FAULT STUDY: CO2 BYPASS IN REBREATHER MOUTHPIECES

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ORIGINATOR:	**Dr. Bob Davidov, Victor Sudakov**
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_____Dr. Alex Deas______________ Project Leader	____14th March 2011___ Date
____Dr. Vladimir Komarov__________ Quality Officer	____14th March 2011____ Date

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Revision History

Revision	Date	Description
A1	8th Nov 2010	Decision to compile the various test logs into a releasable document, draft initiated
A2	30th Nov 2010	Issued for review
A3	2nd Dec 2010	Issued for review after first round comments
A4	7th Dec 2010	Approved for release to parties under NDA, with a view to future publication once approvals received (Copyright release on photo, client feedback etc)
A5	9th Dec 2010	Clarification of method used to measure dead space.
A6	13th Dec 2010	Proof reading
A7	5th January 2011	Minor edits following review with NB in Dec. Approved for release.
A8	14th March 2011	Pictures added of IDA valve for clarity.

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1. PURPOSE AND SCOPE

The scope of this report is disclosure of a pernicious fault exhibited by soft one-way valves used in some rebreathers that causes the diver to be exposed to much higher levels of CO2 than intended, under particular conditions of depth and respiratory load. Most pliable valves appear to suffer the fault, to a greater or lesser degree under appropriate conditions, but rigid valves do not. For example, the rigid one-way valves on KAMPO IDA rebreathers[1] from 1950 to 1971 would not have had the fault.

This report characterises the fault mode, supported by detailed flow analysis and breath-by-breath CO2 measurements taken at seven locations around the rebreather breathing loop, and compares eight different types of one-way valve.

The purpose of this report is to support a FMECA by providing the evidence that the one-way valve in the ALVBOV as shipped is likely free of the fault, and also to provide the data to enable the fault mode to be exploited to manage certain performance features during compliance and evaluation processes prior to products being supplied onto the market.

This report also considers the extent to which this fault mode is detected by the CO2 monitor in the O.R. rebreathers (Umbilical/Incursion/Apocalypse), should the fault occur.

2. BACKGROUND

The Deep Life rebreather development team and project are substantial: one of the benefits of a large team of dedicated professional engineers is that separate lines of investigation can be run simultaneously to provide full coverage of an issue – often a problem is attributable to multiple causes. In this case, the opposite occurred; separate lines of enquiry converged on a single fault at roughly the same time. These were:

1. **CO2 Monitor Unexpected Alarms.** Risk of hypercapnia is a known rebreather hazard. Deep Life first developed a diveable CO2 monitor in 2001 to counter this. This monitor was gradually enhanced, moving from the inhale CO2 measurement to exhale measurements: volume weighted mean exhaled CO2 and tidal volume measurements are used to compute peak exhaled CO2 in real time on the rebreather. A third measurement of respiratory rate provides a reliable alarm for boundary cases, where rapid respiration occurs with very low tidal volumes. During dive trials of this CO2 monitor, the CO2 high alarms were triggered even with new scrubber media. Initially this was put down to a presumed fault in the CO2 sensor, but investigation found the sensor was operating correctly and in any case would fail low rather than high. Moreover, the failure events were too regular to be explained by sensor failures. Breath-by-breath measurements of CO2 levels were then carried out and it was found that the one-way valves on all rebreathers tested leaked at some combinations of flow and depth, even though they passed tests where they completely blocked high reverse pressures.
2. **Accident studies** carried out as part of the Open Revolution rebreather project found a higher-than-expected proportion of plausible root causes that involved hypercapnia but where the scrubber media could not have been exhausted. These hypercapnia accidents included those with CNS at relatively low oxygen exposures (hypercapnia reduces CNS limits considerably), accidents that started with the diver apparently confused, and hypercapnia symptoms at low scrubber durations. A diver is likely to survive a mild or moderate hypercapnia incident, so the appearance of these accidents on a fatal accident list was considered to imply a much higher proportion of incidents with the same root cause, and therefore was important enough to warrant mitigation and investigation. This work involved analysing the

[1] KAMPO OAO, 1 Gagarina St, Orehovo-Zuevo , Moskovskaja province , Russia 142602

characteristics of third party rebreather scrubbers and DSV/BOVs, and found several serious problems. One of these was that the DSV/BOVs tested had a bypass, with the gas after the exhale one-way valve leaking back into the mouthpiece. The cause of this bypass was turbulence during inhale, creating positive pressures on portions of the exhale one-way valve, causing it to open.

3. **Anomalies in CO2 scrubber endurance testing** by different laboratories: none appeared to be measuring CO2 in the mouth as required by EN 14143:2003. There were large differences in scrubber endurance when mouth measurements were made compared to measurements where the inhaled CO2 was sampled upstream of the inhale one-way valve.

4. **IDA curiosity:** why do KAMPO IDA rebreathers have such a complex and expensive one-way valve? Over three decades, KAMPO used a mica and stainless steel one-way valve, rather than a pliable flapper valve, based an 1932 German design. Russian engineering normally favours simple solutions over complex. For example, the USA chose to spend millions of dollars developing pens that work in space, Russians used pencils. This simplicity works: today if an American goes into space, it is on a Russian rocket designed in 1960. The most reliable dive microphone in the world is a Russian noise cancelling design developed in the 1950s, still used today by astonauts, helicopter pilots, tank crew and divers. The AK47's reliability legend needs no explanation. So with this engineering culture, why is such a complex valve used in KAMPO IDA rebreathers? It had been assumed previously that the reason was to provide the best work of breathing, or perhaps due to limited availability of elastomers, but the secret is that a discovery was made by KAMPO relating to CO2 that resulted in their unique one-way valve valve design. The designer involved had retired by 1972.

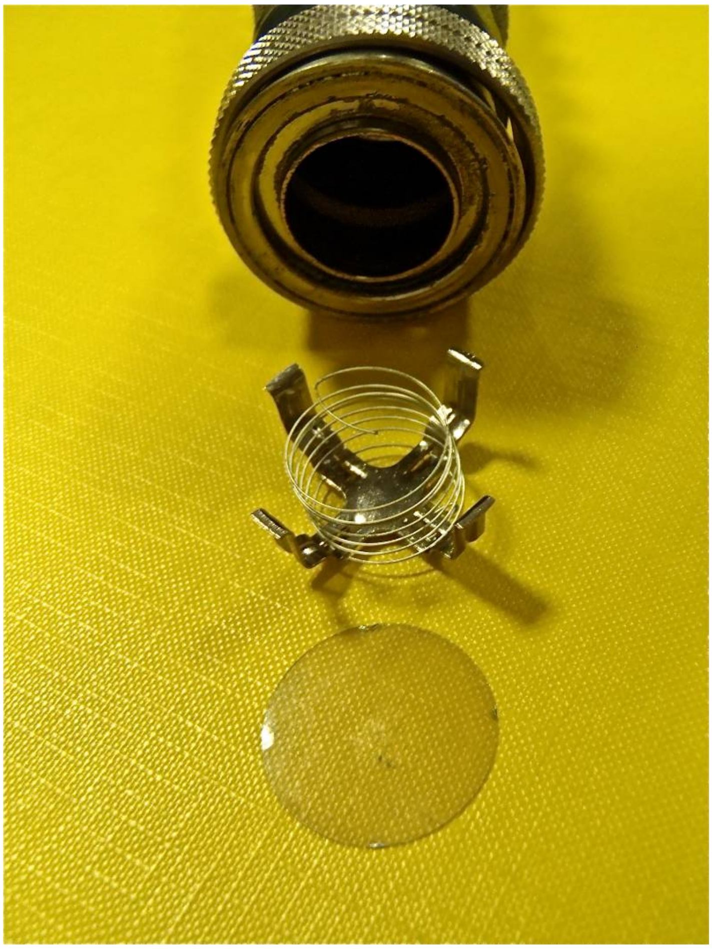

Figure 2-1: IDA-71 inhale valve. The valve has an opening pressure of around 1mbar, and provides an extremely low work of breathing. It cannot suffer from turbulent bypass: the fault mode considered in this report.

However, this valve does suffer from a slight static bypass because the seal is hard mica onto a hard bronze seat. A modern implementation would not suffer this static bypass because the seat would be a silicone elastomer and a thin plastic disk would be used instead of mica (the mica wears against the legs of the spring support: the IDA-71 is supplied with a pack of replacement mica disks).

The main drawback of this valve, other than its cost, is that it takes a lot of space on the inhale side, which translates into mouthpiece deadspace. It is also difficult to make it tamper proof.

Deep Life actively investigated the first three of these issues, using respiratory mass spectrometry to carry out breath-by-breath measurements at each point of the rebreather loop, synchronised to the inhale – exhale cycles. These tests were done over an 18 month period, covering dives from surface to 100m, using air and heliox mixtures with a wide range of RMVs.

These lines of enquiry converged when it was discovered, through the data they collected, that the majority, if not all, of contemporary rebreather mouthpieces using pliable flapper valves appeared to suffer a fault, to a greater or lesser degree, whereby even with fresh scrubber media the diver could be inhaling as much CO2 as with a scrubber at the CE breakthrough levels.

The fault was traced to turbulent gas vortexes (swirls) in the respective DSV/BOVs which opened the pliable exhale flapper valve during inhale, resulting in exhaled gas with a high CO2 being re-inhaled. The amount of CO2 re-inhaled varies across different DSV/BOVs, but in some cases, it is a very high level. Exposure to high CO2 throughout the dive can impede the diver, and can create a sensitivity to CNS toxicity whereby CNS seizures occur at a much lower oxygen exposure than would be the case had the diver been breathing gas free of CO2.

To the alert observer, the valve fault can be detected during machine testing, by the following symptoms:

1. When scrubber endurance is measured, the CO2 levels contain short spikes. Measuring the CO2 levels immediately after the scrubber, or in the inhale counterlung, reveals that these CO2 spikes are not caused by scrubber bypass, as some groups suggest. In some cases[2], the extraction of gas for sampling immediately before the one-way valve can itself create the fault in an otherwise good DSV/BOV, but in most cases, the presence of the spikes is evidence of the one-way flapper valve failure. For CE testing, scrubber endurance is usually carried out at a fixed 40lpm RMV with a sinusoidal breathing waveform. That flow rate is enough in some DSVs/BOVs for the fault to occur.
2. Scrubber endurance measured is shorter than expected, in some cases, much shorter.
3. The end-of-inhale CO2 measured at the mouth is not zero when fresh scrubber media are fitted.

The probability of the fault occurring at a given RMV is higher for any specific valve if it is used with a scrubber or loop with a low breathing resistance: radial scrubbers are worse than axial, and scrubber media with low resistance can cause the DSV/BOV to manifest the problem where highly resistant or densely packed scrubber media do not (because some of the exhale gas increases pressure on the rear side of the inhale one-way valve, actively sealing it).

The existence of this fault mode, or a related issues, appears to have be known or suspected within certain elements of the industry for years. When Deep Life first met with its Notified Body for CE approval of rebreathers in 2006, Deep Life were asked specifically where the gas for scrubber endurance was sampled: at that time, Deep Life and BAI sampled the gas immediately prior to the inhale one-way valve, as did three other labs who do scrubber measurements. The Notified Body said this was not correct, and pointed out that in EN 14143:2003 it stipulates that the Volume Weighted Average CO2 be measured during the scrubber endurance test “at the mouth”. This means at the diver’s mouth, not

[2] The ALVBOV uses a vortex to reduce the breathing resistance across the mouthpiece inhale, and in this mode, gas sampled prior to the inhale one-way valve will produce figures approximately equal to the VWAI CO2 of the mouthpiece. The vortex technique cannot be used safely for exhale valves.

somewhere else, such as upstream of the inhale one-way valve. The Notified Body rejected all of Deep Life's scrubber endurance data presented in 2006, due to it being measured prior to the inhale one-way valve. The Notified Body required the VWAI CO2 measurements to be taken at each point of the dive, including at the start of the dive, to ensure the end-of-inhale contained zero CO2. Now that this one-way valve fault mode has been discovered during our trials, the wisdom of this requirement: has become apparent. Measuring end-of-inhale CO2 prior to the inhale one-way valve gives false scrubber endurance and VWAI CO2 results in many rebreather designs when this fault condition occurs.

3. BACKGROUND DOCUMENTS

The following documents are relevant to the present study:

- GreenB_BaseUnit_RevG_090614.doc describing the design and electronic validation of the Deep Life CO2 sensor. (*DL confidential: not for release)
- DV_OR_CO2_Gas_Monitoring_070825.pdf (196 pages) providing the full design characterisation of the DL CO2 sensor, including variance with temperature and humidity, for 1 to 21 bar pressures, in air and heliox mixtures, for 16 samples of the Deep Life CO2 sensor, along with the spectral spreading correction factors. (*DL confidential: not for release)
- DV_Study_InfraRed_Emitter_071016.doc contains a full verification and chacterisation of the DL IR emitters.
- DV_Respiratory_Sensor_101115.pdf contains a full verification of the DL respiratory rate sensor.
- DV_End-of-exhale_CO2_0405017.pdf contains a verification of the tidal volume measurement using Respiratory Rate and O2 metabolic data, the latter from the difference in the slope of the rising and falling change in the O2 sensors breath-by-breath. (*Presently DL confidential: pending release)
- Measurement_Method_gas_phase_offset_101213.pdf describing the method of gas impulses to synchronise gas measurements at different points around the rebreather with the respiratory cycle.
- FMECA_OR_V4_101116.pdf contains an analysis of flapper valve designs.
- FMECA_OR_V6_100826.pdf contains an analysis of the high level fault of one-way valve leakage.
- V. Golovko, “Modeling of IR absorption spectra of the mixture CO2-He at moderate and high pressures”, Laboratory of Theoretical Spectroscopy, Institute of Atmospheric Optics SB RAS, 1 Akademicheski Av, Tomsk 634055, Russia. Published at Tenth Joint Int. Symp. on Atmospheric and Ocean Optics/Atmospheric Physics I: Radiation Propagation in the Atmosphere and Ocean, G. G. Matvienko, G. M. Krekov, SPIE Vol. 5396 (SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.548204
- Breath by Breath Metabolism Analysis Method From: http://www.innovision.dk/Files/Filer/PDFfiler/Manuals/Innocor_Breath-by-Breath_Method_A-1.pdf
- D. Warkander. “Comprehensive Performance Limits for divers' underwater breathing gear: consequences of adopting diver-focused limits.” January 2007, NEDU TA05-12
- G. Anthony, Qinetiq. Presentation at the DAN Technical Diving Conference, Durham, NC, USA, 2008.

*Some of the above documents are not disclosed publically at this time, so effort will be made to provide additional material herein to enable the reader to understand the work in context.

4. FMECA REVIEW

The FMECA V4 referenced above contains a detailed analysis of mechanical failures of pliable flapper one-way valves, and removes failure causes due to materials, tamper resistance, spider design and function.

The FMECA V6 referenced above contains the fault modes that are the subject of study in this report.

The Deep Life ALVBOV pliable flapper valve design withstands 60mbar without observable leaking using a 20 Dur. Shore A valve, and 100mbar using a 50 Dur. Shore A valve.

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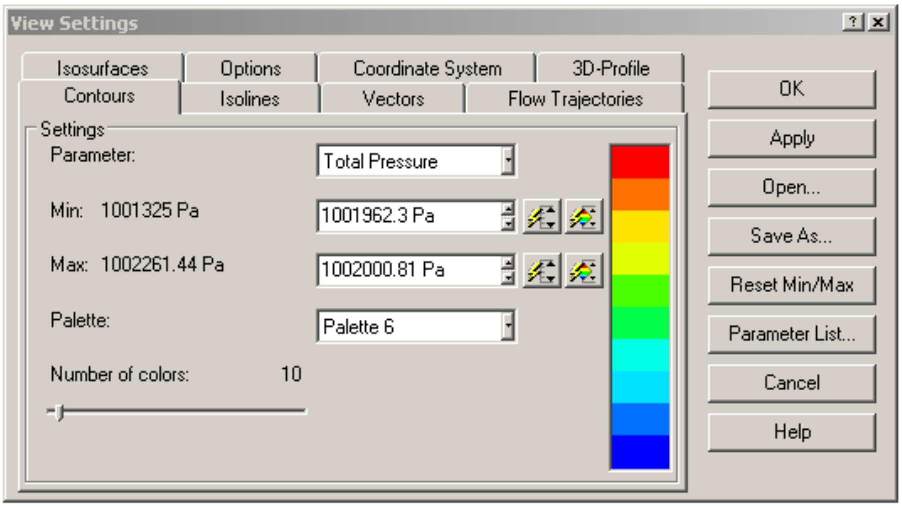
5. DSV Flow Dynamics

Extensive flow simulations were carried out when developing the Deep Life ALVBOV design. These simulations showed the potential for a fault at the valves due to turbulence. All DSV/BOV designs simulated showed similar turbulence. The use of flow diverters reduced turbulence, but did not eliminate it, and may reduce the negative pressure on closed valves.



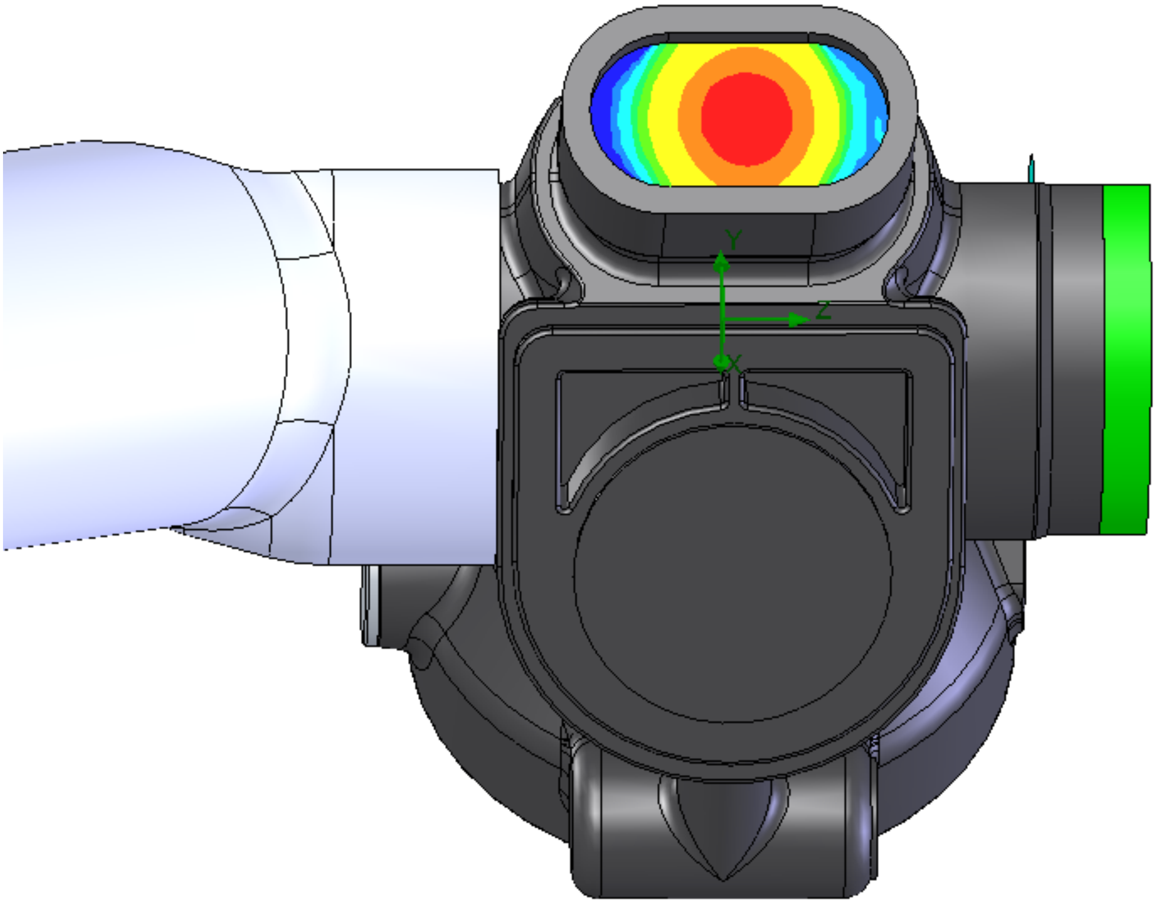


Figure 5-1: Flow simulations used a 3D model of the ALVBOV, at depths to 40m using air and to 100m using heliox, with diver respiration simulated by steady inhale or exhale flows into the centre of the mouthpiece. A range of RMVs were used, but these examples show the figures for a 40lpm RMV, as used in EN 14143:2003 for scrubber endurance testing.

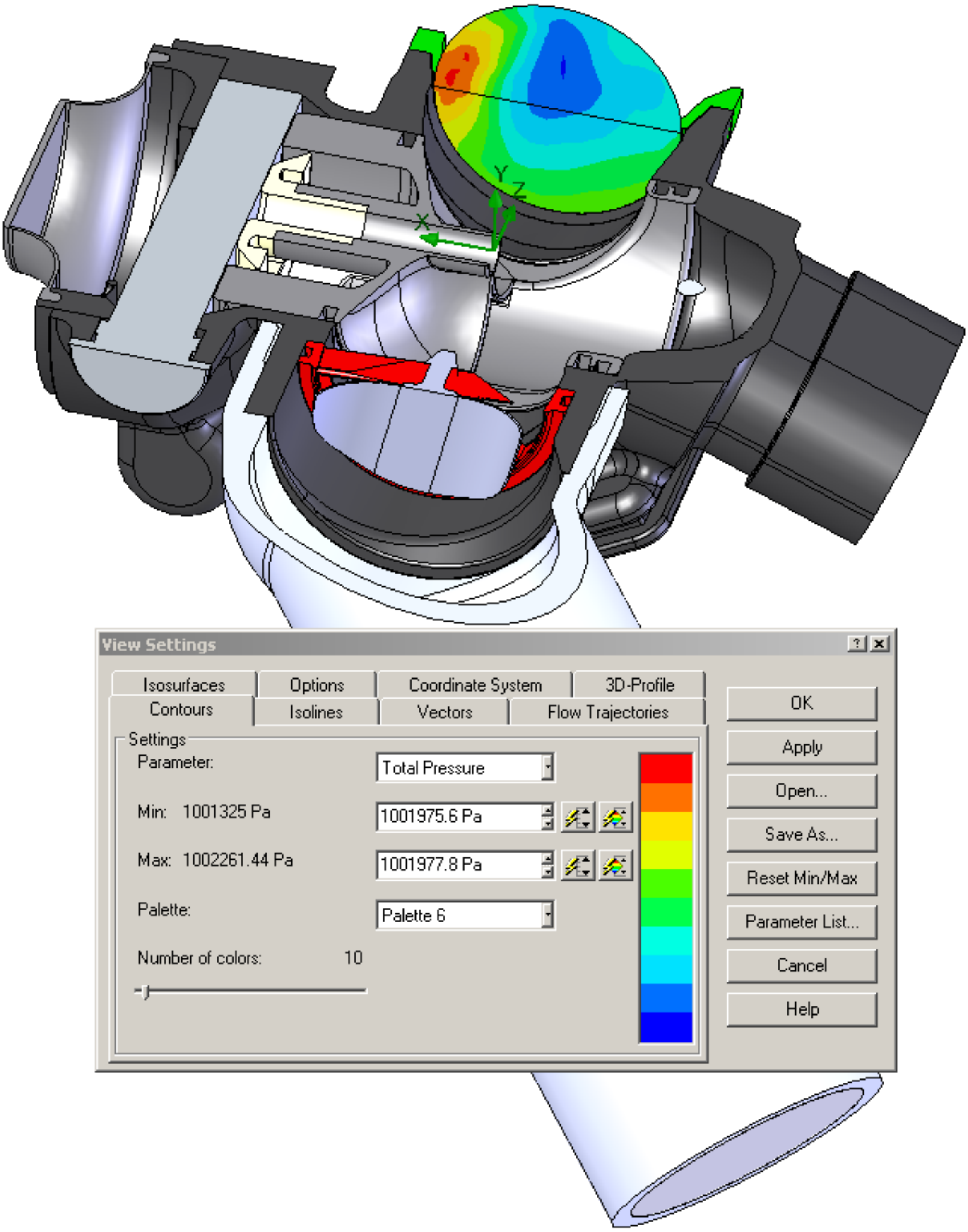


Figure 5-2: Flow simulations reveal that if the one-way flapper valve is pliable then there is potentially a bypass in which gas exhaled leaks back into the inhale part of the respiratory cycle. This is due to turbulence within the mouthpiece creating positive and negative pressures, present simultaneously on different regions of the one-way valve. This can occur in both inhale and exhale portions of the respiratory cycle.

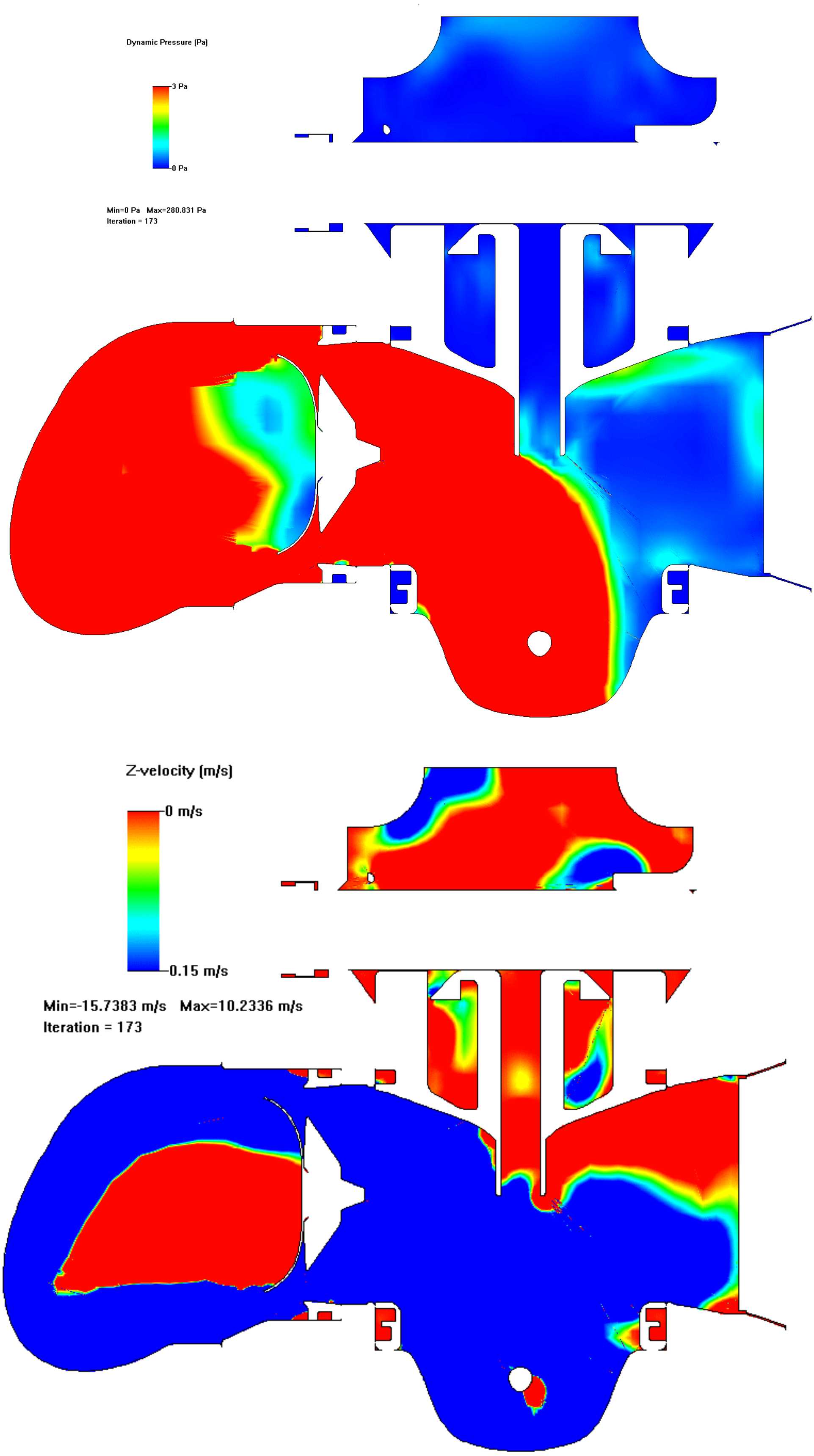
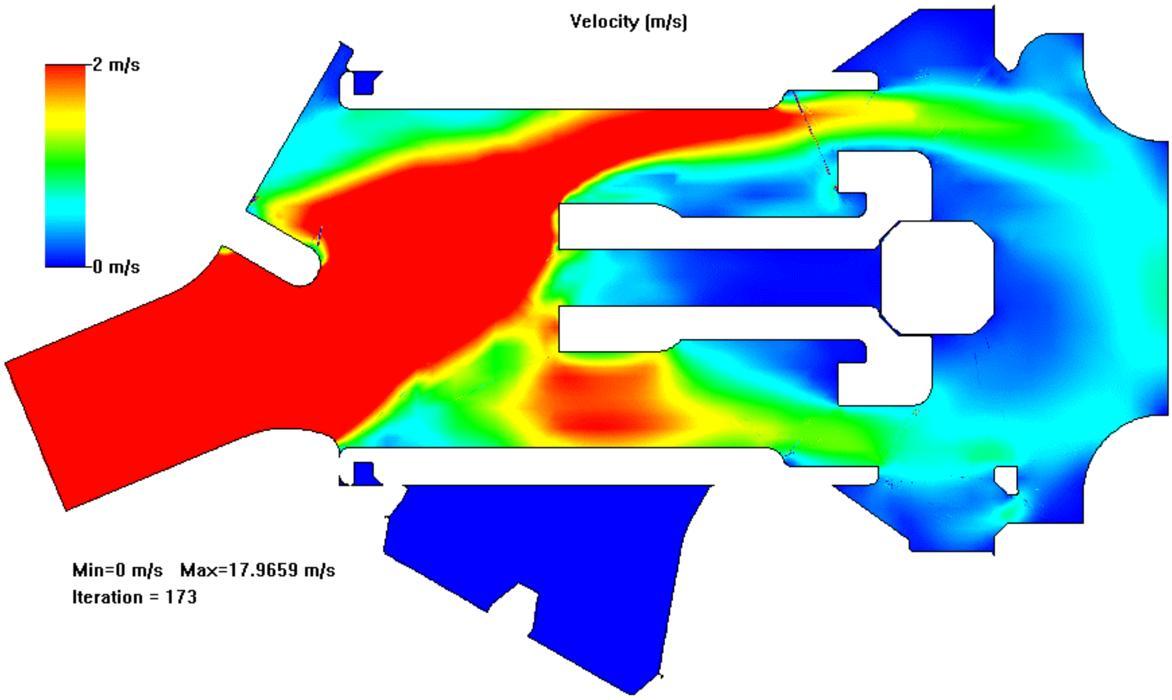


Figure 5-3: Gas pressure and velocity during exhale. Note the vortex over the inhale valve, and pressure differentials on the valve surface.



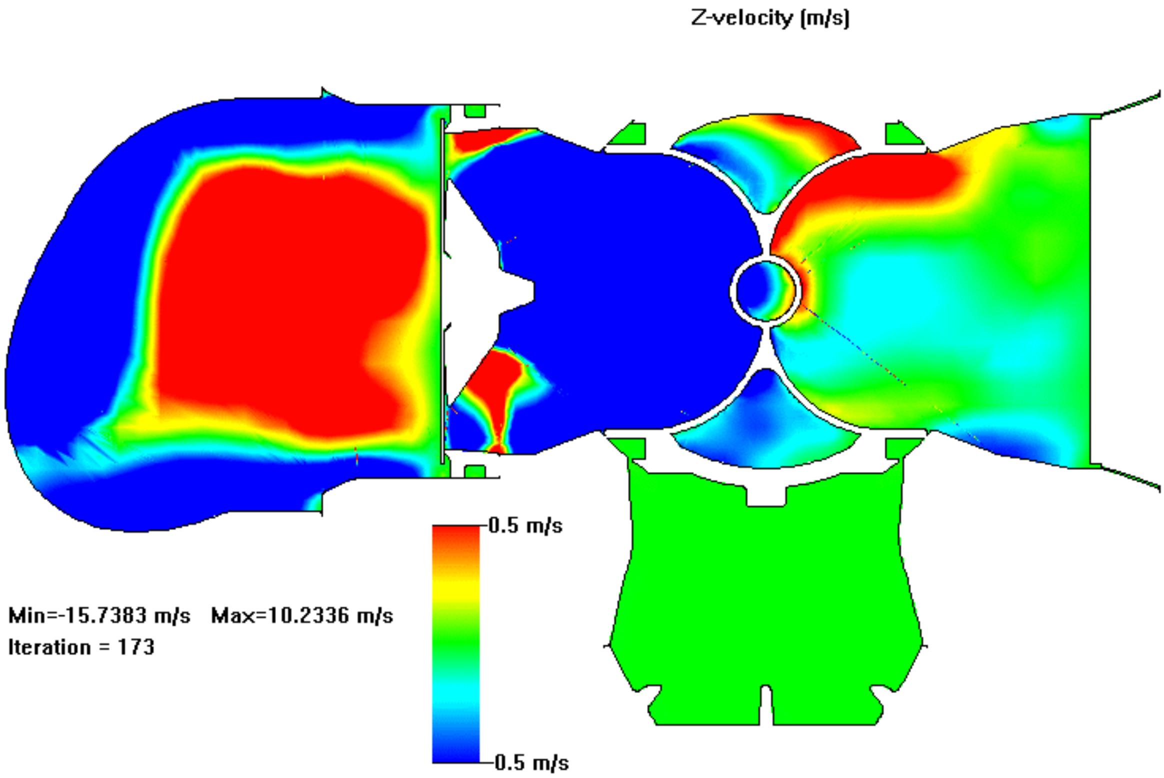


Figure 5-4: Gas velocity in X and Y cross sections in flow simulations show the ALVBOV design blocks the dead space around the Bail Out Valve very effectively: it has almost no flow, and does not contribute materially to dead space for Volume Weighted Inspired CO2 purposes. However, note the turbulent areas just in front of the exhaust valve. Here the effect of the flow diverters can be seen: they reduce turbulence considerably compared to a conventional DSV/BOV, but there is still a residual swirl on the valves.

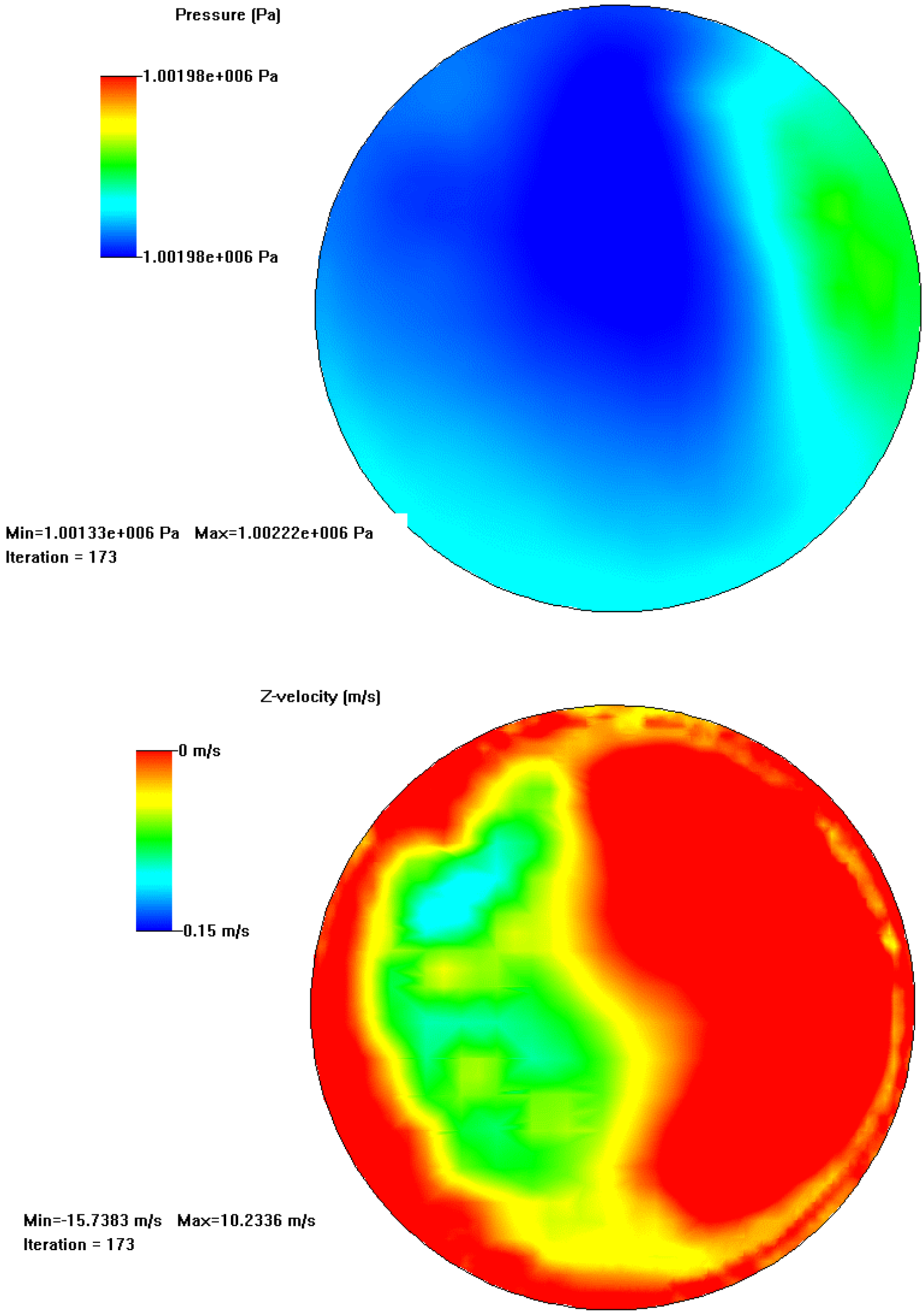


Figure 5-5: The pressures and velocity on the inhale ALVBOV valve are uneven. Turbulence within the mouthpiece is high, even using air guides to smooth the flow.

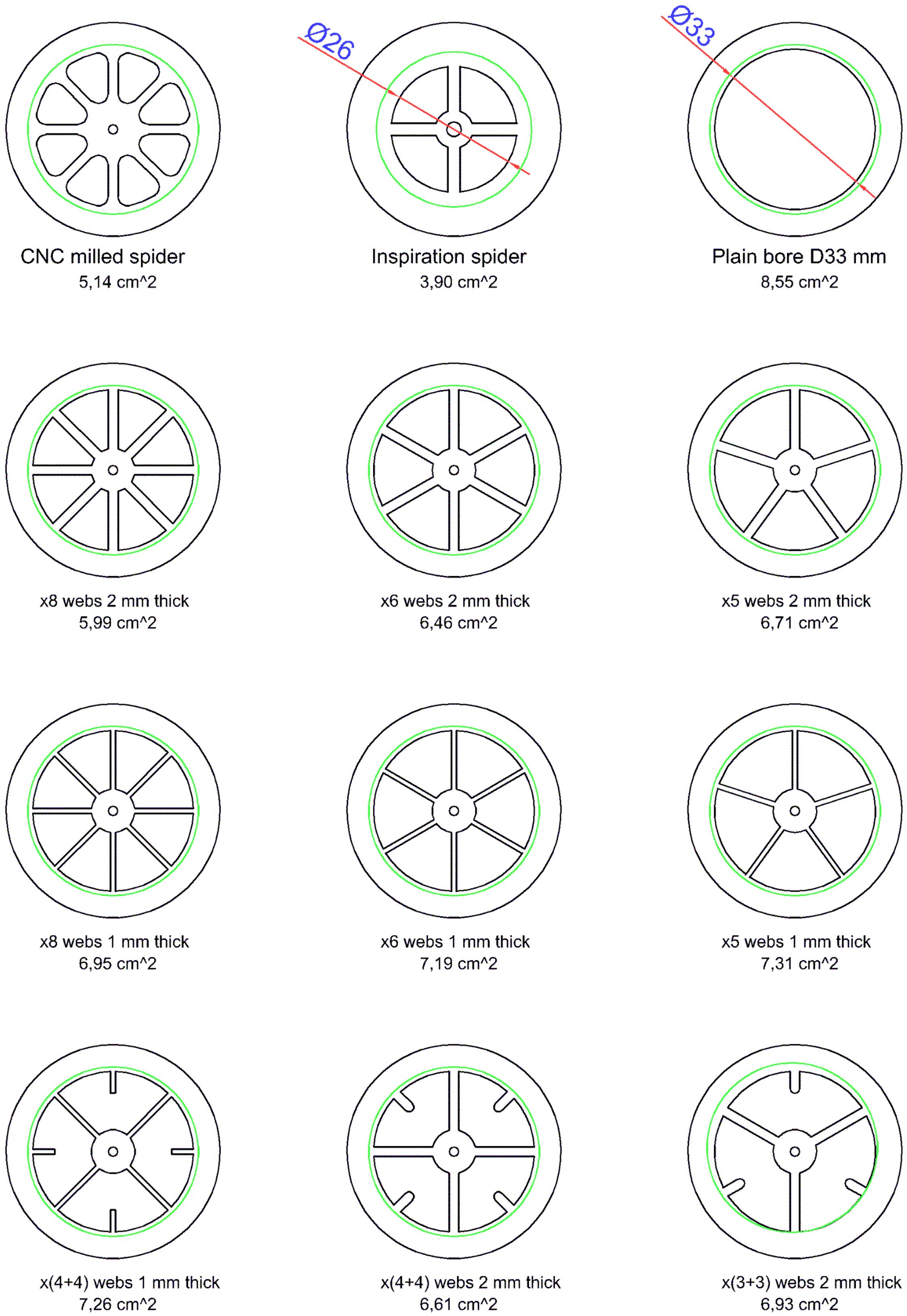


Figure 5-6: The pliable flapper valve webs tested by Deep Life. All tests reported herein use the 8 finger 1mm thick web, 1st web in the 3rd row above. This web withstands 100mbar pressure even with 20 durometer mushroom valves fitted, and does not suffer the fault where the edge of the valve is trapped near the periphery. The mushroom valves are all injection-moulded or compression-moulded valves made from silicone. Flat valves cut from fabric will almost always have lower performance and are not considered.

5.1. Valve Classifications: Disk, Mushroom and Umbrella Valves

Pliable one-way valves in rebreathers may use one of several different types of flapper disk:

1. Plain disks, cut from a sheet material such as polyurethane or silicone, usually fixed in position using a stake through their centre.
2. Mushroom valves. These are injection moulded disks, with a rim causing them to flop back to their flat state, and by pretensioning the stem, a cracking pressure can be set up..
3. Umbrella valves. These are disks where the edge turns downwards, creating a cracking pressure with a lower pretension than for the mushroom valve.

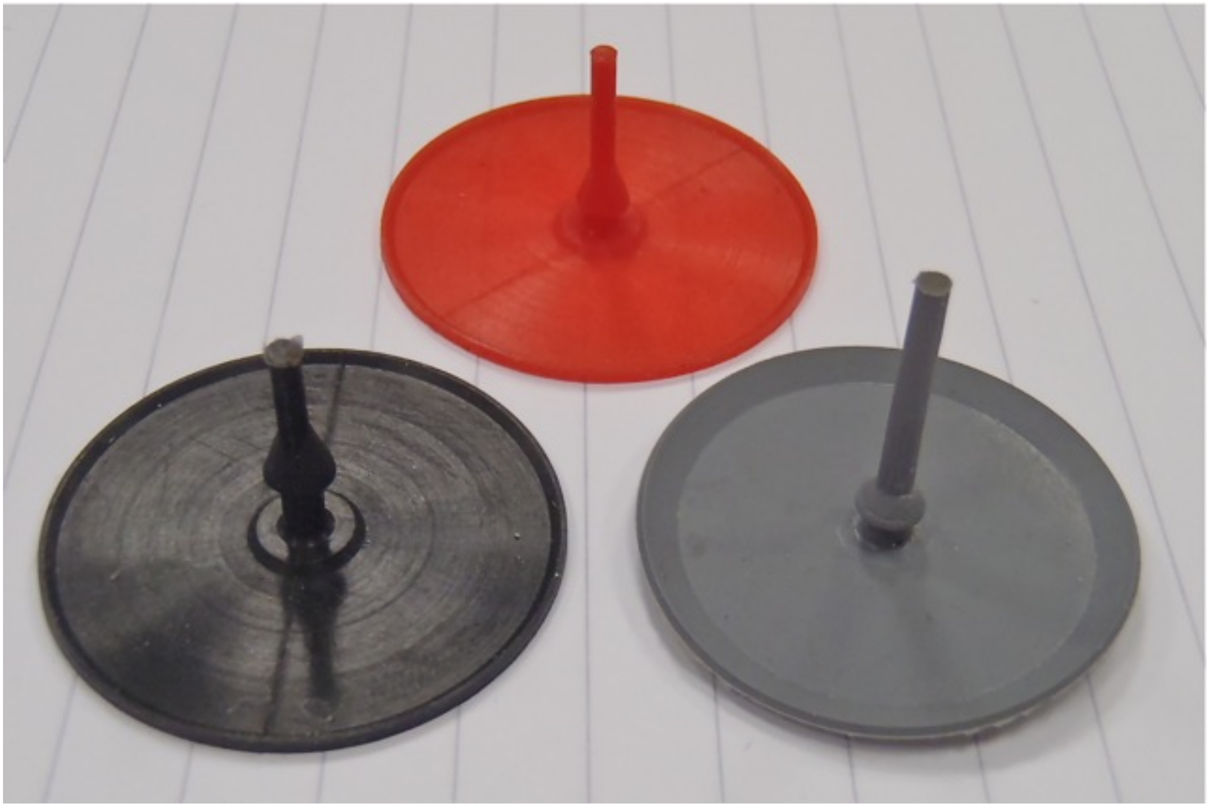


Figure 5-7: Examples of two mushroom valves (red and black), showing the flat disk with a rim. The Grey valve is an umbrella valve: it turns in the direction of the stem at the edge.

The plain disk valves examined suffer badly from this turbulent bypass fault, and most manufacturers have moved to either mushroom or umbrella type valves.

5.2. Excacerbating Factors

The following factors are known to reduce the pressure differential which keeps pliable flapper valves shut during the opposing portion of the respiratory cycle:

1. Very low work of breathing loops allow the inhale gas to pull open the exhale flapper valve because the pressure increase from the exhaled gas flows very rapidly around the loop, and on exhale the same effect reduces the pressure closing the inhale valve.
2. Radial scrubbers and EACs both reduce the resistance in a rebreather loop, compared to granular axial scrubber designs, making the turbulent fault mode worse or more likely.
3. Flow guides of the form used in the ALVBOV may increase the suction on the inhale flapper valve during exhale, by a venture effect.

4. Very soft pliable flapper valves are more liable to open partially with turbulence than valves made from less compliant materials.
5. Small bore hoses from the mouthpiece involve greater flow velocities for any given RMV, resulting in more turbulence, and greater imbalances on the one-way valves.

It is clear from the above list that this valve fault mode can be a side effect of innocent changes to what would appear to be unrelated parts of the breathing loop. Full screening for this fault should therefore be applied initially and on every design change.

6. Mitigation Measures taken by Deep Life

As well as efforts to avoid the risk of hypercapnia from valve bypass etc, in their rebreather designs, Deep Life have taken the following mitigating measures:

1. Provided VWAI CO2 as the basis for scrubber endurance, until such time as as the fault mode is eliminated by design. This data is conservative.
2. Provided a Respiratory Rate (RR) monitor that detects both the boundary conditions for the accurate operation of the CO2 monitor, and provides a direct monitor that is triggered by the rapid breathing that occurs during hypercapnia in divers.
3. Provided a CO2 monitor that is claimed to detect hypercapnia directly, by measuring end of exhale CO2.

6.1. Conservative CO2 Endurance Data

Deep Life have so far only published CO2 scrubber endurance data for their rebreathers based on VWAI CO2. This gives considerably more conservative endurance figures than the true scrubber endurance, and covers the worse case flapper valve performance tested.

When the true scrubber endurance figures for the O.R. rebreather designs are advised to end users, then data showing the absence of this turbulent leakage fault mode shall also be presented.

6.2. Respiratory Rate Monitor

The Respiratory Rate (RR) measurement is precise. If the RR is outside a safe range, an alarm is triggered.

The relevant Design Verification report is referred to in Section 3: this is published on www.deeplife.co.uk/or_dv.php .

6.3. End of Exhale CO2 Monitor

A summary of the Deep Life End of Exhale CO2 monitor will be given, as the relevant DV reports referred to in Section 3 remain confidential at this time.

The Deep Life CO2 monitor for the O.R. rebreather is controversial and currently unique, because it measures Volume Weighted Average Exhaled CO2 and then applies a correction for the effect of the dead space, which is done by determining tidal volume using a novel method.

Deep Life's rebreather CO2 monitor design was used from 2001 to 2007 for monitoring inhaled CO2. It was relocated to the exhale CO2 path to monitor end of tidal exhale CO2 in 2007 when it became possible to do so due to technological developments. The measurement of end of exhale CO2 is a much more demanding application than simply monitoring inhale gas, requiring a multiple step compensation chain because direct end tidal CO2 measurement cannot be made physically on a rebreather using currently available technology[3].

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[3] Deep Life has a sol gel technology that may provide in the mouth measurements of CO2 in future releases.

The Deep Life CO2 monitor computes a peak end of exhale CO2 from:

1. Direct measurement of the Volume Weighted Mean Expired CO2 (VWAE CO2) at the scrubber inlet, minute average O2 flow and Respiratory Rate (RR)
2. Determination of RMV from N * surface minute volume of oxygen metabolised + 2, where at the surface, N is 26.6 on the surface.
3. Calculation of tidal volume, as Tidal volume = RMV / RR
4. Conversion of the mean CO2 to peak exhaled CO2 by a linear transform correcting for dead space using Tidal Volume.

The CO2 measurement has a typical accuracy within 3% of the volume weighted mean exhaled CO2, at depths to 200m using air and heliox. If the mean CO2 is outside a safe range, an alarm is triggered regardless of the end of exhale CO2.

A tidal volume calculation is used to convert the volume weighted mean exhaled CO2 that is measured to an end of exhale CO2. Tidal volume is determined from a metabolic chain that will be described later.

The typical dead space of the diver plus the ALVBOV dead space, measured using trace gas methods, is 230ml. The ALVBOV dead space is significantly less than the volume it entraps, as there is no material gas flow in the space between the barrel and front diaphragm. However, very large divers may have a larger anatomical dead space: a figure of 150ml is used to obtain the total dead space of 230ml. Conversely, petite divers may have a smaller volume.

The dead space means that for each exhalation, there is 230ml of clean gas mixed with the expired gas. The end of exhale peak CO2 is calculated from the tidal volume and mean volume weighted exhale CO2, as:

If Tidal volume > 300 Then

End of exhale CO2 = Mean_CO2 * Tidal volume / (Tidal volume – 0.230) * $\sqrt{2}$

Else if RR > 0

Alarm (Low Tidal volume); End of exhale CO2 = Undefined.

In practice the low tidal volume alarm is not triggered, because if the diver does not metabolise enough oxygen, then the PPO2 in the rebreather will rise in all Deep Life O.R. designs (all use orifices to control flow), causing an oxygen warning, then alarm: this occurs well before the tidal volume drops anywhere near 300ml. This high PPO2 occurs in the iCCR at a tidal volume of less than 1 litre per minute with a RR of 14: this appears to be a safe lower limit because all mCCRs have this behaviour – there is a constant flow of oxygen, around 0.7 lpm, which if the diver does not metabolise the PPO2 in the rebreather will result in an excessive rise in PPO2 and the diver would have to flush. If this high PPO2 occurs repeatedly, the dive would be, or should be, abandoned. There are around 1000 mCCRs in use worldwide, where this problem apparently does not occur, which means that an effective tidal volume of 1.3 litres appears to be around the lowest tidal volume in recreational diving at least.

Divers normally breathe deeply: they are trained to do so. However, a dive attendant, mine clearance diver or underwater photographer may be stationary for a long time in water, and respiratory tidal volumes may reduce to close to the dead space. In these circumstances, the CO2 alarm may produce false alarms.

6.4. Tidal Volume

Tidal volume is computed by the RMV divided by the RR. On a plot of ventilation to tidal volume (a Hey plot), this relationship is linear up to the Vtmax: a limit that should not reached in diving – to do so would require RMVs over 65 lpm, and the change in the Hey plot at these high RMVs would result in the tidal volume being over-estimated, which in turn would overestimate the end-of-tidal CO2 – a desirable effect at very high RMVs as it effectively lowers the warning and alarm levels for CO2 when the diver is working very hard.

The method by which RMV is measured may be of special interest, i.e. it may be disputed, because unlike RR and CO2 which are taken from a direct physical measurement, or tidal volume which is calculated as the relationship (RMV / RR), the RMV is determined from physiological relationships that are true only under normal conditions (healthy diver, respiring within a certain range). Attempts to measure RMV directly using pressure or flow sensors have not produced reliable sensor data, so these indirect relationships became essential. Recognising the limits of this method, the RR alarm provides protection of the boundaries, where the possible error in the RMV calculation increases.

The RMV in Deep Life rebreathers is determined from the amount of oxygen the diver metabolises, on the basis that for each breath the diver inhales 5% SEV more oxygen than he exhales, and the rebreather makes up the lost oxygen. The RMV is calculated from the the amount of oxygen metabolised, which before adjusting for the effects of pressure, is:

RMV = 80* minute_oxygen_volume / 3 + 2

The pressure compensation does nothing more than reduce the volume taken by the partial pressure of oxygen in the overall RMV. This relationship is claimed to be valid up to the Owles point.

This relationship between RMV and oxygen metabolism was first reported by Durnin & Edwards, in 1955: heat production in kJ/min was a linear relationship with the pulmonary ventilation in l/min, and the constant multiplier in this linear equation varied from 0.75 to 1.25 kJ/l, with a mean of 0.97 kJ/l. The relationship between metabolism and RMV has been found to be better than the relationship between metabolism and pulse rate (Datta & Ramanthan 1968). The respiratory efficiency varies much less than the respiratory quotient in healthy adults.

The measurement of the oxygen metabolised compensates for oxygen added and lost in depth changes to produce a mean oxygen consumption for the diver as a one minute moving average. Other than during fast depth changes when very close to the surface, this produces an oxygen consumption figure that is used to calculate both tidal volume (based on the respiratory exchange ratio), and the scrubber life remaining (using a Respiratory Quotient of 0.8, temperature, pressure and helium compensation).

This RMV calculation assumes a gas exchange providing 97% arterial gas saturation, and a ratio of inspired to expired O2 of 20.9:15.9. This is valid for a resting to moderate level of work in a healthy adult, which is sufficient for diving (because persons with serious respiratory diseases should be precluded from diving). The underwater enviroment precludes higher sustainable work levels.

As a side note: given that Deep Life deduce RMV from oxygen metabolism, the question has been posed of why Deep Life do not try to deduce the CO2 from oxygen readings: the VCO2 and VO2 is just as linear as the RMV is with metabolism in the lab, but not on a dived rebreather. The end of exhale O2, has no relationship to end of exhale CO2 on rebreathers during scrubber breakthrough, or in the presence of the flapper valve bypass considered here.

As a further side note, it is possible to estimate accurately cardiac output from the oxygen metabolism values, as Qt = 6.1 * Vo2 + 3.4, with a SD of 0.9 l/min[4].

The O2 metabolised is measured in all eCCR and iCCR O.R. systems.

[4] J. Coates, D. Chin and M. Miller, "Lung function: physiology, measurement and application in medicine", p399, 6th Ed, Wiley-Blackwell Press. ISDN 13:978-0-6320-6493-9

Deep Life originally measured tidal volume from pressure sensor data, but the reliability of the pressure sensors in this application proved inadequate. Improvements in the O2 injector provided another route which is now used exclusively on the eCCR products. In the eCCR the amount of O2 added to the loop is measured (it has a flow meter on the O2 injectors in the latest version and the orifice opening was used to calculate flow in earlier versions). The O2 is then adjusted for depth changes using the loop math model we published (O2 added from Make Up Gas (MUG) on depth increase, O2 lost on ascent), to give a minute volume of O2 metabolised by the diver. The size of the error from this depth change correction for MUG and O2 loss in deeper dives is normally negligible, but very close to the surface, it can be significant.

For the iCCR product, the slope of the decrease in O2 is compared with the slope of the increase within a specific range: increases are caused by the diver injecting gas which is at a known rate, and by comparing this to the rate at which the oxygen falls, the effect of a variable loop volume and diver lung capacity can be removed to leave a minute volume of oxygen consumption.

6.5. Practical Performance

During manned dive testing, the CO2 alarms were triggered in the following circumstances:

1. Before starting a weld, the diver would hold his breath, causing the first exhale to have a high CO2 level, tripping the alarm. This false alarm source was removed by increasing the averaging period.
2. Divers talking for long periods using intercoms, would reduce their tidal volume, which increased the calculated end of tidal CO2. The dive supervisor should be aware of this.
3. Some flapper valve combinations cause the CO2 warning to trigger. This is one of the lines of investigation that led to this report describing the issue and its resolution.

6.6. Application of ALARP

Overall, the mitigation measures taken by Deep Life pushes the edge of ALARP: they extend the current technology to establish the best means for detecting high end of exhale CO2.

The requirement remains to remove the sources of high CO2 at the design level, and the primary source in the equipment other than scrubber breakthrough appears to be one-way valve bypass. The boundary conditions in which this occurs in the ALVBOV is considered in the following sections of this report.

7. METHOD USED FOR EMPIRICAL CO2 TESTS

7.1. Equipment

The following equipment was used to conduct the tests reported herein.

Equipment	Serial Number	Calibration Next Due
DL, Human Respiratory Emulator (Breathing simulator) DL Rev C2	DL 001	July 2011 and Check cal prior to test
Differential pressure sensor. Druck LPM9381	2393261	Aug 2011
Test chamber high pressure sensor Keller ECO1	004630	July 2011
High pressure sensor ME 705	DL 004	July 2011
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
Deep Life OR_Umbilical and Incursion rebreathers	SN16, SN12, SN18	N/A
Mass spectrometer, Amis 2000 with suitable span gases	SN 0911243	Uses certified span gases to calibrate at each test
Certified pure gases, He, N2, O2, CO2		

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*.

7.2. Method

Breath-by-breath CO2 was measured at high resolution, while the rebreather controlled the PPO2 to a set point of 0.7 atm (the normal set point for saturation diving, though the set point is irrelevant to this trial), using breathing simulators to emulate respiration.

One-way valve leakage faults were induced covering from 0% (no fault) to 10% of exhaled breath by making appropriate changes to a test mule O.R. ALVBOV. A 10% leakage is not a safety critical fault: safety issues start in earnest at leakage rates around 25%.

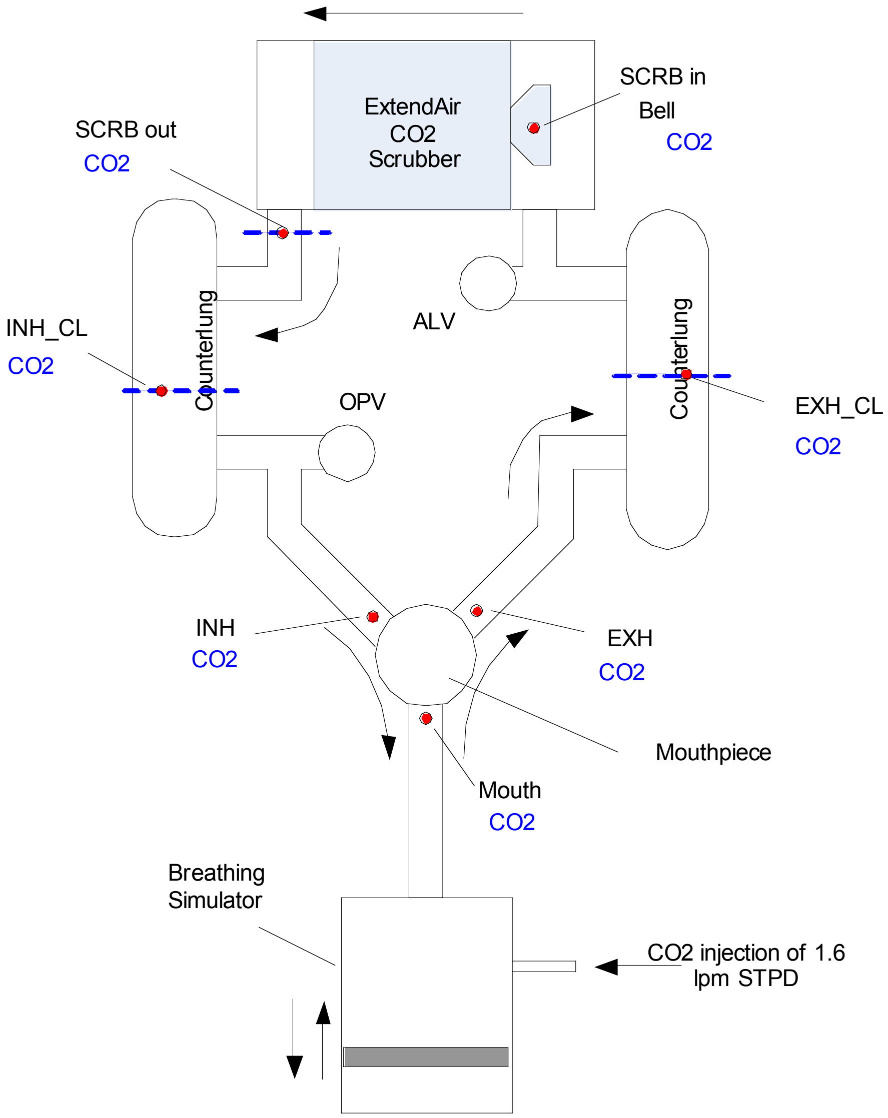


Figure 7-1..CO2 was measured in 7 points around the breathing loop shown above..

The gas fraction is measured in the following seven points of the breathing loop.

1. Mouth (**MOUTH**)
2. Exhale channel immediately downstream of the exhale one-way valve (**EXH**)
3. Centre of the exhale counterlung (**EXH_CL**)
4. Inside the base board bell membrane immediately prior to the scrubber (**SCRB in**)
5. Scrubber output tube (**SCRB out**)
6. Centre of Inhale counterlung (**INH_CL**)
7. Inhale channel immediately upstream of the inhale one-way valve (**INH**)

Cutting slots in the one-way valves to induce the fault changed the gas flow considerably within the ALVBOV, and are atypical of field faults. The valve faults were therefore induced simply by installing softer one-way valves and reducing their pretension. To provide direct comparison with contemporary DSB/BOVs, in two tests the ALVBOV barrel was swapped, with one having no flow diverter.

Water temperatures of 4C were used. The results shown herein are for tests where the RMV was 40 lpm, at a depth of 100m using helium as the make-up-gas with a CO2 flow rate of 1.6 lpm STPD, corresponding to 1.72 lpm NTPD or 1.78 lpm at BTPS. The results here are typical results, extracted from a large body of results from tests where EN 14143:2003 Table 4 RMVs were used, at depths from the surface to 200m, with air and heliox.

7.3. Litres Per Minute

Litres per minute, of a gas, references a volume at a particular temperature, pressure and water vapour load. The following conventions are used:

- **BTPS** means the flow is standardised to **B**ody **T**emperature, barometric **P**ressure at sea level, **S**aturated with water vapour.
- **ATPS** is measured at **A**mbient **T**emperature, **P**ressure, **S**aturated with water vapor and is used for expired gas which has cooled down.
- **ATP** is ATPS but not saturated with water vapor (e.g. room air). The room temperature has to be specified.
- **STPD** is **S**tandard **T**emperature (i.e. 0 ºC), barometric **P**ressure at sea level (101.3 kPa), **D**ry gas. Oxygen consumption and carbon dioxide delivery are standardised to STPD in standards.
- **NTPD** is STPD but at **N**ormal **T**emperature (i.e. 21C which is deemed to be average room temperature), barometric **P**ressure at sea level (101.3 kPa), **D**ry gas. Most mass flow controllers and meters are calibrated to NTPD. This means that to provide a flow specified in a standard such as EN 14143, a correction factor must be applied to flow rate shown on a mass flow controller of 1.6/1.72 (the fraction is chosen here to be one easily recognisable, as the flow rate requires is usually 1.6 lpm of CO2 at STPD). That is, a mass flow controller calibrated with CO2 should be set to 1.72 lpm NTPD, to provide a 1.6 lpm STPD flow, assuming the mass flow controller has perfect temperature compensation – for CO2 this is particularly important, but the phase diagram of CO2 requires special care, and there may be other compensations carried out at the same time[5]. In practice the flow rates are set higher still, around 1.82 lpm, to compensate for the CO2 lost in the sample gas, and due to the CO2 is not at the 21C assumed by NTPD: the BAI Test Manual contained detailed information on the process by which this is performed.

All CO2 measurements will be given in % SEV (percentage Surface Equivalent Volume), rather than kPa, mbar, or mmHg, as % SEV is more familiar to a lay reviewer. In normal respiration, the gas exhaled contains 4 to 5% SEV of CO2: this is the same as the partial pressure of CO2, PP(CO2), in units of atm, times 100.

[5] There are two other compensation factors that must be applied to the mass flow controller. The first is the gas type, in the case where a gas other than CO2 is used for calibration (CO2 can be difficult tocalibrate with), and also for the pressure. The Mass Flow Controller (MFC) should compensate for temperature automatically. All these compensation factors are checked by Deep Life on each test, by weighing the CO2 cylinders continuously during the test to ensure the correct mass of gas is used and is used linearly throughout the test, and by observing the level of the CO2 on exhale using a mass spectrometer to ensure the correct fraction is flowing. After all compensations are taken into account, to achieve a flow rate of 1.6 lpm on a CO2 MFC at 100m depth, settings of 1.6*(273+(CO2_cylinder_pressure_in_bar-36))/273 lpm are used. The calculation CO2_cylinder_pressure_in_bar-36 is a direct temperature measurement of the CO2 exploiting its pressure-temperature phase diagram.

7.4. Mouthpiece configurations tested

As well as contemporary DSV/BOVs tested for comparision purposes, the following ALVBOV configurations were tested:

1. ALVBOV, using 20 dur. mushrooms pretensioned to 1mbar in water.
2. ALVBOV with 20 dur mushrooms, no pretension
3. ALVBOV without the flow diverters, using 20 dur mushrooms. That is, as per a wide bore low WOB conventional DSV/BOV with soft flapper valves.
4. ALVBOV without the flow diverters, using 50 dur mushrooms. That is, as per a wide bore low WOB conventional DSV/BOV with stiff flapper valves.
5. ALVBOV with 50 dur mushrooms, no pretension.
6. ALVBOV with 50 dur exhale with flat mushroom, and umbrella on inhale, pretensioned.

7.5. Quantifying the Measurement Phase Delay

To align the breathing simulator respiratory cycles with the measured data, it is necessary to determine the time delay between the breathing simulator piston switching from inhale to exhale, and the gas at the measurement point changing, along with the delay in the measurement channel.

To minimise the gas transit delays, a gas flow rate of 1.82 lpm NTPD was used: this is comparable to the amount of gas removed by metabolism by a diver and effects the scrubber endurance because it removes some of the exhaled CO2. This removal is compensated using the method described in the Scrubber Endurance DV reports, and the BAI Test Manual. Another issue with this high flow rate is that it can disturb the gas flow at the periods of low flow in the sinusoidal breathing waveform that was used in these tests for measurements very close to the one-way valves. Care was taken to position the probe such that it was in the middle of the flow, rather than on the walls, to avoid this error. It has been noted that some third party test labs initiated the valve fault simply by taking their gas samples on the hose periphery just upstream of the inhale valve, so particular care was taken to avoid this type of disturbance.

The phase delay includes the gas delays to input to the mass spectrometer along with ts measurement pipe, and the gas delays in the measurement tube in the chamber.

<u>Theoretical Delays in the Mass spectrometer</u>
According to the spec of AMIS 2000 mass spectrometer its gas consumption is 15 ml/min and the orifice pressure drop is ~1 Atm. A formal orifice model shows that the orifice diameter is 13 um to transmit 15 ml/min air flow when the pressure drop is 1 bar.

The specification of the AMIS 2000 mass spectrometer includes the following parameters.

- Rise time: < 50 ms.
- Transmit time: 400 ms
- Gas consumption: 15 ml/min

The test transport delay is 0.57s. The calculated size of the inlet tube is 1.06×10^{-4} litre. The flow of 15ml/min takes 0.424s to traverse the inlet tube. This time corresponds to the transit time of 0.4s specified in the mass spectrometer user manual.

7.5.1. Theoretical Delay in the chamber sampling tube

- Tube diameter: 0.1 cm
- Tube length: 150 cm
- Flow rate is 1800 cm3/min

The delay in the tube is 40ms, from 150cm*(pi*0.1cm2/4)/30cm3/min).

7.5.2. Total theoretical measurement delay

The total delay of the gas fraction measurement, from the sum of the above, is ~0.6s (as 0.57s + 0.04s).

However, the delay observed for measurements taken at the mouth, where there a clear transition in CO2 can be observed, was 1.4s. Errors in the phase delay compensation would cause fundamental errors in determining Volume Weighted Average Inspired (VWAI) CO2, and in assessing the Deep Life CO2 sensor: the CO2 Lissajou figure would be incorrect. To eliminate this source of error, the phase delay at each measurement point was calibrated using the method described below.

7.6. Calibration of the Gas Measurement Phase Delay

The method for calibrating the phase delay involves injecting a short impulse of a marker gas at the mouthpiece, that is synchronised electronically to the breathing simulator. This marker can be moved in phase to align the change in the simulator's piston direction from inhale to exhale, with the observed change in CO2 from inhale to exhale at the mouthpiece. The marker can then be traced at any point of the rebreather loop, as being the start of the increase in the marker or tracer gas.

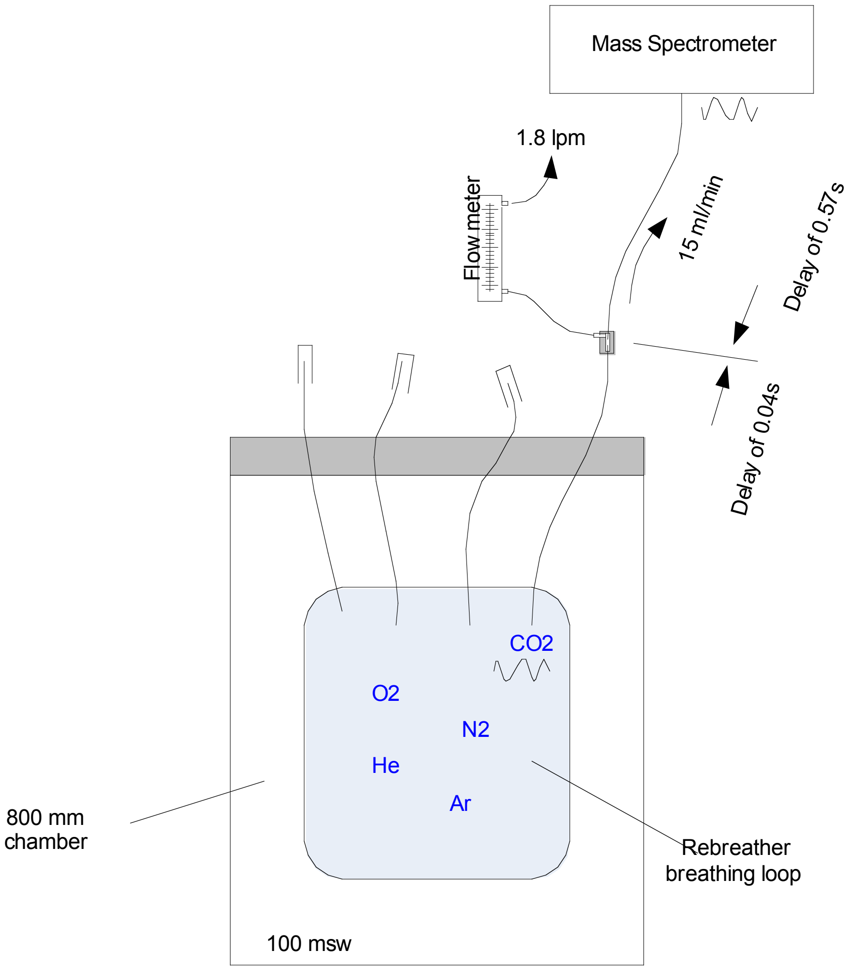


Figure 7-2.. Theoretical gas propagation in the sampling channel.

The marker impulse must not change the original gas flows so the size of the label was optimised by making it the smallest pulse that could be detected, and using N2 as a marker in the otherwise heliox environment. Methane and other gases could be used as markers, but were undesirable within the rebreather.

Once the phase offset was determined, the phase stability was checked over a one hour period and found to be within 2 sample periods (45 samples being taken to cover the whole of the breathing cycle).

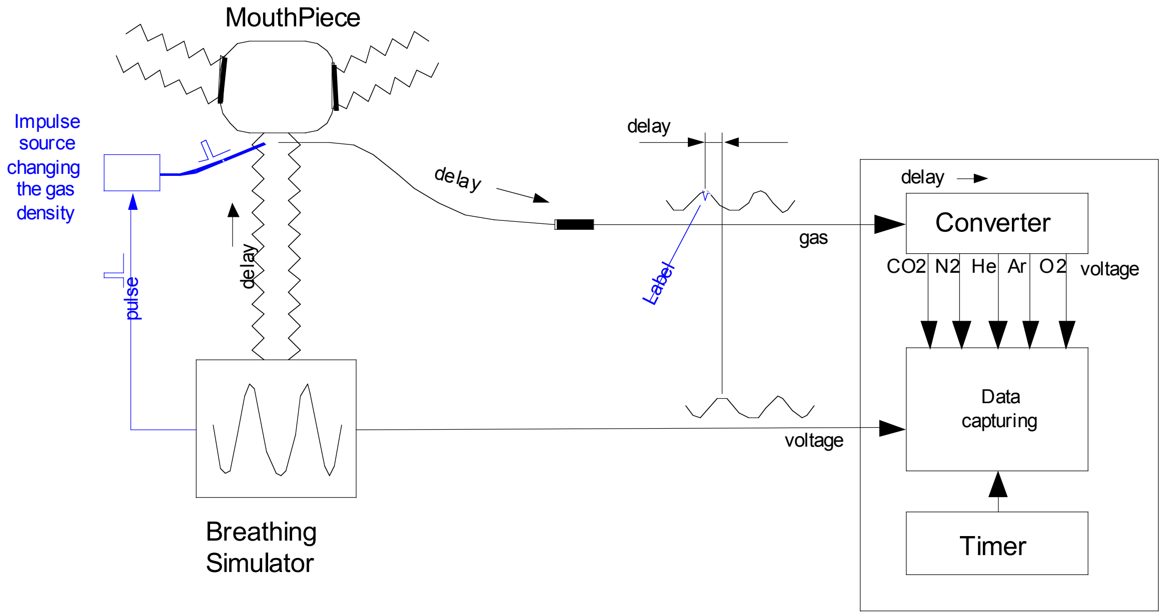


Figure 7-3.. Marker method for calibrating the phase delay, by changing the gas density at the mouthpiece using a marker that changes the gas density using a synchronosed impulse.

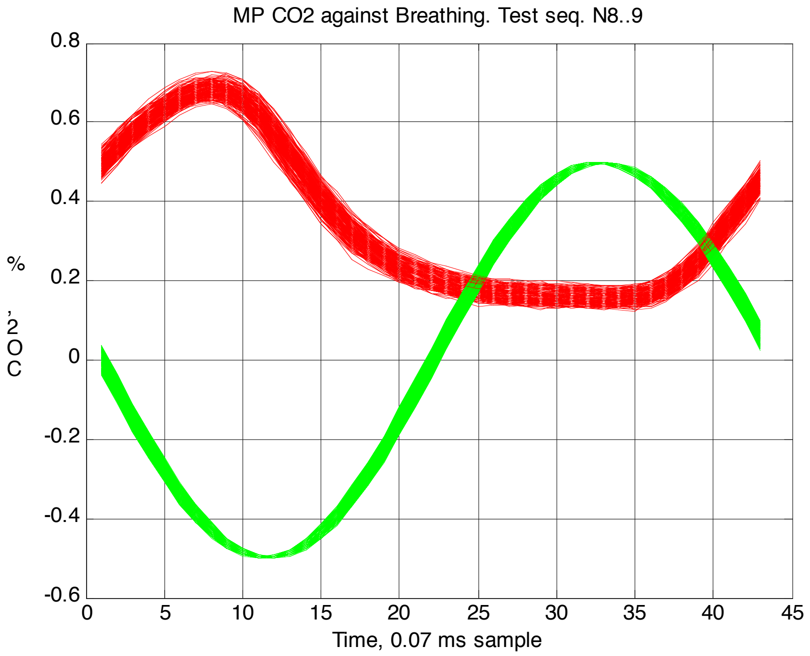


Figure 7-4.. Stability of phase delay over a one hour period at the mouthpiece. Dither is 2 samples. Peak of CO2 is on the 38th sample and peak of exhale at the breathing simulators is 26 samples earlier. The vertical dither on the CO2 is due to the mass flow controller maintaining a constant CO2 flow over a one hour period, and is a normal distribution with the limits shown above.

8. Fault Symptoms

The fault mode will be described as symptoms, so it may be identified if and when it occurs during testing. All results are taken from actual ALVBOV, DSV or BOV mouthpieces measured at 40 lpm at 100m.

8.1. CO2 Waveforms when no fault is present

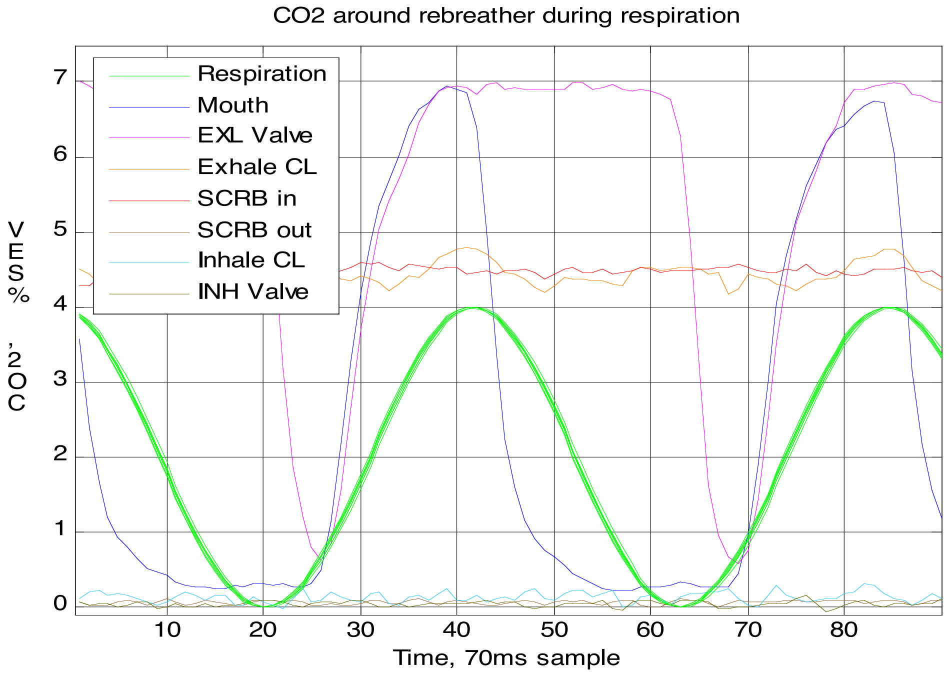


Figure 8-1. Breath-by-breath measurements of CO2 taken in the positions shown in Figure , Figure 9-1 for a properly functioning ALVBOV with fresh scrubber media.

In the figure above, it can be seen that the CO2 in the gas sampled immediately prior to the inhale valve is the same as that immediately downstream of the scrubber, and the same as that in the inhale counterlungs.

It can also be seen that the CO2 measured in the mouth is close to zero at the end of inhale.

At the start of the exhale cycle, the CO2 immediately downstream of the exhale flapper valve approaches zero, and the offset is the same as the VWAI CO2.

The gas sampled just upstream of the scrubber is the same as the Volume Weighted Average Exhaled (VWAE) CO2 measured in the mouth at 4.5% SEV in the above test, however, the CO2 in the gas just downstream of the mouthpiece can be actually higher under some conditions! This curious phenomenon occurs because the exhale valve acts as a peak detector, and the helium flows faster than the CO2, so once a packet of gas moves through the exhale valve, the helium settles out of it rapidly, with the result that the fraction of CO2 in that point grows slowly, until there is another packet of gas in the next breath.

The Deep Life CO2 monitor measures the same average CO2 as that measured by the mass spectrometer just upstream of the scrubber, but displays 7.0 % SEV when the consumption of 1.78lpm is simulated: this is correct. The actual RMV is 40lpm, with a 20 bpm RR, but the oxygen metabolised is 1.78lpm STPD at 1.6lpm, so the calculation used by the CO2 monitor concludes the RMV is 49lpm, and the tidal volume is 2.45 litres. Applying these numbers to the formula described for determining the peak CO_2 in the previous section of this report, results in 7.0 % SEV of CO_2, and the actual number measured using the mass spectrometer is 6.9% SEV. Following this check, oxygen metabolism simulation was switched off, so not to interfere with CO_2 measurements.

In EN 14143:2003, it requires the VWAI CO_2 to be measured throughout the scrubber endurance test **<u>at the mouth</u>**. This is not upstream of the inhale valve, but actually in the mouth – for example, a sample taken from the mouthpiece bite. If this measurement is taken on a breath-by-breath basis, the end of inhale offsets identify the fault immediately. The problem generally arises with laboratories that avoid the issues of synchronising the breathing simulator with the sampled gas by taking a measurement upstream of this point.

8.2. CO2 Waveforms when the Turbulent Leakage Fault is present

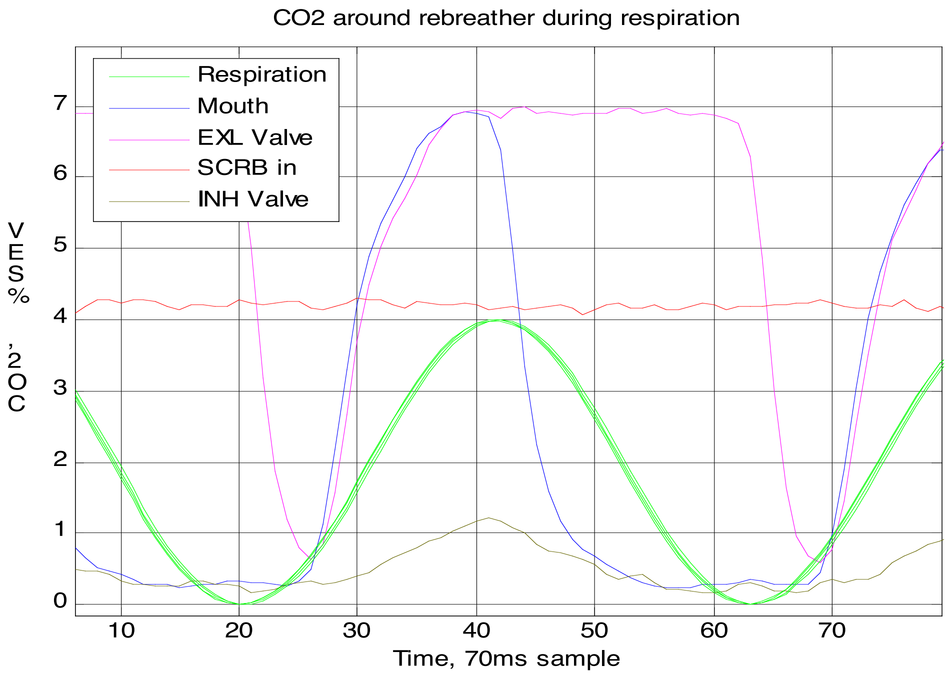


Figure 8-2. Breath-by-breath measurements of CO_2 taken in relevant positions shown in Figure 9-1 showing the effect of turbulent leakage across the one-way valves.

The mean exhale CO_2 appears to be the same as in the case when there is no fault, because what is happening is the CO_2 flow has been adjusted to 4.2% SEV. That will itself result in an overstatement of scrubber endurance, because the flow rate does not take into account that there is some inhaled CO_2 that is being transferred to the output. It is very important that the peak to peak CO_2 flow is the correct gas fraction: 4% before STPD to BTPD correction in EN 14143:2003 or 5% BTPD in other cases.

An increase in VWAI CO_2 in a human will produce a corresponding increase in the VWAE CO_2, and end of exhale CO_2. The same should occur in the breathing simulator if the correct flow rates are used.

8.2.1. Effect of Inhale Valve Leakage

The effect of turbulent leakage through the inhale valve is that peaks of CO_2 can be seen in the gas sampled immediately before the inhale one-way valve. This are shown in detail in the above figure.

In a CO2 scrubber endurance measurement, taken by sampling gas immediately prior to the inhale one-way valve, one of two symptoms will be visible, depending on the sample flow rate. Either:

1. At moderate sample flow rates, there will be peaks visible in the endurance curve, that look like a low level noise overlay. These peaks are generally not present when a sample is taken immediately downstream of the scrubber.
2. At slow sample flow rates, an offset will be seen even with fresh scrubber media, and that offset is not present if gas is sampled immediately downstream of the scrubber.

8.2.2. Effect of Exhale Valve Leakage

The effect of turbulent leakage through the exhale valve is apparent only when measuring gas at the mouth, or downstream of the exhale valve.

The end of inhale CO2 in a breath-by-breath measurement taken in the mouth is not zero: there is an offset. This offset can be seen clearly in the figure above.

The CO2 waveform taken just downstream of the exhale valve is also abnormal in that the start of exhalation is much smaller than normal, with an offset. As there is always some offset, it can be difficult to identify the fault from the exhale valve sample point, unless the fault is gross, as it is the example given above.

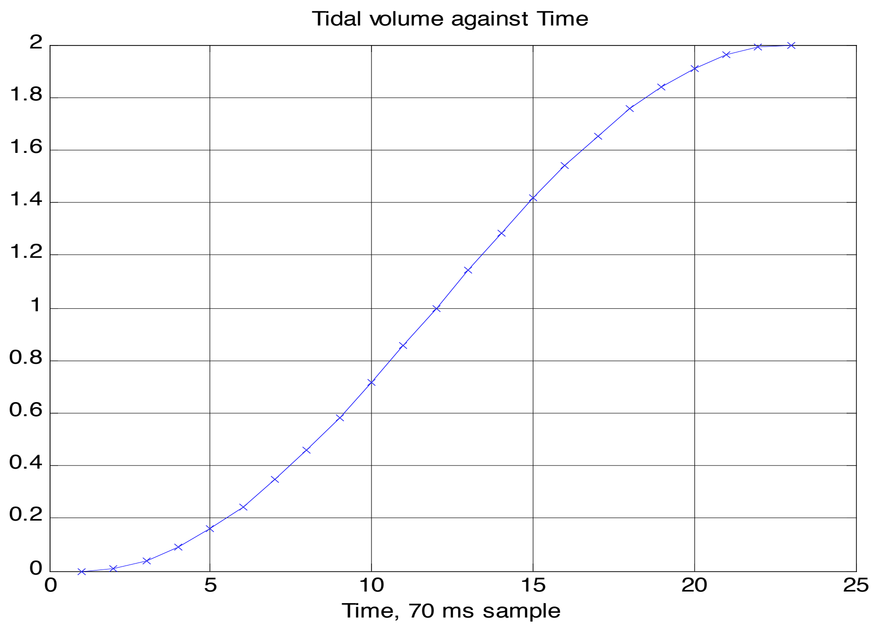


Figure 8-3. The inhale, or exhale, tidal volume as a function of time. X axis is samples, in units of 70ms (so this curve can be used directly with the other plots in this report), and the Y axis is volume in litres, for a stroke of 2 litres. This curve enables the dead space in the mouthpiece to be measured, by measuring the time taken for the falling edge of the CO2 waveform to crosses its mean (from the peak to peak), and then look up the volume at that time, on the above plot.

8.2.3. Effect of fault on DSV Dead Space

The breath-by-breath method described by Innocor[6] describes a simple method of determining dead space, from the integral of the respiratory volume, from start of inhale to the 50% point on the inhale or exhale curve. This is far more accurate than the CE method.

When the CO2 is sampled at the mouth, using the falling CO2 curve, then all of the dead space calculated from this integral is the effective dead space of the DSV. Correspondingly, the rising CO2 curve is the dead space of the breathing simulator: this is immaterial, other than increasing the deadspace from the 150ml used for scrubber endurance testing to 800ml provides an asymptotic CO2 waveform in the mouth that allows the inhale pattern to be studied in more detail than using a 50:50 duty cycle.

The ALVBOV has a very low true dead space, which results in a very rapid fall of the CO2 on inhale seen in **Figure 8-1**: the CO2 falls to 50% of the figure at start of inhale, in just 4 sample periods, i.e. 280ms. Looking up that time interval on the plot of the 2 litre tidal volume against time shown in **Figure 8-3**. The true dead space in the ALVBOV measured by the rate of CO2 clearance at the start of the inhale cycle is 70ml to 100ml. This is less than the 150ml measured using water, because the space between the flow diverters and the open circuit diaphragm is not swept, virtually at all in closed circuit mode.

Contrast this to the plot below, where the inhale one-way valve has turbulent bypass. The falling CO2 edge is visibly slower than that in in **Figure 8-1**. Using the Innocor dead space method, the time taken for the CO2 to fall by 50% is 7 samples, of 70ms (i.e. 490ms), and from the curve in **Figure 8-3**, it can be seen that 7 samples corresponds to a dead space of 350ml. This is a huge difference, and brings the VWAI CO2 above safe thresholds.

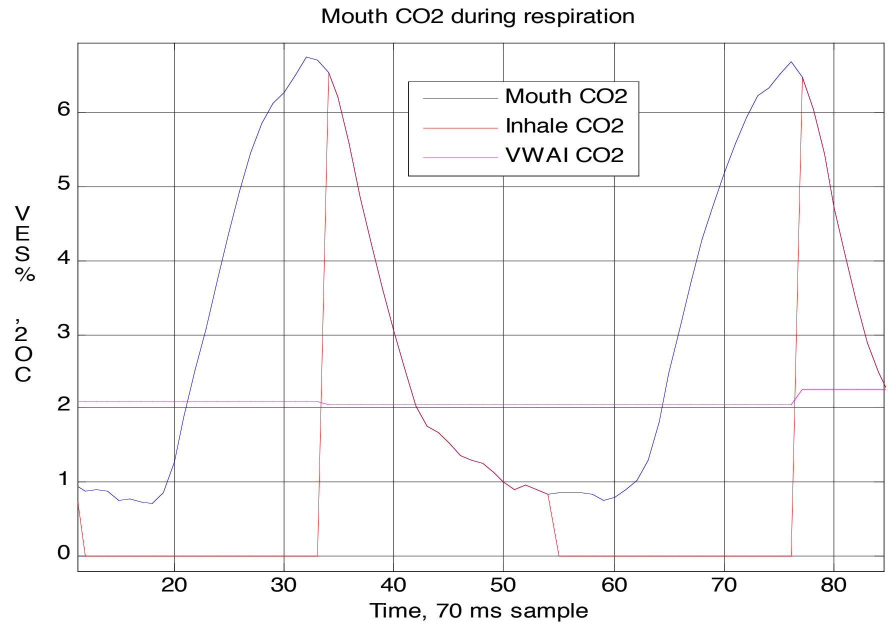


Figure 8-4. Example showing the apparent increase in dead space from inhale one-way valve turbulent bypass. This DSV with a 70ml to 100ml true dead space, performs as a device with 350ml dead space when the bypass fault occurs.

[6] Innocor Breath by Breath Method, document COR-MAN-0000-005-IN / UK Available from Innocor or from http://www.innovision.dk/Files/Filer/PDFfiler/Manuals/Innocor_Breath-by-Breath_Method_A-1.pdf with a capture date of 7th December 2010

It is important that the CO2 is sampled right at the point where the gas leaves the DSV into the diver's mouth. The figure below shows how quicky that gas fraction changes as a function of time. Failure to position the sample point right at the mouth, will result in significant errors when observing the effect of the valve failure on dead space.

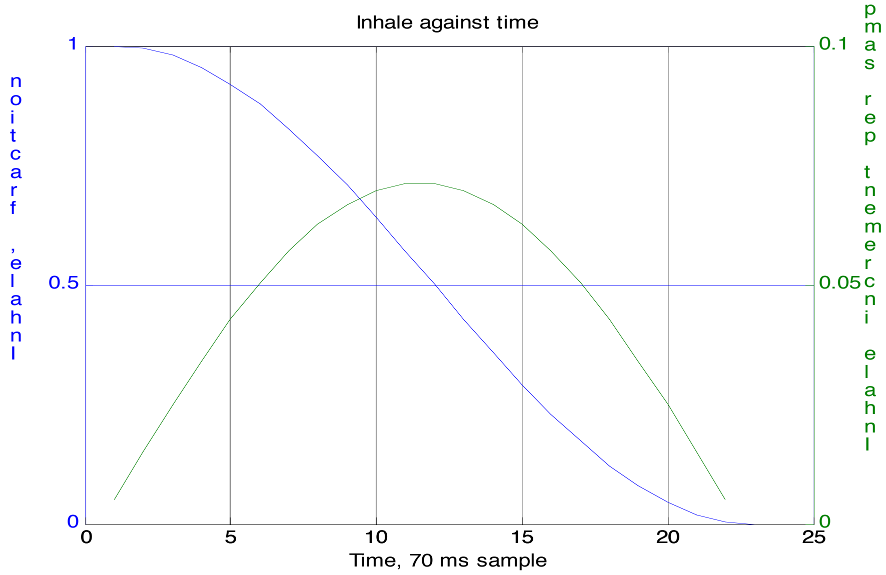


Figure 8-5. The normalised integral of the flow of the inhaled gas against time. The rate of the gas flow is not constant: it is driven as a SINE function.

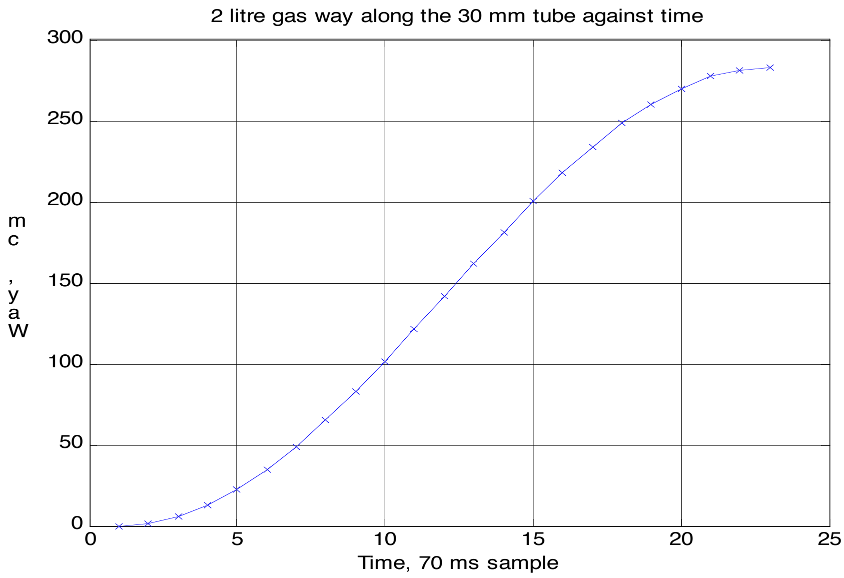


Figure 8-6. Plot showing the time delay in distance, compensating for the SINE waveform. Very small offsets in the position of the CO2 sample tube in the mouth can cause large errors in time because the above curve is almost flat for small offsets. If the inhale gas is sampled 1.4 cm away from the Inhale mushroom valve into the mouth measuring point direction, it needs two 70 ms samples to pass a 7.2 cm waypoint from the valve. One

sample delay increases Average Inspired CO2 on 0.32% as 7%/22_inhale_sample. The distance between the furthest away point of the inhale valve and the mouth is ~7 cm.

8.2.4. Effect of fault on VWAI CO2 measurements

The inhale valve turbulence fault has an identical effect on the VWAI CO2 measurements as scrubber breakthrough. The margin available for scrubber breakthrough is much less than may be imagined from a cursory look at standards such as EN 14143:2003.

The end of inhale CO2 is not near zero with fresh scrubber media: it is around 0.2 % SEV in a mouthpiece with 70ml dead volume, with the dead space common to breathing simulators (which are designed to simulate a human). It can be seen that the margin allowed for scrubber breakthrough is actually very small indeed: just 0.3% SEV typically.

Gas density impulse methods have been used to confirm the phase of the inhalation cycle is correct in the figures reported herein. It can be seen that the Volume Weighted Average Inspired CO2 in the plot in **Figure 8-3** is just above the 2% SEV limit. This is despite the mouthpiece having an effective dead volume of less than 70ml. However, if the phase of the breathing respiratory is shifted, such that it covers 50% of the respiratory cycle, with the inhale phase aligned with the VWAI CO2 minima, then we obtain the plot below: this is a much lower VWAI CO2, for what is in fact the same data. Now the device under test suddenly meets EN 14143 limits, whereas in fact it fails dismally even with a new scrubber due to this valve fault. This critical dependence on phase led to the use of gas impulses to synchronise the measurements with the breathing simulator piston position repeated earlier.

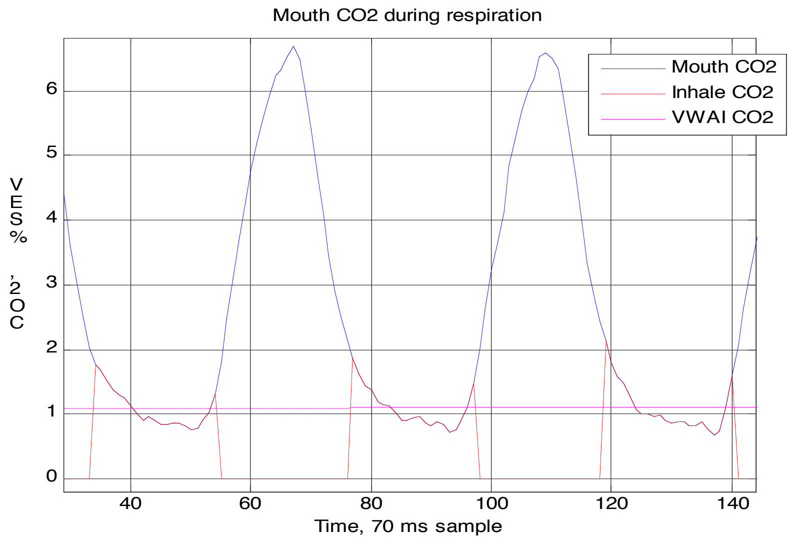
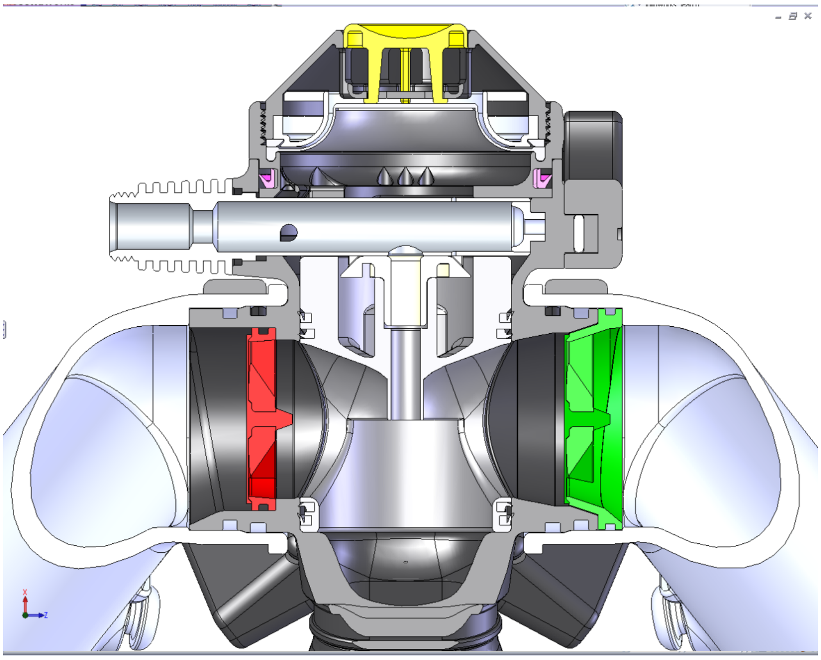
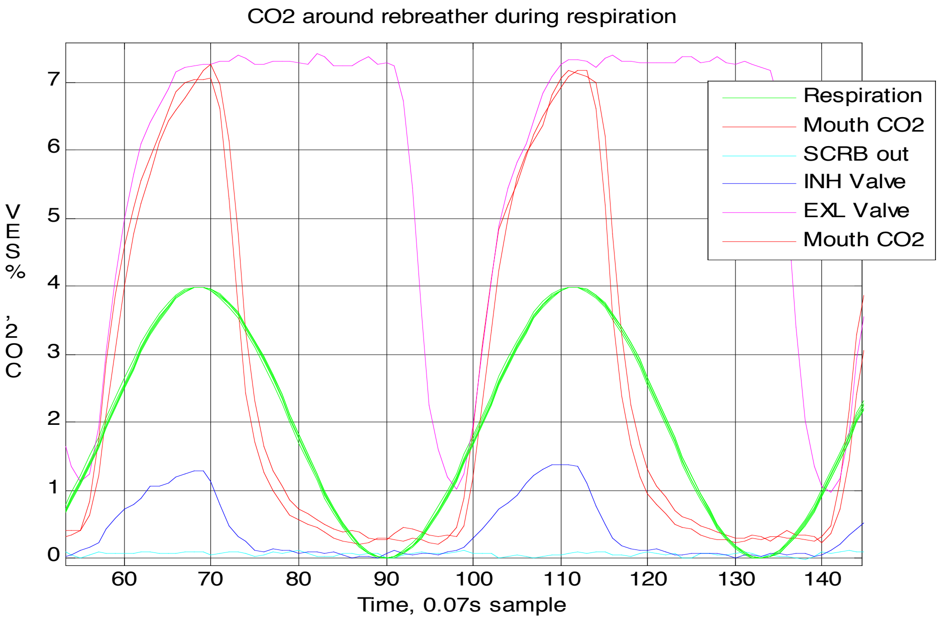


Figure 8-7. CO2 in the mouthpiece using the standard ALVBOV, plotted against time, with the calculated volume weighted average inhale PPCO2 of 1.1% SEV at 100m depth. Inhale takes half of breathing period. Inhale finishes when the CO2 in the mouth reaches its minimum. This is the same inhale waveform as in the previous image, and shows how hazardous it is to assume the phase of inhale is that where the VWAI CO2 is at its minimum: this is never the case. In this example the VWAI CO2 appears to be well within the EN 14143:2003 limits, at the point where the scrubber is close to the 1% SEV (10mbar) scrubber endurance limit, but in fact, the VWAI CO2 exceeded the 2% SEV (20mbar) limit even before the scrubber got to the 0.5% SEV (5mbar endurance limit)!

9. Screening Tests on the O.R. ALVBOV

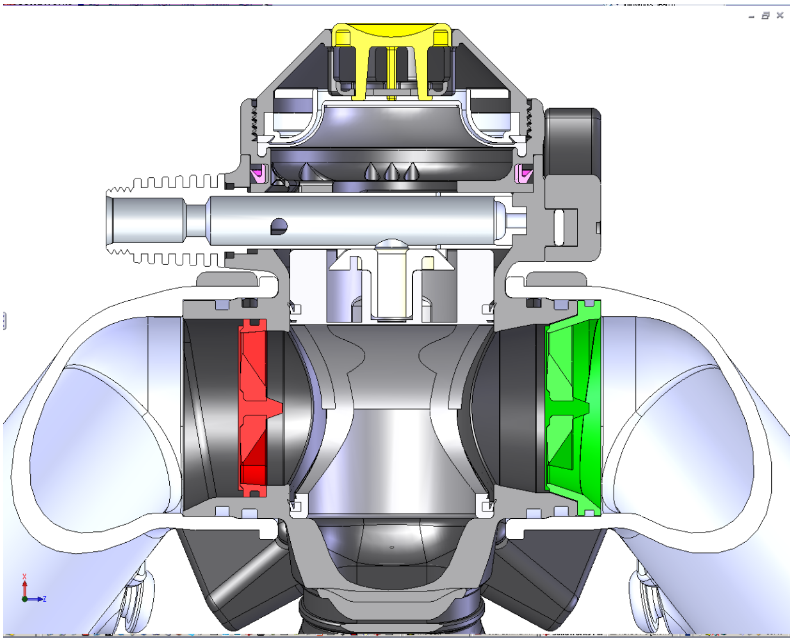
9.1. TEST M1, using 20 dur. mushrooms no pretension, with flow diverters

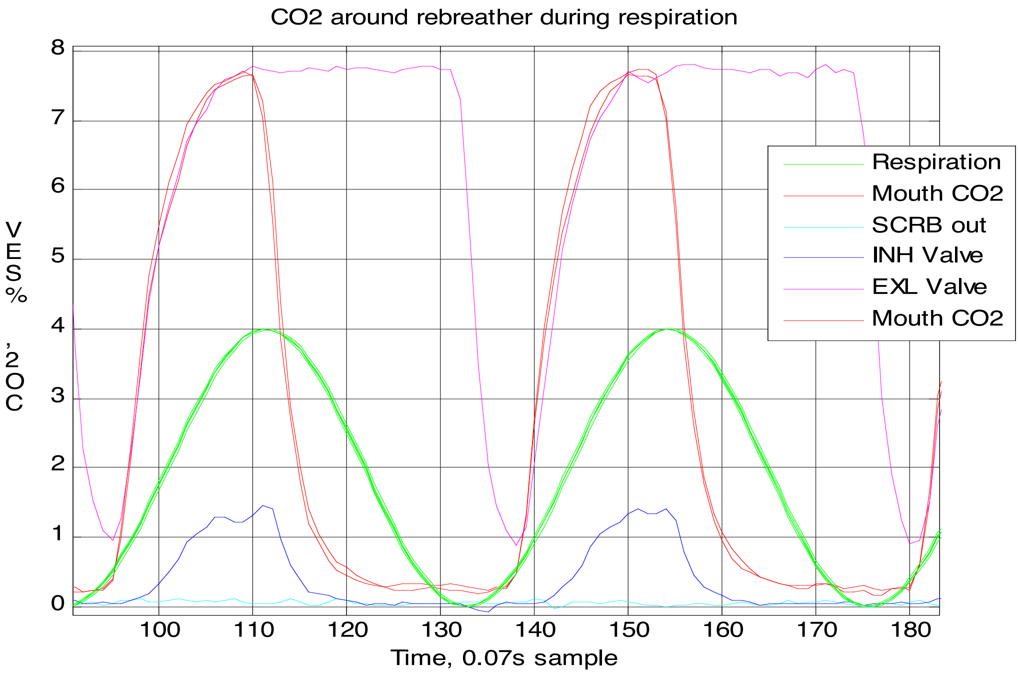




Parameter	CO2 %SEV N1_1, % SEV
Max MP/ Min MP	7.1/0.25
Min / Max SCRB output	0.05
Max inhale/ Min inhale	1.25/0.05
Min exhale / Max exhale	7.3/1.1

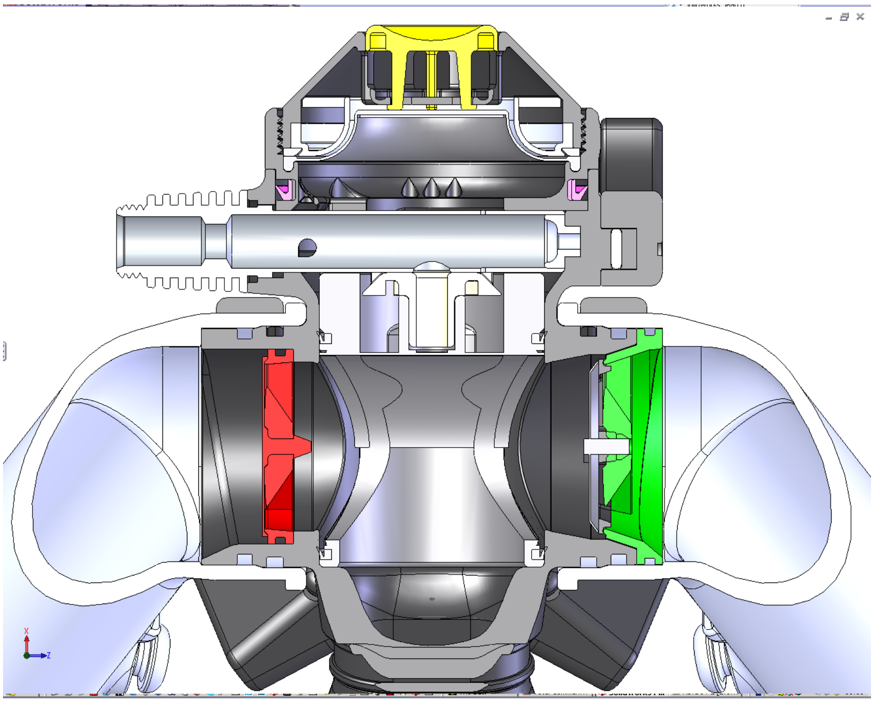
9.2. TEST M2 using 30 dur. mushrooms, no pretension, straight barrel

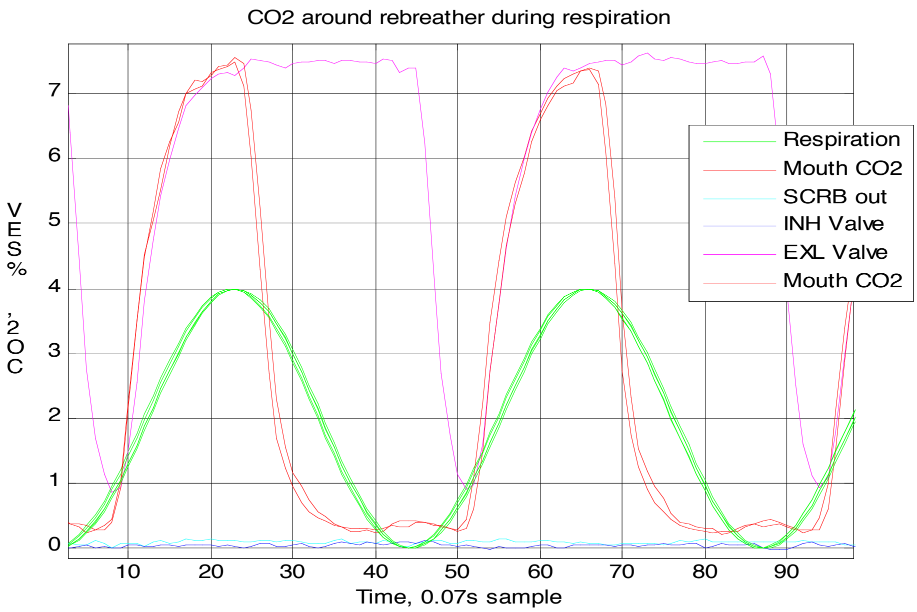




Parameter	CO2 %SEV N2, % SEV
Max MP/ Min MP	7.6/0.3
Max / Min SCRB output	0.05
Max inhale/ Min inhale	1.45/0.05
Max exhale / Min exhale	7.75/1

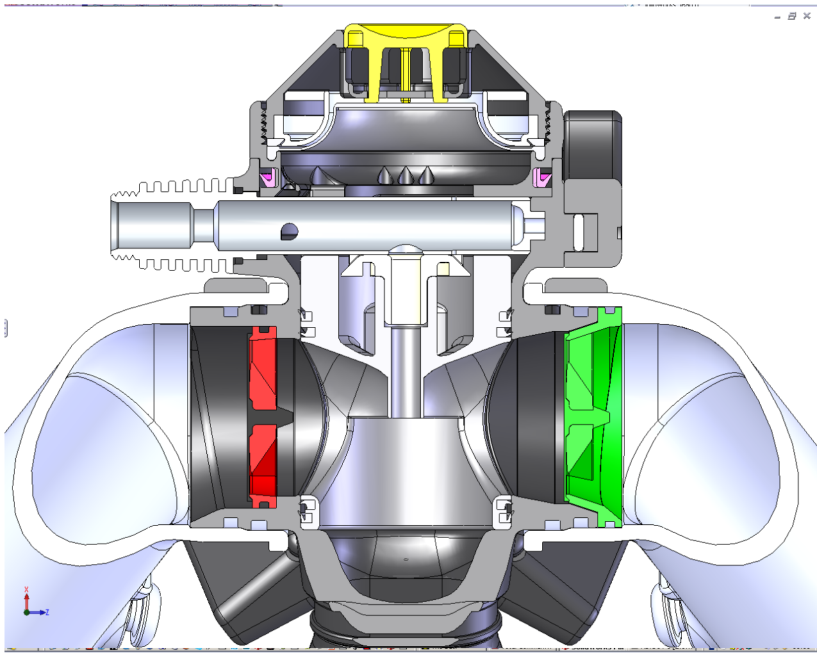
9.3. TEST M3 with barrel red mushrooms, with +5 mbar pretension umbrella exhaust mushroom, straight barrel (without the flow diverters)

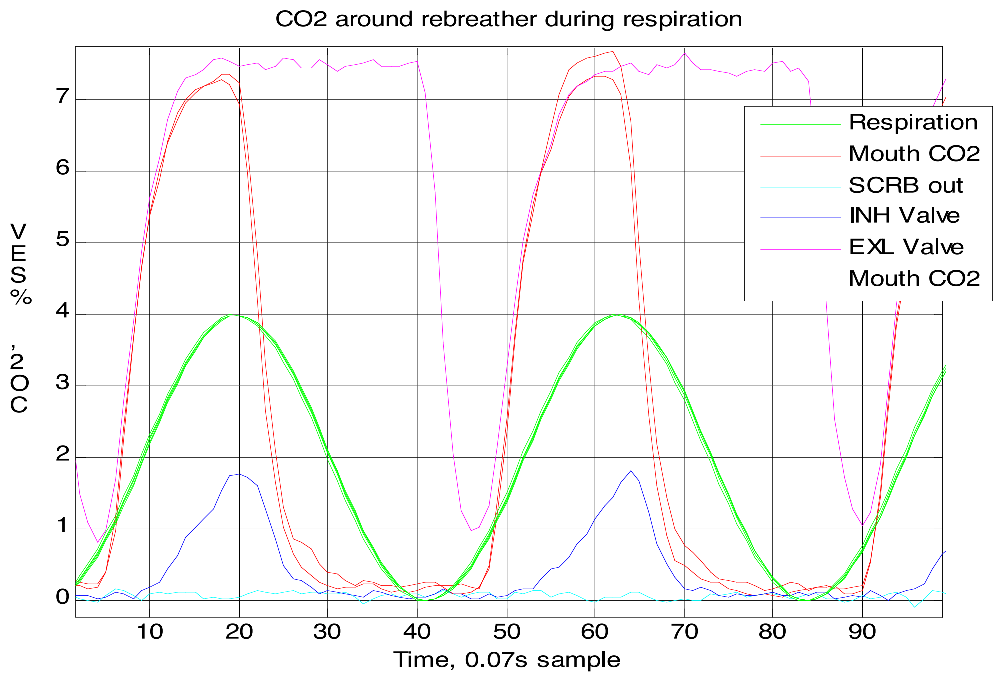




Parameter	CO2 %SEV N3_1, % SEV
Max MP/ Min MP	7.4/0.3
Max / Min SCRB output	0.05
Max inhale/ Min inhale	0.05
Max exhale / Min exhale	7.5/0.9

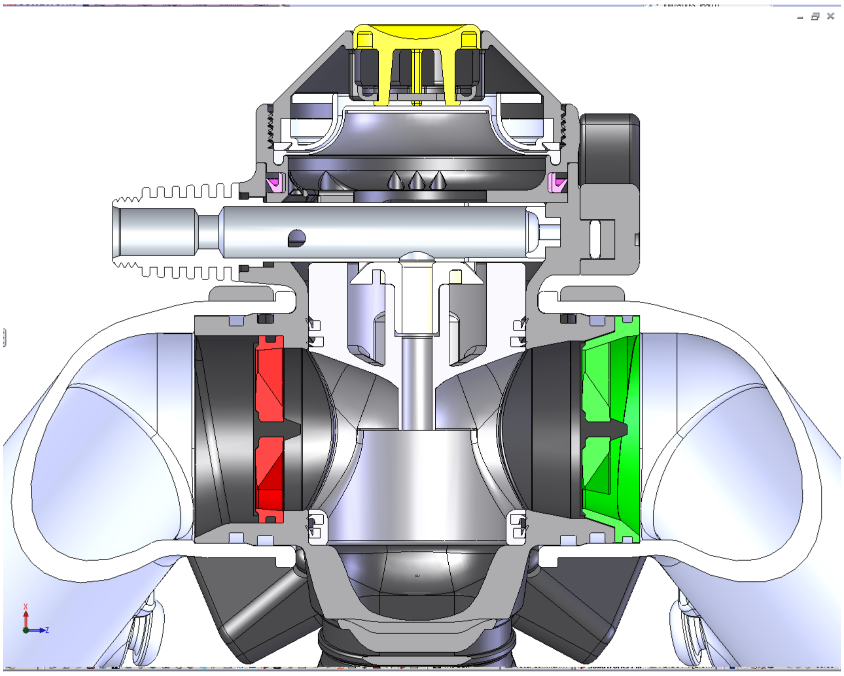
9.4. TEST M4 with 30 dur. inhale and 50 dur. exhale, no pretension, with flow diverters.

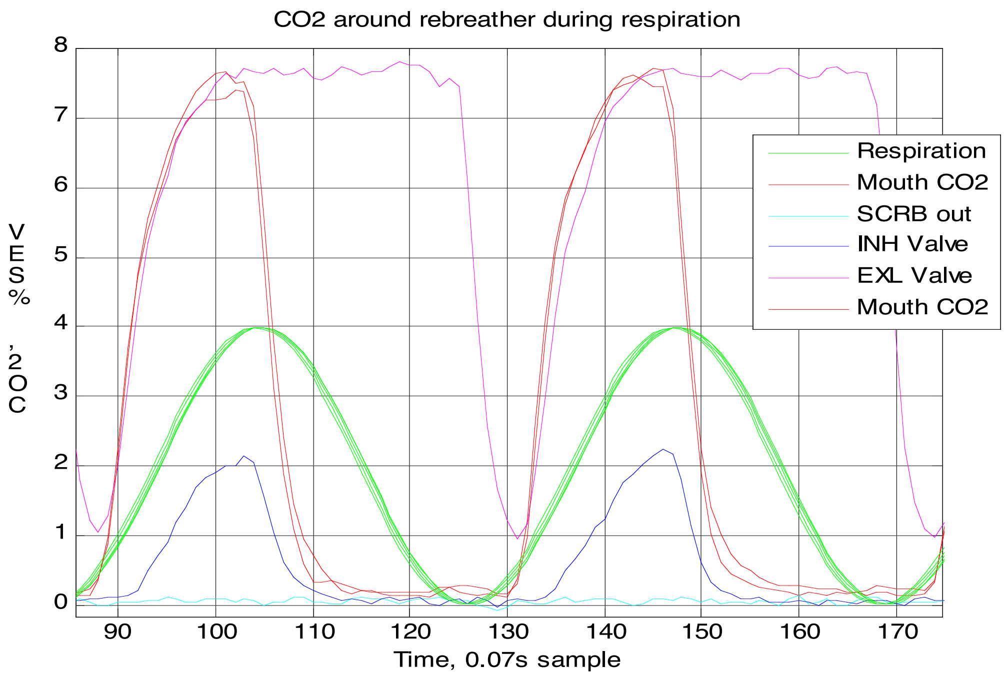




Parameter	CO2 %SEV N4, % SEV
Max MP/ Min MP	7.3/0.07
Max / Min SCRB output	0.05
Max inhale/ Min inhale	0.13/0.05
Max exhale / Min exhale	7.5/0.95

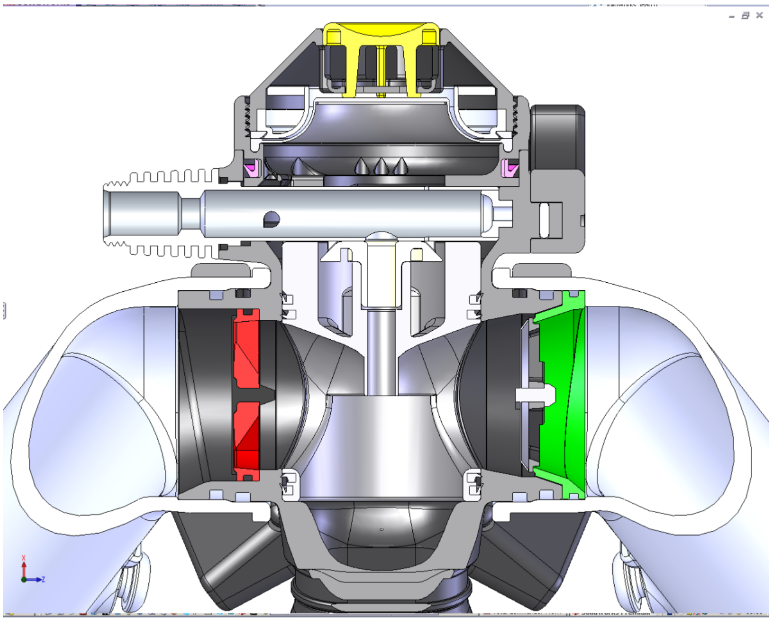
9.5. TEST M5 with 50 dur. Inhale and exhale mushroom, with flow diverters.



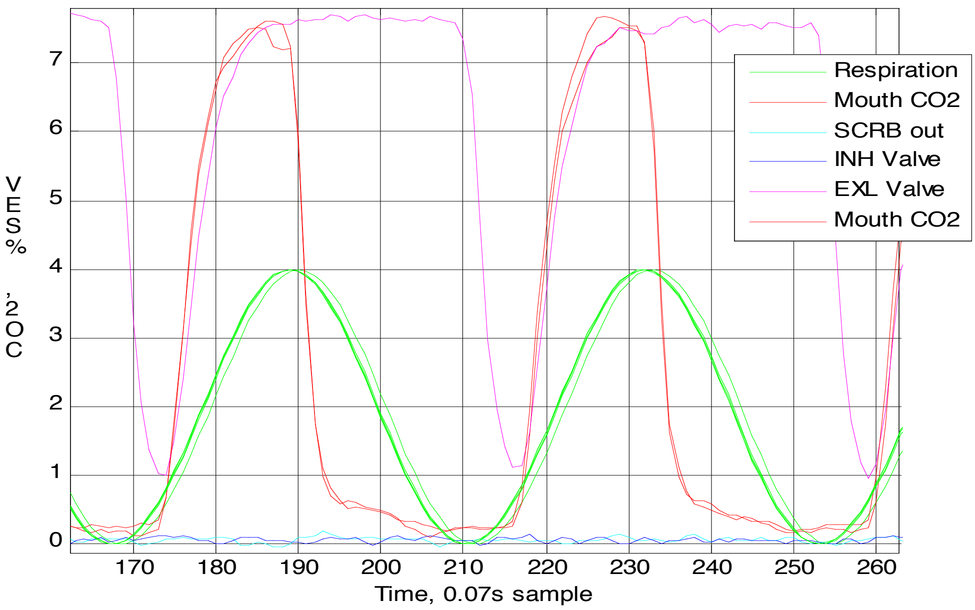


Parameter	CO2 %SEV
Max MP/ Min MP	7.6/0.15
Max / Min SCRB output	0.05
Max inhale/ Min inhale	2.15/0.05
Max exhale / Min exhale	7.7/1.0

9.6. TEST M6 with 50 dur. exhale mushroom and with +5 mbar pretension umbrella inhale with 1mbar pretension, with flow diverters.



CO2 around rebreather during respiration



Parameter	CO2 %SEV
Max MP/ Min MP	7.5/0.07
Max / Min SCRB output	0.05
Max inhale/ Min inhale	0.05
Max exhale / Min exhale	7.7/1.0

The above test was repeated three times, with closely correlating results.

9.7. Detection of the Fault

The magnitude of the valve turbulence fault is enough to increase the VWAI CO2 by 1% typically. This would be reflected in a higher end of exhale CO2, and also a higher mean CO2 in a human. A 1% increase in end of exhale CO2 is detectable by the Deep Life CO2 monitor.

9.8. Summary of Results

The configurations M6 is the configuration shipped to customers on the rebreather above. There are other configurations tested, that are not described above to avoid clouding the issue in a mass of data. Some of these other configurations are also free of the fault, such as using pretensions umbrella type flapper valves on the inlet and outlet.

Where the ALVBOV is sold on its own, the probability of the fault occurring is significantly lower than on the Deep Life rebreathers, because the resistance through granular scrubbers is higher than for EACs, so there is less flow-through of exhaled gas pressure during the exhale part of the respiratory cycle onto the inhale flapper valve that would reduce its seating pressure.

Configuration M1 is the worst case for scrubber endurance testing at laboratories that use sampling upstream of the inhale valve. BAI do not use this method for scrubber endurance testing, since the requirement to sample in the mouth was highlighted by the CE Notified Body in 2006, but it is used almost universally elsewhere.

None of the configurations have any observable effect on WOB or breathing resistance.

ALVBOV configuration	Turbulent Reverse Leakage through inhale valve	Turbulent Reverse Leakage through exhale valve
ALVBOV M1, using 20 dur. mushrooms no pretension, with flow diverters	Yes	Yes
ALVBOV M2 using 30 dur. mushrooms, no pretension, straight barrel (without the flow diverters)	Yes	No
ALVBOV M3 using 30 dur inhale and pretension umbrella exhaust mushroom, straight barrel (without the flow diverters)	No	No
ALVBOV M4 with 30 dur. inhale and 50 dur. exhale, no pretension	Yes	No
ALVBOV M5 with 50 dur. Inhale and exhale mushroom, no pretension	Yes	No
ALVBOV M6 with 50 dur. exhale mushroom and pretension umbrella inhale	No	No

10. ANALYSIS OF ALVBOV SCREENING RESULTS

10.1. Effect of valve configuration on breathing resistance and WOB

All tests reported here were carried out at 100m using heliox, with the rebreather operating as required for EN 14143:2003 testing. The OR_Umbilical was used, as it has a higher breathing resistance than the SRB (Incursion and Apocalypse) models, due its breathing manifold and longer hoses. All tests were made by sweeping the tidal volume and recording the maximum peak to peak before the ALVBOV is triggered: these peaks are much larger than under normal diving conditions. The peak to peak pressures were measured, and the Lissajous were examined.

There was no material difference in any Lissajou in any tests. The differences in cracking pressures of the difference valve combinations cover a 1.5mbar peak to peak range: too small to be observed reliably because the end of tidal flows are almost vertical on the Lissajou figures. Using swept volumes, no material change to the minimum Work of Breathing and breathing resistance was observed.

The very soft valves stick slightly to their web when wet, and some variability is seen as a result, from breath to breath: this is very small effect, of around 0.5mbar (in waveforms which peak under these conditions around 50 to 60 mbar.

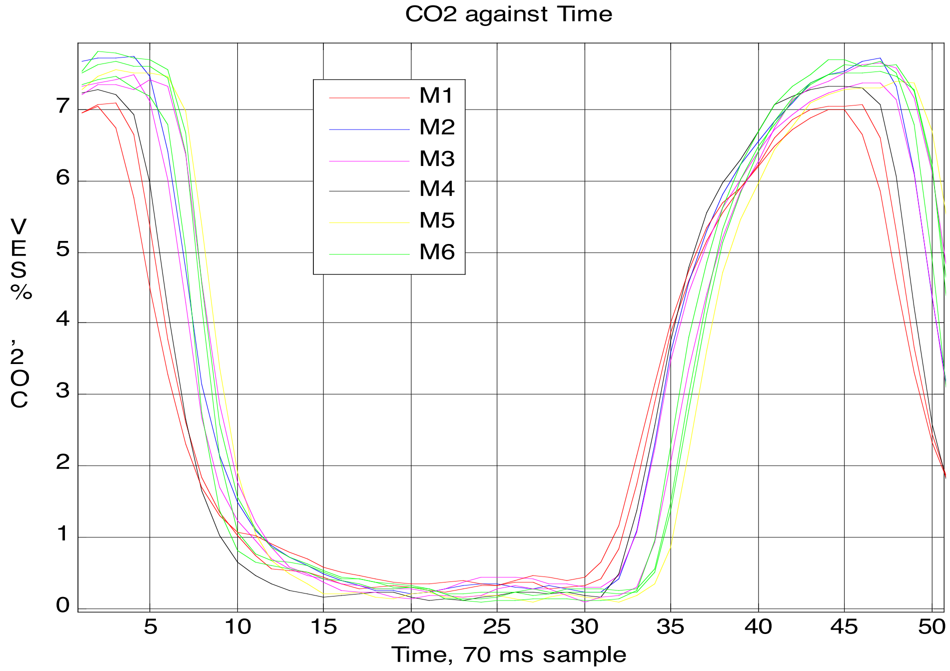
Table 1. Pressure drop p-p amplitude.

ALVBOV structure	Maximum Peak to Peak Prressure drop, mbar				
	MP	EXH	SCRB out	INH	MP
M1 / scan 1	47..65	45..64	45..64	45..64	45..64
M2	45..62	44..63	44..63	45..63	44..63
M3 / scan 1	47..67	48..65	47..63	48..65	48..65
M3 / scan 2	43..63	44..64	44..64	44..64	44.64
M4	48..66	48..66	48..66	49..67	48..66
M5	49..67	48..66	48..66	48..67	48..67
M6 / scan 1	47..67	47..67	47..67	47..67	47..67
M6 / scan 2	45..65	45..66	45..66	45..66	45.66
M6 / scan 3	44..64	44..64	42..61	45..65	44..64

Note:

1. Differences in the rebreather peak to peak pressures across the different ALVBOV configurations tested, were less than 1mbar of the mean measurements.
2. The flow diverters are known to have a large positive effect on the open circuit performance, by providing a venture, and have negligible effect on the closed circuit performance of the ALVBOV.

10.2. Effect of valve configuration on CO2 waveform in mouth



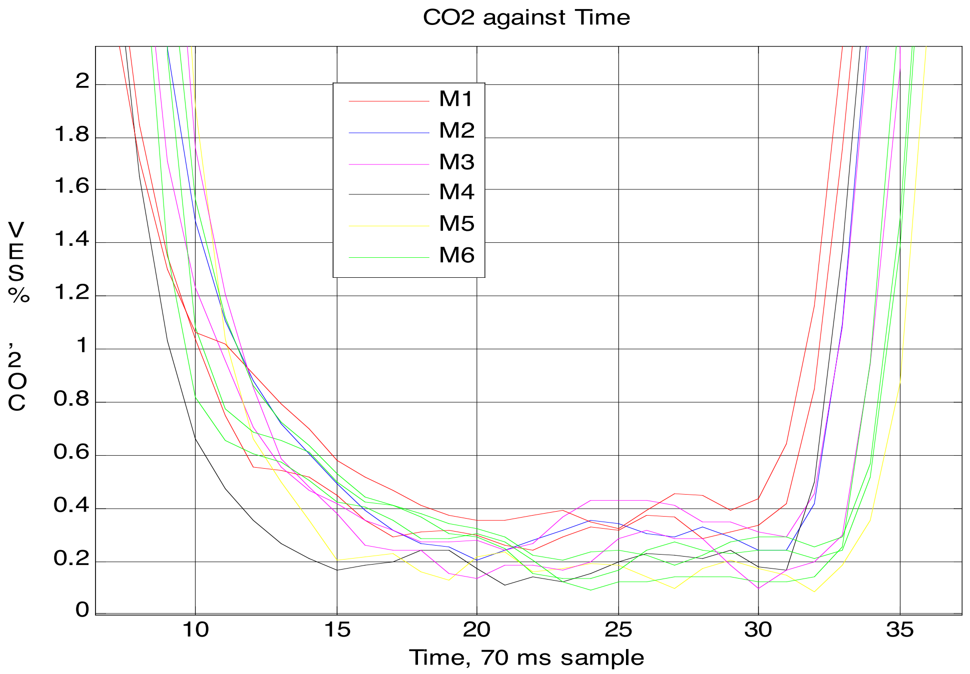
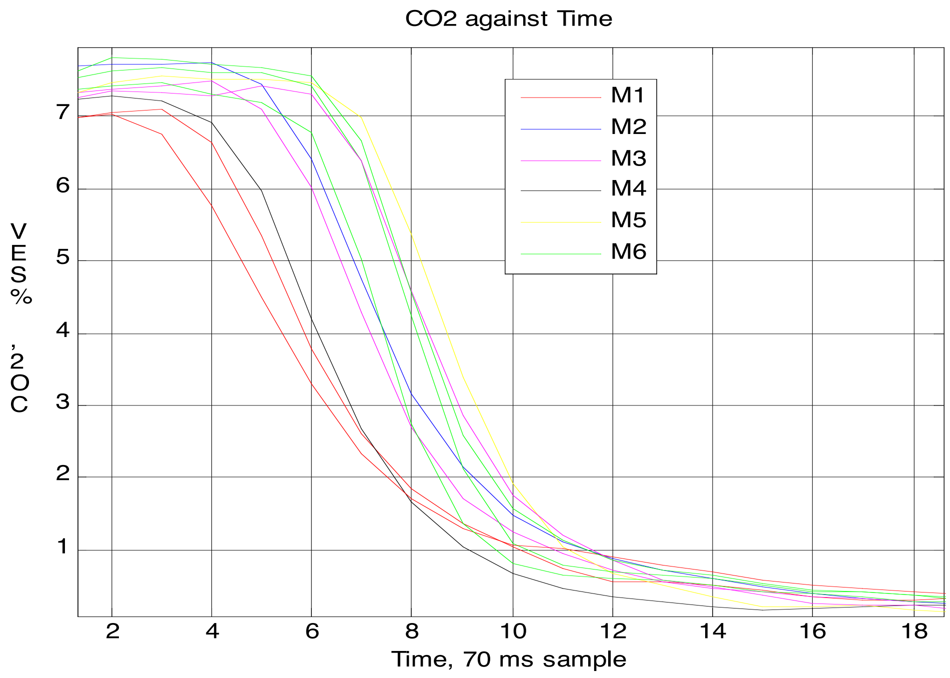


Figure 10-1. Effect of each configuration on the inhale cycle seen by the diver. Lower plot is a zoom into the upper plot to show the inhale cycle.



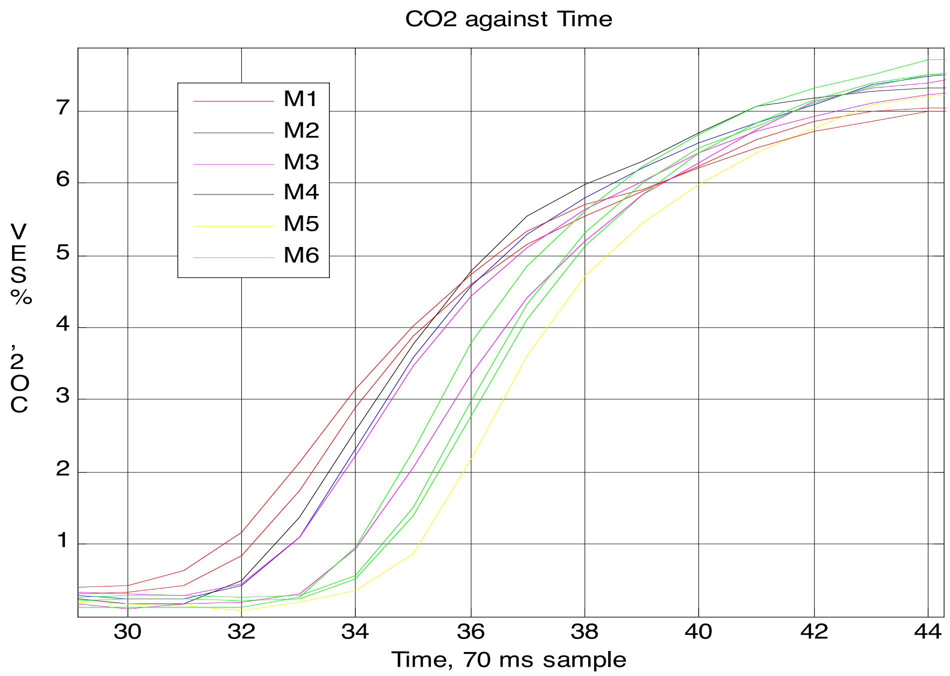


Figure 10-2. Effect of each configuration on the inhale and exhale rise and fall times.

10.3. Effect of valve configuration on CO2 waveform at inhale valve

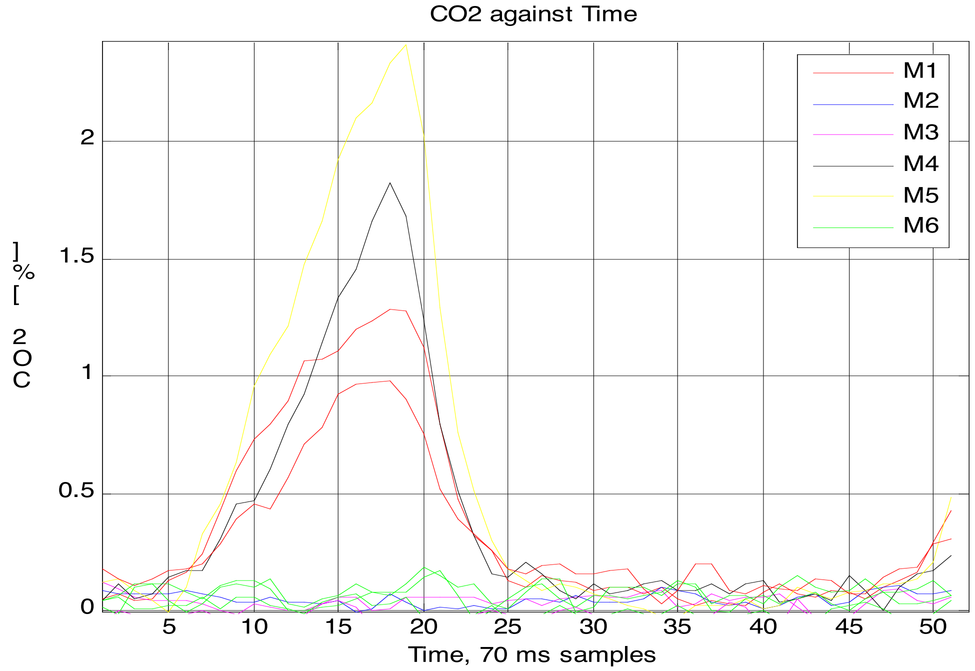
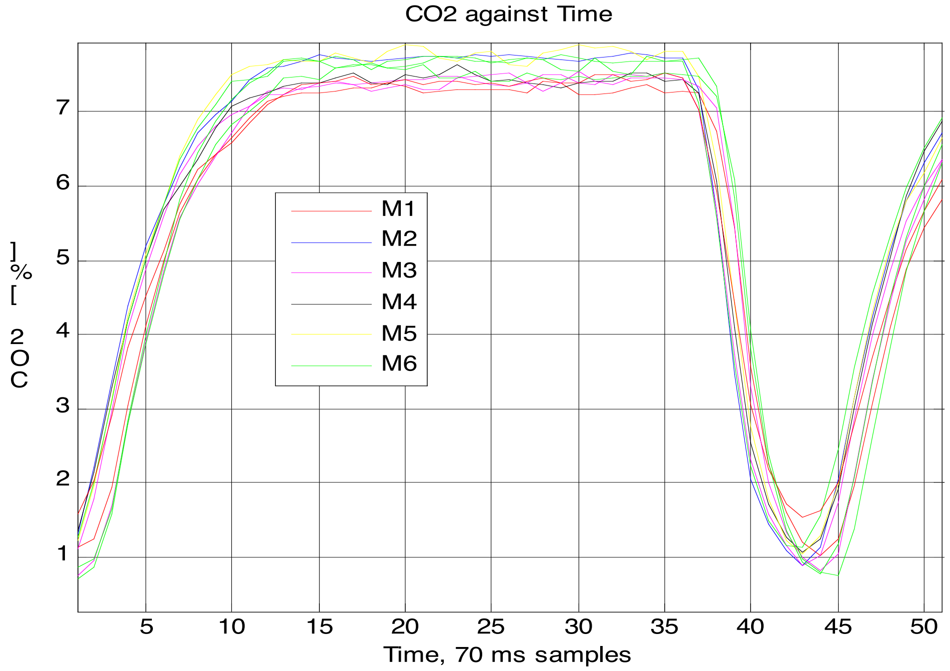
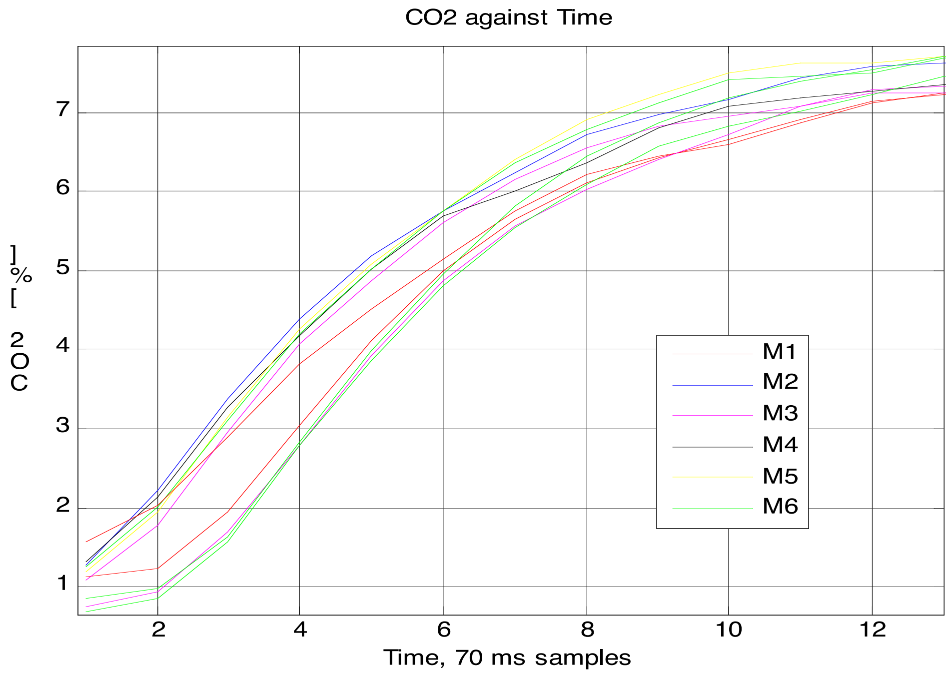


Figure 10-3.. The turbulent fault mode is very apparent in this plot. Valve configurations M1, M4 and M5 result in large amounts of exhaled CO_2 passing to the sampling point upstream of the inhale valve. These figures can be compared to the VWAI CO_2: the combination M1 corresponds to the VWAI CO_2, but the configurations M4 and M5 are even higher because gas is leaking back through the exhale valve into the mouthpiece, and then to the sampling point.

There were two tests of the 1st structure, one of the 2nd , two – 3rd, one - 4th , one – 5th, three of the 6th structure (structures numbered M1 to M6 respectively), hence there are multiple curves in the same colour revealing the range of results in the above figure, and in appropriate plots overleaf.

10.4. Effect of valve configuration on CO2 waveform at exhale valve





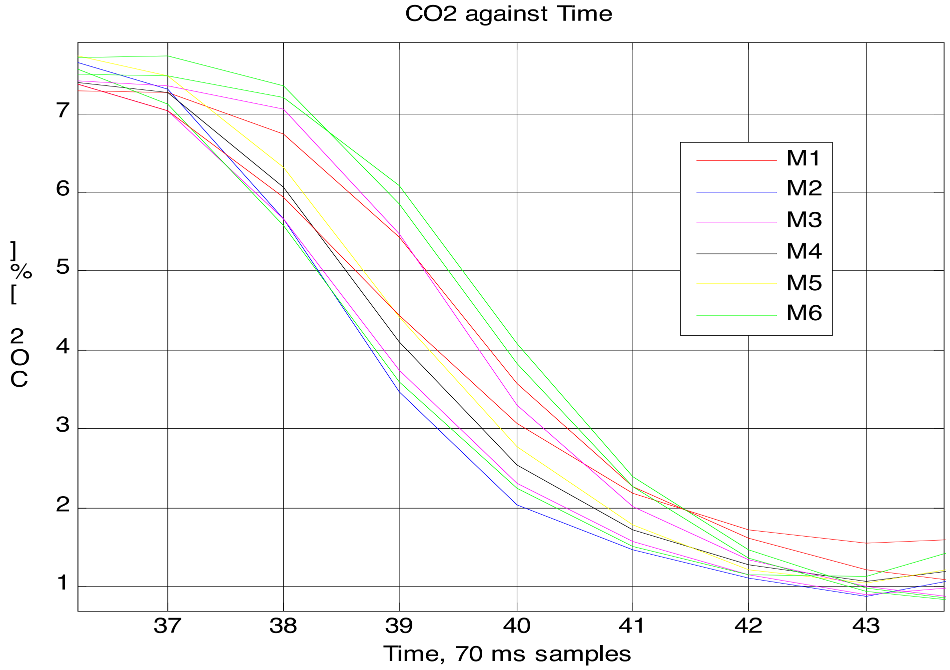


Figure 10-4.. EXL CO2 against Time and ALBOVE structure

It can be seen from the above plots, that the fault mode is represented as a small change in the dead space (i.e. the time constant with which CO2 falls during inhale is longer for valves with bypass, as would be expected), but cannot be detected reliably by observing the CO2 levels immediately downstream of the exhale valve. This is due to partially due to the effect whereby the CO2 molecules are so much heavier than the helium atoms, that the peak CO2 can be actually higher downstream of the valve than it is in the mouthpiece. This is due to the exhale valve acting as a peak follower, then after the peak there is a separation of the two gases. CO2 can separate from Helium very rapidly under some conditions.

When the peak to peak CO2 flow is fixed, then there is a difference in the VWAE CO2. This becomes manifest as a peak end of exhale CO2 reading, using the method employed by Deep Life for deriving this value (from VWAE CO2 and a tidal volume correction).

10.5. Effect of the flow diverters on the Mouthpiece CO2 Dead Volume

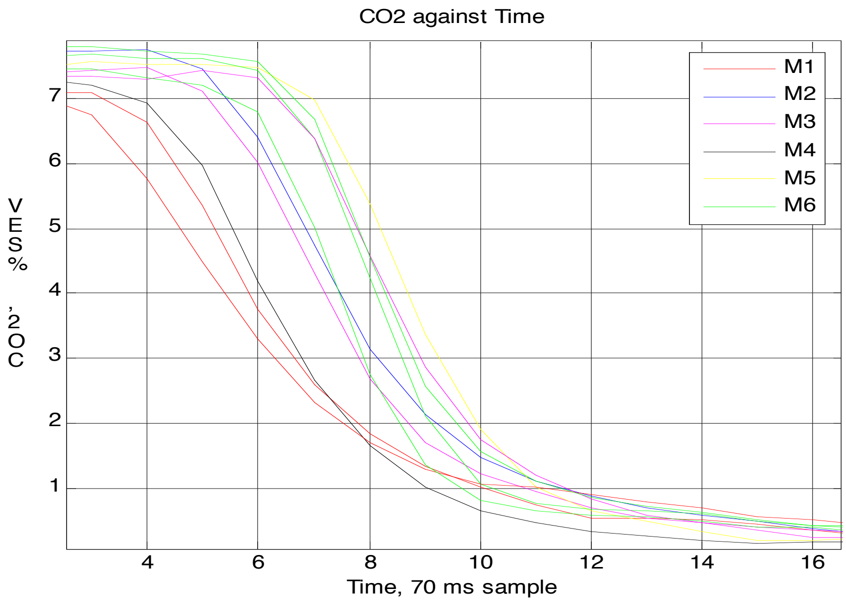


Figure 10-5.. Mouth CO2 against Time. The tests M2 and M3 have the flow diverters removed, all other tests have them fitted. The effect of the flow diverters on dead volume is visible as a slower fall time on the inhaled CO2 at the start of the inhale cycle. The differences in the curves are due wholly to the turbulent leakage in the different configurations. M6 is the standard production ALVBOV.

11. CONCLUSIONS

1. There is a potentially serious fault mode with soft pliable flapper type valves in rebreathers, where turbulence can result in back flow through the valves, increasing the VWAI CO2 breathed by the diver. The magnitude can be very large on some aged valves and some designs from new.
2. The risk of the fault increases with gas density (depth or gas mixture), and at higher RMVs. The risk also increases with low breathing resistance scrubbers and rebreather loops.
3. Very small changes in the flapper valves, similar to those that occur naturally through contamination, moisture, and ageing, can result in large changes in CO2 leakage, increasing VWAI CO2.
4. The configuration M6 seems to be free of the fault, as are other configurations found during separate testing. Umbrella valves are better than mushroom or disk valves in this regard.
5. During ALVBOV design type testing, the worst case configuration was M1 for CO2 measurement, such as scrubber endurance and VWAI CO2. Worse results were seen from some contemporary DSV/BOV designs.
6. There is no observed effect on WOB or breathing resistance from changing from pretensioned mushroom valves to lower tension umbrella valves, though theoretically if very stiff valves were used, there would be an effect: those valves would be outside the range tested here.

7. The use of worst case configurations can result in scrubber endurance tests measuring VWAI CO2 instead of end of inhale CO2, if the measurement is made immediately upstream of the inhale valve.

8. Longer term, it is recommended that soft pliable flapper valves be abandonded in diving rebreather designs, in favour of rigid valves. The rigid one-way valves such as those such as used on the KAMPO IDA rebreathers, from 1950 to 1995, other than for a few models such from 1972 that used a soft valve for shallow diving, appear not to be able to have this fault mode from a fundamental mechanical theory viewpoint.

9. Special care must be taken to ensure the correct phase for VWAI CO2 tests, with respect to the respiratory cycle: it is not possible to use the half cycle that gives the minimum VWAI CO2. It is essential to ensure the breathing simulator dead space is properly calibrated.

10. The Deep Life CO2 monitor does track this fault, but the magnitude of the effect is low. In bad cases, there may be a 2% SEV increase from this fault, which will mean that a rest peak end of exhale CO2 will be 6% SEV instead of 4%. Once the diver then works, such that the end of exhale CO2 is 6% SEV, then this will trigger the alarm limits. This correct function is seen on the examples tested.