

RETEST OF DEEP LIFE INCURSION SRB CO2 SCRUBBER ENDURANCE TO EN14143:2003 AND NORSOK U-101

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Revision History

Revision	Date	Description
A1	9 th Dec 2010	Test report issued
A2	12 th Dec 2010	Combined with VWAI CO2 data. Internal review
A3	15 th Dec 2010	Approved for release

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1 PURPOSE AND SCOPE

The purpose and scope of this report is to provide a retest of CO2 scrubber endurance for compliance with EN 14143:2003 for the Deep Life OR_Incursion model, as previous data on that rebreather had performed the test with the oxygen control switched off to avoid any risk of interfering with the measurement. This is a single scrubber configuration, that has the same scrubber as the Apocalypse model.

This document is one in a series that assesses the CO2 scrubber endurance on the Deep Life Open Revolution rebreathers. These include:

1. Scrubber endurance data provided in the User Manual, supported by data in the Scrubber Endurance directory of the PPE Directive Technical File.
2. DV_OR_Scrubber_Endurance_081124.doc providing data for the single scrubber configurations, with particular regard to the sensitivity to low temperatures (1C to 5C), diver attitude and gaps in scrubber use.
3. DV_OR_ScrubberEndurance_DRB_081202.pdf providing data on the dual scrubber configurations.
4. Fault_Study_CO2_Bypass_101209.pdf providing analysis of a fault mode that may affect the apparent scrubber endurance.

2 REQUIREMENT

The CE EN14143:2003 and the comparable NORSOK U-101 test, specify the following test conditions:

1. Water temperature is 4+/-1C
2. Carbon dioxide injection rate is 1.6 lpm STPD
3. Breathing simulator rate is 40 lpm
4. Breathing frequency is 20 bpm

Scrubber endurance must be measured with < 150ms accuracy and resolution as:

- End of inhale CO2 level in the mouth of 5mbar (0.5% SEV) for EN 14143:2003
- End of inhale CO2 in the mouth of 10mbar (1% SEV), also EN 14143:2003
- A further limit that VWAI CO2 does not exceed 20mbar (2% SEV), EN 14143 and NORSOK U101.

The depths measured are the worst case profile to:

- 6m using oxygen as the make-up gas
- 40m using air as the make-up gas
- 100m using heliox as the make-up gas

The word profile is considered by Deep Life to be unsafe, in that divers may not study the profile where this involves a specific decompression schedule. Deep Life's definition of the worst case profile is therefore constant depth. With the increase in case diving, and use of rebreathers for bottom phases of a dive, this worst case may be the actual worst case dived.

Three scrubbers are measured at each depth.

EN14143:2003 requires that the Volume Weighted Inspired CO2 (VWAI CO2) is measured during the endurance test. BAI store all VWAI CO2 for the entire test, breath by breath.

3 EQUIPMENT USED

The test equipment used is listed below.

Equipment	Serial Number	Calibration Next Due
DL, Human Respiratory Emulator (Breathing simulator) DL Rev C2	DL 001	Calibrated prior to each use
Differential pressure sensor. Druck LPM9381	2393261	Calibrated prior to each use
Highly precise digital manometer Keller LEX1	002333	16 July 2011
High pressure sensor ME 705	DL 004	Calibrated prior to each use
National Instruments Data Capture System PCI-6014	HA4375847	Against TTi 1906, Serial Number 111474 Prior to test
Power supply GPR – 1850	033624	N/A
Scales VSP 60/10– 5	7012	23/11/2011
Mass spectrometer, Amis 2000 with suitable span gases	SN 0911243	Uses certified span gases to calibrate at each test
Deep Life 800 mm chamber, with environmental control, rotateable	CH03	Next hydrostatic Sept 2014
Hot wire anemometer	Q440965	Dec 2011

Note 1: the Breathing Simulator is a complex measurement system and contains additional sensors not listed in the table above. This information is provided at Breathing Simulator Calibration report *Cal_Breathing_Simulator_Assessment_090707.pdf*.

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4 METHOD

The test fixture used for scrubber endurance tests is shown in **Figure 4-3**.

All operations of the test fixture other than connecting gases are computer controlled and logged.

The breathing simulator was calibrated with both NEDU and CE test orifices prior to each test series and following the last test.

CO₂ is injected as a pure gas, into the breathing simulator. Simulator dead space has no affect whatsoever on the inhaled CO₂ waveform: it affects the exhaled CO₂ waveform but not the average after the exhale one way valve. Dead space settings of 150ml and 800ml are used routinely; the later allows gas to be extracted from the mouth for sample purposes without changing the VWAI CO₂ or End of Inhale CO₂ because it inserts a time lag to the exhale cycle during which the mouth CO₂ remains at the End of Inhale level.

The chamber temperature is kept at 4C by a 2.4KW industrial cooler, providing refrigerated liquid around the chamber. For tests of more than 3 hours, water is exchanged from the top of the chamber, to keep the test at 4C, using bleeding and a hydrostatic pressure test pump.

The requirement of EN 14143:2003 is to measure CO₂ in the mouth. This is achieved by taking a 1.8 lpm feed from the mouth (at the interface between the mouthpiece and breathing simulator), to a mass spectrometer which records the breath by breath gas fractions with resolution of 70ms for all gases. Where noise is observed at this bleed rate, such as for shallow tests, the bleed rate is reduced until the noise is removed, the bleed rate is not less than 0.6 lpm.

The rate of CO₂ injection is critical to the test. The injection rate is checked using a variable area sight gauge prior to the test, then monitored throughout the test by:

- Mass Flow Controller reading, the mass flow controller having been calibrated using CO₂ at NTPD. Temperature compensation is applied manually as will be described.
- Mass Flow Meter reading, this being in series with the Mass Flow Controller.
- Mass Spectrometer reading of the average CO₂ immediately before the scrubber, to ensure this is at least 4% SEV at all times.
- Continuous molecular weight monitoring. Precision scales are used to weigh the CO₂ cylinder: a twin 20 litre twin-set (40 litres of gas). This is an absolute reference, that is used to monitor the Mass Flow Controller compensation, to ensure it is always within its calibration.

The pressure of the CO₂ is monitored to determine the temperature of the CO₂ being delivered to the Mass Flow Meter and Controller. The maximum pressure of CO₂ against temperature is shown in **Figure 4-1**. This plot is derived from the CO₂ pressure – temperature phase diagram shown in **Figure 4-2**. The low gas temperature means that the Mass Flow Controller is set to 1.75 lpm of CO₂ flow: the exact number depends on the gas temperature at the time of the test, but is never less than 1.72 lpm. This is more than the 1.6lpm stipulated in the standards, because the standards use STPD and the MFCs are calibrated with NTPD.

A Checklist is used for each scrubber test, prior to the test commencing. The procedures for the setup and execution of the scrubber endurance test is controlled through the BAI Test Manual.

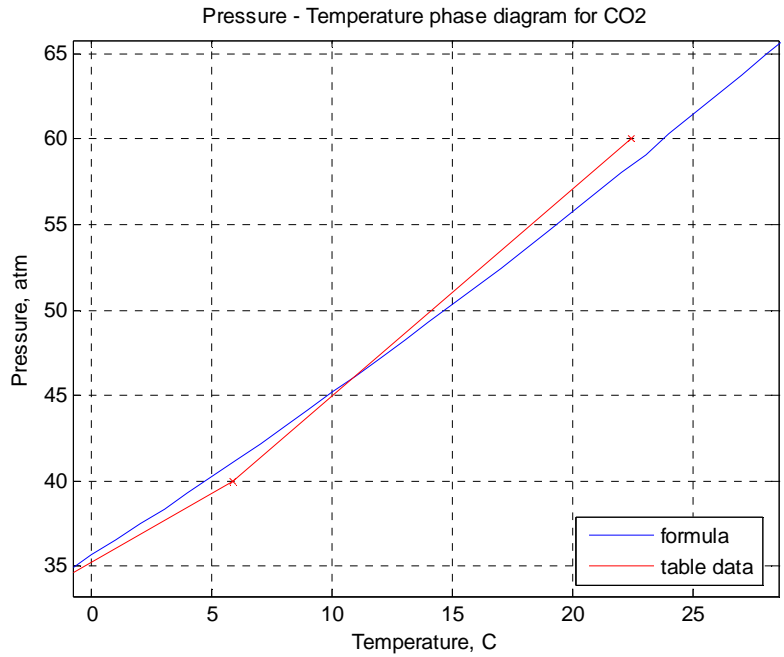


Figure 4-1. Gas – liquid phase diagram of CO₂ (detail). This relationship enables the mass flow of the CO₂ to be compensated for the temperature of the gas, by measuring the pressure of the supply cylinder.

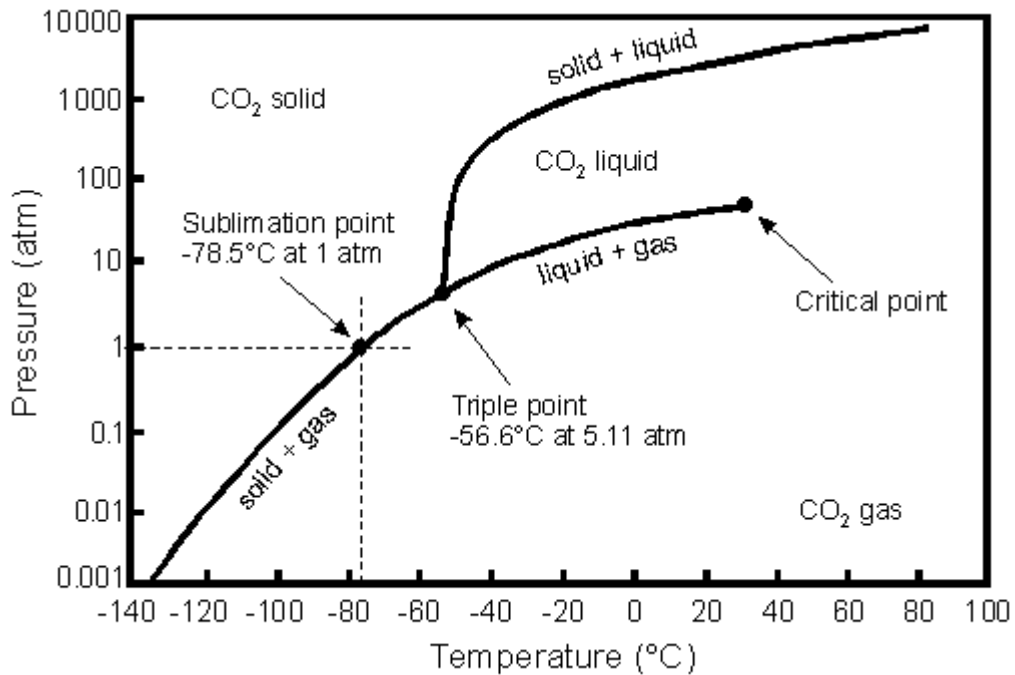


Figure 4-2. Gas – liquid phase diagram of CO₂.

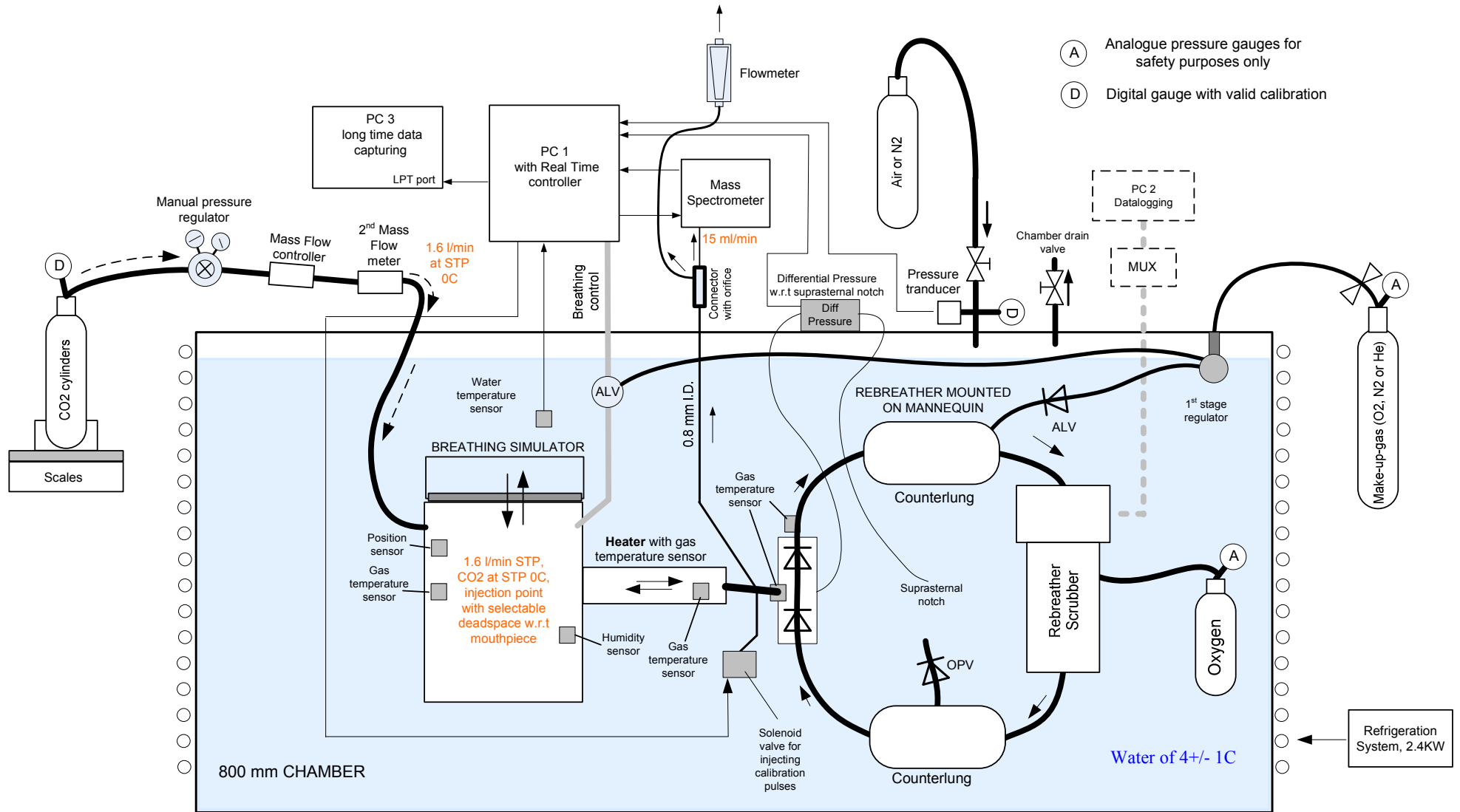


Figure 4-3. Scrubber endurance test fixture.

5 TEST RESULTS: ENDURANCE

5.1 Depth of 6 msw

Test condition:

Rebreather:	OR rebreather Incursion #2 with PPO2 set at 1.2 atm
Ambient pressure:	6 msw
Ambient temperature:	4+/-1C
Exhale temperature:	32+/-4C
BL humidity:	above 85%
Tidal volume:	2 litre
Breathing frequency:	20 min ⁻¹
Ventilation rate:	40 lpm
CO2 injection rate:	1.6 lpm STPD
Make-Up-Gas:	O2

5.1.1 First scrubber sample

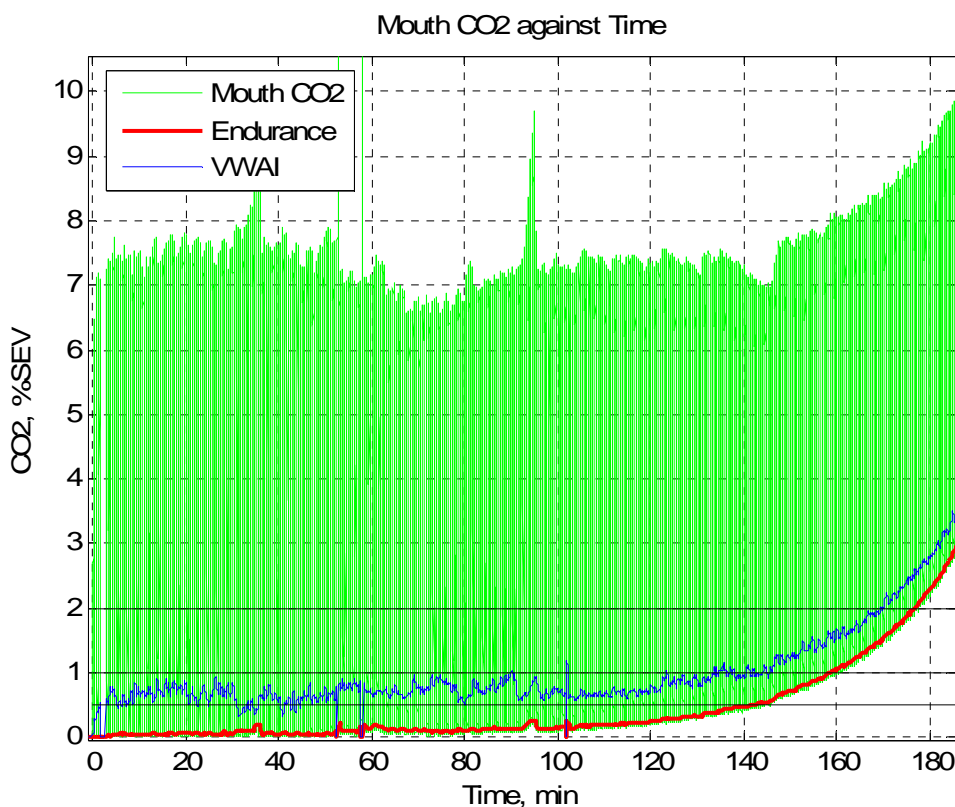


Figure 5-1. Mouth CO2 in the breathing loop against time. Scrubber endurance (5 mbar PPCO2) = 141 min or 2 hour 21 min; Scrubber endurance (10 mbar PPCO2) = 158 min or 2 hour 38 min; Scrubber endurance (20mbar PPCO2) = 177 min or 2 hours 57 min; VWAI reaches the limit of 20 mbar at 170 min. Mass spectrometer calibration was checked online.

To decrease the VWAI noise, the gas flow into Mass Spectrometer was decreased slowly from 1.6 lpm to 0.6 lpm during 60..110 min: this is the reason for the spikes in the peak exhaled gas and the VWAI CO2. The CO2 flow rate was not affected.

5.1.2 Second scrubber sample

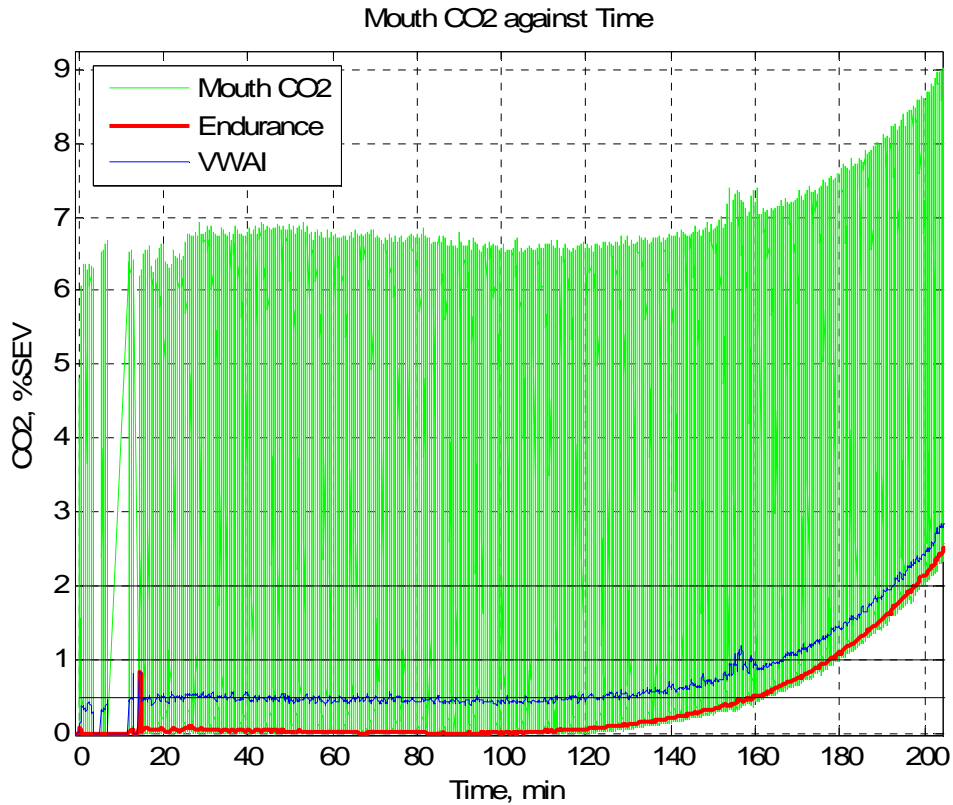


Figure 5-2. Scrubber endurance (5 mbar PPCO₂) = 160 min or 2 hour 40 min; (10 mbar PPCO₂) = 178 min or 2 hour 58 min; (20mbar PPCO₂) = 198 min or 3 hours 18 min; VWAI crosses limit of 20 mbar at 193 min. The mass spectrometer calibration was checked online.

5.1.3 Third scrubber sample

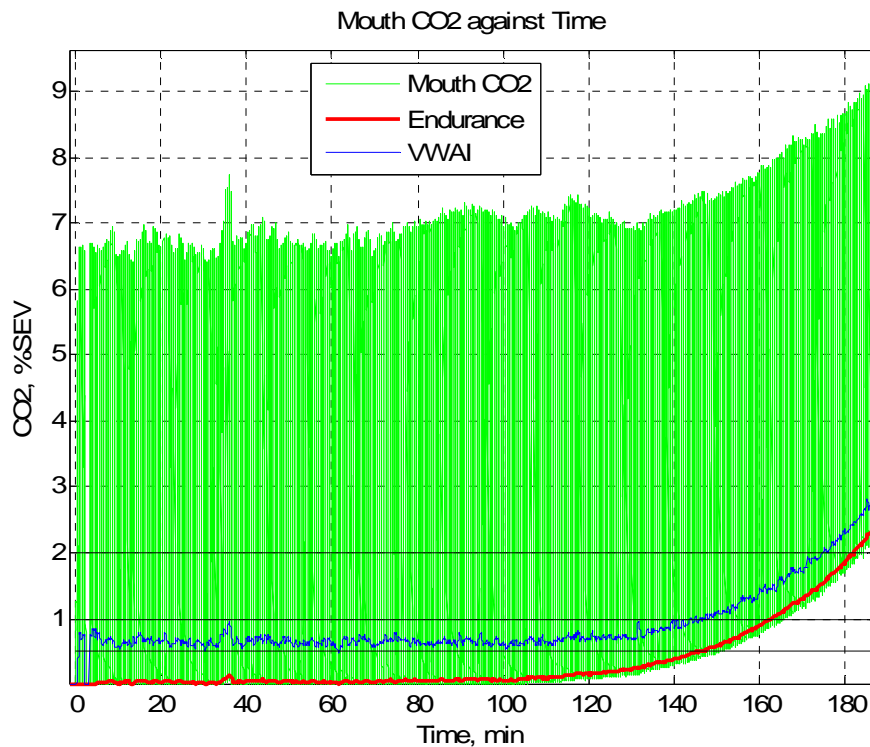


Figure 5-3. Mouth CO₂ in the breathing loop against time. Scrubber endurance (5 mbar PPCO₂) = 146 min or 2 hour 26 min; (10 mbar PPCO₂) = 162 min or 2 hour 42 min; (20mbar PPCO₂) = 183 min or 3 hours 3 min; VWAI crosses limit of 20 mbar at 175 min.

5.2 Depth of 40 msw

Test condition:

Rebreather:	OR rebreather Incursion #2, with PPO2 set at 1.2 atm
Ambient pressure:	40 msw
Ambient temperature:	4+/-1C
Exhale temperature:	32+/-4C
BL humidity:	above 85%
Tidal volume:	2 litre
Breathing frequency:	20 min ⁻¹
Ventilation rate:	40 lpm
CO2 injection rate:	1.6 lpm STPD
Make-Up-Gas:	N2

5.2.1 First scrubber sample

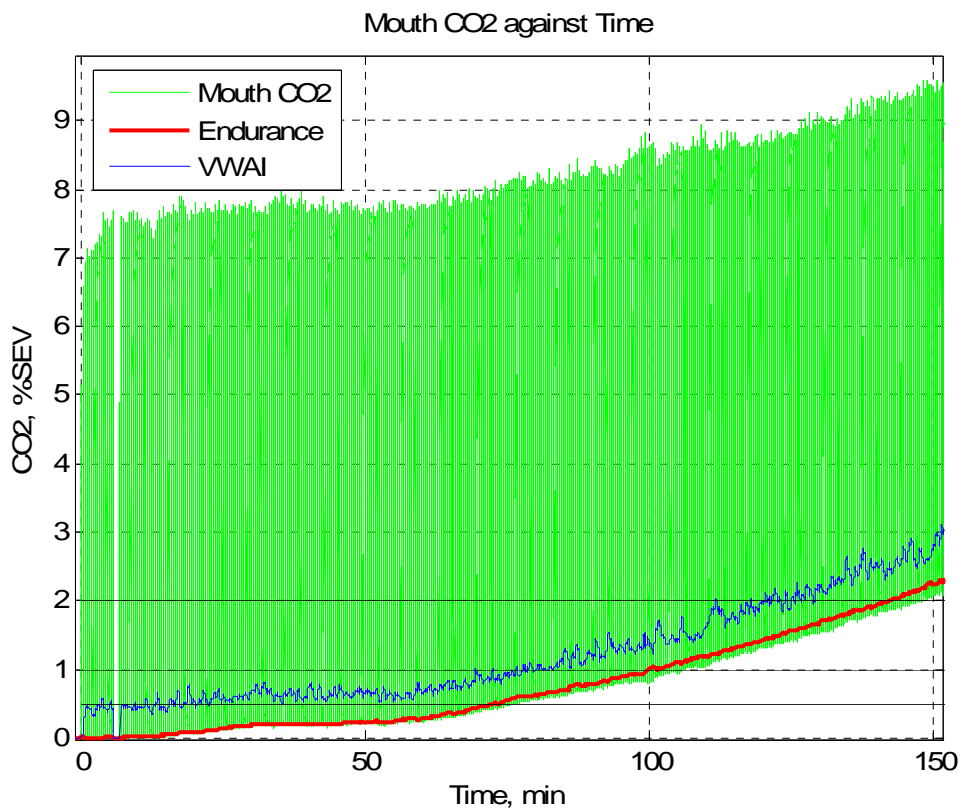


Figure 5-4. Mouth CO2 in the breathing loop against time. Scrubber endurance (5 mbar PPCO2) = 72 min or 1 hour 12 min; (10 mbar PPCO2) = 100 min or 1 hour 40 min; (20mbar PPCO2) = 142 min or 2 hours 22 min; VWAI reaches the limit of 20 mbar at 120 min. The intervals are mass spectrometer calibration checks

5.2.2 Second scrubber sample.

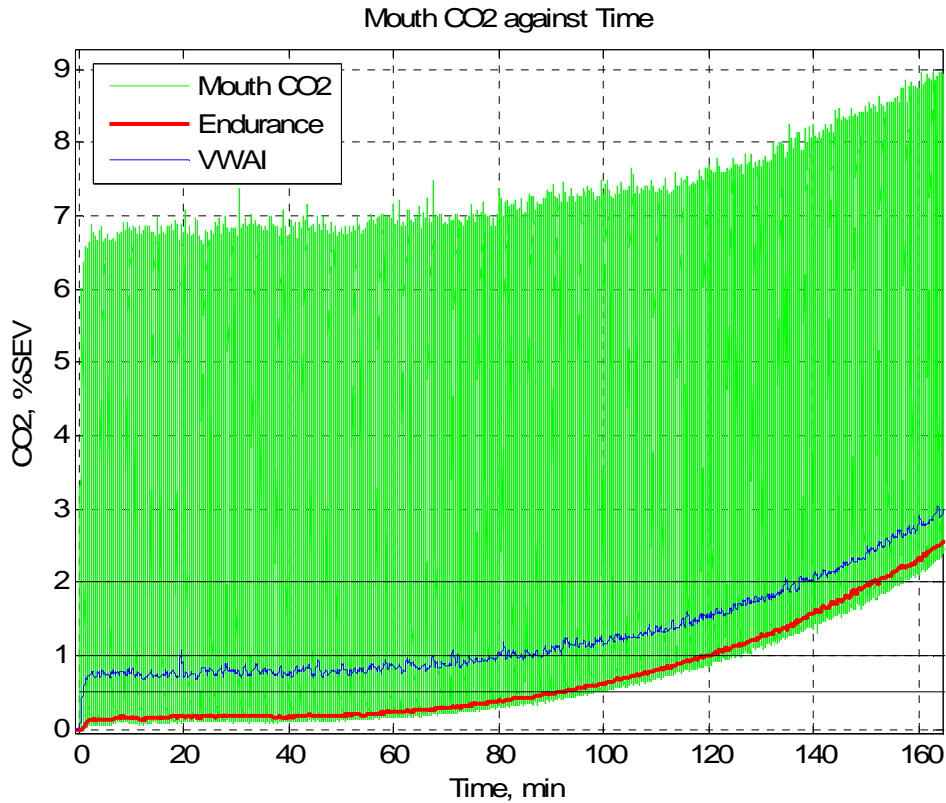


Figure 5-5. Scrubber endurance (5 mbar PPCO₂) = 90 min; (10 mbar PPCO₂) = 119 min or 1 hour 59 min; (20mbar PPCO₂) = 151 min or 2 hours 31 min; VWAI crosses limit of 20 mbar at 135 min. The interval is a mass spectrometer calibration check.

5.2.3 Third scrubber sample

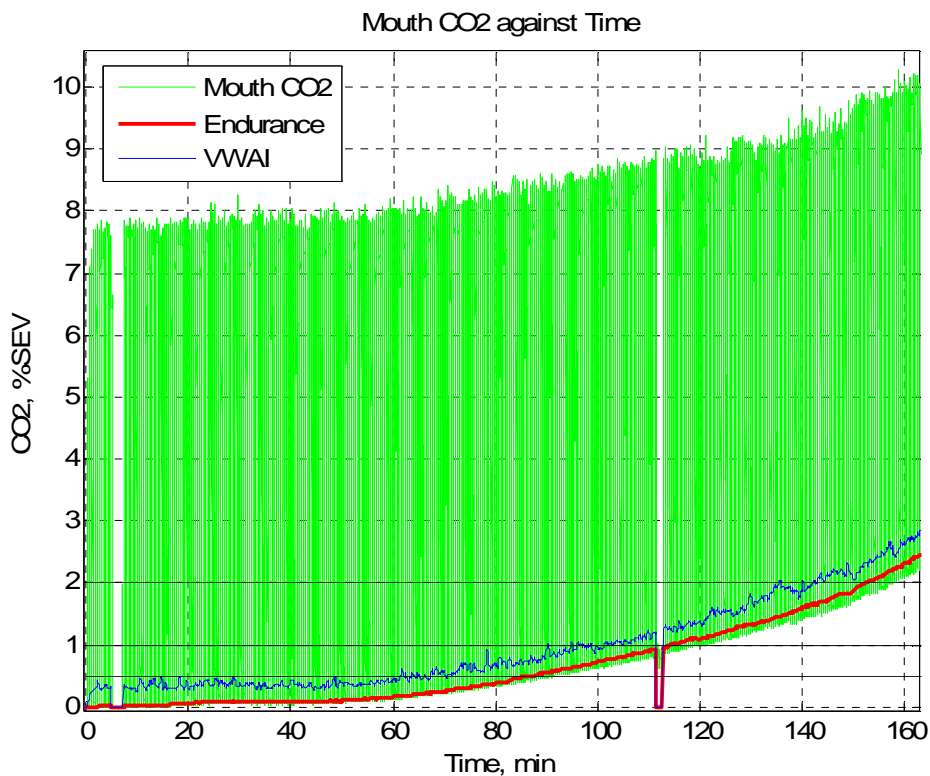


Figure 5-6. Scrubber endurance (5 mbar PPCO₂) = 87 min or 1 hour 17 min; (10 mbar PPCO₂) = 114 min or 1 hour 54 min; (20mbar PPCO₂) = 152 min or 2 hours 32 min; VWAI crosses limit of 20 mbar at 136 min. The intervals are mass spectrometer calibration checks.

5.3 Depth of 100 msw

Test condition:

Rebreather: OR rebreather Incursion #2 with PPO2 set at 1.2 atm
 Ambient pressure: 100 msw
 Ambient temperature: 4+/-1C
 Exhale temperature: 32+/-4C
 BL humidity: above 85%
 Tidal volume: 2 litre
 Breathing frequency: 20 min⁻¹
 Ventilation rate: 40 lpm
 CO2 injection rate: 1.6 lpm STPD
 Make-Up-Gas: He

5.3.1 First scrubber sample

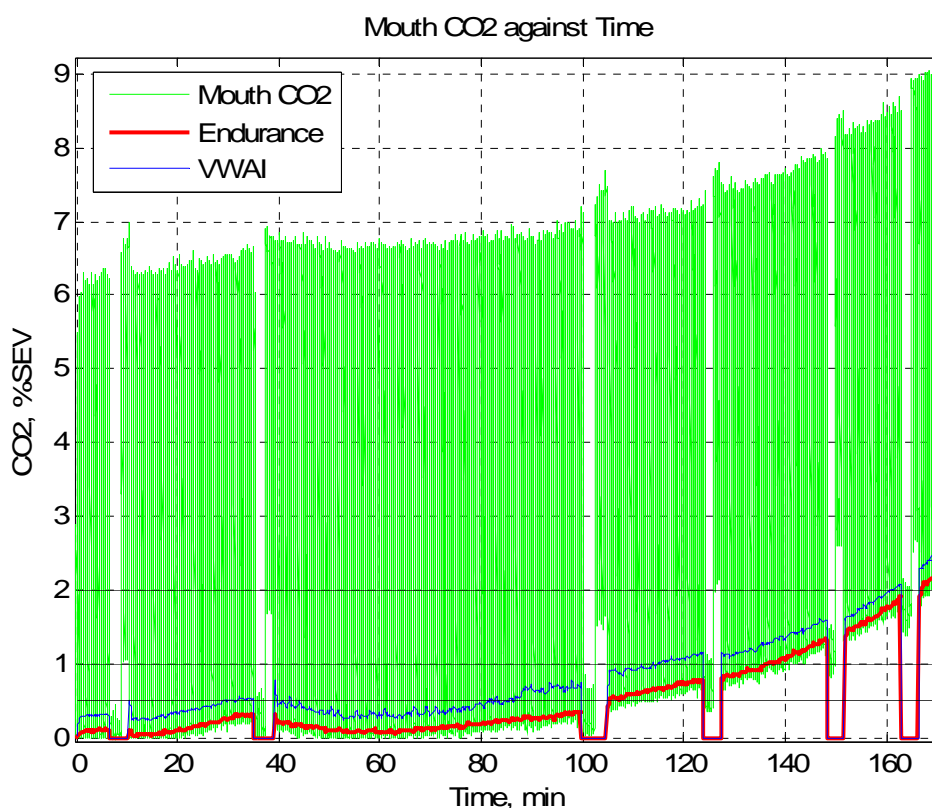


Figure 5-7. Mouth CO2 in the breathing loop against time. Scrubber endurance (5 mbar PPCO2) = 105 min or 1 hour 45 min; Scrubber endurance (10 mbar PPCO2) = 136 min or 2 hour 16 min; Scrubber endurance (20mbar PPCO2) = 167 min or 2 hours 47 min; VWAI reaches the limit of 20 mbar at 161 min. The intervals are mass spectrometer calibration checks

The hump in the scrubber endurance around 35 minutes is a known phenomena, due to the time taken for the moisture balance to even out. In the worst cases, this can breach the CE ceiling, so is given as an endurance limit in manuals. As can be seen from the plot, the real endurance is over 2 hours at this depth. This is an extremely high performance scrubber.

5.3.2 Second scrubber sample

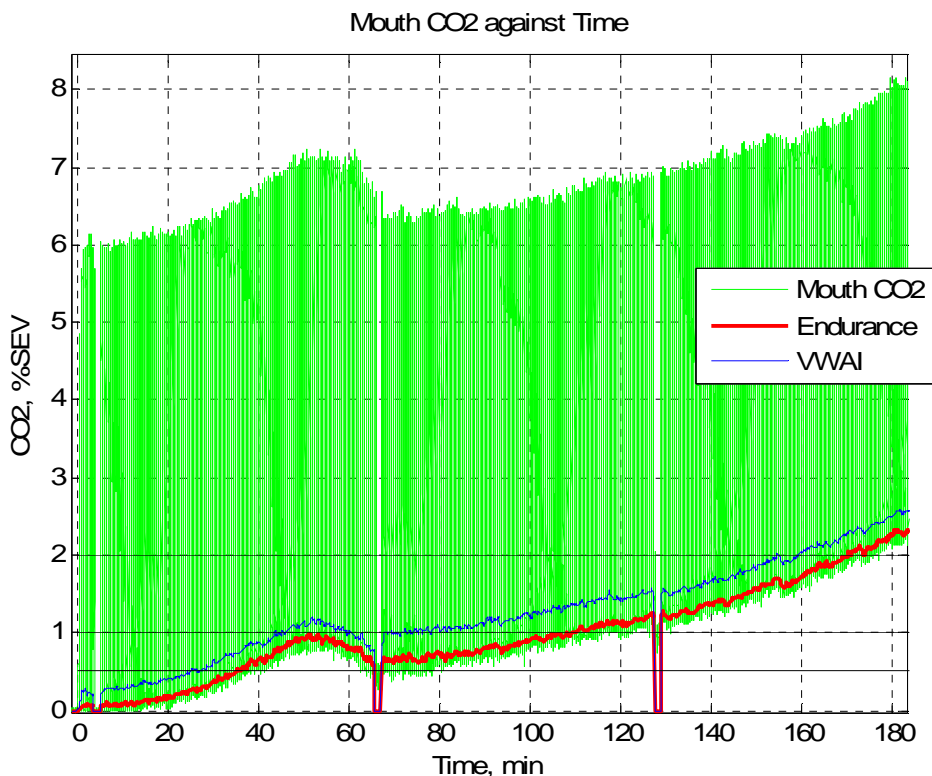


Figure 5-8. Scrubber endurance (5 mbar PPCO₂) = 35 min; (10 mbar PPCO₂) = 108 min or 1 hour 46 min; (20mbar PPCO₂) = 170 min or 2 hours 50 min; VWAI crosses limit of 20 mbar at 154 min. The intervals are mass spectrometer calibration checks.

5.3.3 Third scrubber sample

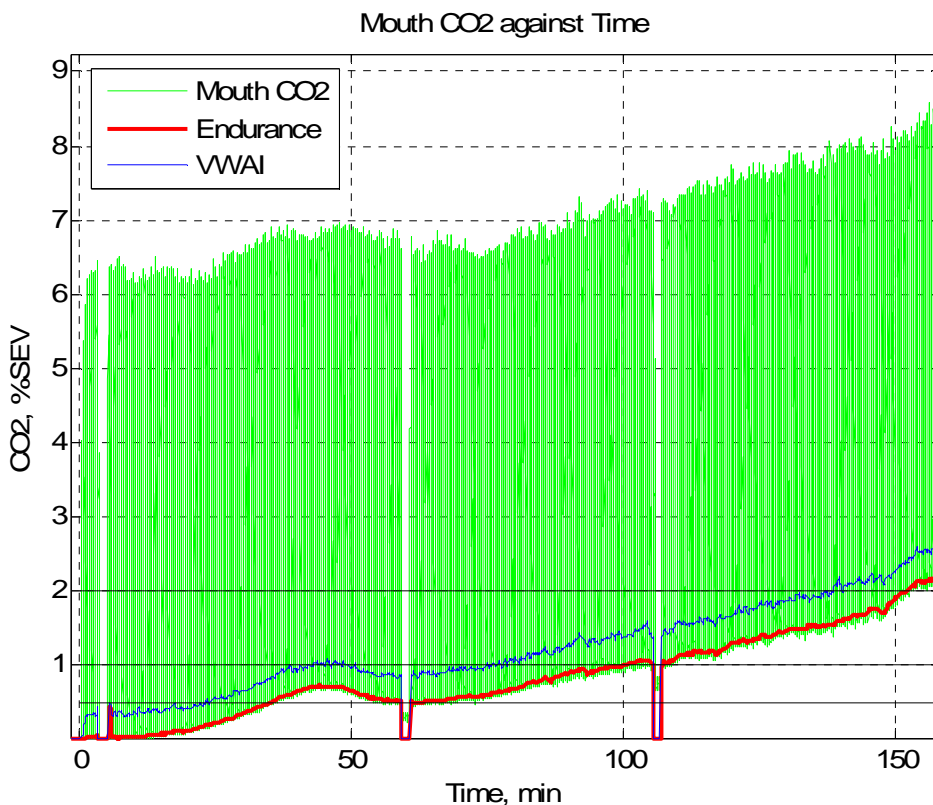


Figure 5-9. Scrubber endurance (5 mbar PPCO₂) = 36 min; (10 mbar PPCO₂) = 100 min or 1 hour 40 min; (20mbar PPCO₂) = 152 min or 2 hours 32 min; VWAI crosses limit of 20 mbar at 138 min. The intervals are mass spectrometer calibration checks.

6 TEST RESULTS: VWAI CO₂

In accord with EN 14143:2003, the Volume Weighted Average Inspired CO₂ was measured in the mouth throughout the scrubber endurance tests. The results are presented below.

6.1 Breath by Breath CO₂ Around Breathing Loop

6.1.1 Check of all CO₂ levels around the breathing loop

The CO₂ levels at seven points around the breathing loop is checked when the endurance test is set up. An example of the results from this is shown below.

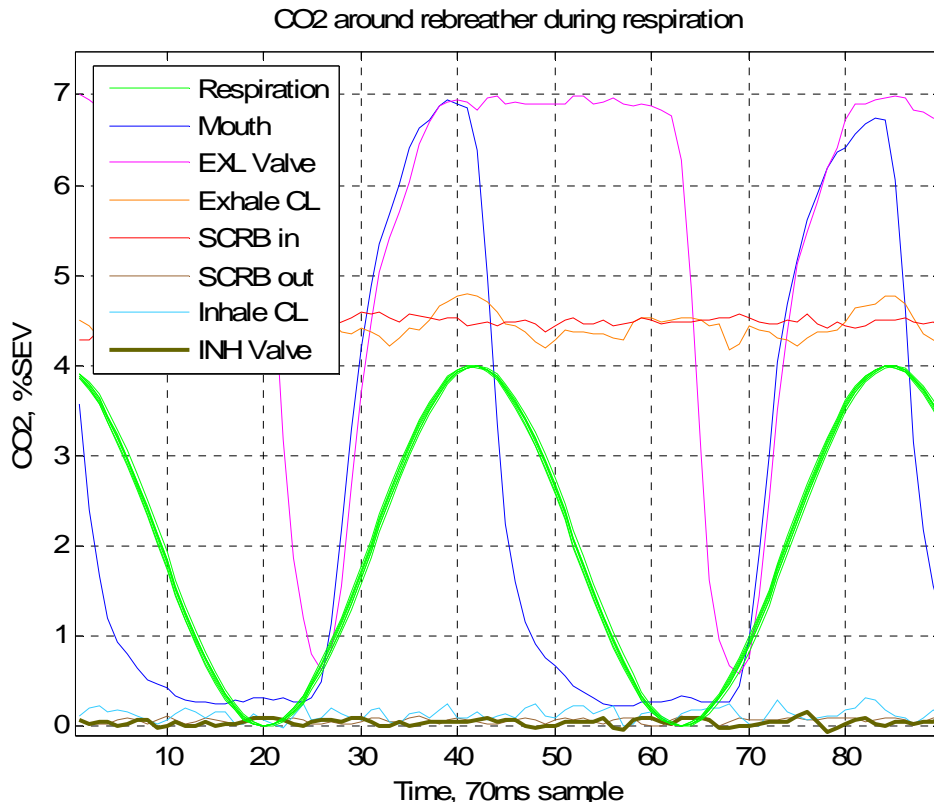


Figure 6-1. . Check of the CO₂ flow rates, example taken from the 100m test setup. This shows the breathing simulator stroke (Respiration, Green), CO₂ in the mouth (Blue), the CO₂ immediately downstream of the exhale valve (Purple), the Exhale Counterlung CO₂ (Orange), the CO₂ immediately upstream of the scrubber (red), the CO₂ immediately downstream of the scrubber (black), the CO₂ in the inhale counterlung (light blue), and the CO₂ immediately upstream of the inhale one way valve (dark green). This checks the entire fixture and in particular, the CO₂ upstream of the scrubber shows the correct fraction of CO₂ is being injected: it is 4.46% SEV at BTPD from 4% of tidal gas at SPTD * $(273+32)/273$.

6.1.2 Breath by Breath Check from 6m test

The CO2 was stored, breath by breath for all tests, with extracts shown below.

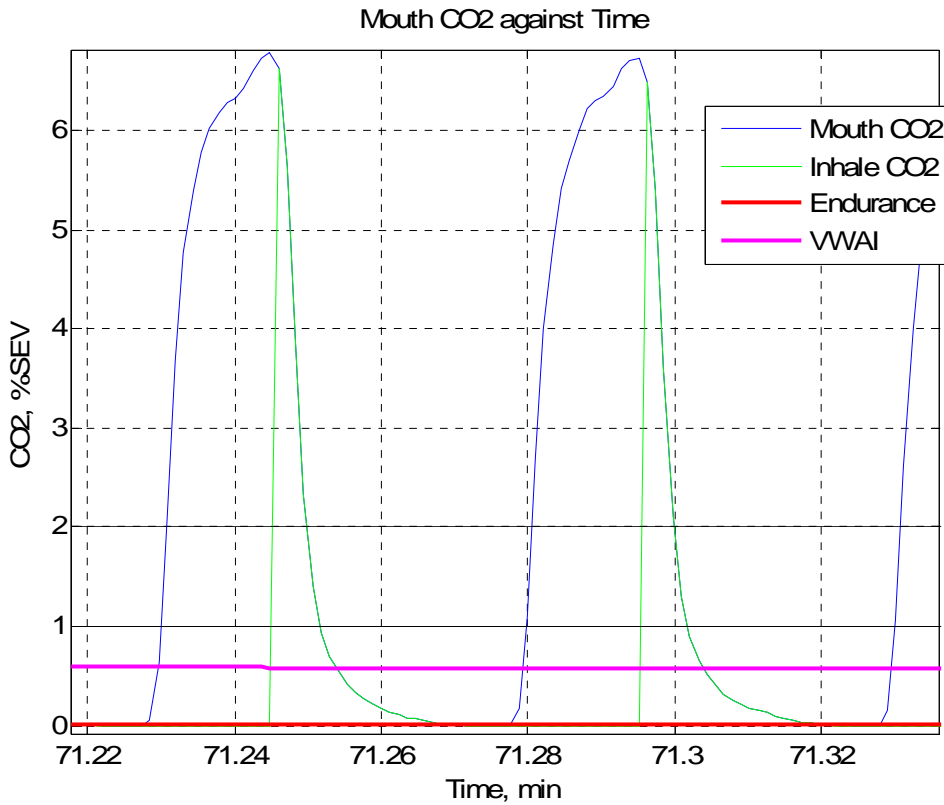


Figure 6-2. CO2 sampled at the mouth, showing levels with a highlight of the inhaled part of the respiratory cycle (in green), the end of inhale CO2 represented as the Endurance CO2 (in red), and the Volume Weighted Average Inspired CO2 (in purple),. All curves are shown in the full scrubber endurance curves in the previous chapter.

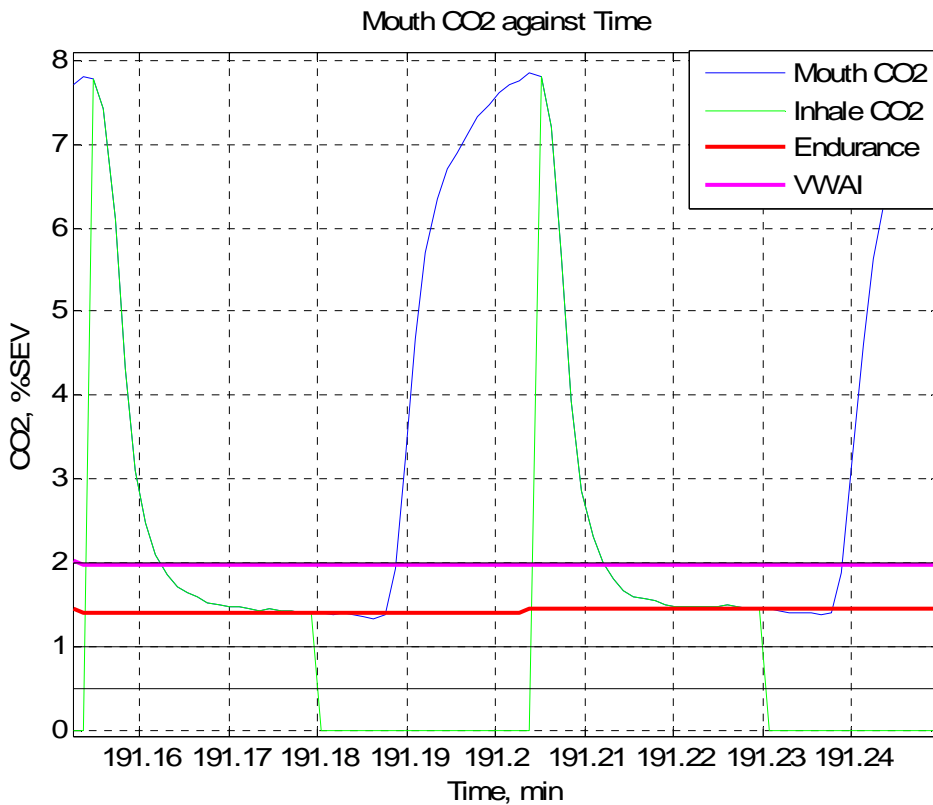


Figure 6-3. VWAI CO2 at the 2% SEV point.

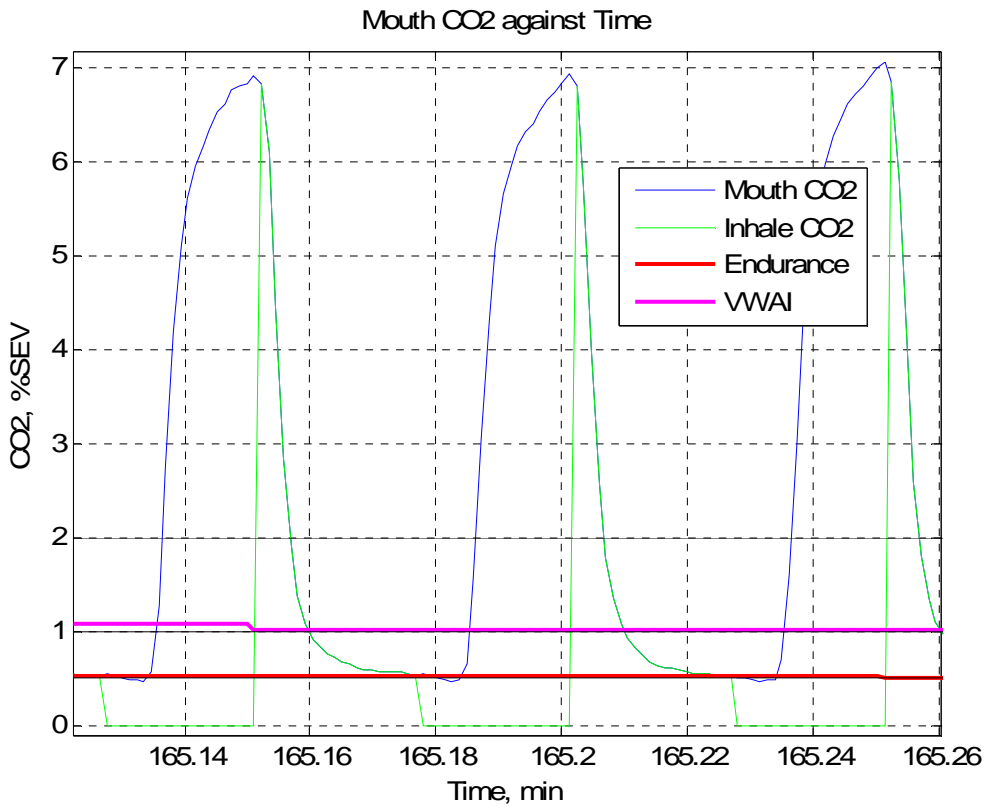


Figure 6-4. 0.5% SEV end of inhale points.

6.1.3 Breath by Breath CO2 Check from 40m test

The CO2 was stored, breath by breath for all tests, with extracts shown below.

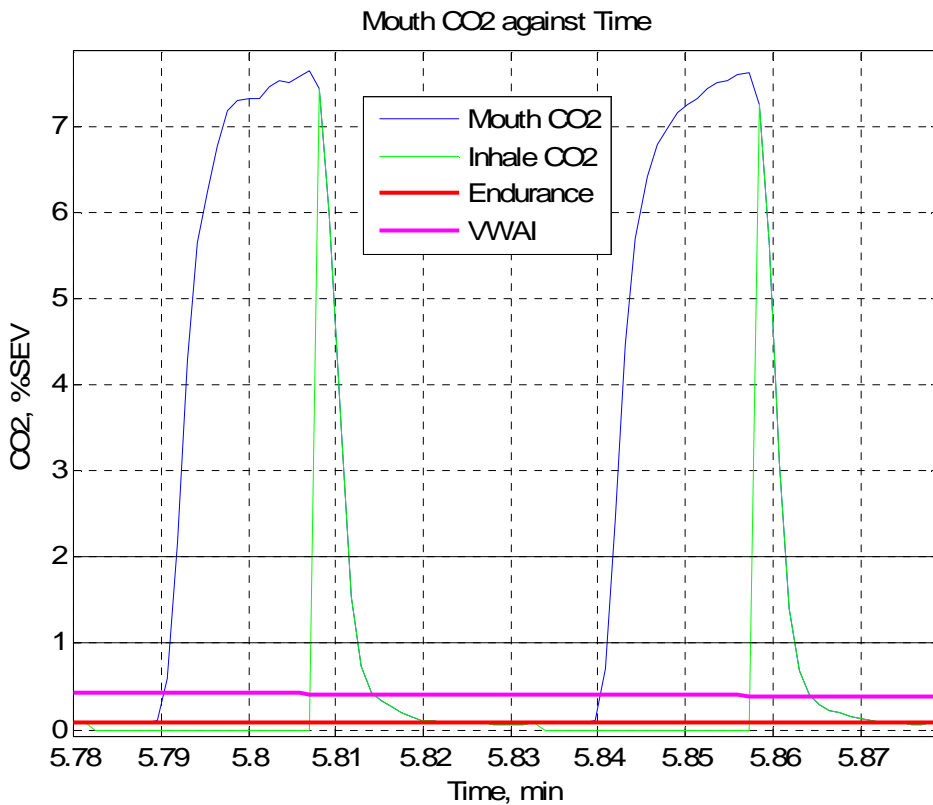


Figure 6-5. . CO2 sampled at the mouth, showing levels with a highlight of the inhaled part of the respiratory cycle (in green), the end of inhale CO2 represented as the Endurance CO2 (in red), and the Volume Weighted Average Inspired CO2 (in purple),. All curves are shown in the full scrubber endurance curves in the previous chapter.

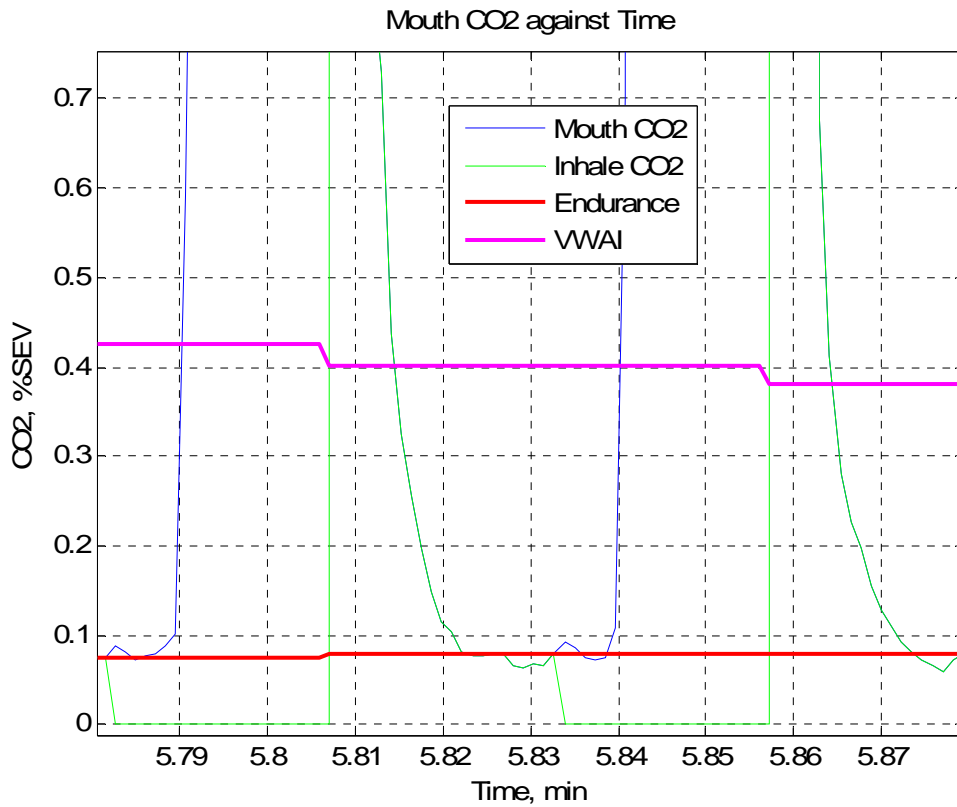


Figure 6-6. . Zoom into the previous plot showing the data of interest in more detail.

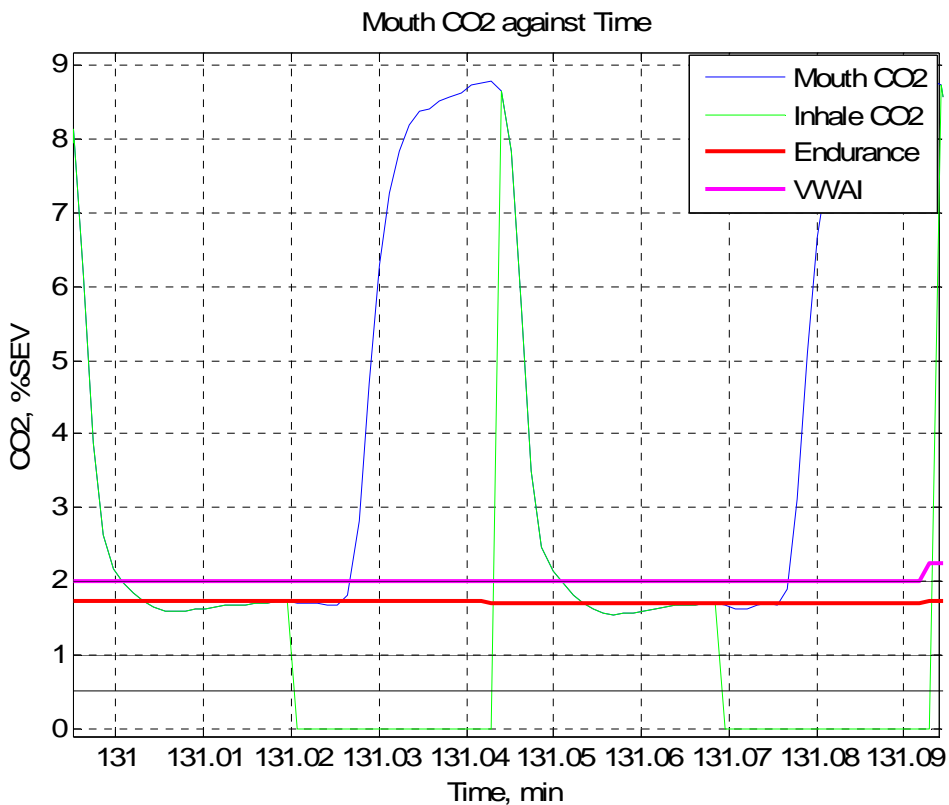


Figure 6-7. VVAI CO2 at the 2% SEV point.

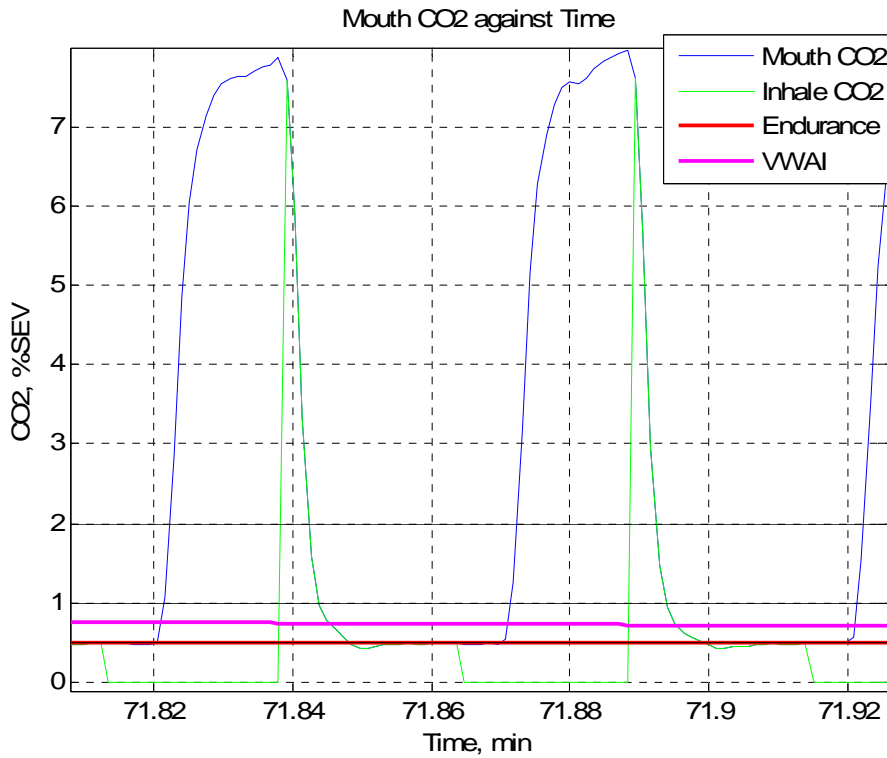


Figure 6-8. 0.5% SEV end of inhale points.

6.1.4 Breath by Breath CO2 Check from 100m test

The CO2 was stored, breath by breath for all tests, with extracts shown below.

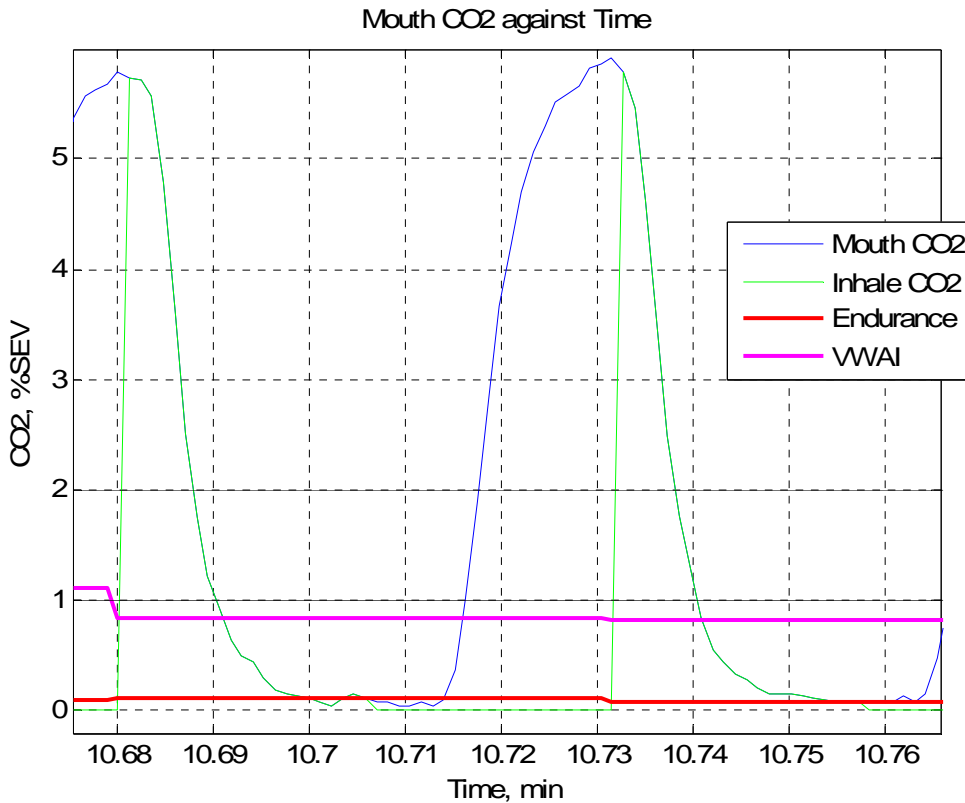


Figure 6-9. CO2 sampled at the mouth, showing levels with a highlight of the inhaled part of the respiratory cycle (in green), the end of inhale CO2 represented as the Endurance CO2 (in red), and the Volume Weighted Average Inspired CO2 (in purple),.

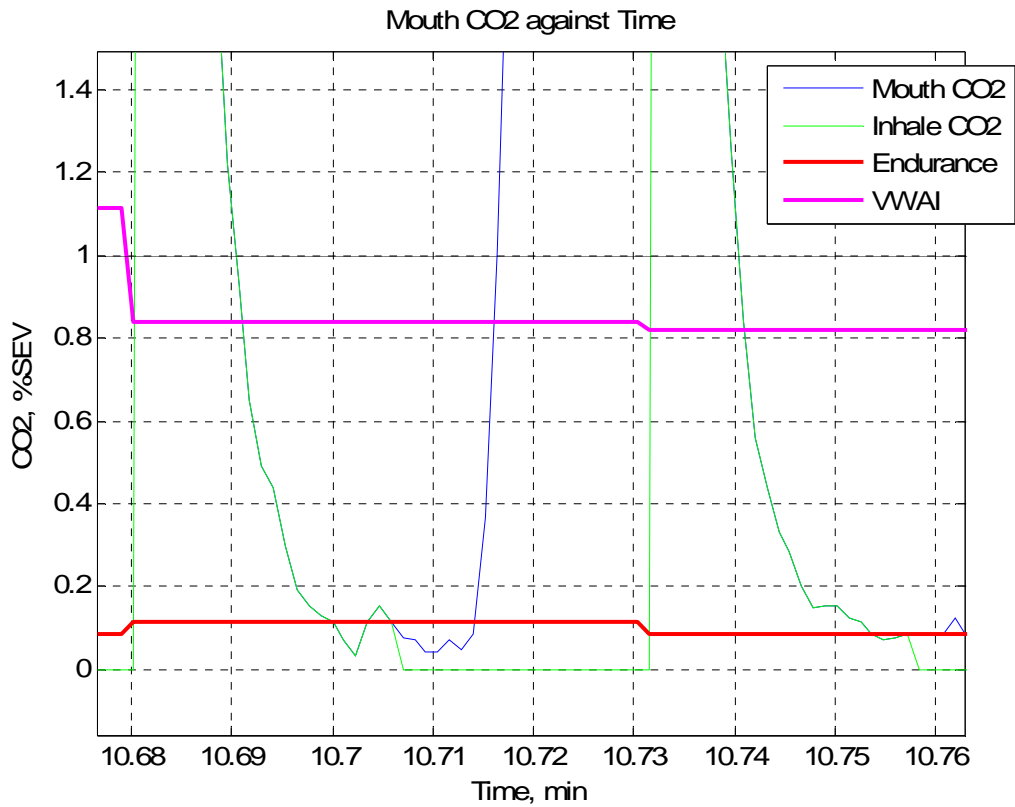


Figure 6-10. Zoom into the previous plot showing the data of interest in more detail.

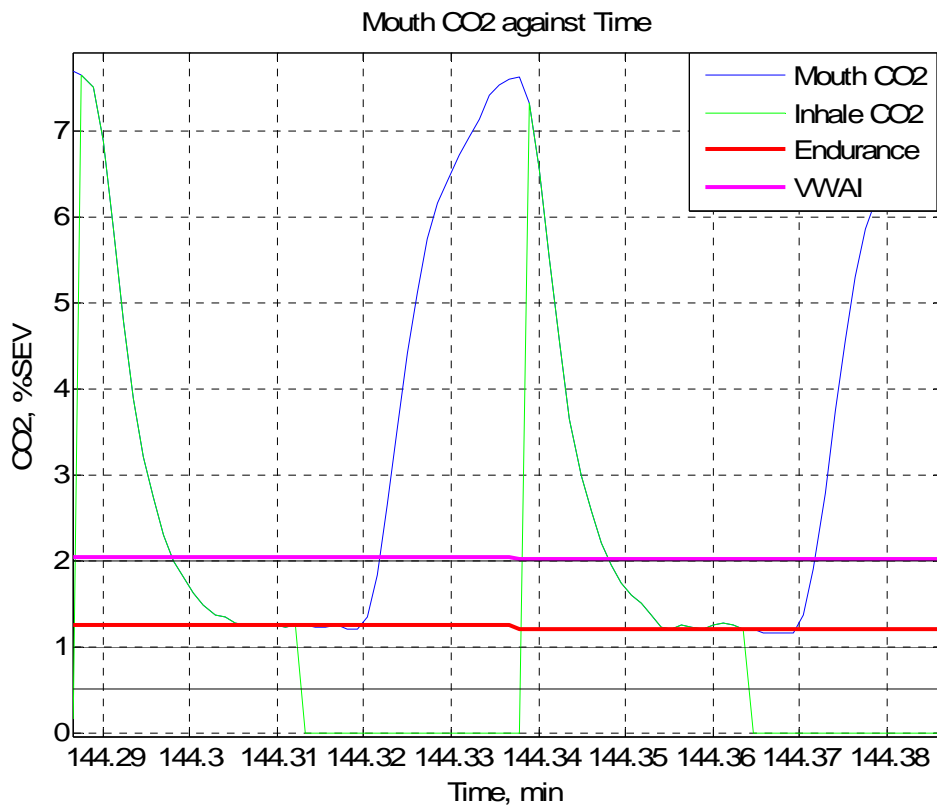


Figure 6-11. Extract at point where VWAI CO2 is 2% SEV.

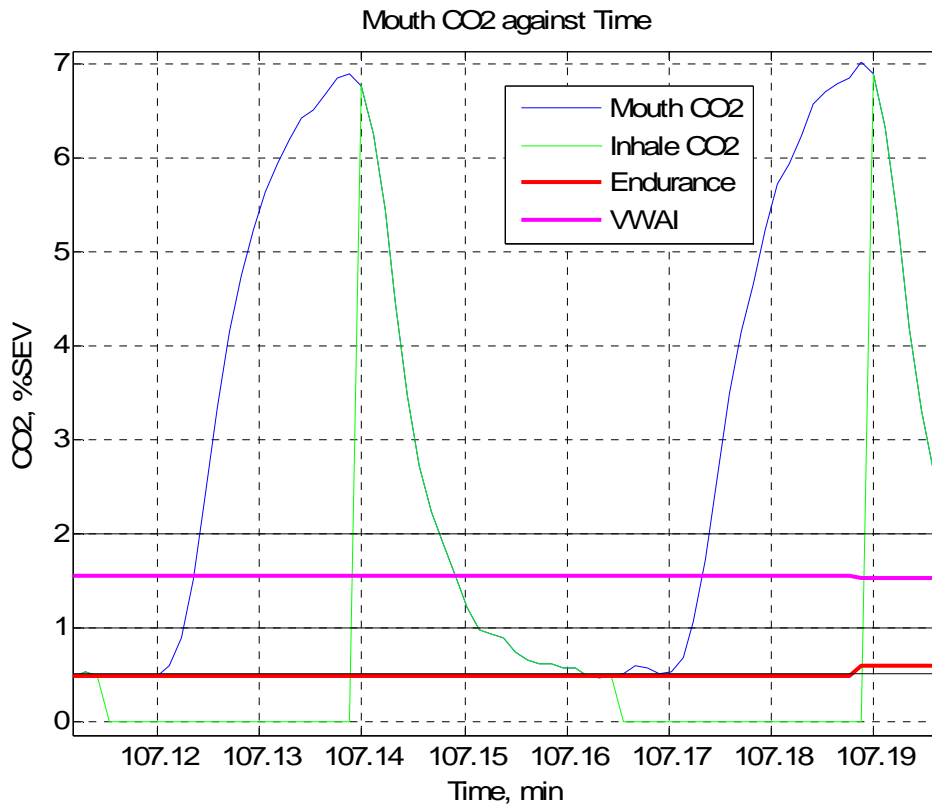


Figure 6-12. 0.5% SEV end of inhale points for scrubber 1

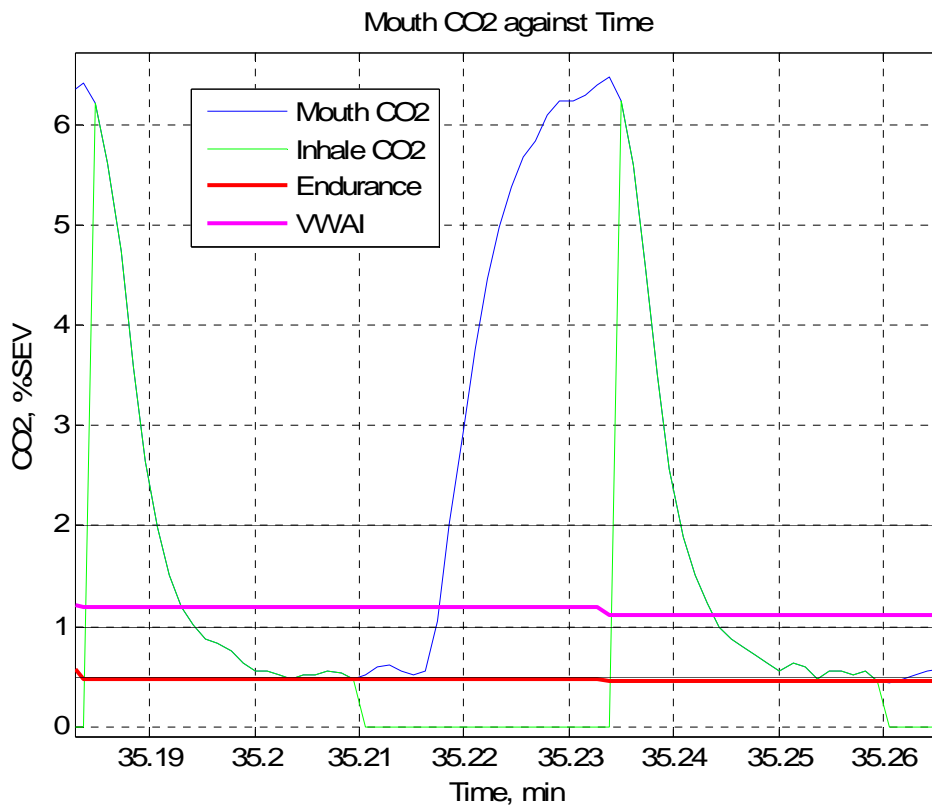


Figure 6-13. 0.5% SEV end of inhale points for scrubber 2

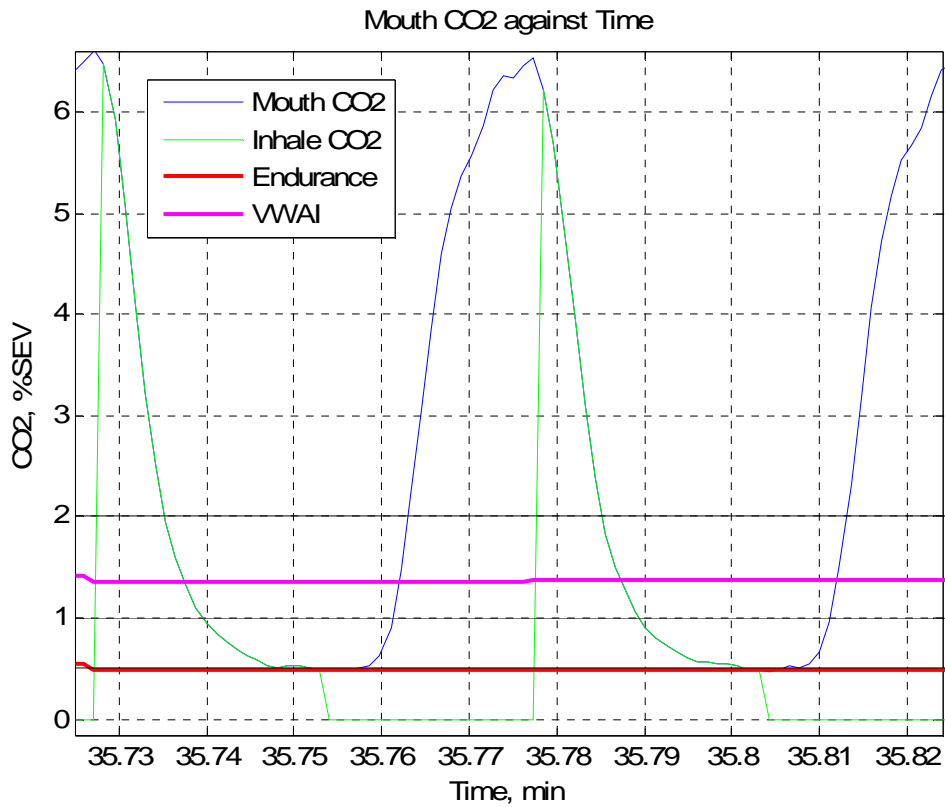


Figure 6-14. 0.5% SEV end of inhale points for scrubber 3. The duration in time using the 0.5% SEV limit varies considerably because of the hump in the characteristic. There is considerably less variation in the VWAI CO2 limit of 2% SEV that Deep Life prefers to use, and is supported by the Open Circuit standards (EN 250) and NORSOK U101:1999.

7 ANALYSIS

7.1 Sample Flow rates

Test		Mouth CO2 amplitude, %SEV to achieve pre-scrubber 4.5% SEV.	Flow in Mass spec. channel, lpm
6 msw N2	1	7.5 then 6.8	1.8 then 0.6
	2	6.8	0.6
	3	6.8	0.6
40 msw N2	1	7.5	1.8
	2	7.8	1.8
	3	7.5	1.8
100 msw, He	1	6.3	1.8
	2	6.2	1.8
	3	6.3	1.8

7.2 Tabulation of Results

Table 1. SCRUB endurance and VWAI CO2 level, for 1.6 lpm STPD at 4C, 40 lpm RMV

Repeat 2nd 40m test.

Test		End of Inhale CO2 durations, min			VWAI duration, min
		0.5kPa	1kPa	2kPa	< 2kPa
6 msw O2	1	141	158	177	170
	2	160	178	198	193
	3	146	162	183	175
40 msw Air	1	72	100	142	120
	2	90	119	151	135
	3	87	114	152	136
100 msw Heliox	1	105	136	167	161
	2	35 (hump)	108	170	154
	3	36 (hump)	100	152	138

7.3 Comparison with previous results

The results presented here are in line with those measured by Deep Life or BAI previously.

Table 2. Scrubber endurance in Micropore results for 1.6 lpm STPD at 4C, 40 lpm RMV

The results presented with the EN 14143:2003 Technical File were

Test		End of Inhale CO2 durations, min		
		0.5kPa	1kPa	2kPa
6 msw Air	1	165		
	2	155		
40 msw Air	1	55	57	82
	2	54	68	
	3	55	68	85
	4	71		
	5	76	93	120
	6	65	74	95
90 msw Trimix	1	34		
	2	32	44	63

The above results are essentially the same as those reported here for 6m depth: no difference is expected between using air and oxygen as the make-up-gas: they have similar density, conductance and permeability, and in any case, the PPO2 control of the rebreather increases the F(O2) considerably when using air.

The above results are more conservative than those reported here for the 40m depth because they were carried out by sampling the gas from immediately prior to the inhale one-way valve, at a flow rate that in itself stimulated the turbulent bypass fault reported in the Deep Life document [Fault_Study_CO2_Bypass_101209.pdf](#)

The Trimix results at 90m are a shorter duration than those here, as the hump in the response is larger. This is expected, as Trimix is a denser gas.

The present results give a basis for claiming significantly longer scrubber endurance than are claimed in the user manual. It is understood that Deep Life have no immediate plans to increase the advised endurance.

8 CONCLUSIONS

The endurance results are within the narrow statistical spread of these results, despite earlier results using measurement sample rates that would have created turbulent bypass of the one-way valves.

The scrubber endurance and VWAI CO₂ results show the presentation of scrubber endurance given in the user manuals for the Apocalypse and Incursion models are conservative.

The following durations appear to be the safe limits for the Incursion Rebreather under the EN 14143:2003 test conditions of 40 lpm RMV, 4C water, 1.6 lpm of CO₂ injection at STPD:

- 6m O₂ or Air:
40 minutes duration to a 0.5% SEV limit,
3 hour duration to the VWAI 2% SEV limit.
- 40m Air:
70 minutes duration to a 0.5% SEV limit,
140 minute duration to the VWAI 2% SEV limit
- 100m Heliox:
30 minutes duration to a 0.5% SEV limit,
150 minute duration to the VWAI 2% SEV limit.

At 90m using Trimix, the limits indicated from the previous tests are considerably more conservative, and these should remain.

For dive profiles, Deep Life recommend that durations at the various depths are used. For example, a scrubber endurance quoted for a 40m dive profile typically consists of just 20 minutes at 40, at the end of which some breakthrough can be seen, then the depth is reduced to 9m or even less, and the rest of the test is at that depth. Deep Life make the point that divers read that a 90 minute duration quoted on a popular rebreather for a 40m profile, as being a 90 minute duration, but in fact the actual duration at that depth to the CE limit is more likely 30 minutes at that constant depth.

By quoting constant depth, the diver can see the endurance at a constant 40m, then if decompression is at 6m, the proportion of the endurance remaining can be determined from the constant depth figure for 6m. In the case of this apparatus, there is a significant difference with depth at the 0.5% SEV limit, but using the Open Circuit VWAI limit of 2% SEV (also the NORSOK U101 rebreather limit is a VWAI 2% SEV limit) then there is no significant difference with depth: the rebreather has a 140min to 180min duration. As the final part of the dive is carried out near 6m depth, then the figure quoted by Deep Life, that the diver does not exceed a 2 hour 45 minute duration for any dive (using the VWAI 2% SEV limit), appears to be reinforced by these test results