COMPLIANCE ASSESSMENT: RESPIRATORY PARAMETERS OF DEEP LIFE ALVBOV REGULATOR IN OPEN LOOP MODE

DOCUMENT: [Filename]	DV_DL_ALVBOV_Breathing_Params_A3_100318.doc
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LAST UPDATED:	**18th Mar 2010**
REVISION:	**A3**

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Revision History

Revision	Date	Description
A1	20.01.2010	Test report issued
A2	17.03.2010	Correction of a typo due to Annex A, and cut of requirement. Consideration added of the EN 15333 WOB limit under the same test conditions as EN 250.
A3	18.03.2010	Cracking pressure description added. Correction to conclusion drawn on TX100. Gas temperatures clarified. Lissajou direction clarified

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1. PURPOSE AND SCOPE

This document reports the results of a compliance assessment of the respiratory performance of Deep Life's Open Revolution ALVBOV in open circuit mode, against the requirements for the Work of Breathing (WOB) and Breathing Resistance in European standard EN 250:2000 with Appendix A1:2006. Consideration is also given to the maximum respiratory limits in EN 15333:2008 under the EN 250:2006 test pressures and RMVs.

The performance of the ALVBOV was tested using Apollo A-320 and Apeks DS4 first stage regulators.

The document is a Design Verification Report in terms of BAI Quality Procedure QP-20 (Safety Critical Systems).

2. SOURCE DOCUMENTATION

The following documentation was provided:

- Bill of Materials Revision B16, by Deep Life Ltd
- Exploded Drawings, by Deep Life Ltd
- CAM 3D model of ALVBOV, by Deep Life Ltd
- European Normative Standard EN 250 January 2000 + Annex A1 May 2006.
- European Normative Standard EN 15333-1 2008

3. REQUIREMENT FOR LIMITS OF PERFORMANCE

In EN 250 The water temperature used is 10C, other than for cold water performance which is tested at 4C +0/-2C.

3.1. EN250:2000 Section 5.6.1 Limits

When tested at 6 bar absolute, in accord with the test in Section 6.5 of the standard,

- **the work of breathing shall not exceed 3.0 J/L;**
- the peak respiratory pressure during inhalation and exhalation shall be within the range +/-25mbar
- the positive work of breathing during inhalation shall not exceed 0,3J/L
- pressure spikes with no measureable positive work of breathing shall not exceed 10 mbar;
- pressure peaks with measureable work of breathing shall not exceed 5 mbar.

The test conditions in Section 6.5 of the standard is 62.5 lpm (25 cycles/min, 2.5 L stroke), wet at 10+0/-1 C. The regulator is in the diver upright position.

The supply pressures of maximum and 50 bar shall be tested.

There are no adjustable sensitivity controls on the apparatus under test.

3.2. EN250:2000 Section 6.1.3 Calibration conditions

The Standard requires that:

> *The performance characteristics of the breathing simulation test rig shall be defined by use of a calibration test orifice shown in figure 4. The test orifice shall be inserted into the test rig in place of the demand valve and tested at 62.5 lpm RMV (25 cyles/min, 2.5 litre stroke) at 6 bar absolute (50mfw). The values for work of*

breathing and inhalation/exhalation pressures shall not exceed 3 J/L and +/-25mbar respectively.

3.3. EN 15333:2008 Section 5.7.1 Performance Requirements

The above standard covers open circuit umbilical supplied diving equipment. The appartus may be used in open circuit mode with umbilical supply only as an emergency bail out device. The performance requirements in that standard for primary regulators was considered. Those requirements are expressed in Section 5.7.1.1 as quoted below:

5.7.1.1 Breathing performance at standard RMV

The breathing performance shall be measured using a sinusoidal waveform from a breathing simulator with

simulated RMV up to 62,5 l min-1 (ATP; Ambient Temperature and Pressure (see Table 6)). The performance of the system shall be determined using air or an oxygen in nitrogen gas mixture at an ambient pressure of 6 bar and where appropriate using an oxygen in helium based mixture at an ambient pressure of 7 bar or a reduced pressure specified by the manufacturer.

The breathing system shall meet the following requirements related to an RMV (BTPS; body temperature at pressure saturated) from 10 l min-1 to 70 l min-1:

a) the work of breathing (WOB) shall not exceed a value of:

$$WOB = 0,5 + 0,03 \times RMV \ [J \times l\text{-}1]$$

The above equates to a work of breathing limit of 2.375 J/L at 62.5 lpm, the EN 250 test conditions.

5.7.1.2 Breathing performance at high RMV

The breathing performance shall be measured using a sinusoidal waveform from a breathing simulator with simulated RMV at 75 l/min (ATP; Ambient Temperature and Pressure (see Table 6)). The performance of the system shall be determined using air or an oxygen in nitrogen gas mixture at an ambient pressure of 6 bar and where appropriate using an oxygen in helium based mixture at an ambient pressure of 7 bar or a reduced pressure specified by the manufacturer.

The breathing system shall meet the following requirements related to an RMV (BTPS) from 70 l min-1 to 85 l min-1:

a) the work of breathing (WOB) shall not exceed a value of:

$$WOB = 0,5 + 0,04 \times RMV \ [J \times l\text{-}1] \ (2)$$

NOTE The WOB specified is considered to be a physiological maximum level and the manufacturers should endeavour to keep the WOB as low as possible.

b) inspired and expired respiratory pressures shall be determined as shown in Figure 1. The inspired and expired respiratory pressures shall not exceed 35 mbar each;

c) the positive work of breathing during inhalation shall not exceed 0,5 J×l-1;

d) pressure spikes with no measurable positive work of breathing shall not exceed 25 mbar;

e) pressure peaks with measurable positive work of breathing shall not exceed 12 mbar.

Testing shall be done in accordance with 6.5.1, 6.5.2 and 6.5.3.

The use on umbilical gas is primarily with heliox, which has a much lower density that air. The EN 250 test conditions are the same as the above test using air at 62.5 lpm RMV, except that the limits for respiratory pressures are lower in EN 250:2006.

4. 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	July 2010 and Check cal prior to test
Differential pressure sensor. Druck LPM9381	2393261	Aug 2010
Test chamber high pressure sensor Keller ECO1	004630	July 2010
High pressure sensor ME 705	DL 004	July 2010
National Instruments Data Capture System PCI-6014	HA4375847	Against TTi 1906, Serial Number 111474 Prior to test
Power supply GPR – 1850	033624	N/A
Deep Life 800 mm chamber, with environmental control, rotateable	CH03	Next hydrostatic Sept 2014
Thermometer, high accuracy. Protek D610 and probe	D61000013	Dec 2010

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*.

4.1. Sample inspection

The samples were diassembled and checked against the 3D CAM model and the reference exploded drawings, and was found to meet the drawings, with a dual lever and spring to change the cracking pressure between CCR and OC mode. The sample were fitted with crown strap and necklace toggle straps.

The samples appeared to be production samples, formed using plastic injection moulding other than metal parts which have the appearance of having been cast and then CNC machined.

4.2. Cracking Pressures

The cracking pressure of both the TX100 and the ALVBOV was set using a slotted screw inline with the gas hose.

There are two factors that determine the optimum cracking pressure:

1. The distance from the diaphragm to the mouthpiece determines the minimum cracking pressure required to prevent **static freeflow**, because when the 2nd stage regulator is immersed in water, such that the diaphragm is downwards and the mouthpiece is just out of the water, the hydrostatic pressure at the diaphragm causes the regulator to freeflow unless the cracking pressure is set higher than the hydrostatic pressure. This requires a significant amount of gas to flow – enough to fill the regulator body with gas, therefore the pressure peak to prevent hydrostatic freeflow occurs not at the very start of the breathing cycle but just slightly afterwards.
2. The hydrostatic pressure arising from physical offset of the diaphragm from the venture outlet determines the minimum cracking pressure required to prevent **dynamic freeflow**. Completely different venturri mechanisms are used in the two regulators under test. On the TX100 there is a baffle very close to the mouthpiece exit which has a venturri effect. On the ALVBOV the venturri outlet is near the middle of the regulator, that is, half way between diaphragm and outlet.

The ALVBOV has a recommended cracking pressure when dry of 6mbar (preventing dynamic freeflow), and this corresponds to a peak inhale pressure 10mbar in water when breathed at 62.5 lpm RMV (preventing static freeflow). The difference in the pressures exists because the former is a pressure at which gas will start to creep from the regulator in air, and the latter is a dynamic peak pressure just after the cracking pressure is exceeded but before there is any significant quantity of gas flowing: the breathing pattern is sinusoidal flow (cosh volume), for the tests reported herein.

It would be expected that the cracking pressure for the ALVBOV would be higher than for the Apeks TX100 because that hydrostatic distance from diaphragm to mouthpiece is higher on the ALVBOV than TX100. However, the greater venturri offset in the Apeks TX100 under the same intermediate pressure meant that both regulators had to be set to 6mbar negative cracking pressure dry to prevent freeflow occuring.

4.3. Calibration references and means

- NATO 1410 Small Calibration Orifice (S/N DL 008)
- EN14143 Calibration Orifice (S/N DL 009)

Calibration orifices, calibration weight set, calibrated graduated volume currently subject to annual calibration, and are inspected for wear on each use.

The gas used was clean air, supplied with certificate recording its purity.

For the Breathing Simulator calibration, the standards specify the performance using test orifices and an elastance test fixture. There are two orifices used: one is the NATO orifice, the second is the EN14143 orifice. The calibration check confirmed the min and max Lissajou pressures were in accord with those obtained in the annual full calibration taken on 22nd April 2009 (NATO orifice) and 7th Aprtil 2009 (EN orifice) respectively. The breathing simulator calibration was retested within a week before and after the tests reported herein.

The calibration of the respirator (DL-BM-Rev.C2) is described in the *Cal_Breathing_Simulator_Assessment_090707.pdf.*

The pressure chamber was recently hydrostatically tested and the working pressure is 140bar (equivalent to 1400msw). Hydrostatic test pressure was 240 bar. Burst pressure is 350bar.

The operation of the refigeration system was checked by a competent person. The temperature of the water is monitored and recorded for each test automatically using Matlab, using a calibrated temperature sensor.

A safety assessment for these specific tests was carried out in addition to a general assessment for all of EN14143 and NORSOK U101 tests. Safety provisions in use of compressed gases were observed. Tests were overseen by a qualified Advanced Gas Technician. All tests were carried out by qualified and experienced graduate engineers.

Lissajous are clockwise from left to right, starting with diver exhale as a positive value, then diver inhale.

Gas temperatures are the average gas temperature to and from the gas inhaled into the breathing simulator. These temperatures are not 10C, or 4C, (the ambient water temperature, because the exhale gas into the apparatus under test (breathing simulator exhale) is heated to 32C by the breathing simulator, and the gas supply is outside the chamber for the tests (at lab temperature for that lab, which is around 16C due to the presence of the cold chambers and pools). Use of this reference will change to Diver Exhale in future.

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5. METHOD

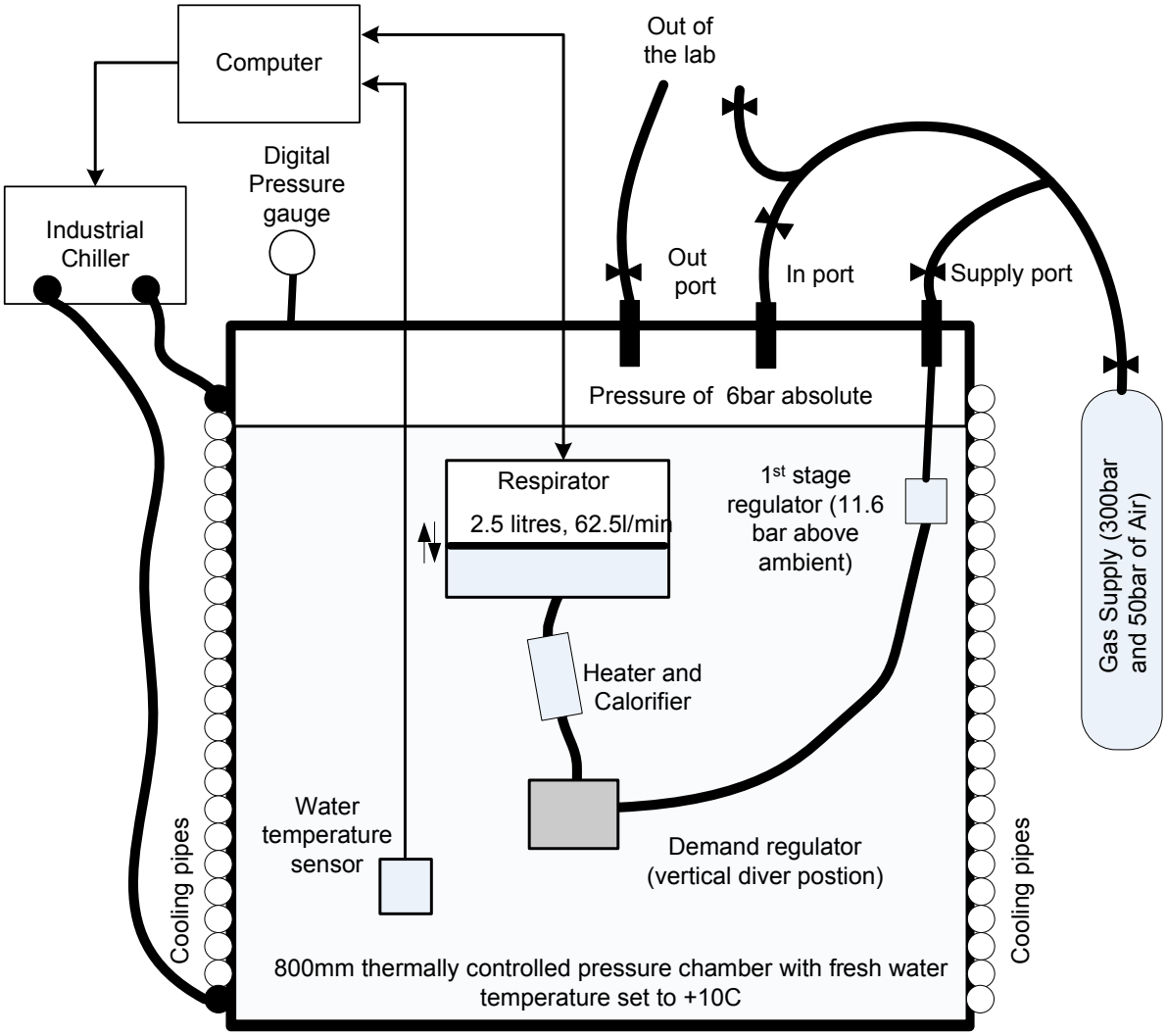


Figure 5-1: The test fixture used for WOB and respiratory pressure measurements. This is used for cold water breathing tests and all O.C. tests because the gas supply is outside the chamber to accommodate a large gas supply, supplying the first stage regulator in the chamber with high pressure gas that is used until the supply is 50 bar. Pressure measurements are taken from the mouthpiece, relative to the water pressure at the same depth.

The intermediate pressure was set to 11.5 bar at surface pressure and lab temperature of 23C, but measured at 17.6 bar at 6 bar absolute (11.6 bar above ambient at depth and in water at 10C and 4C).

The next section contains results on general testing of the regulators according to EN250:2000, with the source gas set to the worst case supply pressure of 50 bar.

6. TEST RESULTS

Two samples of DL ALVBOV regulators were tested, using Apollo A-320 and Apeks DS4 first stage regulators, set to 11.5 bar intermediate pressure on the surface at 23C.

The performance was compared with the requirements of the standard and with the Apeks TX100 regulator as the design uses the same parts. The reasons for the comparison was to determine if fluctuations in pressure were normal behaviour for this type of second stage.

Figure 6-1. ALVBOV sample 1. Sample 2 appeared identical. CCR hoses were plugged as shown for the machine tests.

Figure 6-2. Sample of Apeks TX100 used to quantify the relevance of the flutter characteristics.

RESPIRATORY WORK AND RESISTANCE MEASUREMENT

EQUIPMENT TYPE & SERIAL NUMBER	:	DL ALVBOV sample 2 open circuit	
TEST METHOD	:	EN250:2000 section 6.5.1	SINE FLOW
DATE AND TIME	:	14.01.2010	
TEST CARRIED OUT BY	MS	WITNESS: AD	

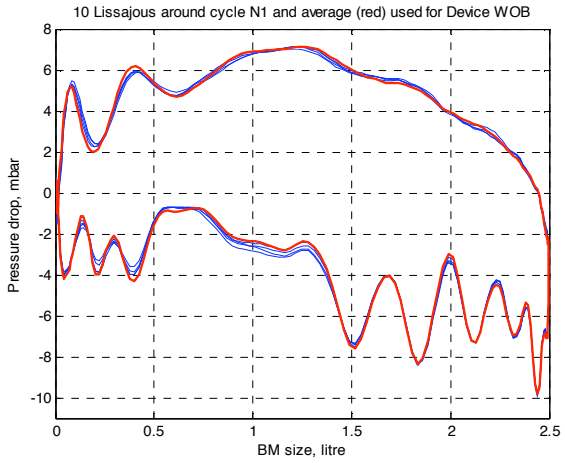
CONDITIONS OF TEST

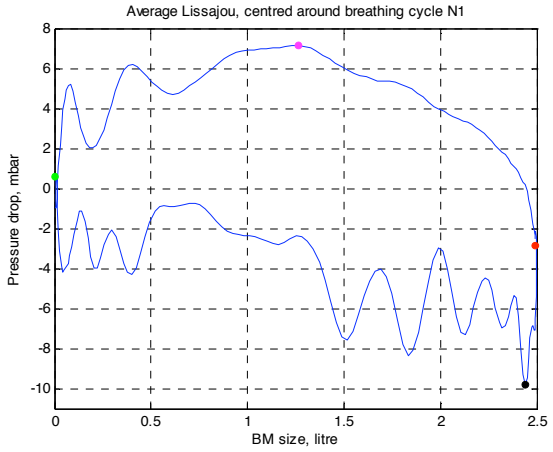
ATTITIDE: PITCH & ROLL	:	90/0	Deg.
GAS MIXTURE	:	air	
DEPTH	:	55.0	msw
ROOM / WATER TEMPERATURE	:	19.0 / 9.9	℃
AVERAGE GAS TEMPERATURE	:	16.7	℃
GAS SUPPLY PRESSURE	:	11.6	barg
TIDAL VOL, RESP RATE, RMV	:	2.5L/24.8bpm/62.2lpm	metric

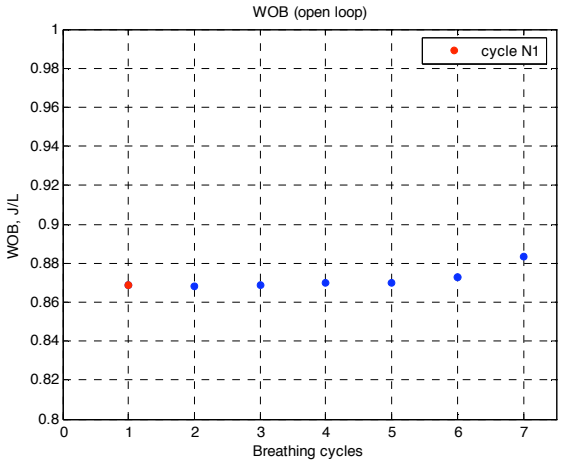
RESULTS

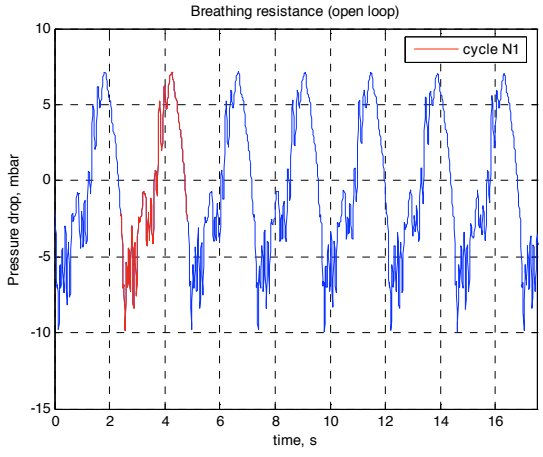
PRESSURE@END EXHALE / INHALE	=	-2.9 / 0.6	mbar
PHYSIOLOGICAL PEAK PRESSURES	=	-9.8 / 7.1	mbar
PEAK TO PEAK PRESSURE	=	16.9	mbar
INHALE/EXHALE RESP PRESSURES	=	-7.0 / 6.5	mbar
TOTAL WORK OF BREATHING (WOB)	=	0.87	J/l
WOB OF BREATHING SIMULATOR	=	0.00	J/l
WOB OF DEVICE UNDER TEST	=	0.87	J/l
TOTAL POS / NEG WORK	=	0.58 / 0.28	J/l
POS / NEG WOB OF DEVICE UNDER TEST	=	0.58 / 0.28	J/l

ALL DATA STORED AS # (DATA FILE): WOB_ALVBOV2_90d_55m_62.5lpm_air_100114_1









Positive / Negative WOB above referst to Exhale and Inhale respectively.

RESPIRATORY WORK AND RESISTANCE MEASUREMENT

EQUIPMENT TYPE & SERIAL NUMBER	:	Apeks TX100 sample 1	
TEST METHOD	:	EN250:2000 section 6.5.1	SINE FLOW
DATE AND TIME	:	14.01.2010	
TEST CARRIED OUT BY		MS WITNESS: AD	

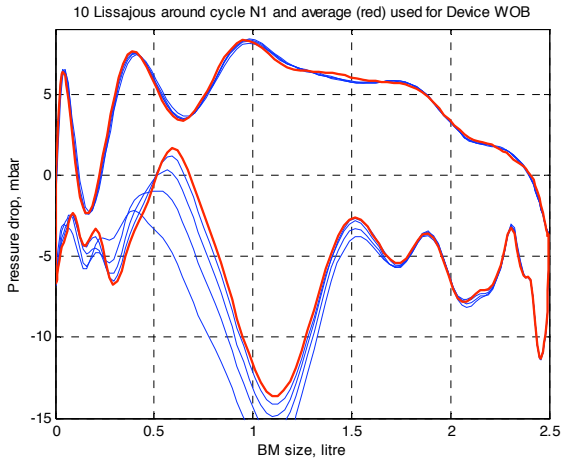
CONDITIONS OF TEST

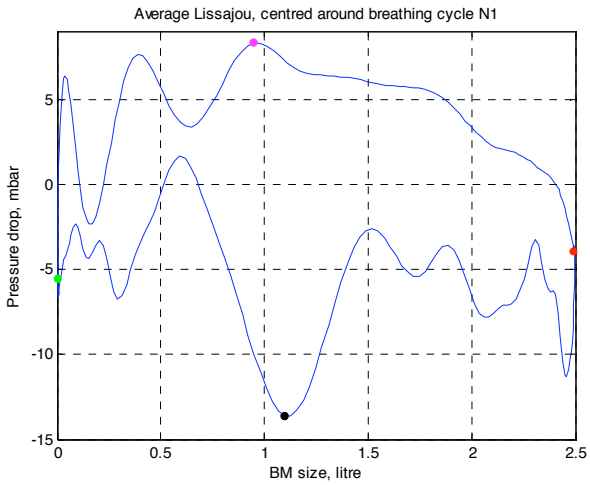
ATTITIDE: PITCH & ROLL	:	90/0	Deg.
GAS MIXTURE	:	air	
DEPTH	:	54	msw
ROOM / WATER TEMPERATURE	:	19.0 / 9.8	℃
AVERAGE GAS TEMPERATURE	:	15.2	℃
GAS SUPPLY PRESSURE	:	11.6	barg
TIDAL VOL, RESP RATE, RMV	:	2.5L/24.9bpm/62.3lpm	metric

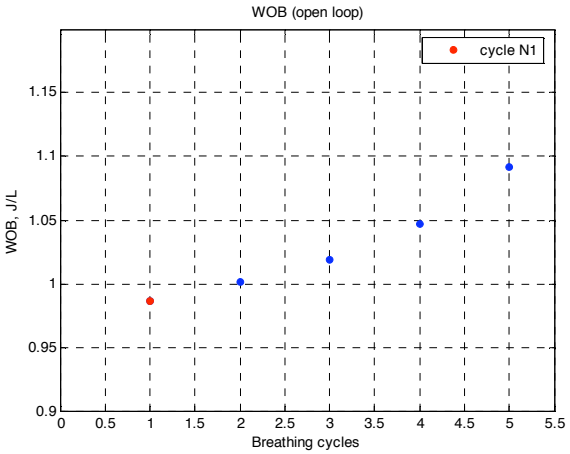
RESULTS

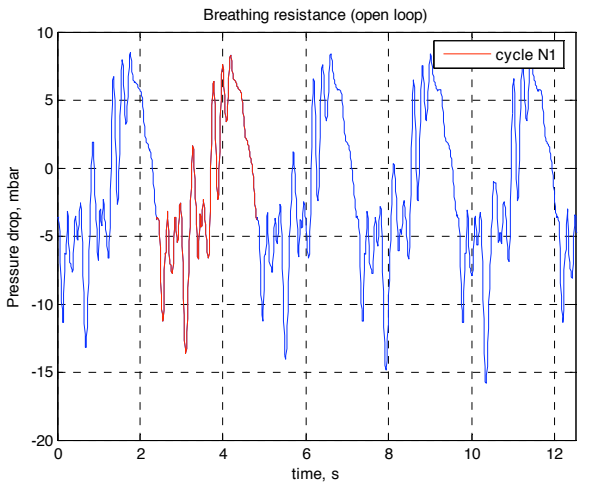
PRESSURE@END EXHALE / INHALE	=	-3.9 / -5.6	mbar
PHYSIOLOGICAL PEAK PRESSURES	=	-13.6 / 8.3	mbar
PEAK TO PEAK PRESSURE	=	21.9	mbar
INHALE/EXHALE RESP PRESSURES	=	-9.7 / 13.9	mbar
TOTAL WORK OF BREATHING (WOB)	=	0.99	J/l
WOB OF BREATHING SIMULATOR	=	0.00	J/l
WOB OF DEVICE UNDER TEST	=	0.99	J/l
TOTAL POS / NEG WORK	=	0.91 / 0.08	J/l
POS / NEG WOB OF DEVICE UNDER TEST	=	0.91 / 0.08	J/l

ALL DATA STORED AS # (DATA FILE): WOB_ApeksTX100_90d_54m_62.5lpm_air_100114_1









Positive / Negative WOB above referst to Exhale and Inhale respectively.

6.1.1. Observations and Results

Due to difficulties in equalisation of the chamber with large amounts of gas pressurising the chamber at each exhale cycle, the test pressures above were 6.5bar and 6.4 bar absolute for the ALVBOV and Apeks TX100 respectively. The results viewed in real time at the start of the test at 6.0 bar were proportionally lower in Work of Breathing and breathing resistance. The pressure control of the chamber was optimised for rebreather testing, and equalisation was performed with a manually set constant chamber purge for these tests.

The result at 6.5bar and 6.4 bar, with 50mbar supply pressure, is the worst case WOB and flutter on both valves.

The tests were run for more than 5 minutes to reduce the supply pressure to 50 bar for the above tests and no freezing was observed (at 3.9C). The equipment was in the test chamber and under pressure for more than 20 minutes before the test.

Parameter	*ALVBOV*	*TX100 Reference*	*Limit*	*ALVBOV Pass/Fail*
Work of Breathing at 62.5 lpm RMV, pressure 6.5 and 6.4bar absolute respectively.	0.87 J/L	0.99 J/L	3 J/L at 6 bar	Pass
EN 15333:2008 WOB limit at 62.5 lpm RMV	0.87 J/L	0.99 J/L	2.375 J/L	Pass
Breathing resistance: inhale / exhale	-9.8 / 7.1	-13.6 / 8.3	+/- 25 mbar	Pass
Positive work of breathing during inhalation shall not exceed 0.3 J/L	0.28 J/L	0.08 J/L	0.3 J/ L	Pass
Positive pressure spikes with no measurable positive work of breathing during inhalation shall not exceed 10mbar	No spikes without measureable WOB	No spikes without measureable WOB	10 mbar	Pass
Pressure peaks with measureable WOB shall not exceed 5 mbar	4.4mbar pk to pk, hence 2.2mbar peak	12mbar pk to pk, hence 6mbar peak	10 mbar peak	Pass
Test at 4C (3.9C)	No material change in results	-	3 J/L, +/-25mbar	Pass
Apollo A-320 and Apeks DS4 1st stages	No change in results	Tested with DS4 only	3 J/L, +/-25mbar	Pass
Flutter performance	Reasonable to Good	Reasonable	Not stated, but would impair practical performance if severe	Pass

7. MANNED TEST DIVE REVIEW

The flutter performance was compared with the Apeks TX100: the ALVBOV uses Apeks parts, but differs in key aspects including, the diaphragm is smaller on the ALVBOv and the venturri effect is increased in the ALVBOV compared to the TX100. The flutter performance was at least as good as the Apeks TX100.

Deep Life provided evidence of manned test dives performed at Wakulla, Florida, USA using the ALVBOV in open circuit mode using oxygen and air, by test divers. The test divers reported the ALVBOV breathed well, “like a good modern regulator”. There was no problem reported by any diver with respect to valve flutter.

Other observations from the manned dives that Deep Life requested be highlighted were:

1. Absence of freeflow in Open Circuit mode with the cracking pressure settings recorded here.
2. Bubbles did not obscure the diver’s vision.

8. CONCLUSION

The Work of Breathing and ALVBOV has a work of breathing of 0.89 J/L under the test conditions, which is well within the EN250:2000 limit of 3 J/L.

The ALVBOV has peak inhale and exhale breathing resistance of -9.8 and 7.1 mbar, with general peaks of -7.0 and 6.5mbar, within the EN 250:2000 limits.

The pressure spikes were within the allowed EN 250:2000 limits of 10mbar and 5mbar peak.

The inhale work of breathing was within the allowed EN 250:2000 limit of 0.3 J/L.

The overall breathing performance is well within the requirements of EN 250:2000.

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