VERIFICATION OF THE AVAILABLE BREATHABLE VOLUME OF THE DEEP LIFE OPEN REVOLUTION FAMILY OF REBREATHERS

DOCUMENT: [Filename]	DV_OR_Tidalvolume_090911
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DATE ORIGINATED:	11th Sept 2009
REVISION:	**B2**

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Revision History

Revision	Date	Description
A0	10th July 2009	Assessment report, Deep Life Mantis Safety Requirement M473
B2	11th Sept 2009	Rev B0 (10th Sept 09): EN 14143:2003 Compliance tests added, also covering Deep Life Mantis Safety Requirement M474. Rev B1 (10th Sept 09): Clarification on request of Deep Life of table labels. Rev B2: Proof-read and passed for general release.

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Table of Contents

1 Purpose and Scope

The purpose of this document is to describe the test requirement, method and results to determine the compliance of the following models of the rebreather, as submitted for test at the date of this report, with safety and statutory requirements for breathable volume:

- OR_Apocalypse Type IV (O2-CCR and iCCR have identical flexible volumes and geometry)
- OR_Incursion,
- OR_Umbilical.

The scope is to perform two types of test relating to breathable volume:

1. Safety requirement tests to determine the maximum breathable volume and accessibility of the gas.
2. Legal compliance tests specified in European Standard EN 14143:2003.

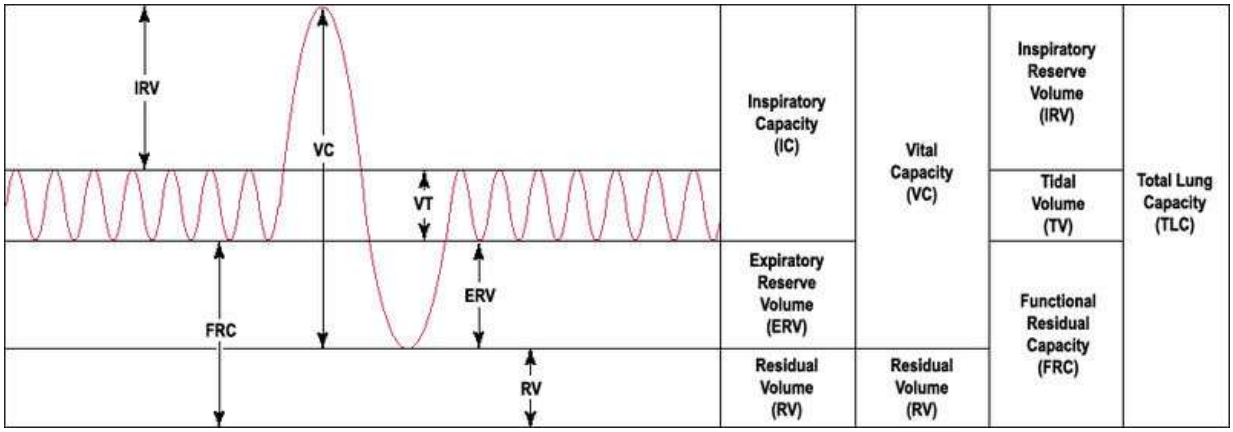
2 Requirement

2.1 Safety Requirement for Breathable Volume to support Diver's Vital Capacity

The HAZID and FMECA for the apparatus (V6 Section 7.10: Counterlungs unable to provide gas) identifies a safety requirement that a diver should be able to get a full lung of gas from the rebreather. This safety requirement is recorded in the Deep Life Requirements tracking system as Mantis 473 and to meet this requires a measurement to verify the maximum breathable volume of the apparatus.

To measure the breathable volume requires that the apparatus be pressurised to 25mbar (the peak loop pressure allowed), measure the displacement, then reduce the pressure to -25mbar, and measure the displacement again. The difference in displacement between maximum and minimum loop volume is the breathable volume of the apparatus.

Mantis states a requirement for between 5.5 and 6.5 litres, which is understood to be based on medical literature and advice. This has been provided using more readily accessible references below for BAI's review. The terms used in the diagam below are adopted[1].



[1] From Wikipedia, Lung Volumes, with a capture date of 1st July 2009.

The underlying safety requirement is that a diver should be able to inhale their Vital Capacity (VC) from the apparatus.

The adoption of 5.5 to 6.5 litres as the limits by the Design Authority for rebreather breathable volume does not cover the VC of all possible divers. For the purposes of the tests to meet the overall safety requirement that there shall be sufficient breathable gas available for a diver to take a full breath, the Design Authority provided the following information:

> *The Wikipedia article from which the above Lung Volume chart is taken states the VC of a 70kg male is 4.6 litres, and that of a female is 3.6 litres calculated as 77.5% of the male figure. A 70kg male is a world average but would be considered small in many countries in which the apparatus will be used, particularly North America and Northern Europe.*
>
> *For larger body sizes, the expected lung capacity can be calculated from body surface area (BSA), which, in turn, can be estimated from height (in centimeters) and weight (in kilograms) using the following equation[2] :*

$$\mathrm{BSA}\ (\mathrm{m}^2) = \sqrt{\frac{\mathrm{height}\ (\mathrm{cm}) \times \mathrm{weight}\ (\mathrm{kg})}{3600\ (\mathrm{cm\,kg/m^4})}}$$

> *It is reported that it is possible to estimate vital capacity (in cm^3), by multiplying BSA by 2500 for males, and by 2000 for females[3]. The largest person likely to use the apparatus is a 150kg male, 2.2m high Swiss diver, with a vital capacity calculated using the BSA equation, of 7.7 litres.*
>
> *Among the largest human lung capacities reported are:*
>
> - ***Peter Reed** is a British Olympic rower, measured at 11.68 litres, roughly twice that of an average person.*
> - ***Grant George Hackett**, an Australian Olympic swimmer reported to have a lung capacity of 13 litres*
> - ***Michael Fred Phelps** is a US Olympic swimmer reported to have a 12 litre lung capacity.*
>
> *The above total capacity figures include the residual volume, which is also large for these individuals. These unusual individuals would not be able to take a maximal inhalation on the apparatus without triggering the ALV because providing an 11 litre breathable volume would create unreasonable buoyancy hazards for the average user.*
>
> *The range 5.5 litres to 6.5 litres appears to be optimal, providing for over 95% of divers, but without adding too large a capacity that might create a buoyancy risk for average divers.*

A further safety requirement is that the apparatus allow the diver to adjust his buoyancy by adjusting the counterlung volume, in the event of a failure of his primary buoyancy control

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[2] Mosteller, R.D., 1987. "Simplified Calculation of Body Surface Area." *New England Journal of Medicine* 317 (October 22): 1098 (letter).

[3] Example provided by Deep Life Ltd from the internet reference: http://www.sciencebuddies.org/mentoring/project_ideas/MamBio_p008.shtml, original source unknown.

devices. This was assessed by manned dives, where a diver used the apparatus without any other buoyancy device: video of this dive provided by Deep Life Ltd was reviewed and found to be satisfactory – the rebreather diver was certainly finding the dive considerably easier than for a diver doing the same test on open circuit in the video.

2.2 Safety Requirement to Support Diver's Access to Breathable Gas

Changes in the diver's position can cause the breathable gas to be unreachable, unless there is an open gas pathway from the highest point of the counterlungs to the exhale port. This gas access is dependent on the position of the counterlungs relative to the diver: that is, it depends on diver attitude. This is a primary safety requirement, recorded in the Deep Life Requirements tracking system as Mantis 474. The Mantis 474 safety requirement is satisfied if the rebreather complies with EN 14143:2003 Section 5.6.3 **in all positions** used for hydrostatic imbalance testing.

2.3 EN 14143:2003 Compliance Requirement

5.6.3 Breathable volume

The apparatus shall be so designed as to provide sufficient breathable volume for the diver whilst in any attitude. It shall allow a tidal volume of at least 4,5 l.

Testing shall be done in accordance with 6.5.1 and 6.15.

6.5.1 Volume

Secure the apparatus on a mannequin according to 6.3.1, as it would be for diving with the exhaust valve at its maximum setting (if applicable).

Immerse the apparatus and mannequin to a depth not greater than 1 m at a pitch of + 90° (see figure 4).

Fill the apparatus with gas until an internal pressure at the mouthpiece of + 25 mbar is achieved or the exhaust valve starts to release gas.

Withdraw 4,5 l of gas from the apparatus recording the internal pressure. Then inject 4,5 l of gas into the apparatus recording the internal pressure.

If a breathing simulator is used it shall be set according to the values specified in Table 5.

The internal pressure when withdrawing the gas shall not exceed - 25 mbar and when injecting gas + 25 mbar.

It is noted that EN 14143:2003 Section 5.6.3 requires the breathable volume to be measured in all positions: it uses the terms "whilst in any attitude" – underlined above. The reference to the apparatus being immersed on a mannequin at a pitch of +90 degrees appears to be an instruction of how to set up the mannequin, but to comply with Section 5.6.3 all positions have to be tested. This means the apparatus will be tested on a Hydrostatic Imbalance test fixture, and requires use of the Hydrostatic Test Pool to accommodate that frame.

The EN 14143:2003 test requires that 4.5 litres be withdrawn, and 4.5 litres be then injected and the pressures recorded. To ensure the requirement is met, 4.52 litres will be withdrawn and injected.

The reference point for the 25mbar to be measured at the mouthpiece is not stated, but it is the lung centroid (not suprasternal notch, in the case of this test). Use of the lung centroid as the reference point is permitted by EN 14143:2003, Section 3. The breathing machine was removed from the mannequin for this test, in order to locate the reference channel at the lung centroid position.

2.4 True Hydrostatic Imbalance

The breathable volume test is related to hydrostatic imbalance safety requirements in Mantis.

EN 14143:2003 contains two tests from which hydrostatic imbalance data can be taken:

1. Section 5.6.1.4 hydrostatic imbalance test. The used in this Section, Table 1, is in fact a table of Lung Centroid reference figures and not the Suprasternal notch figures it is marked with. The hydrostatic imbalance is defined in the related test, Section 6.4, as the peak expired pressure using a 2.5 litre tidal volume, without any adjustment of the loop volume between test positions. The peak expired pressure combines both elastance, hydrostatic imbalance, based on an average loop pressure that is not relavant to normal diving, therefore it is not regarded in Mantis as a safety requirement but as a compliance requirement.
2. Section 5.6.3: The breathable volume test. The average of the peak inhale and exhale pressures is the hydrostatic imbalance a diver would experience if filling the loop to a 25mbar pressure, and the minimum of this figure and zero, is the hydrostatic imbalance a diver would experience after optimising the loop volume (as positive average pressures can be reduced to zero simply by venting gas). This is the practical or true hydrostatic imbalance a diver would perceive.
   The elastance of the counterlungs is tested in the breathable volume test, with greater stringency than in the EN 14143 hydrostatic imbalance test.

In order to pass the EN 14143:2003 Breathable Volume Test, the hydrostatic imbalance using the second method, after optimising the loop, must be in the range -0.5 to 0 mbar. That is, if the apparatus meets the requirements of the EN 14143:2003 Breathable Volume Test, then hydrostatic imbalance is not a safety issue with the apparatus, neither is the elastance.

Separate hydrostatic imbalance test were carried out for compliance with Section 5.6.1.4 using the method in Section 6.4 of the Standard, and reported separately.

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3 THEORETICAL BREATHABLE VOLUMES

Source information is taken from the supplied Exploded Drawings and 2D Drawings SRB5-19-2001 v.A, SRB5-19-1001 v.A, DRB4-29-2001 v.A and DRB4-29-1001 v.A as follows:

Model		Dimensions, mm	Volume, L	Spring volume, L	Other restrictions, L	Theoretical breathable volume, L
OR Apocalypse Type IV	Inhale CL	425x100x90	3.8	0.4	0.2	3.2
	Exhale CL	380x100x90	3.4	0.2	0.2	3.0
OR Incursion	Inhale CL	425x100x90	3.8	0.4	0.2	3.2
	Exhale CL	380x100x90	3.4	0.2	0.2	3.0
OR Umbilical	Inhale CL	380x110x85	3.5	0.5	0.2	2.8
	Exhale CL	380x110x85	3.5	0.5	0.2	2.8

Table 1. Theoretical data of the counterlungs. There are no other material flexible volumes in the apparatus.

From the drawings, the maximum breathable volume of the OR_Apocalypse_Type_IV and OR_Incursion is 6.2 litres, and the OR_Umbilical is 5.6 litres.

4 EQUIPMENT USED

The apparatus under test matched that described in drawings, in Exploded Drawings and 2D Drawings directory “DL SGS Set 2”, except as stated relating to the helmet, DSV and side cylinders.

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

Equipment	Serial Number	Calibration Log Number	Calibration Next Due
Deep Life 600 mm chamber, with environmental control, rotateable	CH03	N/A	Next hydrostatic Sept 2009
Differential pressure sensor. Druck LPM9381	2393261	D22	Aug 2010
National Instruments Data Capture System PCI-6014	HA4375847	L15	Against TTi 1906, Serial Number 111474 Prior to test
Power supply GPR – 1850	033624	N/A	N/A
4.5 Litre syringe	DL 015	See Test Specific Calibration	N/A
Hydrostatic Imbalance test pool with artificial sea water fill	BAI 016	N/A	N/A
Hydrostatic Imbalance test frame	BAI 017	N/A	N/A
Volumetric Displacement Reference Standard	N/A	See Test Specific Calibration	N/A
Thermometer, high accuracy. Protek D610 and probe	D61000013	L61	Dec 2009
Ice, mashed, as required to control temperature	N/A	N/A	N/A

5 Test Specific Calibration

5.1 Volumetric Displacement

The safety requirement test (but not the EN 14143 test), requires a calibrated displacement.

The Calibration Volume is a displacement cylinder used to calibrate the displacement, shown in the figure below.

Figure 1. Calibration Volume (2 litres).

The displacement calibration using the Calibration Volume involves the following steps:

1. The mannequin with apparatus to be tested is placed in the 600 mm diameter chamber with the water level at the suprasternal notch, checking that counterlungs are underwater: if not, then the test fails.
2. The water level in the chamber is measured by an electronic vernier by zeroing the vernier at the water level, and a second fixed vernier is set to the water level and clamped into position.
3. The calibration volume is immersed into the water in the chamber.
4. The vernier is adjusted until it touches the water level. In this position the vernier displays the increment of the water level. The vernier offset is checked against that of the clamped offset to ensure no material error occurs.

The test fixture is shown in figure overleaf.

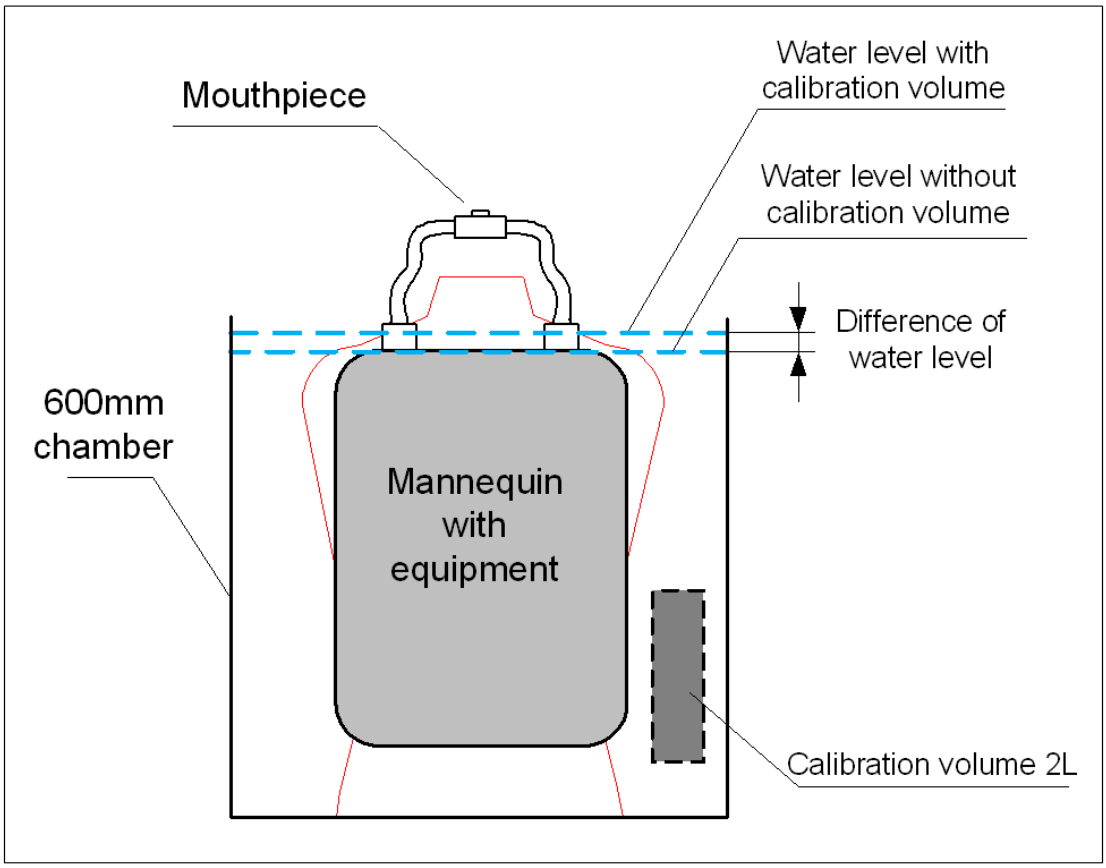

Figure 2. Calibration scheme (shown for the Safety Requirement M473 test, where the water level is at the suprasternal notch instead of above the apparatus for the EN14143 test).

The displacement calibration for each type of apparatus is recorded in the table below.

Model of rebreather	Difference of water level, mm	Volume of water, L/cm
OR Apocalypse Type IV and OR Incursion	8.09	2.47
OR Umbilical	7.65	2.61

Table 2. Displacement calibration coefficients for each type of apparatus tested.

5.2 Gas Injection Volume

The EN 14143 test requires 4.5 litres of gas be withdrawn and injected. This is performed using a syringe built for the test. The calibration of the syringe was performed by:

1. Checking the syring is gas tight in both withdrawing gas and injecting gas, by blocking the syringe outlet at ten points along its stroke then checking that the block locks the syringe position.
2. Mechanical measurement of the syringe dimensions using a calibated vernier: the bore is 105mm (i.e. 86.59 cc per cm of length), and for 4.5 litres, the length is set at 520mm using lock nuts.

   As the standard requires a minimum of 4.5 litres, the syringe was set to 4.52 litres to ensure the apparatus complies.

Figure 3. Gas Syringe set to 4.52 litres (to ensure at least 4.5 litres is withdrawn and injected), and lock nuts. Syringe fixture provided by client (Deep Life Ltd), then calibrated and used by BAI.

6 Safety Req. M473: Maximum breathable volume

6.1 Test Method

1. Fit the apparatus to be tested to a mannequin using the harness supplied with the apparatus.
2. Immerse the apparatus and mannequin in a water filled chamber with the minimum surface area, with the counterlungs of the apparatus completely below the water level.
3. Fill the apparatus with gas until an internal pressure at the mouthpiece of + 25 mbar is achieved relative to the lung centroid: for simplicity, the Druck sensor is connected to the mouthpiece on one side and the ambient air on the other side, with the mannequin at the height where the water level is at the suprasternal notch.
4. Check that all parts of the apparatus to be tested that yields in response to a +/-25mbar change in loop volume is under the level of the water.
5. Electronic vernier is then zeroed when its measuring stick touches water surface, and a second vernier is fixed at the level of the water for reference.
6. Withdraw gas from the apparatus recording the internal pressure, until the pressure is -25mbar. Record the vernier reading of the water level and check the offset against the second vernier.
7. Place a calibrated volume into the water and measure the change in level. From this, calculate the change per litre of displacement per millimetre of water rise.
8. Using the calibrated displacement, the maximum breathable volume is determined from the difference in displacement in steps 4 and 6 above.
9. For the requirement to be met the breathable volume must be in the range 5.5 to 6.5 litres, and the loop pressure within the range -25mbar to +25mbar. Compare results against requirements to determine Pass / Fail.

6.2 Results: OR_Apocalypse and OR_Incursion

The OR_Apocalypse and OR_Incursion models are identical for the purposes of breathable volume testing, so the OR_Incursion was selected for this test.

The OR_Incusion rebreather was mounted on the mannequin. The mannequin was then immersed in water, upright (see figure below).

In order to connect the test equipment to inject gas, the mouthpiece was replaced with a DSV of the same dimensions. The DSV mouthpiece has no flexible parts so does not affect the test.

The Technical Harness option was used. No side cylinders were fitted, but internal cylinder was fitted. Side cylinders have no bearing on the test.

Figure 4. Apparatus in the 600mm chamber (configured to be 600mm deep instead of its normal 800mm for this test, for ease of access). The two verniers that were used are visible on the right of this picture: one marks start position, other marks displacement.

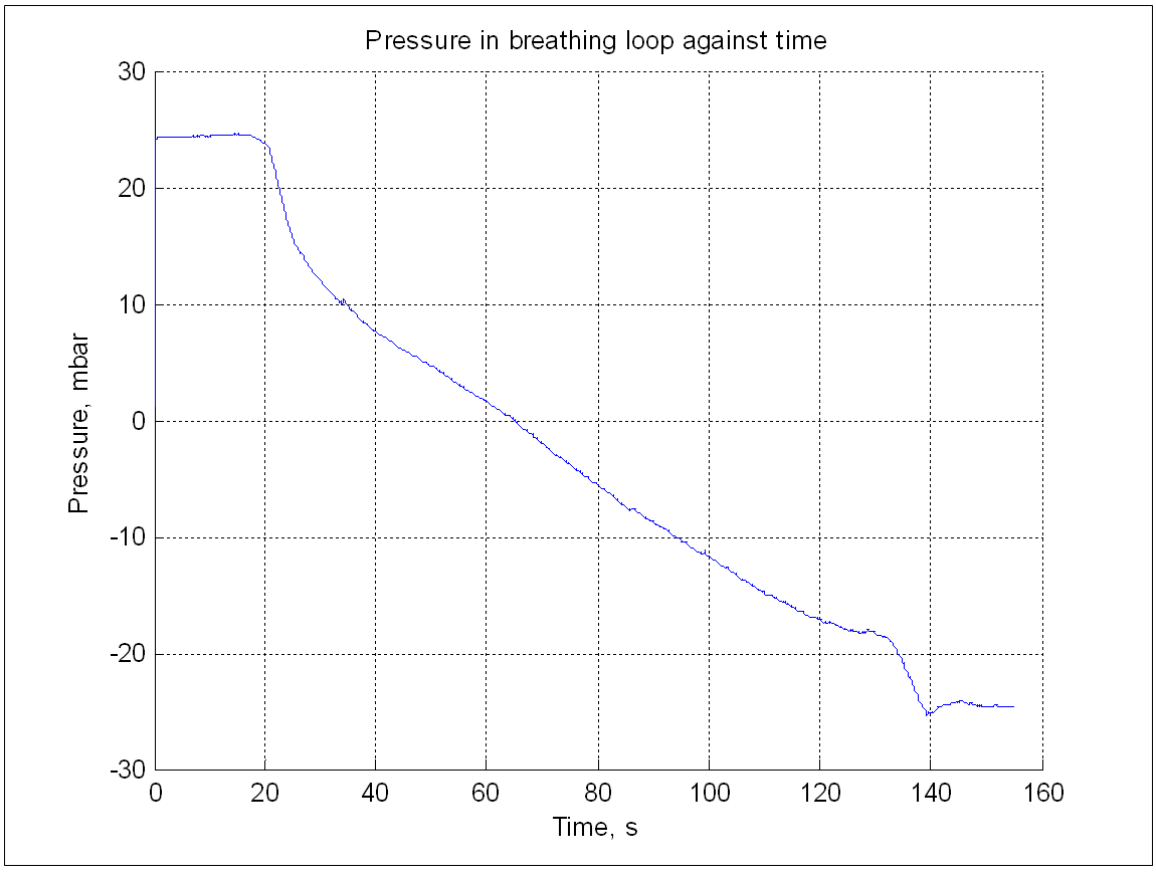

Figure 5. Pressure in breathing loop relative to suprasternal notch from max to min volume.

6.3 Results: OR_Umbilical

Figure 6. Apparatus in the 600mm chamber during set up. All material compliant parts are under the water level, which is adjusted to the suprasternal notch position. No helmet was fitted, and no side cylinders.

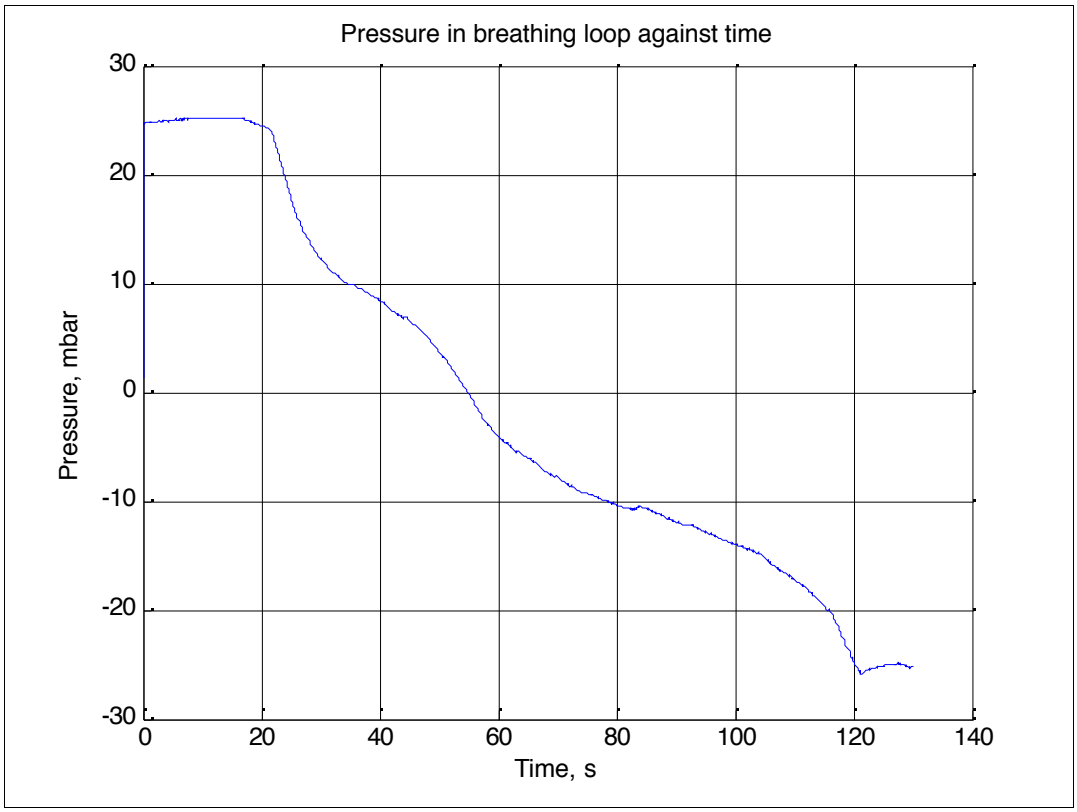

Figure 7. Pressure in breathing loop relative to suprasternal notch from max to min loop volume.

6.4 Tabulated Test Results of Safety Requirement M473 test

Model of rebreather	Difference in water level, mm	breathable volume in Litres
OR Apocalypse Type IV / OR Incursion	25.02	**6.19**
OR Umbilical	21.45	**5.61**

Table 3. Results of maximum breathable volume tests.

The pressure within the breathing loop was within +/-25mbar with respect to ambient pressure at the suprasternal notch throughout the test.

All models of the apparatus meet the safety requirement in Deep Life's Requirement Tracking System, Mantis 473.

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7 EN 14143:2003 Min Breathable Volume Test

7.1 Test Method

1. Use a mannequin on a hydrostatic imbalance test fixture and hydrostatic imbalance test pool.
2. One port of the Druck differential pressure sensor is connected to the mouthpiece and other port was connected to Lung Centroid point on the mannequin. Fix the mouthpiece to the mannequin at the point of the diver's lips.
3. Check the water is artificial sea water, and set to 4C by refrigeration and adding ice to the water.
4. Set the exhaust valve (Over Pressure Valve) to the dive position if it is adjustable.
5. Immerse the apparatus and mannequin to a depth not greater than 1 m at a pitch of + 90, 0 and check that all parts of the apparatus are fully submerged.
6. Fill the apparatus with gas until an internal pressure at the mouthpiece of + 25 mbar relative to the Lung Centroid is achieved or the exhaust valve starts to release gas.
7. Withdraw 4,5 l of gas from the apparatus recording the internal pressure.
8. Inject 4,5 l of gas into the apparatus recording the internal pressure relative to the Lung Centroid.
9. Repeat for all other positions of pitch and roll as listed for hydrostatic imbalance tests in Section 5.6.1.4, Table 1, of the Standard.

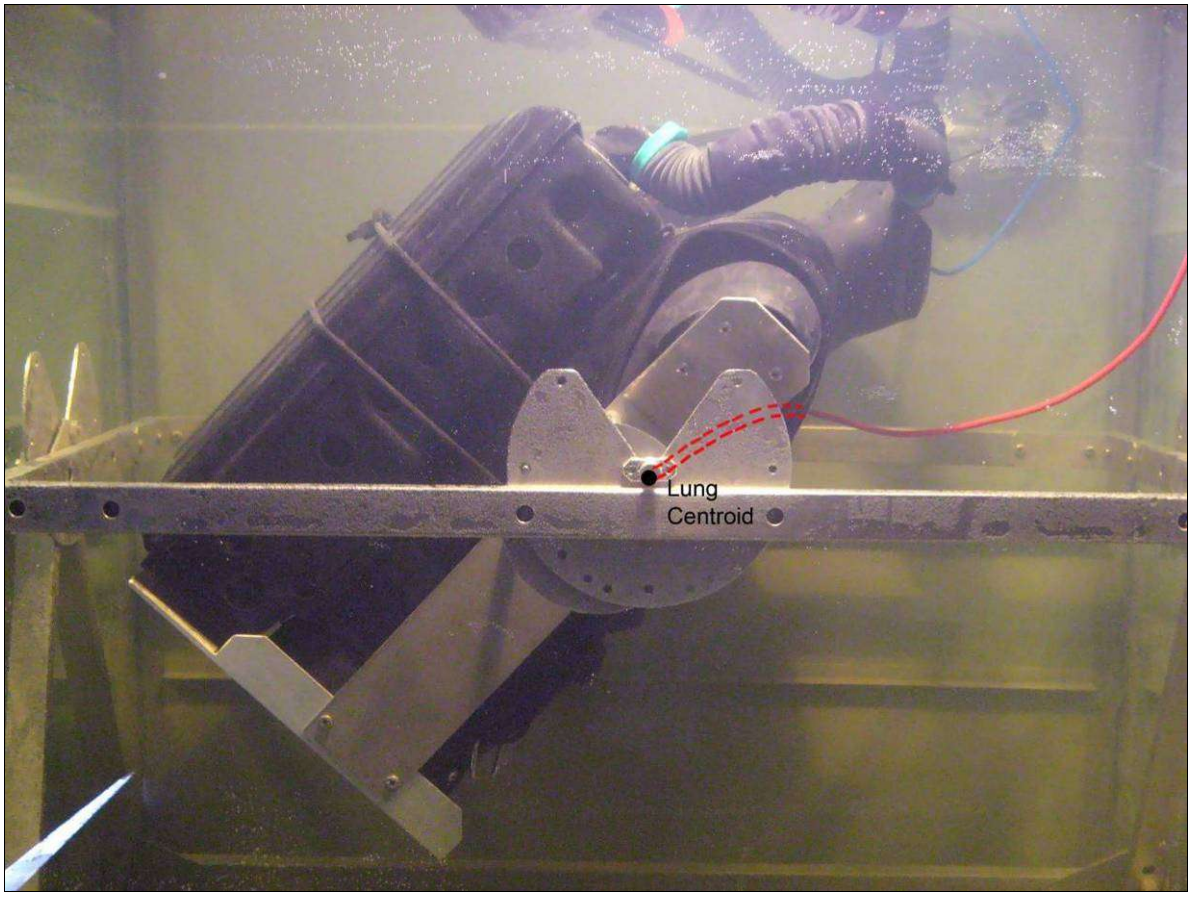


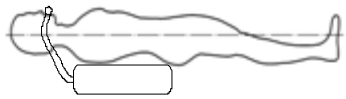
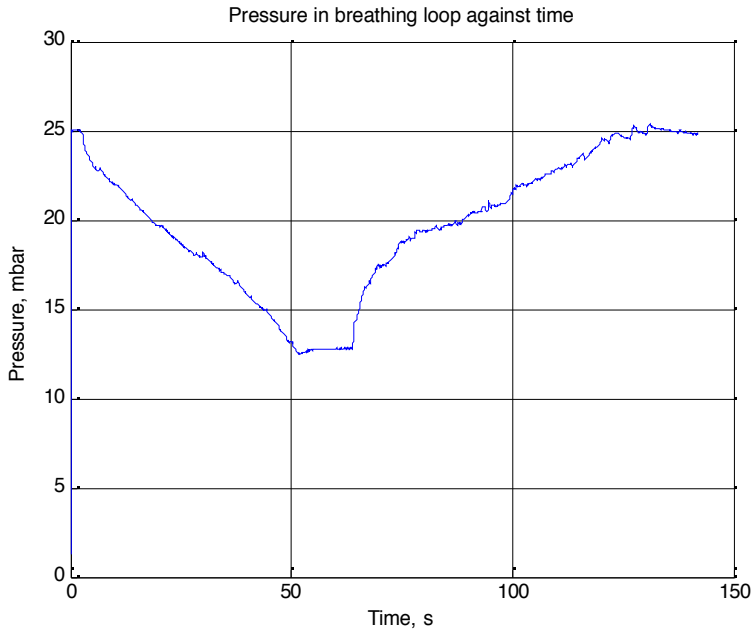
Figure 8. Apparatus on the mannequin in the process of setup on the hydrostatic imbalance fixture and immersed in hydrostatic pool. Differential pressure sensor connected to the mouthpiece (blue tube) and to the lung centroid point (red tube).

7.2 Plots of pressure in breathing loop for OR_Apocalypse / OR_Incursion

The OR_Incursion rebreather as it is identical to the OR_Apocalypse for the purposes of breathing volume measurement.

No side cylinders were fitted to the apparatus for these tests and the intermediate pressure gas input was blocked. The Technical Harness option was used for the as it is the worst case harness thickness. A 5mm spacer was inserted into the harness to allow for the case where a diver is using a buoyancy device, as this would be the worst case mounting position.

The plots below are the pressures recorded during the tests, withdrawing and injecting 4.52 litres of gas. Each test starts at 25mbar, before withdrawing gas.

Position	Plot of pressure in the breathing loop against time.
 Pitch 180 deg. Roll 0 deg.	

Pitch 90 deg.

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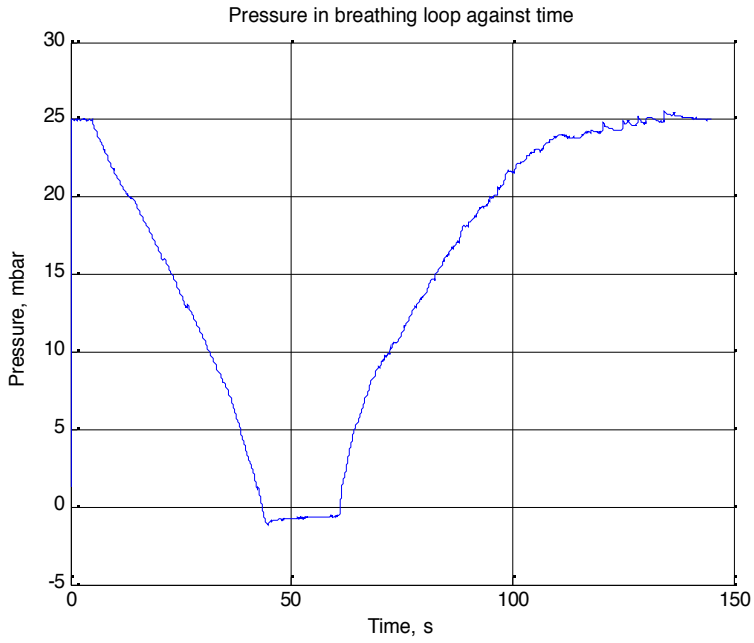

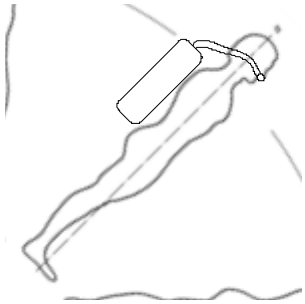

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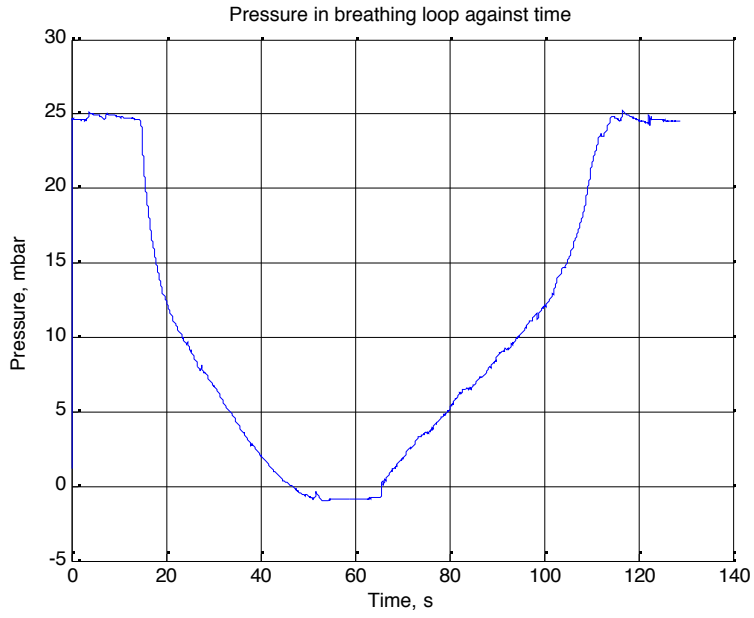

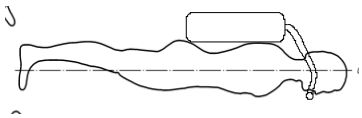

Pitch 0 deg.

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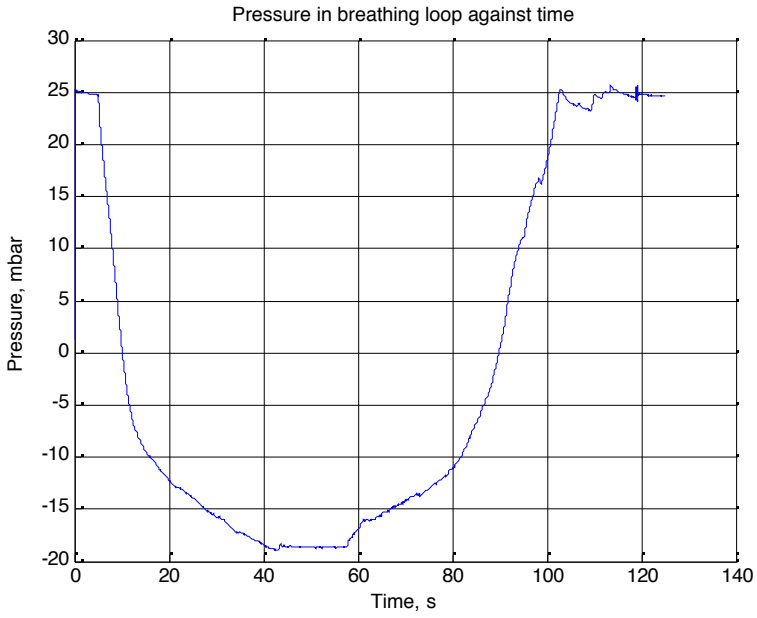

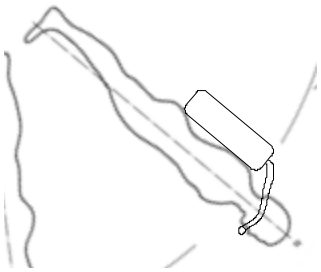

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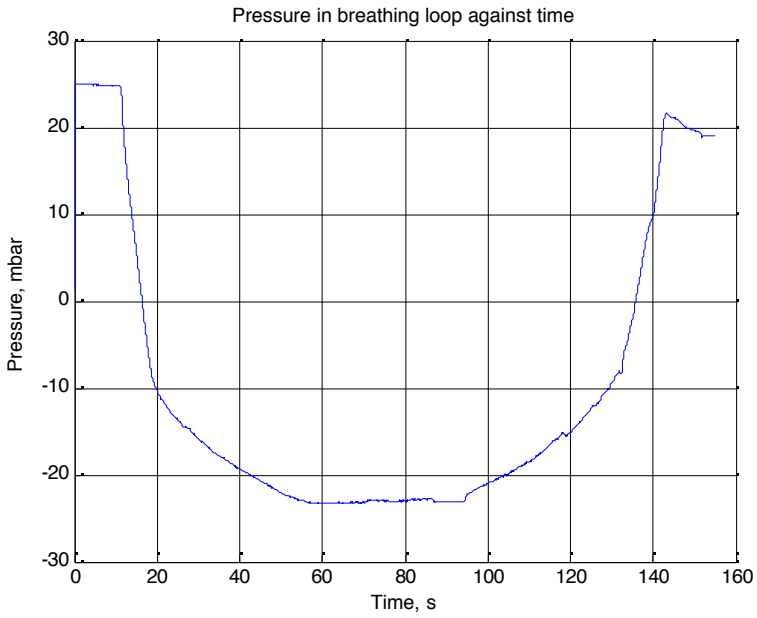

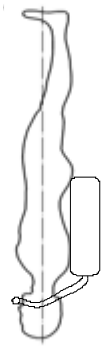

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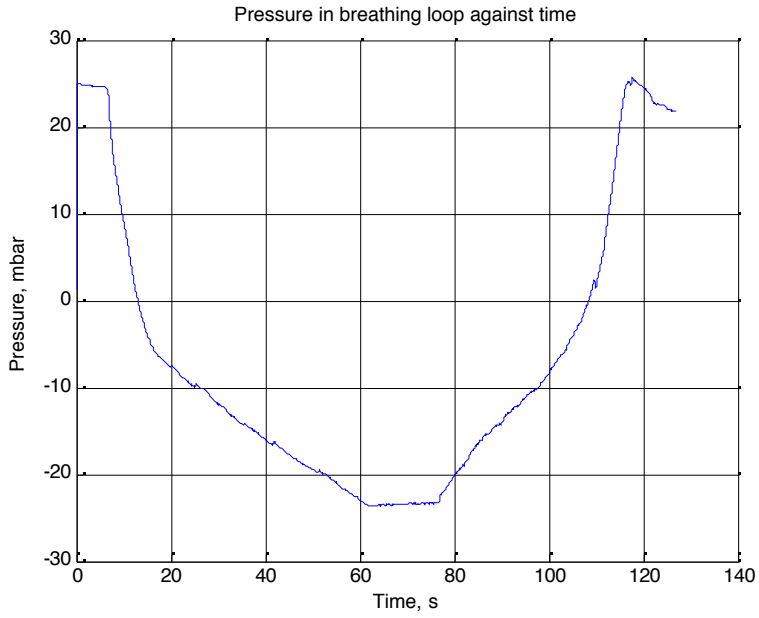

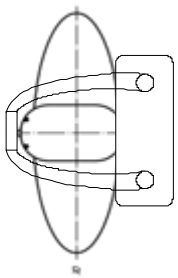

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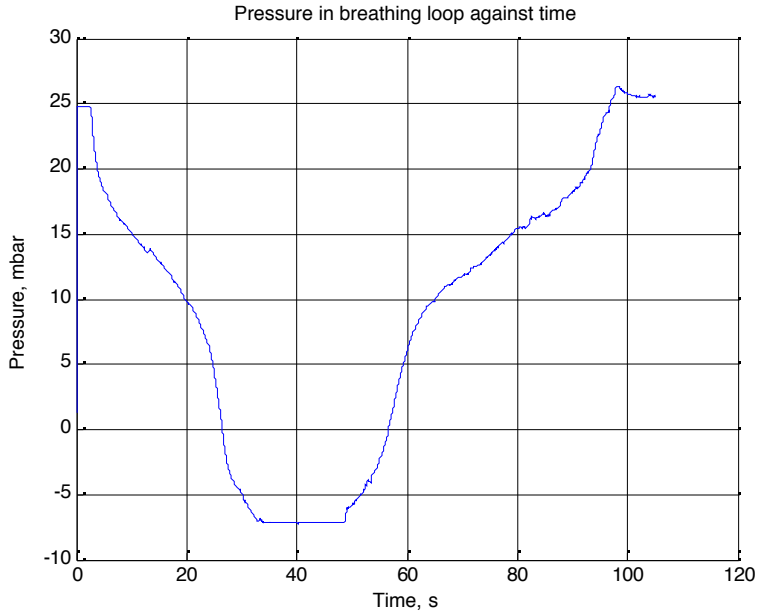
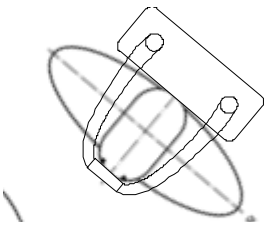
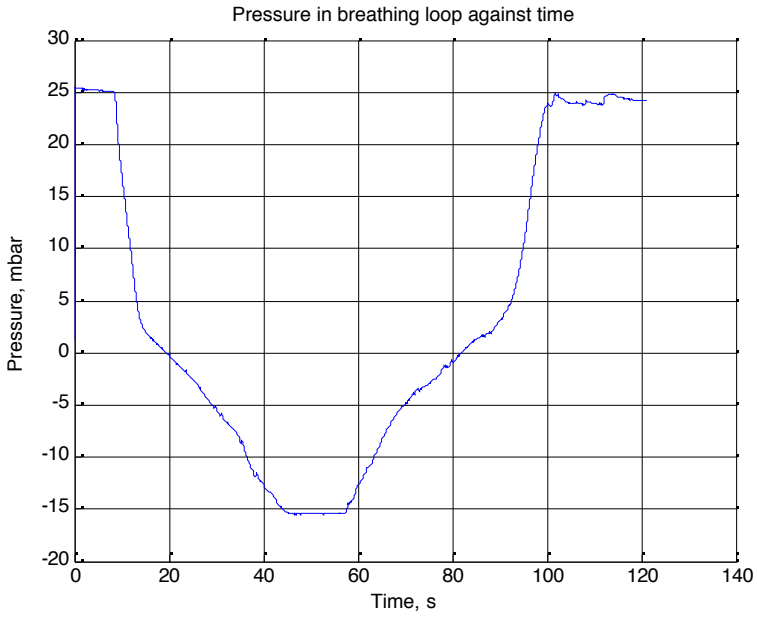
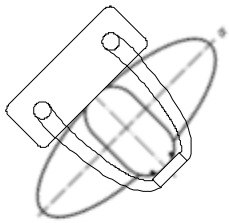




Pitch 0 deg.

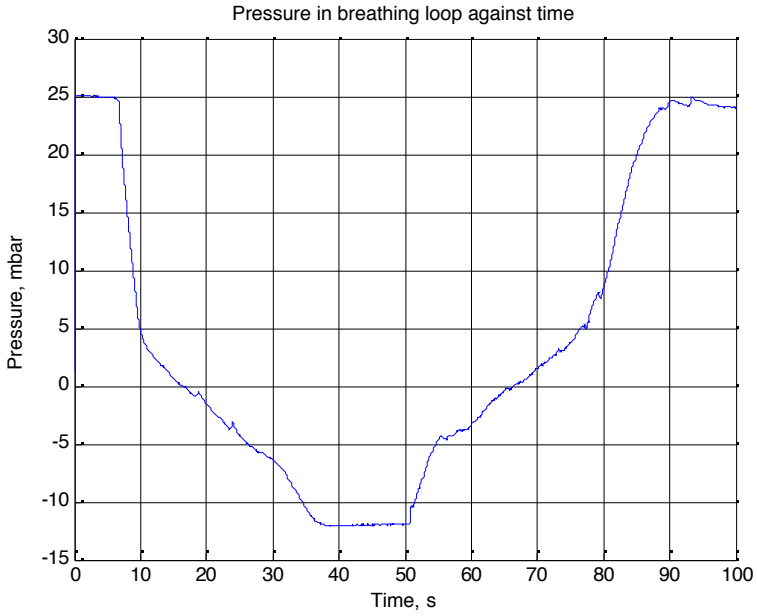
Roll 45 deg.

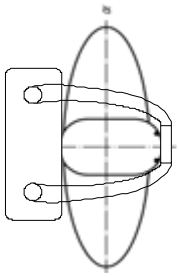




Pitch 0 deg.

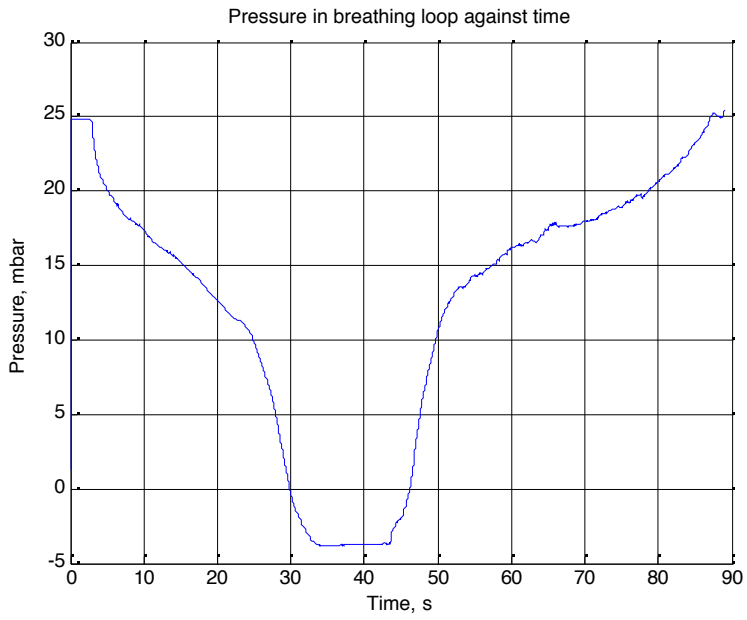
Roll -45 deg.





Pitch 0 deg.

Roll -45 deg.



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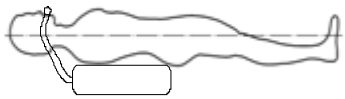
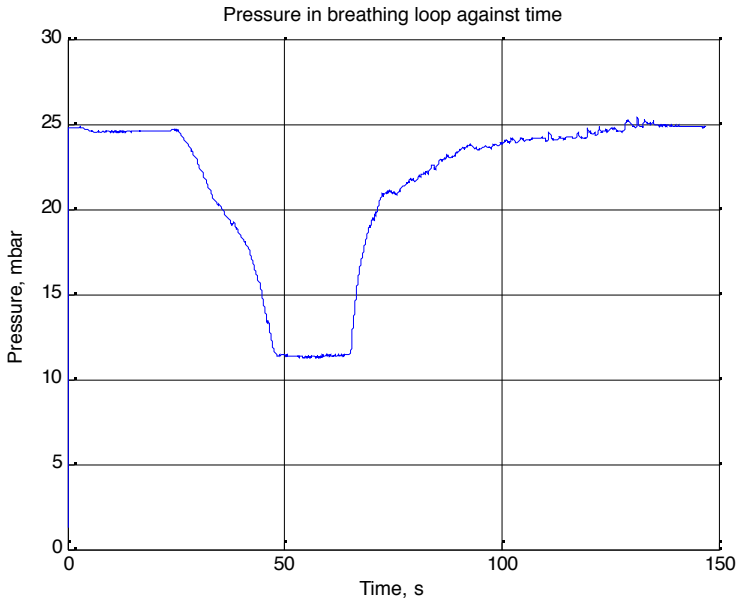
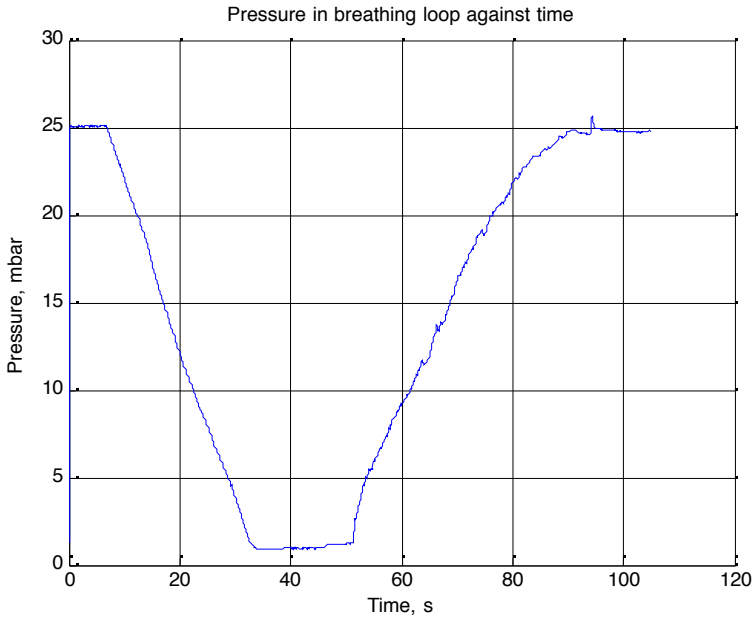
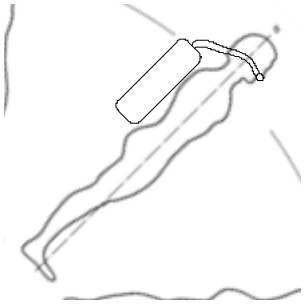
7.3 Plots of pressure in breathing loop for OR_Umbilical

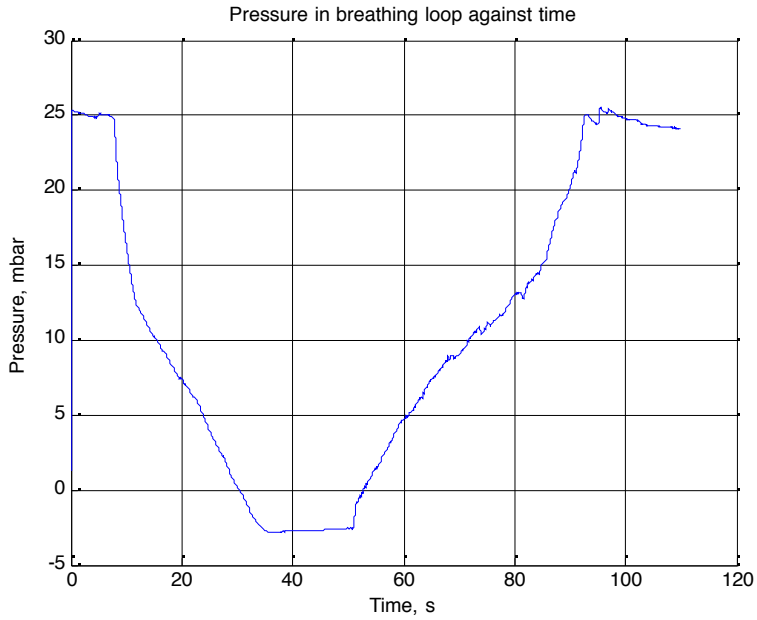
No helmet was used on the apparatus for these tests, and no side cylinders.

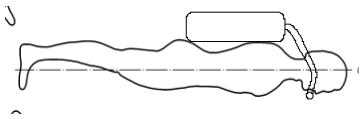
Position	Plot of pressure in the breathing loop against time.
 Pitch 180 deg. Roll 0 deg.	
 Pitch 90 deg. Roll 0 deg.	



Pitch 45 deg.

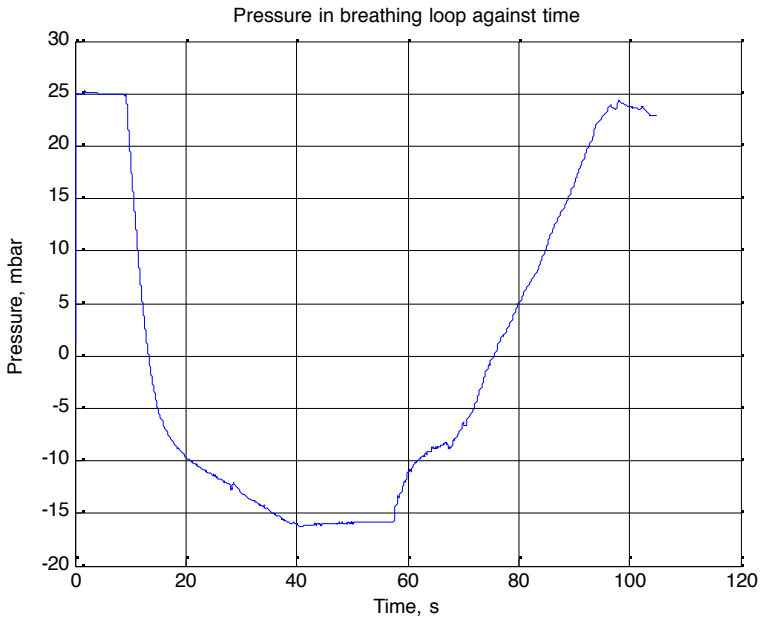
Roll 0 deg.

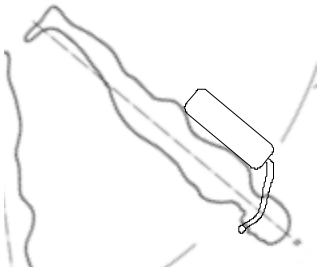




Pitch 0 deg.

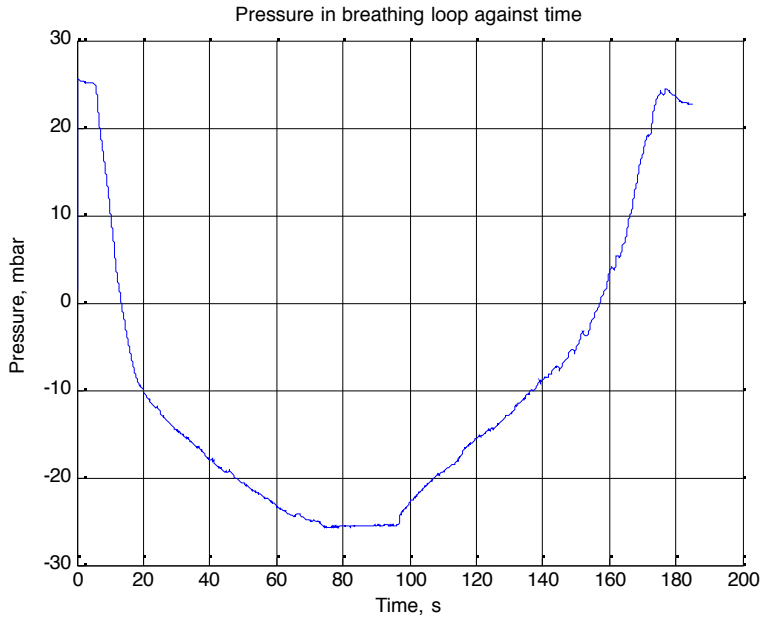
Roll 0 deg.

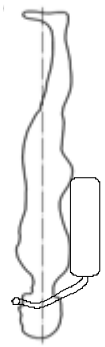




Pitch -45 deg.

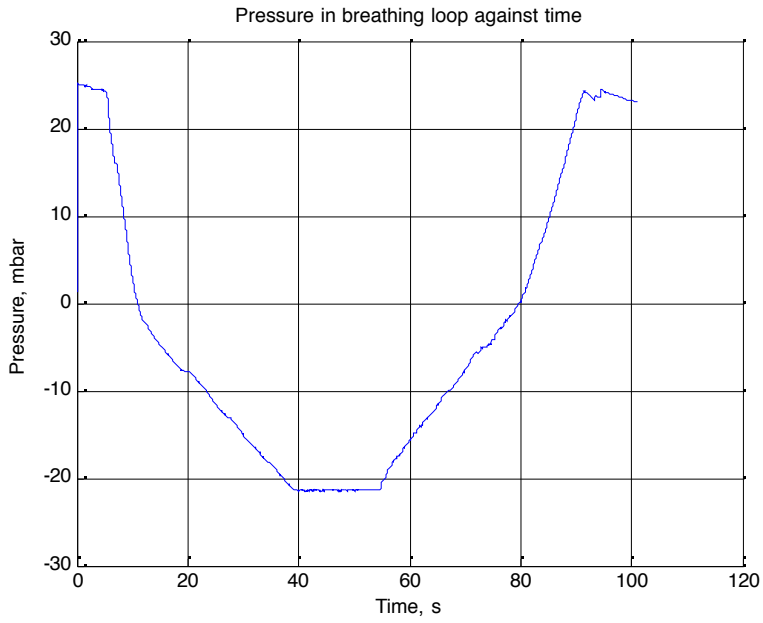
Roll 0 deg.

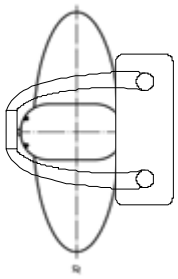




Pitch -90 deg.

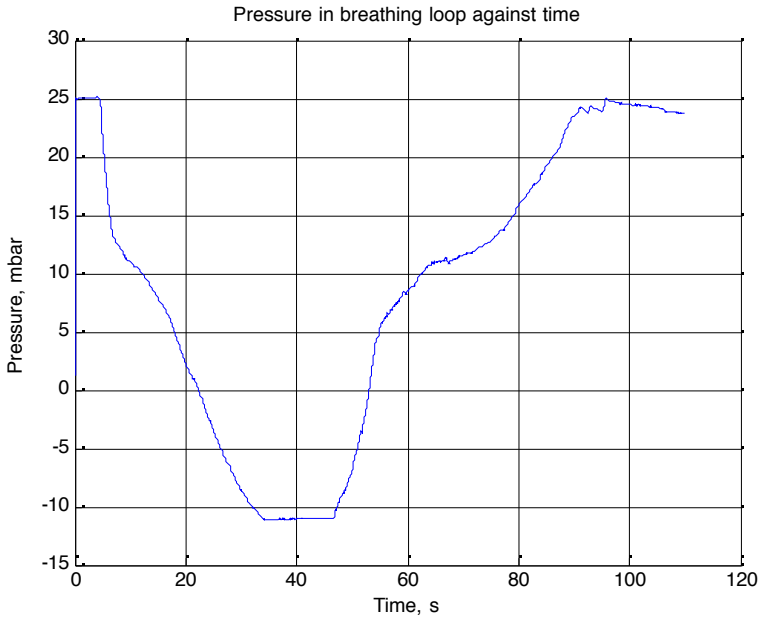
Roll 0 deg.

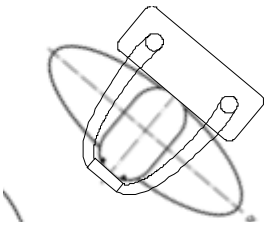




Pitch 0 deg.

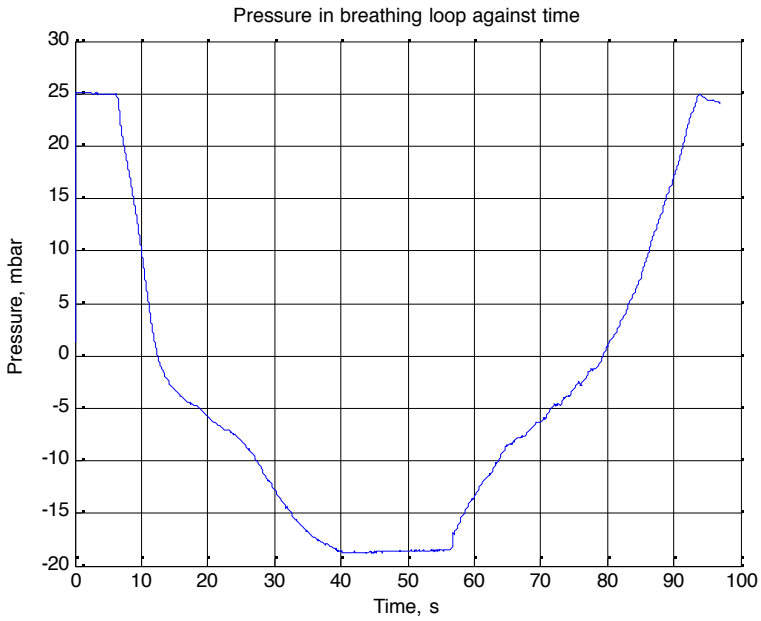
Roll 90 deg.

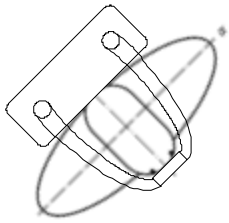




Pitch 0 deg.

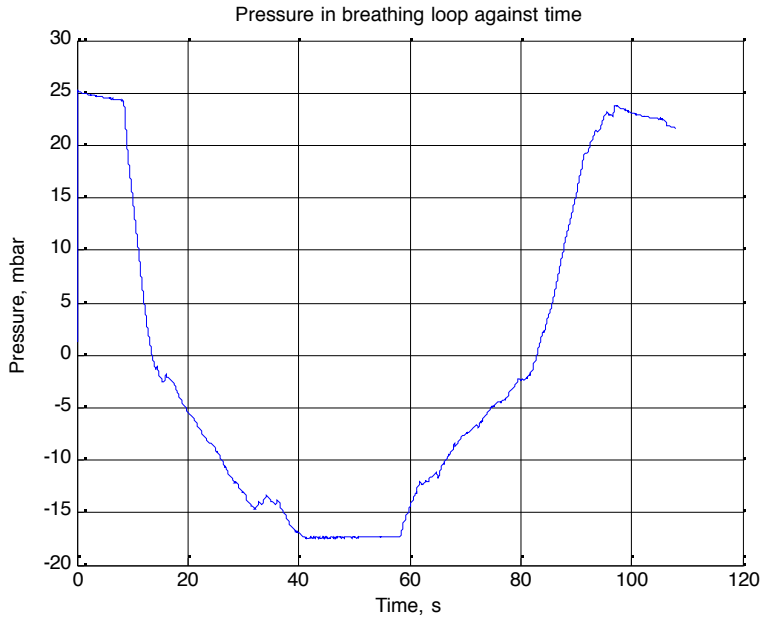
Roll 45 deg.

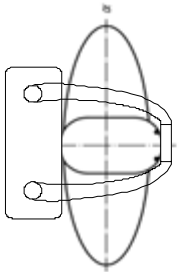




Pitch 0 deg.

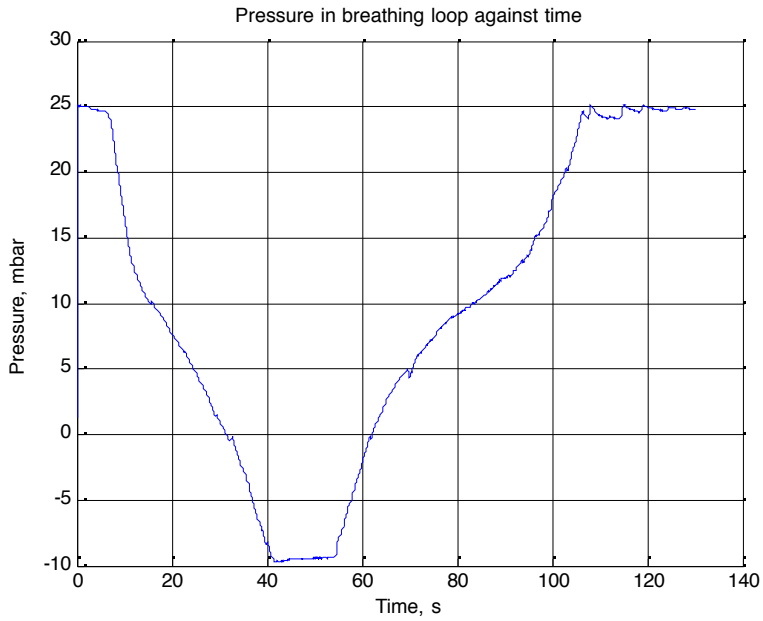
Roll -45 deg.





Pitch 0 deg.

Roll -45 deg.



The shape of the above graphs is not relevant: only the minimum and maximum pressures are used.

7.4 Tabulated Results of EN 14143:2003 Breathable Volume Test

Pitch	Roll	Model of Rebreather			
		OR Apocalypse IV and OR_Incursion		OR Umbilical	
		Inhale	Exhale	Inhale	Exhale
180	0	12 mbar	25 mbar	12 mbar	25 mbar
90	0	-1 mbar	25 mbar	1 mbar	24 mbar
45	0	-1 mbar	25 mbar	-3 mbar	24 mbar
0	0	-19 mbar	25 mbar	-16 mbar	23 mbar
- 45	0	-23 mbar	22 mbar	-25 mbar	24 mbar
- 90	0	-23 mbar	25 mbar	-21 mbar	24 mbar
0	90	-8 mbar	25 mbar	-11 mbar	24 mbar
0	45	15 mbar	24 mbar	-19 mbar	24 mbar
0	-45	-12 mbar	24 mbar	-18 mbar	23 mbar
0	-90	-4 mbar	25 mbar	-10 mbar	25 mbar

Table 4. Results of EN 14143:2003 Breathable Volume Test. Note that the Exhale is set to 25mbar at the start of the test, so it will always be 25mbar or close to 25mbar at the end of each test.

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8 CONCLUSION

The results are tabulated below for the tests verifying whether all models of the apparatus meet the safety requirement for breathable volume and accessible volume.

All samples and models of the apparatus submitted pass the safety requirement breathable volume tests and meet the EN 14143:2003 requirements for breathable volume.

	OR_Apocalypse and OR_Incursion	OR_Umbilical	Requirement (litres)	Pass/Fail
Theoretical Breathable Volume				
Inhale CL Theoretical Breathable Volume	3.2	2.8	-	-
Exhale CL Theoretical Breath Volume	3.0	2.8	-	-
Combined Theoretical Breathable Volume	6.2	5.6	5.5 to 6.5	Pass
Safety Requirement: Empirical Breathable Volume Test (Mantis 473)	6.19	5.61	5.5 to 6.5	Pass
Safety Requirement: Breathable Gas (Mantis 474) and EN 14143:2003 Breathable Volume Requirement	-23/25 mbar	-25/24 mbar	+/- 25mbar	Pass