Body for the Design Type Approval of the apparatus under European Personal Protective Equipment Directive rules, that the helium sensor accuracy was not stated in the EN 14143:2003 compliance documentation.

3. APPARATUS UNDER TEST

Sixteen samples of the helium sensor used in the OR_Incursion and OR_Umbilical were presented, and four samples of the helium sensor in the CO2 monitor pod of the OR_Apocalypse Type IV iCCR.

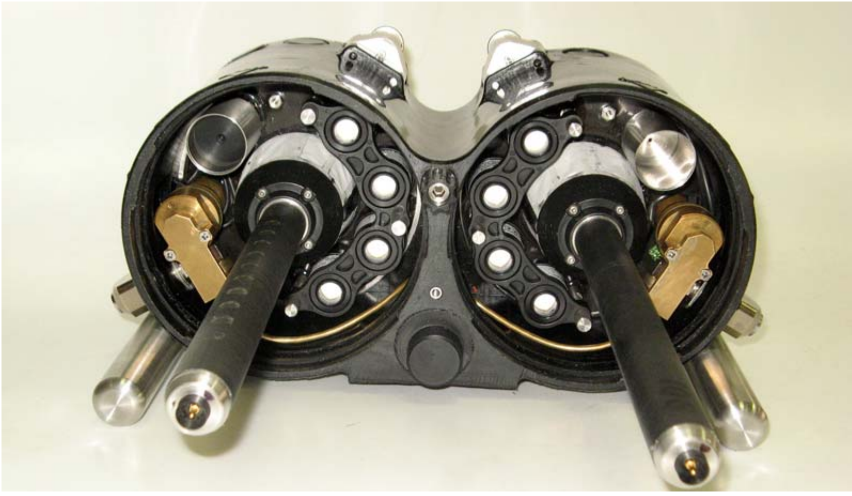

Figure 1. One pair of helium sensors fitted to an OR_Umbilical rebreather sample. The sensor is located in the "scrubber stick", in the sensor bell. This is screened by a hydrophobic membrane, in white at the bottom of the "scrubber stick".

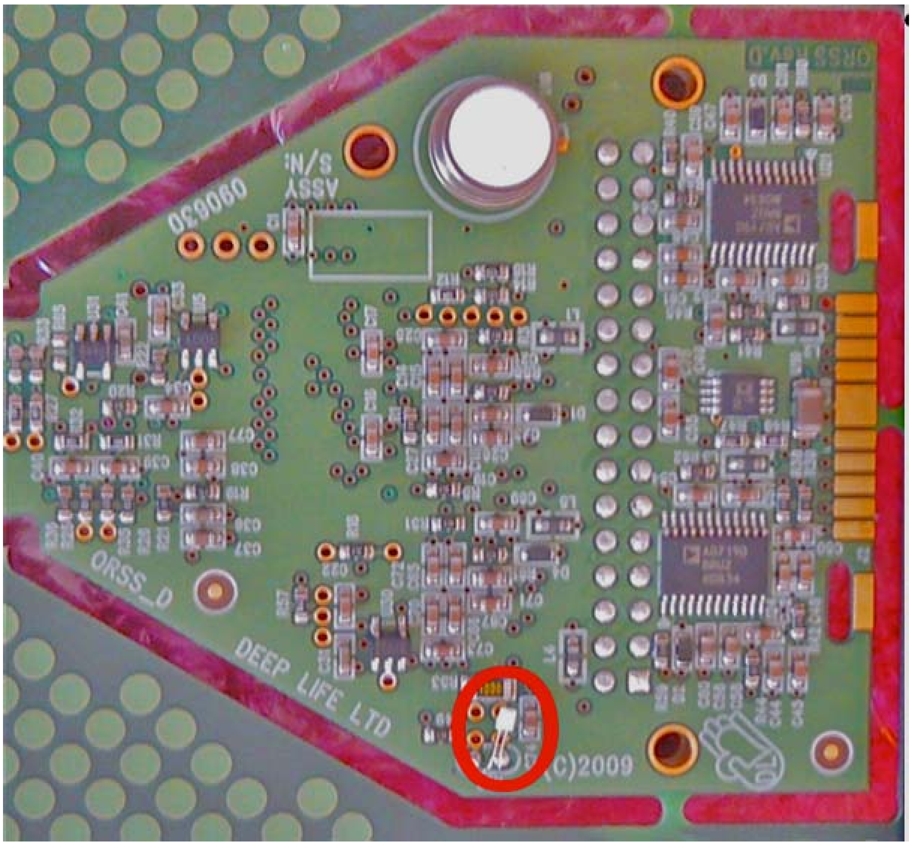

Figure 2. Subassembly provided by Deep Life Ltd to enable the sensor to be photographed because the sensor inside the sensor bell was not readily visible. Mounting fixture is removed to show the sensor. The platinum film resistor sensor is the small white object on leads in the bottom middle of this image, highlighted in RED.

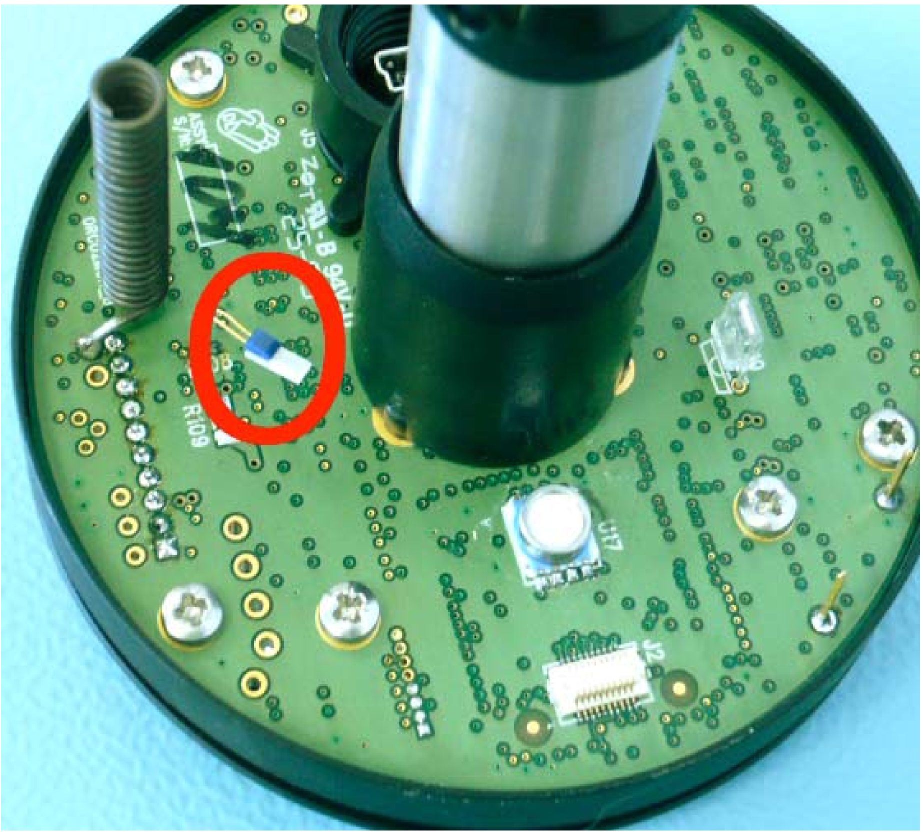

Figure 3. Subassembly provided by Deep Life Ltd to enable the OR_Apocalypse sensor to be photographed: on the OR_Apocalypse CO2 pod: the sensor is not normally scarcely visible inside a mounting fixture. The entire area is covered with a gel on the finished products, making the sensor even harder to visualise. The sensor is the small white object on leads in the left middle of this image, highlighted in RED. This is the same component as on the OR_Umbilical and OR_Incursion “scrubber stick” in the previous figure.

There are two circuit versions of the helium sensor: the OR_Incursion and OR_Umbilical locates the sensor within a condensation protected areas called “the sensor bell” and OR_Apocalypse iCCR presents the sensor and in a low condensation location on the OR_Apocalypse. The OR_Incursion and OR_Umbilical helium sensors are identical, using the same physical subassembly. The OR_Apocalypse iCCR uses a different physical subassembly, but the sensor, circuit and operation of the sensor is the same as for the OR_Incursion and OR_Umbilical .

The range of sensor resistances that may be fitted is expressed as a resistance to loss equation: with the low loss fixings it is 100 Ohms, and with the high thermal loss fixings it is 22 Ohms.

The helium sensor is difficult to photograph: it is not normally visible in any of the three rebreather models. BAI require sight of the item being assessed: to meet this Deep Life provided an assembly prior to final assembly shown above, and a similar OR_Apocalypse assembly.

All Bills of Material for Rev D show the same sensing device: a platinum film resistive sensing device, in the same circuit configuration, other than the OR_Apocalypse being a subset (i.e. Fixed 100 Ohm resistor with low thermal loss fixing, or 22 Ohm resistor with a high thermal loss fixing. The driving voltage ranges from 4.85V to 6V: the 4.85V drive voltage is clearly the worst case, as it will take longest for the sensor to reach its threshold temperature.

4. METHOD

The requirements set down in the previous section require a traceable helium accuracy statement that recognises that the equipment is used under a wide range of pressures, helium concentrations and pressures.

The helium sensor is calibrated during manufacture using an Innovision Amis 2000 Mass Spectrometer, with an error of 0.5%., and span gas of 0.4% accuracy (a combined sum of squares accuracy of 0.65%) This means that there is no point in measuring the sensor against the reference under the same conditions: it will always be the same because the calibration sets it to be the same. Moreover, measurement against the reference provides data only under the reference conditions but the operational conditions of the helium sensor cover a wide range of depths, gas mixtures, ambient temperature, condensation and helium fractions.

The approach that is taken herein is to measure the operation of the sensor, after calibration to 0.5% accuracy, and determine the variation with each of the environmental parameters.

It was of benefit to BAI that Deep Life provided the formal models describing the theoretical performance of the sensors: these were used extensively by BAI in this assessment and are compared with empirical measurements. An analogue output from the sensor was also provided by Deep Life to enable BAI to log the sensor output values.

Examination of the formal models for the sensor supplied by Deep Life Ltd, revealed that the worst case for the helium sensor is a high resistance with a high thermal loss fixing. The borderline case was the high thermal loss fixing with a 33 Ohm resistance because the thermal loss would be closest to the energy input, so at low ambient temperatures it would not reach its threshold temperature. BAI therefore requested that configuration, and the standard 100 Ohm low loss and 22 Ohm high loss configurations, for the test samples.

Deep Life provided two outputs from the helium sensor: period and output voltage.

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5. EQUIPMENT USED

Sixteen samples of the helium sensor in the OR_Incursion and OR_Umbilical were presented, serial numbers N001 to N016. Of these, N003 and N004 was picked at random. These are marked as circuit revision Rev D.

Four samples of the OR_Apocalypse helium sensor, marked A_PPO2, helium sensor circuit revision Rev D.

The samples match the circuit schematics in all material regards, and were measured against a formal model for the sensor supplied by Deep Life Ltd for that circuit.

In addition to the apparatus under test, the following equipment was used:

Equipment	Serial Number	Calibration Log Number	Calibration Next Due
Deep Life 800x600 mm chamber, with environmental control, rotatable	CH03	N/A	Next hydrostatic Sept 2009
Deep Life 200mm chamber	B05	N/A	Next hydrostatic 2nd Sept 2010
Innovision AMIS 2000 Mass Spectrometer	0911243	41	Calibrates automatically against certified span gas prior to and after each use
Tektronix TDS 94D Oscilloscope	B031889	18	15th Dec 2009
HP 1663 Logic Scope	US37040105	14	15th Dec 2009
Tektronix Active Scope Probe P6245	X003386	19	15th Dec 2010
Analox 5S Mk II CO2 transducer	DL010	9	Calibrated before each use
Tektronix Active Scope Probe P6248	B014979	20	15th Dec 2010
Time Instruments, Laboratory Grade Digital Computing Multimeter, 8.5 Digit, TTi 1906	111474	13	14th Dec 2009
Keller LEX1 Pressure Sensor	002333	37	16th July 2012
Digital Pressure Sensor MS5535A	DL004	6	Calibrated against Keller LEX1 during test
National Instruments Data Acquisition System PC6014	HA4375847	15	Calibrated against TTi 1906 during test

6. HE SENSOR SOURCES OF ERROR

6.1. Effect of Ageing and Drift

The sensor was exposed to the normal laboratory environment for a month: there was no observed drift other than short term drift which is visible over an interval as short as 90 seconds. All the materials used in the sensor are of a type that would be expected to be stable over time.

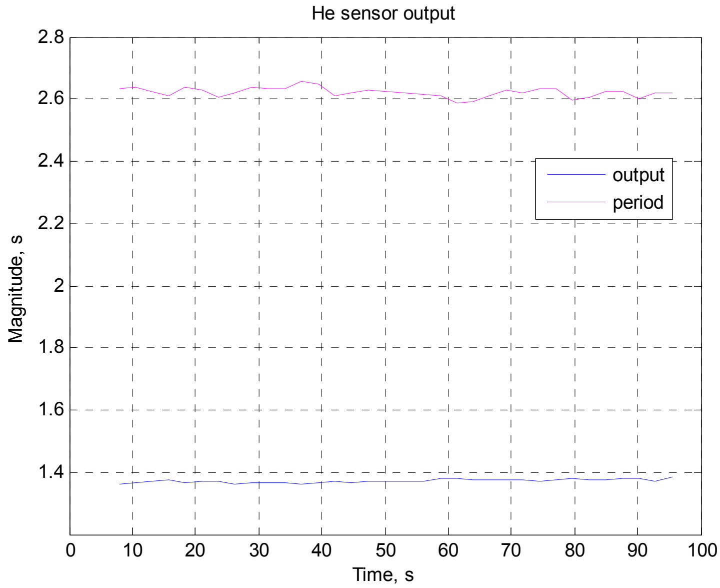
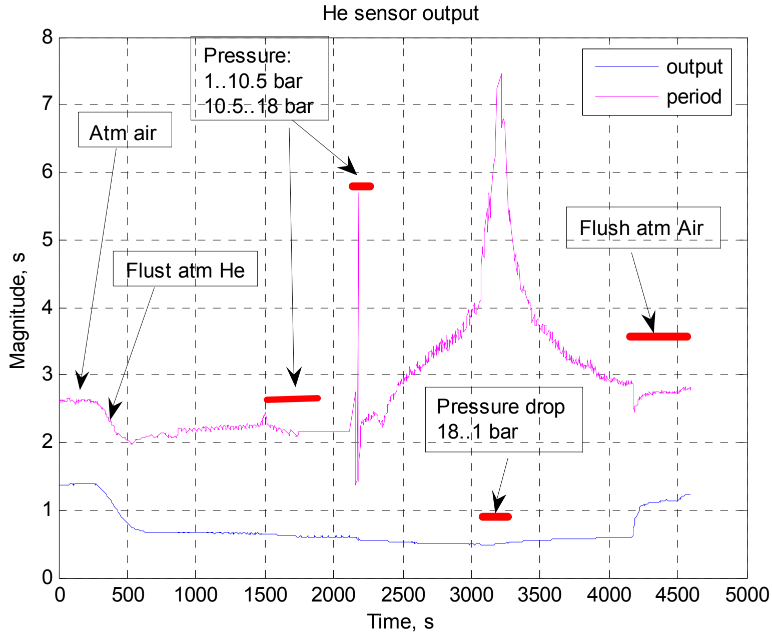


Figure 1. He sensor output short term drift in open laboratory conditions. He: min = 1.3605, max = 1.3830, range = 0.0225. mu_He = 1.3719 [1.3697 1.3741], sigma_He = 0.0061 [0.0049 0.0081]. He_period: min = 2.5890, max = 2.6560, range = 0.0670. mu_He_period = 2.6220 [2.6163 2.6277], sigma_He_period = 0.0159 [0.0127 0.0211]. Data file: scr_st_long_data_0051.mat.

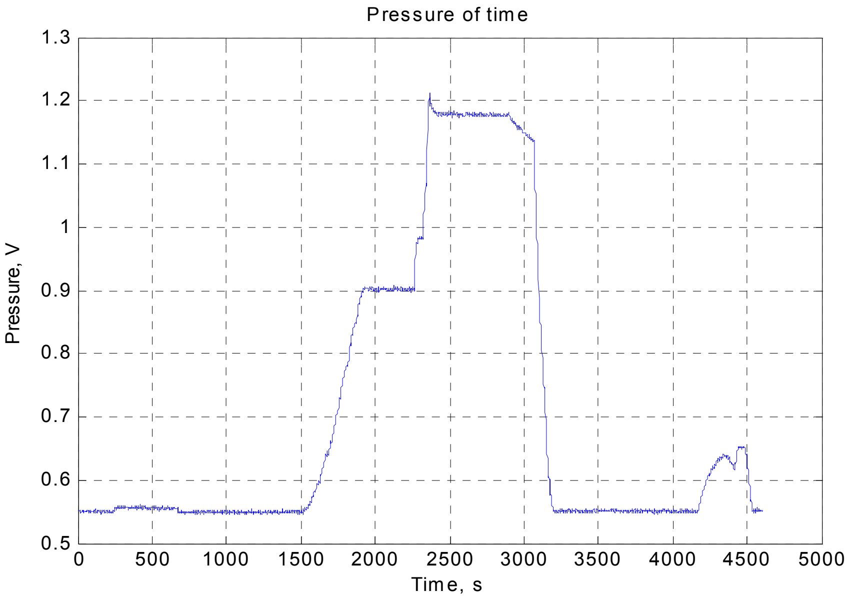
6.2. Effect of pressure

Samples N003, N004 and A001 of the helium sensor was placed in a pressure vessel that was flushed with helium, then pressurised with helium to 18 bar. During pressurisation and depressurisation rapid changes in temperature occurred. Pressure, temperature and the helium sensor output were logged. The results appear to be the same, except that samples N003 and N004 displayed a rise in sensor heating time as the temperature dropped, as shown overleaf.



He: min = 0.4820, max = 1.4020, range = 0.9200

He_period: min = 1.3710, max = 7.4490, range = 6.0780



Raw output from the pressure sensor. 0.56V corresponds to 1 bar, and 1.18V corresponds to 18 bar.

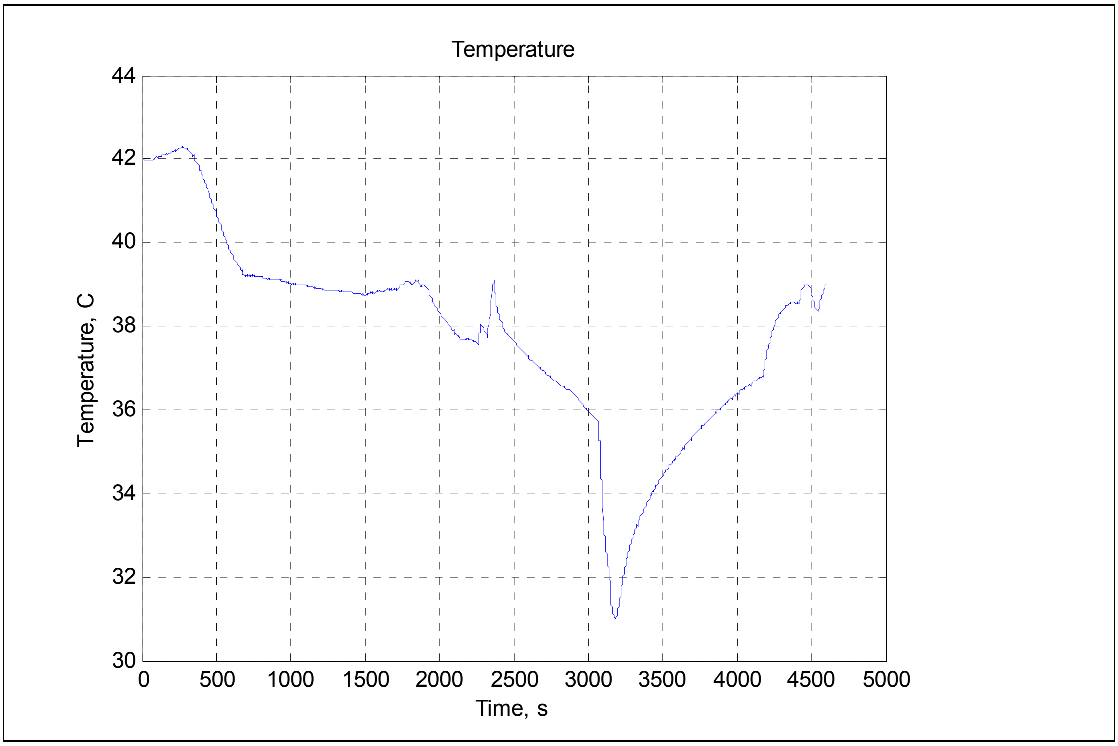


Figure 2. He sensor N003 output during a pressure sweep from 1..18 bar, and back to 1 bar. The He sensor output and period changes as a function of temperature and He gas concentration, but does not depend on pressure. Data file: scr_st_long_data_0052.mat. (Empirical data)

It is noted that the operational pressures for the equipment may extend to in excess of 600msw, but it is was clear already by the 18 bar test, that the output from the helium sensor is not a function of pressure.

This result validates the assertion by Deep Life that the sensitivity to helium pressure is not significant. The test results affirm the claim made by Deep Life that the helium thermal conductivity coefficient increases from 0.152 watt/(m*K) to 0.157 watt/(m*K) when pressure increased from 1 bar to 100 bar for temperature=300K. That is, there is a 3.2% change over a 100 bar range, and under 2% over the range for which diving operations are carried out. It would be a simple matter to compensate for this error, but the samples examined do not. Dr. Deas of Deep Life Ltd was asked about this and answered that the pressure effect causes an error of less than 0.4% over the normal diving range of surface to 100msw, so the extra complexity of the compensation is not justified. Dr Deas explained that the compensation is not trivial, because pressure sensors have a high failure rate, so to prevent one sensor causing a cascade failure it would be necessary to bracket the compensation in any case. These values quoted by Deep Life for the pressure related error agree with those concluded by BAI above.

6.3. Effect of Ambient Temperature on He sensor heat stabilisation

The helium sensor operates by heating a platinum resistor above ambient, and monitoring the cooling time. The temperature that the equipment heats the sensor to is designed to be at least 30C above ambient, with a maximum of 80C and a minimum of 50C. The correct function of this was assessed by sweeping the ambient temperature and measuring the performance of the sensor in place in the rebreather.

During the tests, the rebreather and the carbon dioxide sensor prevented a wide temperature sweep: the ambient temperature in the measurement bell appears to self stabilise at between

30C and 37C because the CO2 sensor is heated, and the helium sensor is located next to the CO2 sensor. To perform a full range test would involve creating artificial conditions outside the scope of this assessment.

The ambient pressure was held constant, and the helium concentration was increased. Data was taken directly from the sensor, bypassing all compensation and calibration. The helium sensor heating time was taken to be the Helium sensor period minus the He sensor output. The He sensor cooling time was the He sensor direct output.

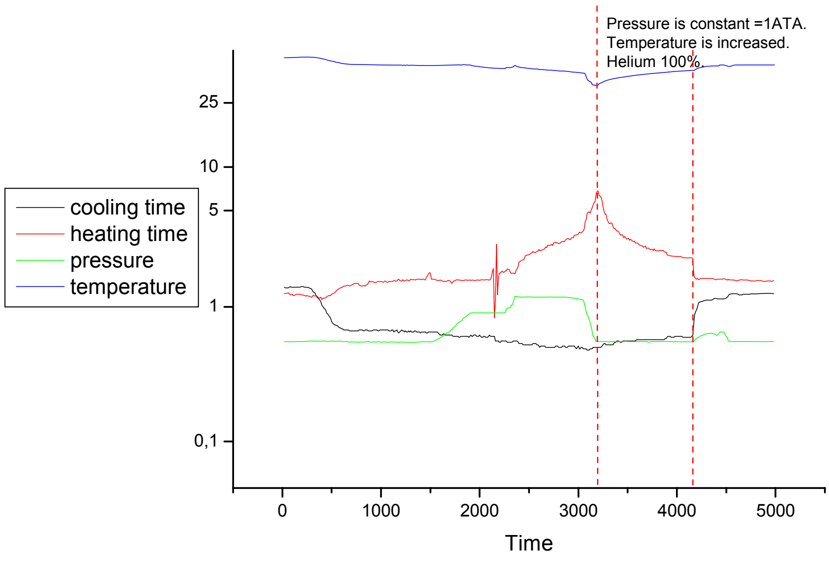


Figure 3 He sensor cooling time (seconds), He sensor heating time (seconds), ambient pressure (bar absolute) and temperature (Celsius). (Empirical data). The output in air at the start and end of the test is shown: for the test the environment was flushed to be 100% O2. This test indicates an interesting increase in heating time as the temperature falls, which was then considered in detail.

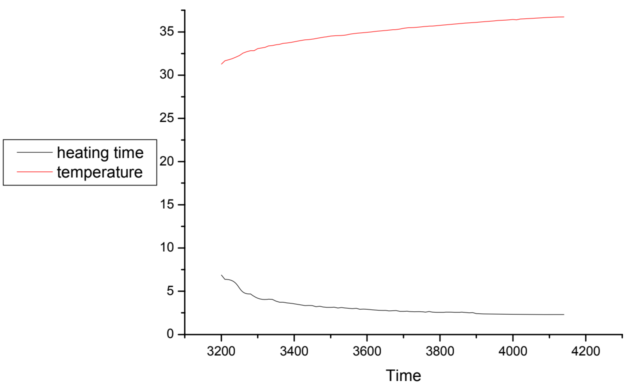


Figure 4 He sensor heating time and temperature for a constant pressure interval in Helium. (Empirical data)

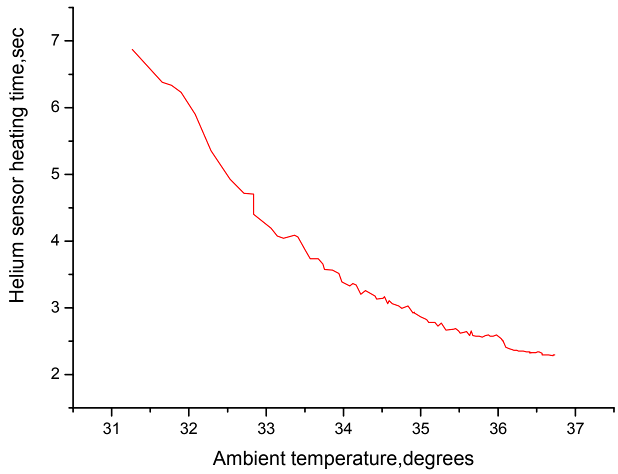


Figure 5 He sensor heating time vs. temperature for constant pressure interval in Helium. (Empirical data)

The empirical data was compared with that produced by Deep Life's formal model for the sensor. The model used first order differential equation for thermal current that Deep Life solved manually to obtain a Heating Time equation:

$$T + \left(\frac{d}{dt}T\right)\cdot Rt\cdot C = \frac{V^2}{Re}\cdot Rt + Te$$

$$\text{Heating Time} = Rt\cdot C\cdot \ln\left[\frac{\left(\frac{V^2}{Re}\cdot Rt + Te - T2\right)}{\left(\frac{V^2}{Re}\cdot Rt + Te - T1\right)}\right],$$

Where

- Rt - thermal resistance between He sensor and environment((second*degree)/(joule))
- C - He sensor thermal capacity(joule/degree),
- V- Heating resistor supply voltage (V),
- Re- Heating resistor resistance (Ohm),
- Te- Ambient temperature (Celsius degrees),
- T1 – Trigger threshold temperature to start cooling (Celsius degrees),
- T2 – Trigger threshold temperature to start heating (Celsius degrees),
- T - Helium sensor temperature (Celsius degrees),
- t- Time(seconds).

The constants for the circuit being tested, at the highest temperature setting, are defined in the circuit examined as:

$$Rt := 69.961 \quad C := 0.058 \quad T2 := 75 \quad T1 := 80$$

$$Re := 33 \quad V := 4.85$$

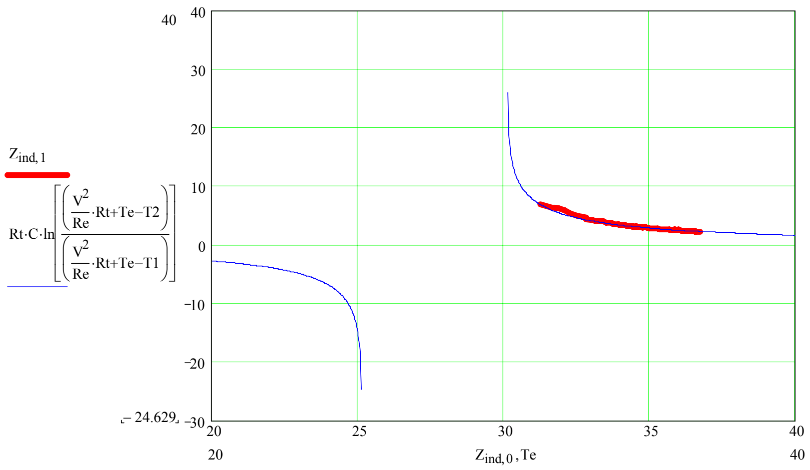


Figure 6 He sensor heating time vs. temperature for constant pressure interval (1ATA) in Helium 100%. Blue – mathematical model. Red –empirical data.

The figures Rt=69.961 and C=0.058 match exactly the figures obtained by the temperature sweep. The constants T1=80 C and T2=75 C are established by examining He sensor schematics parameters. Re=33 Ohm for the high ambient setting, and 22 Ohms at low ambient: the OR_Apocalypse is fixed at 22 Ohms. V was measured at 4.85V on two samples, but is varied automatically over the range 4.85V to 6V, to achieve the target heating temperature. The OR_Apocalypse sensor is fixed at 5V.

Near Te=30 C, with the 33 Ohm resistor the He sensor heating time becomes infinity because there is insufficient heating power to reach the 80C threshold. When this occurs, the circuit increases the drive voltage from 4.85V up to a maximum of a 6V drive voltage to achieve the desired heating power at ambient conditions under 30C, and below 10C ambient, reduces the heater temperature to a 50C to 55C range. This system is claimed to allow the Helium sensor work down to 1C. This scheme was validated by comparing the models, as the calibration process removes the error to the extent that the empirical measurements are correct (artificially, because they are calibrated against a mass spectrometer to be correct). This mathematical process is described below.

$$Rt := 69.961 \quad C := 0.058 \quad T2 := 75 \quad T1 := 80$$

$$Re := 33 \quad V := 6$$

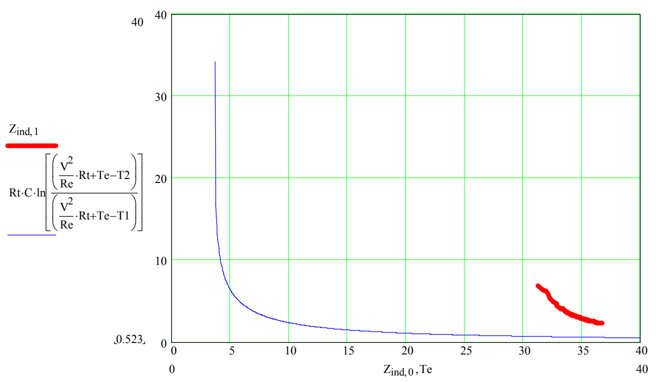


Figure 7 He sensor heating time vs. temperature for constant pressure interval in Helium. Blue – formal model for V=6V. Red –empirical data, prior to switching to 6V. This confirms the 6V switch does extend the range as stated by Deep Life ltd.

In the Apocalypse version of the sensor, the limit of operation is 5V, with a lower drive resistor of 22 Ohms. This was checked as below.

$Rt := 69.961 \quad C := 0.058 \quad T2 := 75 \quad T1 := 80$

$Re := 22 \quad V := 5$

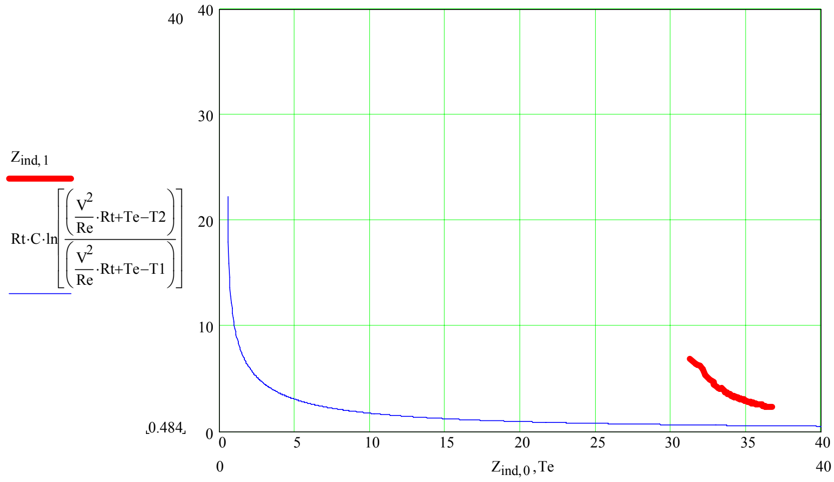


Figure 8 He sensor heating time vs. temperature for constant pressure interval in Helium. Blue – approximation for Re=22 Ohm. Red –empirical data from 33 Ohm drive.

$Rt := 69.961 \quad C := 0.058 \quad T2 := 50 \quad T1 := 55$

$Re := 33 \quad V := 5$

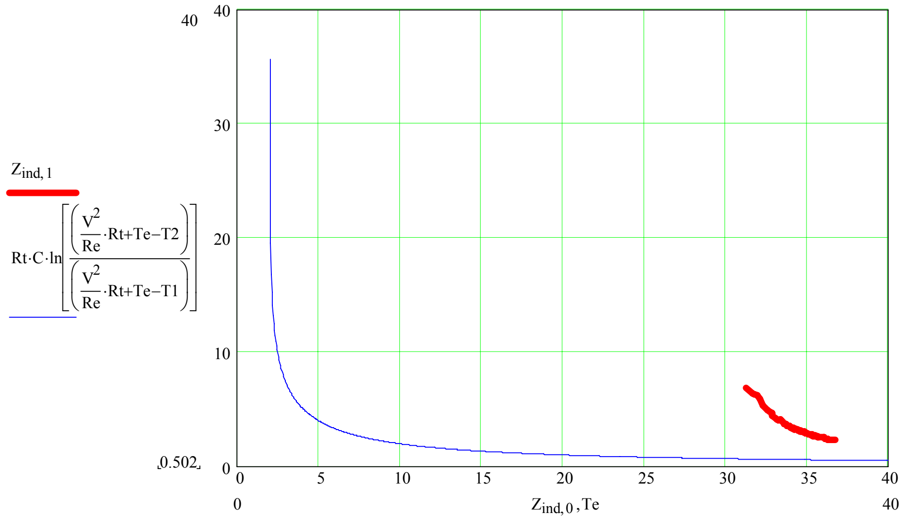


Figure 9 He sensor heating time vs. temperature for constant pressure interval in Helium. Blue – approximation for T2=50 C and T1=55 C. Red –empirical data for comparison with the 80C threshold.

$Rt := 100 \quad C := 0.058 \quad T2 := 75 \quad T1 := 80$

$Re := 33 \quad V := 5$

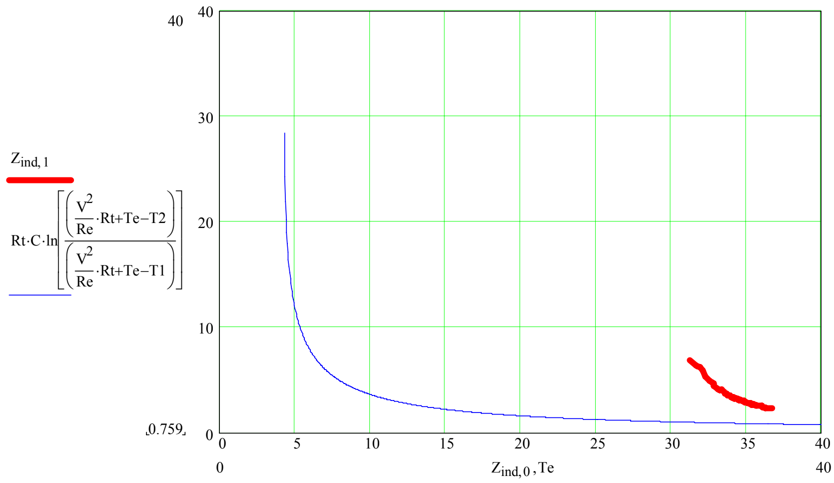


Figure 10 He sensor heating time vs. temperature for constant pressure interval in Helium. Blue – approximation for Rt=100 joule/(second*degree). Red –empirical data.

6.4. He sensor cooling

The dependence of cooling rate on the ambient temperature was assessed by establishing the theoretical relationship and the actual response of the sensor relative to that relationship.

Deep Life obtained the Cooling Time equation in its formal model by solving manually the first order differential equation for thermal current:

$$T + \left(\frac{d}{dt}T\right)\cdot Rt \cdot C = Te$$

$$\text{Cooling Time} = Rt\cdot C\cdot \ln\left[\frac{(T1 - Te)}{(T2 - Te)}\right],$$

Where

- Rt - thermal resistance between He sensor and environment((second*degree)/(joule)
- C - He sensor thermal capacity(joule/degree),
- Te- Ambient temperature (Celsius degrees),
- T1 – Trigger threshold temperature to start cooling (Celsius degrees),
- T2 – Trigger threshold temperature to start heating (Celsius degrees),
- T - Helium sensor temperature (Celsius degrees),
- t – Time(seconds).

Constants used by the circuit during the sensor cooling test were:

$$Rt := 69.961 \quad C := 0.058 \quad T2 := 75 \quad T1 := 80$$

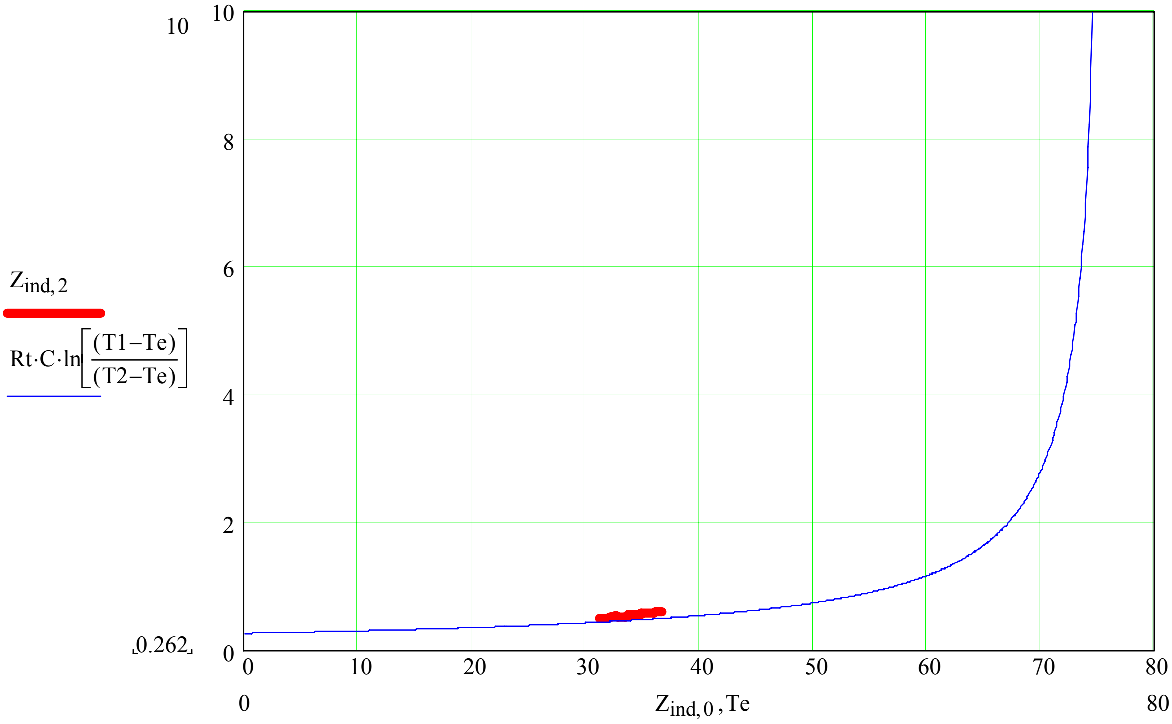


Figure 11 Cooling time (second) vs. ambient temperature (Celsius).
Red – empirical. Blue – mathematical model, using direct readings from the sensor (without any calibration compensation of the helium sensor).

A small difference between the empirical results and mathematical model was observed, and appears to be due to the low accuracy of the ambient temperature measurement within the rebreather used to compensate for ambient temperature. This accuracy error is calibrated out when the helium sensor is calibrated: it appears to be the main source of error within the helium sensor circuitry, and above 50C ambient that error is significant (greater than 10%).

The cooling time sensitivity to ambient temperature is negligibly small if ambient temperature is less than 50C (the maximum ambient operating temperature of the equipment).

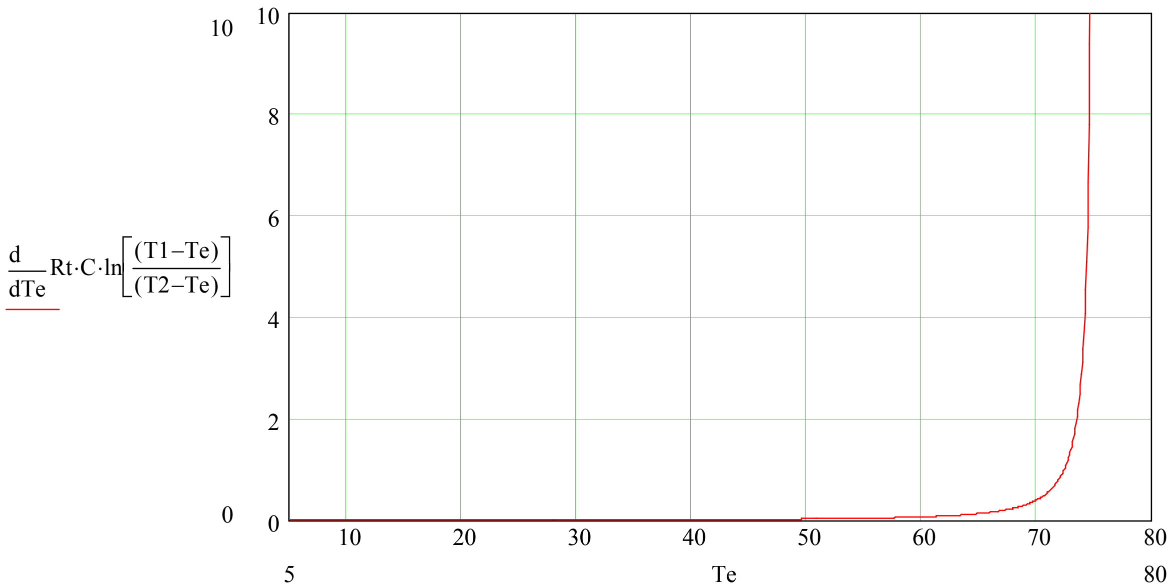


Figure 12 Cooling time sensitivity to ambient temperature vs. ambient temperature (Celsius).

From the graph, the ambient temperature inaccuracy of 4C appears to be the reason each sensor has to be calibrated, but due to the large difference between ambient temperature and sensor temperature threshold, there is no significant effect on the cooling time from these errors.

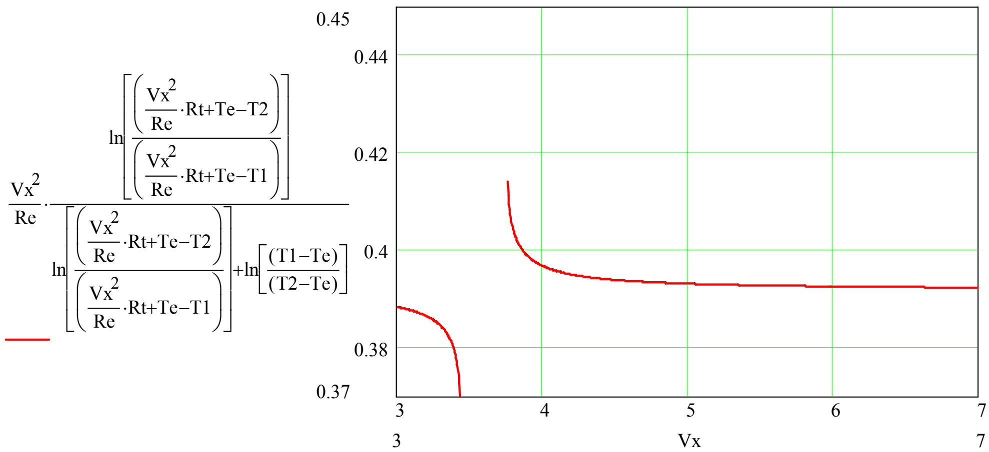
6.5. Heating resistor power supply

The error from the heater power supply was checked using the mathematical model, as it was not possible to induce errors in the power supply of the sample apparatus. The power supply to the sensor is varied automatically. BAI observed power supply switching during tests.

The formal model developed by Deep Life for the sensor was used to understand the operation of the sensor in this assessment, and the reason for the power supply voltage and resistor selection or switching became apparent: it is used by Deep Life to optimise power consumption - see the plots below.

$Rt := 69.961 \quad C := 0.058 \quad T2 := 75 \quad T1 := 80$

$Re := 33 \quad Te := 50$



$Rt := 69.961 \quad C := 0.058 \quad T2 := 75 \quad T1 := 80$

$Re := 33 \quad Te := 5$

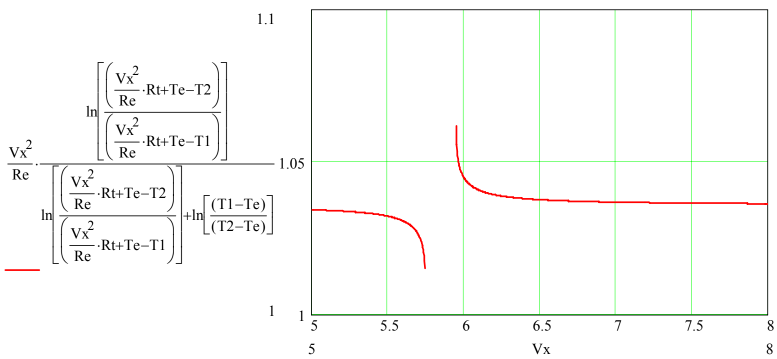


Figure 13 Heating resistor mean supply power vs. supply voltage for Te=50C and Te=5C, with 33 Ohm resistance.

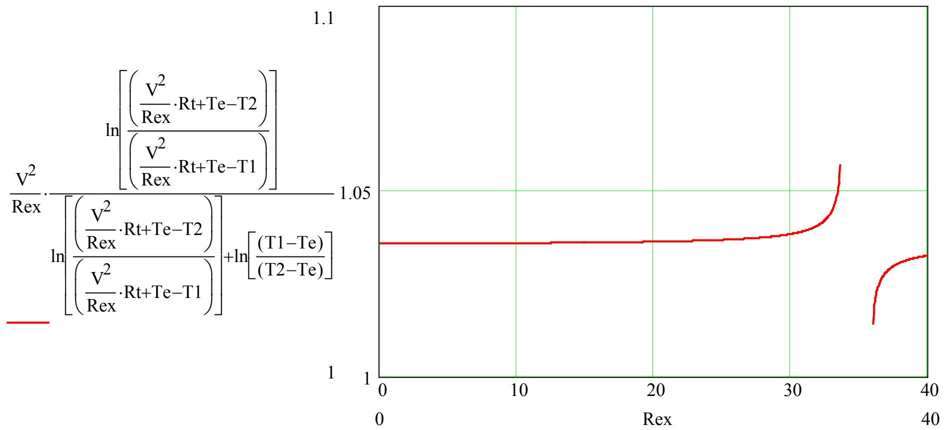


Figure 14 Heating resistor mean supply power vs. heating resistor electrical resistance for Te=5C. For Rex> 35 Ohm heating time becomes infinity, which appears to be why both 22 Ohms and 33 Ohms is used.

6.6. Effect of condensation or flooding

Placing droplets of water on the sensor causes the apparatus to show no helium reading (and using direct measurements, the sensor does not achieve its threshold voltage). The thermal conduction needed to achieve this was assessed using Deep Life's formal model as it was impractical to sweep a full range of thermal conductance materials across the physical samples.

For this part of the assessment, Rt = 69.961, C= 0.058, T2=75C, T1=80C, Re=33 Ohms, Te = 5C, V = 6V as this is the worst case, but it is apparent from the model there is no strong dependence on Re, T1 or V when large changes in conductance occur. The calculations in the model were checked and shown here.

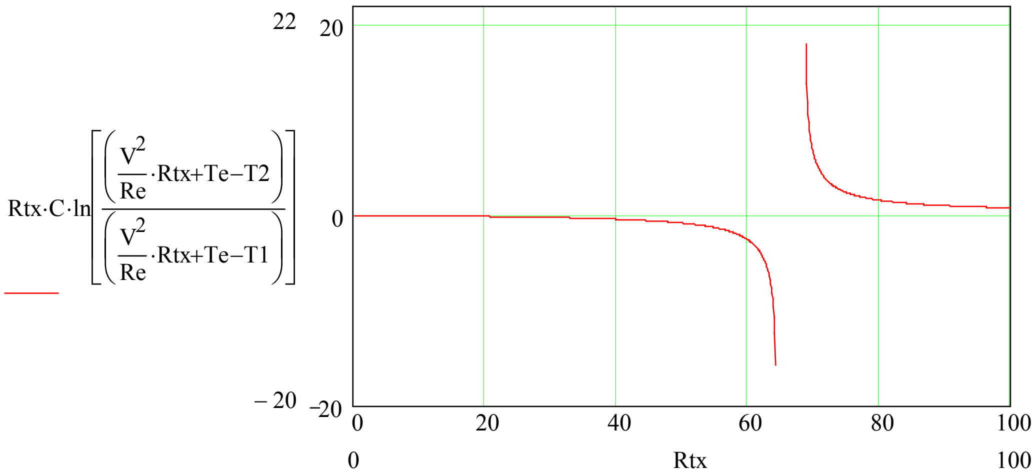


Figure 15 Heating time vs. thermal resistance between He sensor and environment.

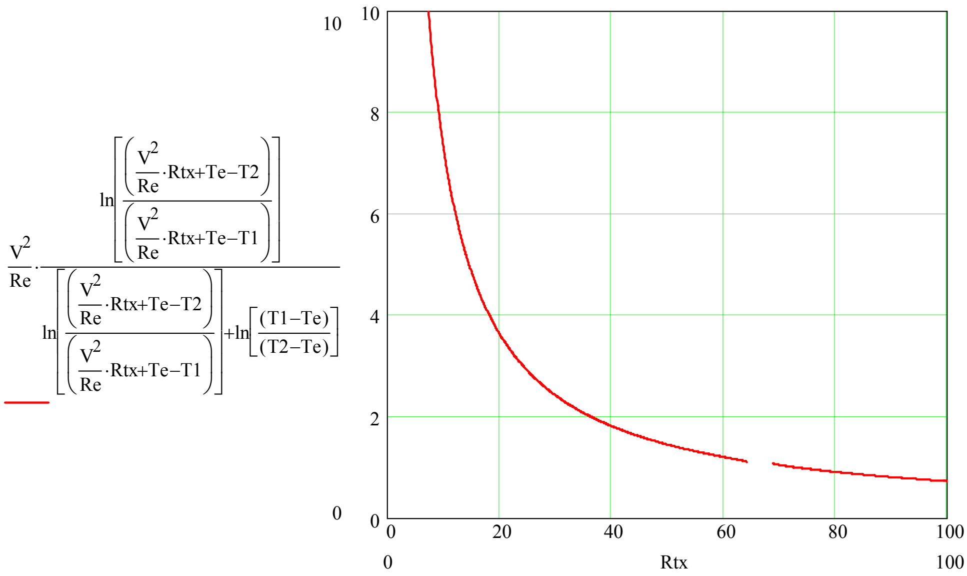


Figure 16 Heating resistor mean supply power vs. thermal resistance between He sensor and environment. . For Rtx<69 (second*degree per joule) heating time becomes infinity because there is insufficient drive to the heater to operate in low resistance media, e.g. water has a resistance of less than 1.

It is concluded that the failure to achieve T1 does achieve the flood detection that is claimed for it. Similarly, short circuit and open circuit faults are detected reliably.

7. Comparison of apparatus samples N 003 and N 004 near 30C boundary condition.

The function of the samples appear identical other than a difference in the exact temperature in which they appear to switch power levels around 30C switching point (below which it uses the 22 Ohm load rather than 33 Ohm, and increases the drive voltage).

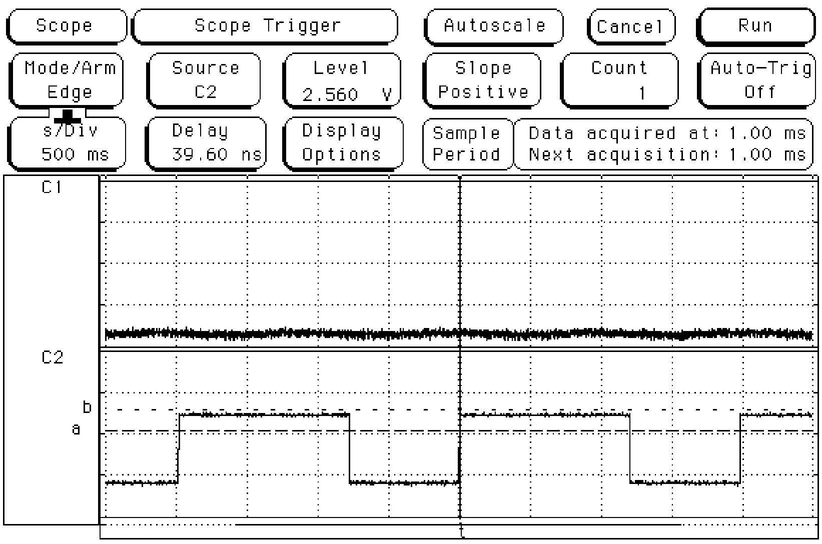


Figure 17 C1 – Power noise. C2 - Heating time “1” and cooling time “0” for He sensor N 003. In air. V=6.46V, Te =30C. (Empirical data)

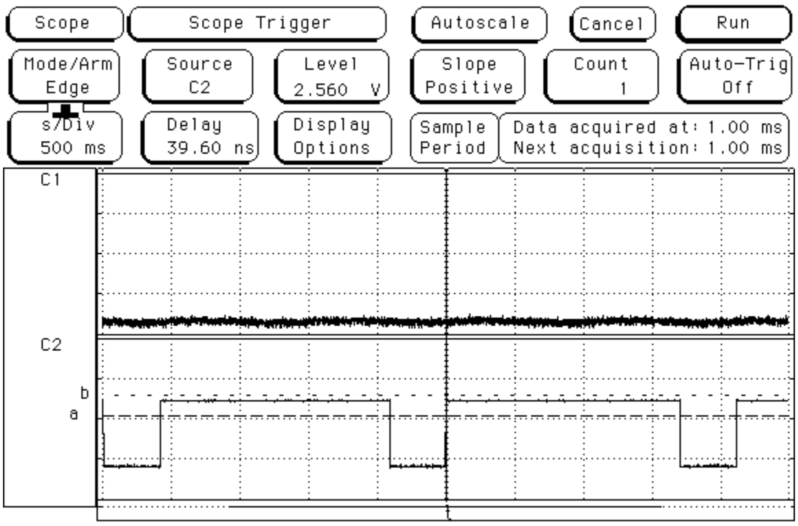


Figure 18 C1 – Power noise. C2 - Heating time “0” and cooling time “1” for He sensor N 004. In air. V=6.46V, Te =30C. Thermal resistance between He sensor and environment more than one for the He sensor N003.

These outputs were checked against Deep Life’s formal model and the calculations it contains, and found to be correct.

Figure 19 Heating time vs. thermal resistance between He sensor and environment. For Rtx> 70 (second*degree)/joule heating time becomes infinity.

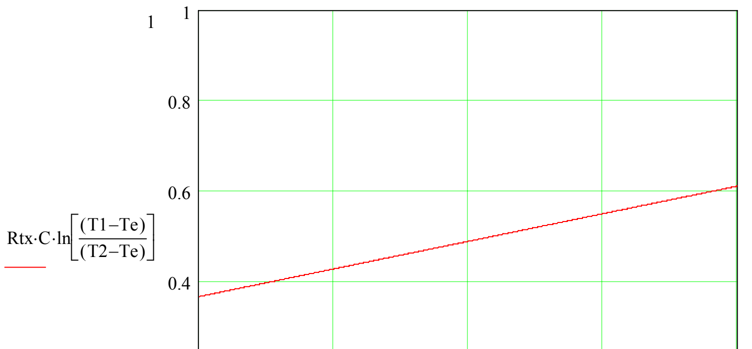


Figure 20 Cooling time vs. thermal resistance between He sensor and environment.

8. CONCLUSION

After calibration, the helium sensors are within +/-0.6% at one atmosphere under the calibration conditions of 35C: they are calibrated against a mass spectrometer of 0.5% accuracy and a span gas accurate to 0.4%[1]. The error pre-calibration is between 2% and 3%.

No discernable ageing of the helium sensor was observed.

Changes in pressure cause errors of 0.035 % per bar, which is negligible.

The apparatus has a fixed power/loss ratio in the sense resistors, determined by setting the resistor value to match the fixture (22 Ohms with a high loss fixture, 100 Ohms with a low loss fixture). With the high loss fixture, the heating resistor's mean supply power (1.04 Watt) for Te=5C is 2.6 times more than heating resistor mean supply power (0,39 Watt) for Te=50C. Limitations in the power supply mean that the ambient temperature variations can result in helium sensor errors of +/- 2%.

Heating power limitations appear to be avoided by the resistor values used in the apparatus: 22 Ohms with high thermal loss mounting fixture, and 100 Ohms with low loss fixture. The borderline case is values above 30 to 33 Ohms in the high loss fixture, and 140 Ohms in the low loss fixture – the actual resistance values are well away from these boundaries.

When condensation falls onto the sensor, or it is flooded, the failure is detected reliably as the sensor does not reach its threshold temperature. This prevents a false reading due to a moisture film on the sensor. Similarly short circuits and open circuit faults are detected reliably.

Combining the errors as a sum of squares, a total error of +/-3% can be claimed for the sensor. This is well within the error band derived from the safety requirement of the sensor.

[1] Errors are combined as the root sum of squares, so a 0.5% mass spectrometry error distribution, and a 0.4% span gas error distribution, is sqrt(0.5^2+0.4^2) = 0.64. The distributions are not stated, but are assumed to be Normal.