Testing for Re-Inspired Carbon Dioxide

By Michael F. Ward

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TABLE OF CONTENTS

SECTION ONE

SECTION TWO

GLOSSARY OF ABBREVIATIONS

ALPM	Actual Liters Per Minute
ATA	Atmospheres Absolute - 1 ATA=14.7 psig
BAR	Bar - one bar = 14.5 psig
BPM	Breaths Per Minute
CE	Symbol for European Conformance
ET	End Tidal - the end of exhalation where gas flow stops
ET CO2	End Tidal Carbon Dioxide **-** The level of CO2 in exhaled gas at the very end of exhalation
EU	EuropeanUnion
	KPA Kilopascals
FSW	Feet Sea Water
J/L	Joules Per Liter
LPM	Liters Per Minute
MBR	MILLIBARS - pressure measurement often used for atmospheric pressure readings and partial pressure reading of gases within a mixture of gases
MSW	Meter Sea Water
PSI	Pounds Per Square Inch
PSIG	Pounds Per Square Inch Gauge
RMV	Respiratory Minute Volume - the volume of gas moved in and out of the lungs in one minute. Volume in liters multiplied by the number of breaths per minute equals the RMV
SEV	Surface Equivalent Value
SLPM	Standard Liters Per Minute
WOB	Work Of Breathing - measurement of breathing effort

1.0 MEASURING RE-INSPIRED CO2 CONCEPT

The definition of re-inspired Carbon Dioxide (CO2) is simply the physical volume of re-inhaled CO2 after exhaling. This is also often referred to as breath-by-breath washout. As a person exhales, the typical measured CO2 at the very end of the exhalation will be in the range of approximately 4.5-4.8% CO2. When breathing any type of device such as a respirator, dust mask, full-face masks or anything that adds physical volume around the mouth and nose area, will result in an increase of CO2, due to re-inhaling of the previously exhaled air which is rich in CO2. Examples of items that increase re-inspired CO2 are firefighting masks, diving full face masks, diving helmets, dust respirators and gas masks to name a few. The concept of measuring re-inspired CO2 is relatively simple, however making accurate measurements requires some very expensive and highly specialized equipment.

Dive Lab measures re-inspired CO2 based on our interpretation of the current standards. Dive Lab does not claim to be the authority on this subject, however we have been doing this type of testing for many years, and we do it regularly on diving helmets, full face masks and wide variety of breathing apparatus. We are always looking for ways to improve our equipment, techniques, and procedures. When testing equipment to standards or requirements, the testing is done in accordance with the standard being used. In some cases, Dive Lab also performs tests that are not in accordance with specific standards, this is done to draw a parallel with established test standards and procedures. It must be noted that Dive Lab is not qualified to establish standards or policies. Dive Lab primarily performes unmaned testing, and should not be considerd as man physiological test facility. Dive Lab testing is done to existing standards and requiremts.

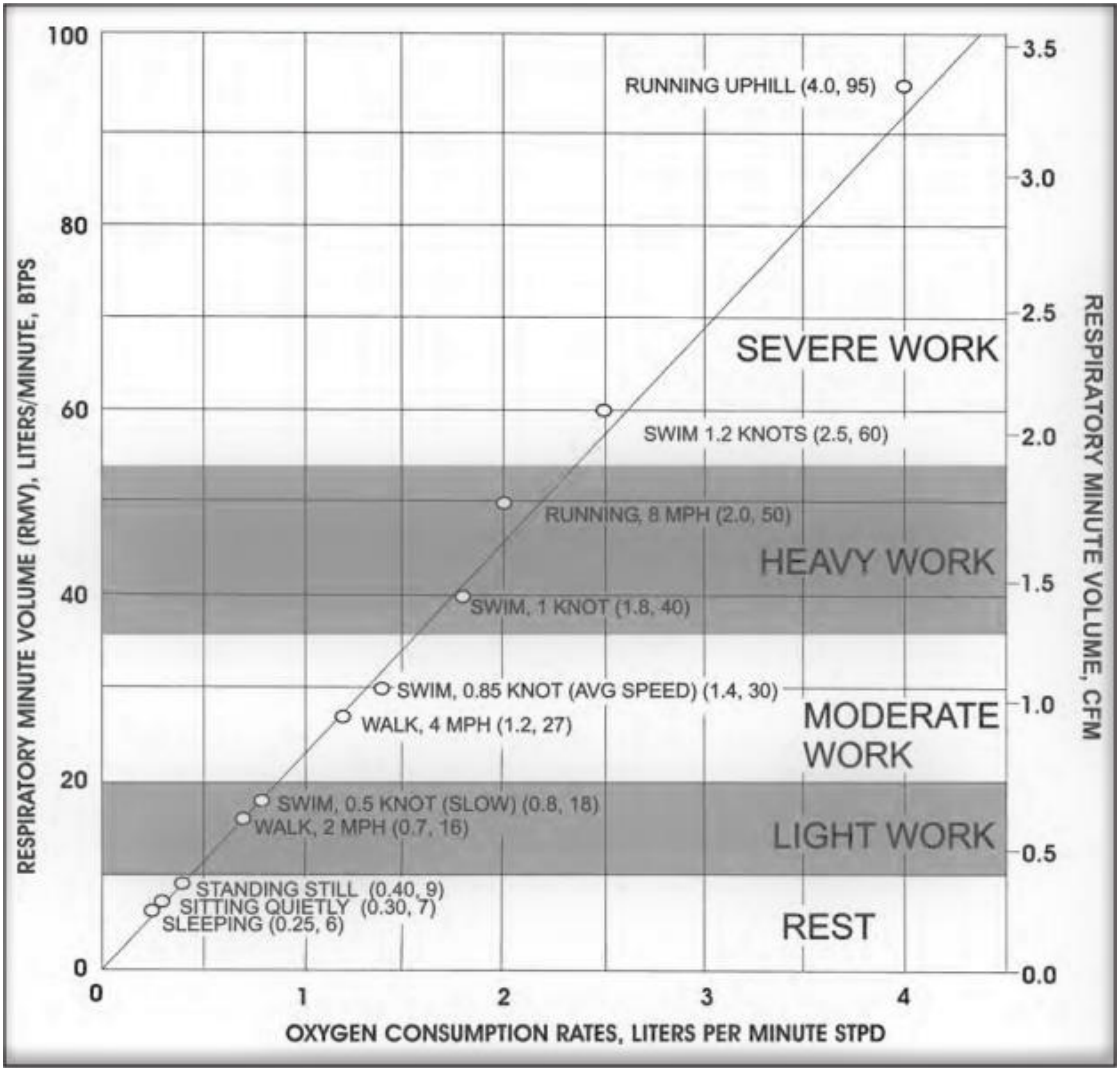
To accurately measure the amount of re-inspired CO2, it requires the use of a mechanical breathing simulator, high speed CO2 analyzer and a data acquisition system that can record, analyze, and store measurements. The CO2 analyzer and data recording system needs to process at least 1000 samples per second or greater, to 95% of the sample reading step change in 150 milliseconds or less. In addition, the mechanical breathing simulator system needs to be capable of accurately producing both tidal volumes (TV) and breaths per minute (BPM), that make up each test RMV. Measuring the CO2 content at surface conditions (1 ATA), is far easier than measuring at depth. Measuring at depth requires not only a fast analyzer system, but a good data acquisition system capable of displaying proper resolution and most important, proper scaling due to the partial pressure of CO2 at depth. Getting reliable, accurate dalta on re-inspired CO2 is generally limited to depths of 60 MSW (200 FSW) or less due to the analyzer, speed, accuracy, and scaling for depth.

1.1 BREATHING RATE/WORK RATE/RESPIRATORY MINUTE VOLUME (RMV)

Physiologist and professionals both Military and in private industry specializing in respiratory studies have developed standard breathing rate categories for different activities. The proper term for the breathing rate is respiratory minute volume (RMV). The U.S. Navy as well as others use several different RMV'S to evaluate diving helmets, full-face masks and other man worn breathing equipment. The blood CO2 level can be significantly affected by the type of the breathing apparatus used, so for the diver understanding how to use the equipment properly, to keep CO2 levels as low as possible is very important for the safety of the diver.

This article will focus on work rates established for diving equipment, and accepted test practices performed by those testing for CO2 which can differ from rates and procedures used for testing firefighting equipment or other equipment intended for use in non-hyperbaric environments. Here in the U.S., re-inspired CO2 limits are established by the department of Occupational Safety and Health Agency (OSHA). OSHA sets the maximum re-inspired CO2 partial pressure at 2% surface equivalent value (SEV). SEV CO2 is often also expressed as a Kilopascals (KPA) and / or Millibars (MBR). US Navy also uses a limit of 2% SEV. In Europe, there are CE harmonized standards that EU member countries use, which fall under personal protective equipment. For diving equipment such as SCUBA and full-face masks the standard is EN-250, for rebreathers EN-14143, and for surface supply diving helmets/full-face masks EN-15333. The EU SCUBA standard EN-250 states requires that any item such as a full-face mask, that has a volume greater 200 Milliliters requires testing for re-inspired CO2. Testing must be done at both the surface (1 ATA), as well as 164 FSW (50 MSW), at the resting rate of 10 RMV, and the extreme rate of 62.5 RMV. For 10 RMV the limit for re-inspired CO2 is 2% SEV, (2 KPA) 20 millibar (MBR) and for 62.5 RMV, the limit was cut in half, to 1% SEV,10 MBR, 1.0 KPA. The rational for the difference in allowable CO2 for 10 RMV and 62.5 RMV, is not explained. When the surface supplied diving standard EN-15333, as well as the rebreather standard EN-14143 was introduced, they required CO2 testing at four (4) RMV'S - 10, 22.5, 40, and 62.5 RMV. The CO2 limit was also set at 2% SEV at rates of 10 & 22.5 RMV but only 1% at rates of 40 & 62.5 RMV. The US Navy, and OSHA use the same re-inspired CO2 limit of 2% regardless of RMV. We believe It makes more sense to base the limit of reinspired CO2 on work rate, rather than just cutting it in half at rates greater than 22.5 RMV. There are many full-face masks or even dust respirators that cannot pass the 1% (10) mbr requirement when tested at the 40 RMV test rate.

Internationally there are several RMV's used as pertaining to diving equipment, typically ranging from 7.5 to 90 RMV. The U.S. Navy respiratory rates start at 10 RMV. 10 RMV is made up of a one 1-liter TV and 10 BPM, and represents a diver at rest. Light to moderate work is regarded as 22.5 RMV and is made up of a 1.5 TV and 15 BPM which represents a diver doing light work such as performing an inspection, photography, or a light rigging task. Next, is heavy work, 40 RMV. 40 RMV is made up of a 2-liter TV and 20 BPM. 40 RMV would be equivalent to swimming at one knot or running at 7 miles per hour. Next, the severe rate of 62.5 RMV this uses a 2.5-liter TV and 25 BPM. This rate can usually be maintained by very fit divers for 1-5 minutes. Finally, the extreme rates of 75 RMV (3.0 TV X 25 BPM) to 90 RMV (3.0 x 30), which is considered extreme work and generally cannot be maintained for more than 1 minute by most fit divers. Chart below is from U.S. Navy Dive Manual.


100
80
60
40
20
0
0
1
2
3
4
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
RESPIRATORY MINUTE VOLUME (RMV), LITERS/MINUTE, BTPS
RESPIRATORY MINUTE VOLUME, CFM
OXYGEN CONSUMPTION RATES, LITERS PER MINUTE STPD
RUNNING UPHILL (4.0, 95)
SEVERE WORK
SWIM 1.2 KNOTS (2.5, 60)
RUNNING, 8 MPH (2.0, 50)
HEAVY WORK
SWIM, 1 KNOT (1.8, 40)
SWIM, 0.85 KNOT (AVG SPEED) (1.4, 30)
WALK, 4 MPH (1.2, 27)
MODERATE WORK
SWIM, 0.5 KNOT (SLOW) (0.8, 18)
WALK, 2 MPH (0.7, 16)
LIGHT WORK
STANDING STILL (0.40, 9)
SITTING QUIETLY (0.30, 7)
SLEEPING (0.25, 6)
REST

1.2 PRIMARY FACTORS INFLUENCING RE-INSPIRED CO2

There are three primary factors that influence the amount re-inspired CO2. Physical Dead Space Volume, Gas Flow Path, and Breathing Resistance.

DEAD SPACE

Dead space is the physical volume of the item being breathed through. Probably the best example is a simple snorkel. With a snorkel the volume of air within the tube and mouthpiece is drawn into the lungs before any fresh air is delivered. However, should that snorkel be open to a full face mask the dead space volume can suddenly get very large. With a simple SCUBA regulator or snorkel, the physical volume is very small, (less than 200 ml) and generally the potential for significant re-inspired CO2 is minimal. However, if you take the same regulator or snorkel and attach it to a full-face mask with an oral nasal that does not seal well, exhalation gas may escape from the oral nasal mask to the interior space of the full-face mask or diving helmet. Full face masks and helmets that have large compliant volumes can produce an accordion or bellows effect, which can significantly affect the volume during inhalation and exhalation especially if the breathing resistance is high. Keep in mind, CO2 is 50% heavier than air and has a tendency to collect in the lower section of the mask/helmet, thus leading to increased re-inspired CO2.

GAS FLOW PATH

The gas flow path is simply how smooth, and how well the gas can move through and exchange within the space. Gas flow path is important because even though the actual dead space volume may be relatively small (if the gas swirls and eddies), the CO2 level can show a higher value.

BREATHING RESISTANCE

Breathing resistance and compliant volume are directly linked when using a Full-Face mask or Diving Helmet. As previously mentioned, if compliant volume is present - high inhalation and/or exhalation pressure will cause expansion and contraction of the physical breathable volume within the Helmet or Full-Face mask, due to the face seal or neck dam expansion and contraction. This volume change acts much like an accordion/bellows, and is especially true with Diving Helmets that have excessively large neck dams. Some Full-Face masks can also have significant compliance of the face seal. Keeping inhalation and exhalation effort as low as possible, helps reduce the compliant volume exchange effect.

2.0 BASIC TEST CONFIGURATION

Test Head Form - Dive Lab has several test heads of various sizes primarily for testing full face masks with various size mask skirts. When testing diving helmets the fit of the oral nasal mask is obtained by varying the head cushion padding, in the same manner the person would do. Testing of full-face masks can be the most challenging due to leakage around the oral nasal mask. In many cases the oral mask is often a one size fits all, therefore when testing a full-face mask or a diving helmet, the measured re-inspired CO2 will probably always be slightly than that of an actual person, because the test head mouth does not have lips and flesh, which takes up volume and reduces dead space. It is estimated a human face planted comfortably in the oral nasal mask, could account for up to 25% less volume than a rigid test head, due to the reduced volume created by of lips and better seal against facial flesh. When EN250 was being developed back in the 1990's, they used the test head form from the UK Ministry of Defence. Testing at that time was based on 2% SEV CO2, in which previous testing of full face masks and helmets showed that <u>most passed</u> even though the physical dead space due to lacking soft flesh and lips. Later on in the 1990's the Co2 limit for work rate above 22.5 was cut in half resulting in 1.0 % SEV (10 mbr) limit.

2.1 CO2 SAMPLING

During testing, sampling is done at the center of mouth, 3-4 mm inward from the leading edge. For surface testing, at very shallow depths, we use a single sample catheter having an inside diameter of 0.050", approximately 2.0 meters long. The sample is drawn into the sample cell of the CO2 analyzer, using a high-speed vacuum pump. For testing to depths of 30 to 60 MSW, we use two different size catheters joined together. A 0.050 for surface and shallower (<10 msw), and a 0.010 ID sample line from the test head through the top the test chamber, which is approximately one meter long to the top of the chamber lid. At the top of the test chamber the 0.010 sample line mates to the 0.050 surface catheter, which delivers the sample to the analyzer. This set up is critical in order to get a good solid sample wave form when testing at depth. The gas sample traveling from the test mannequin head to the special interface fitting at the lid of the chamber is under pressure, so it travels slightly quicker than using the 0.050 catheter tube used for surface testing. The special fitting has a vent port which allows excess pressure to escape, thus allowing the vacuum pump to maintain a steady and uniform sample draw. The sample delay time of the two catheters is adjusted by trimming back the 0.050 catheter 1 inch at a time, until the delay time of the start of inhalation matches that of the surface head only tests. This configuration has shown to be extremely accurate and repeatable, works well with Dive Labs ANSTI test system, because the CO2 analyzer and sample system is located next to the top of the test chamber, (<1.5 meter). The longer the sample catheter, the greater the possibly that mixing will occur. Sample tubing line of more than 3 meters in length can become distorted due to sample gas mixing in route to the analyzer. The longer the sample line, the greater the gas mixing and possible reduction in accuracy.

2.1 CO2 SAMPLING - continued

Sample Catherder

Sample Point

2.2 SYSTEM CALIBRATION

Accurate calibration of the CO2 analyzer is critical. After analyzer calibration is complete, then the test head alone with each of the test RMV's and CO2 flow rates is done, as well as the CE test tube check. Once this is complete, the flow and sample delay numbers will be used to test the item being tested. In general, the test head alone, will show a re-inspired CO2 value of between 0.80 to 1.4 MBR, depending on the RMV. Normally at a breathing rate of 10 RMV with the head alone, the CO2 value will be highest, because the velocity of the breathing gas is very low. As the RMV increases the re-inspired CO2 value will drop, due to the velocity of the sample at the mouth of the test head, variation in room temperature and/or the number of people in the room, can affect background CO2 levels. The 0.80-1.4 MBR re-inspired CO2 is considered the starting point for the head alone. This value represents the atmospheric background CO2 combined with the small residual CO2 in front of the head. On average, the typical background CO2 in air at 1 ATA is 0.04% (400 PPM), add to this the small amount exhaled by the test head only, and you will be about 0.080 - 0.140 percent CO2, which if expressed as MBR, would be 0.80 – 1.40 MBR. European (CE) testing also requires a check using a calibration tube having a volume of 110 milliliters. With this check 2.5 alpm CO2 is injected while breathing at 62.5 RMV . If everything is correct, this test will result in an end tidal (ET) reading of 4.0 - 4.2 MBR. This tube check is just a simple test, to show that the test system is working properly.

Going from testing the head alone, to anything that adds space around the oral nasal cavity such as a full-face mask, diving rebreather dive surface valve (DSV), diving helmet, or even just a plain dust mask, the re-inspired volume of CO2 will always be substantially higher than the head alone. Normally, items such as a SCUBA regulator, simple snorkel or rebreather DSV with a floodable volume of less than 200 milliliters, will show low levels well within the European CE standards requirements.

2.3 CO2 EXPRESSION

The data test sheets Dive Lab produces during re-inspired CO2 testing shows the CO2 in millibar (MBR), as partial pressure measurement. The measurement can also be expressed as "Percent PCO2" by simply moving the decimal point *two places* to the left, or as KPA by moving the decimal point *one place* to the left. The Dive Lab data sheets are scaled based on the depth of the testing.

2.4 CO2 INJECTION

U.S. Navy testing of full-face masks and equipment for re-inspired CO2 injects CO2 into the system based on 4% of the test ventilation rate. The E.U. CE testing bases the injection rate on what is required to achieve a steady 5% end tidal value (E.T.) for each RMV test rate. Using a straight 5% E.T. results in a slightly higher than actual average E.T. CO2 value as compared to that of a healthy human, which has an end tidal CO2 between 4.6% to 4.8%. However, it must be noted that these methods are intended to give worst case for any given RMV based on the assumption that for every liter of oxygen consumed, 0.90 liters of CO2 is produced. The actual number may be as low 0.75 liters of CO2 produced for each liter of oxygen consumed. For this reason it is understandable why there can be disparity in how much CO2 the average human produces, and what value is used for test purposes. With a breathing simulator system when measuring the re-inspired CO2 in diving masks and helmets. The E.U. standards are intended to error against the equipment being tested by using a slightly higher % to the ultimate benefit of the user, which makes the testing more conservative than using the U.S. Navy system of 4% ventilation.

2.5 STABILIZING END TIDAL

During testing, Dive Lab injects CO2 into the breathing simulator just after the test head one-way valve on the suction side of the breathing simulator. The CO2 is injected into the breathing simulator via a six-foot long 1.125" I.D. suction hose. The amount of time required for the end tidal CO2 to stabilize is dependent on the respiratory rate. At the low rate of 10 RMV it can take 5 to 8 minutes to fully stabilize depending on the overall volume of the item being tested. The greater the RMV test rate, the faster the system stabilizes. At high work rates of 40 RMV or greater, stabilization takes less than 2 minutes. Using the 4% of ventilation as a starting point, then adjusting the CO2 mass flow controller until the end tidal CO2 reading at the mouth is steady at 5%. This is what Dive Lab uses when testing to the EU standards involving diving apparatus. During testing, once the end tidal has stabilized the computer records & averages at least 5 consecutive loops and then prints out two print out sheets. One printout represents the breathing volume, the other time. The time loop is used to adjust for the sample delay time during calibration between the sample at the mouth and the time it takes to get a peak reading at the sample cell of the analyzer. Example of these are shown further on.

2.6 SAMPLE DELAY

A vacuum pump within the CO2 analyzer draws a suction on the sample line from the sample point at the test head mouth, to the sample cell within the CO2 analyzer. The sample delay time is simply the time it takes for the gas to travel from the test head mouth, through the sample tube to the analyzer sample cell to give a reading. The sample delay is then coordinated with the breathing machine/breathing pressure loop, so that the start point of inhalation can be determined. The start of inhalation is determined by adding or subtracting time in milliseconds until the timeline lines up with the start of inhalation on the test loop.

NOTE: At Dive Lab, the determination of the delay is done starting at the at the highest ventilation rate first, and that delay time is then used for all the other RMV test rates. We do it this way because at the higher ventilation rates, the sample travels faster (20-30 ms), due to slight pressurization from the breathing machine velocity. The head alone is tested at each RMV, see test loops pages 12 through 15 which show the head alone and then with the 110 milliliter CE test tube.

2.7 UNDERSTANDING THE TEST LOOP

The test sheets shown on page 13, marked A1 shows the wave form for the test head only, for 10 RMV on the surface at 1 ATA. With Dive Labs ANSTI system, the wave form moves clockwise. At the top right of the test loop is where exhalation stops, and inhalation starts, this loop shows the test stroke. The- loop is then expanded using a second printout. "A2" on page 12 shows "time", so that the sample delay can be determined. The shaded area as marked between the timeline 3, to approximately 3.65 represents the re-inspired CO_2 Volume of the test head alone. For this low breathing rate (10 RMV), the re-inspired CO_2 was 1.40 MBR. Test sheet B1 is an example of the the test head re-inspired CO_2 when the head is equipped with a 110 ml CE test tube and injecting for 2.5 ALPM CO_2. Note: At the very low breathing rates of 15 RMV or less, the gas is traveling so slow, that the head alone CO_2 will often show slightly higher re-inspired CO_2 than that of moderate to heavy work rates, where the gas is moving at much higher velocities, allowing for a more consistent test loop. At 40 RMV with the head only, we generally see re-inspired values of less than 1 MBR. At 10 RMV, 1.0 to 1.40 is normal.

Continue to next page..

Carbon Dioxide & Diving Apparatus

ANSTI TEST SYSTEMS - Dive Lab

File	LSTF-0615_20191226_144755.co2m
Date: 12/26/2019	Time: 2:47:55 PM
Run Time (s)	30.028
Equipment	
Serial Number	CEW TUBE CHECK
Room Temperature (C)	20
Water Temperature (C)	19C
Depth (msw)	0
Tidal Volume (l)	1.00
Breathing rate (BPM)	9.99
Ventilation (l/min)	9.96
Remarks	HEAD ONLY BROOKS 358

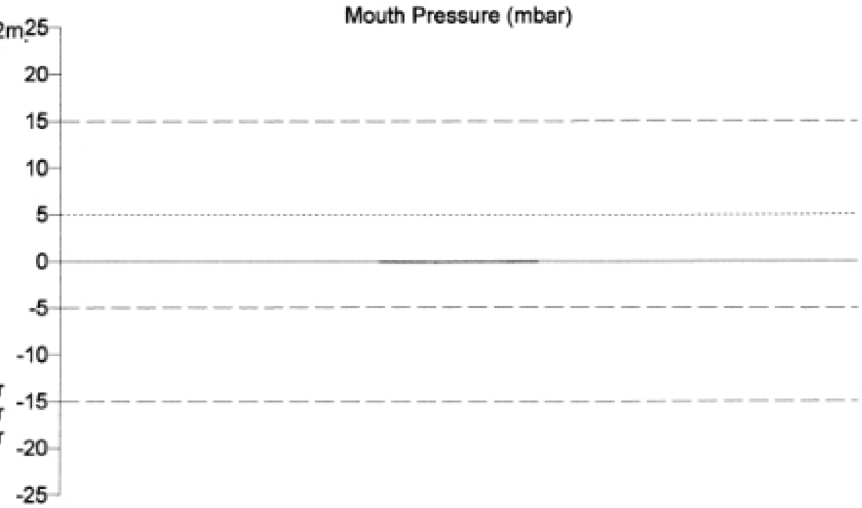
Mouth Pressure Results (5 loops)

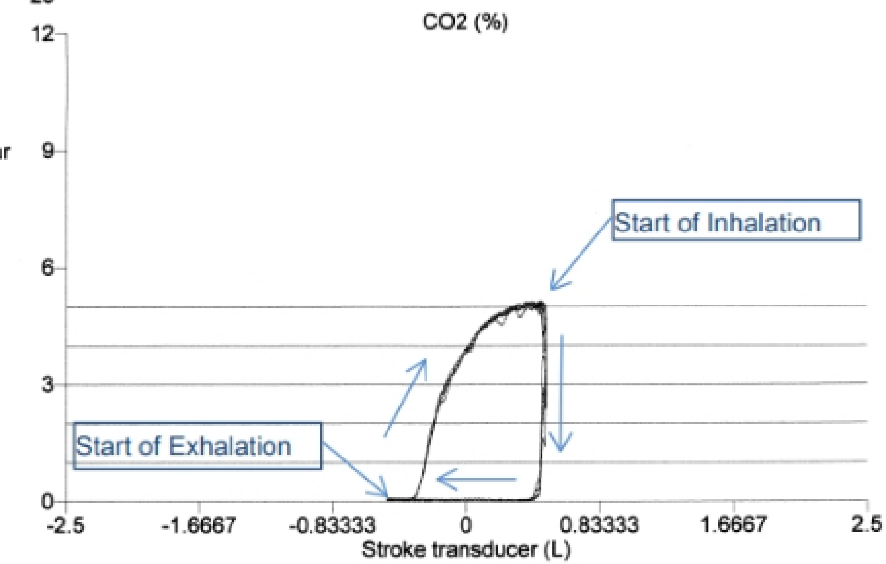
	Mean	Min	Max
Inhale Pressure	0.11 mbar	0.10 mbar	0.13 mbar
Inhale Pos Pressure	0.00 mbar	0.00 mbar	0.00 mbar
Exhale Pressure	0.09 mbar	0.08 mbar	0.10 mbar
Ext Work of Breathing	0.01 J/l	0.01 J/l	0.01 J/l
Ext Inhale Work	0.01 J/l	0.01 J/l	0.01 J/l
Pos Inhale Work	0.00 J/l	0.00 J/l	0.00 J/l
Pos Exhale Work	0.00 J/l	0.00 J/l	0.00 J/l

CO2 (%) Results (5 loops)

	Mean	Min	Max
Offset Time	660 ms		
VWA PCO2	1.40 mbar	1.05 mbar	1.77 mbar
Equivalent Deadspace at 5% CO2	27.63 ml	20.59 ml	34.76 ml
Time average CO2	0.36 %	0.27 %	0.44 %

Head Only 10 RMV





A1

CARBON DIOXIDE & DIVING APPARATUS

ANSTI TEST SYSTEMS - Dive Lab

File	LSTF-0615_20191226_144755.co2m
Date: 12/26/2019	Time: 2:47:55 PM
Run Time (s)	30.028
Equipment	
Serial Number	CEW TUBE CHECK
Room Temperature (C)	20
Water Temperature (C)	19C
Depth (msw)	0
Tidal Volume (l)	1.00
Breathing rate (BPM)	9.99
Ventilation (l/min)	9.96
Remarks	HEAD ONLY BROOKS 358

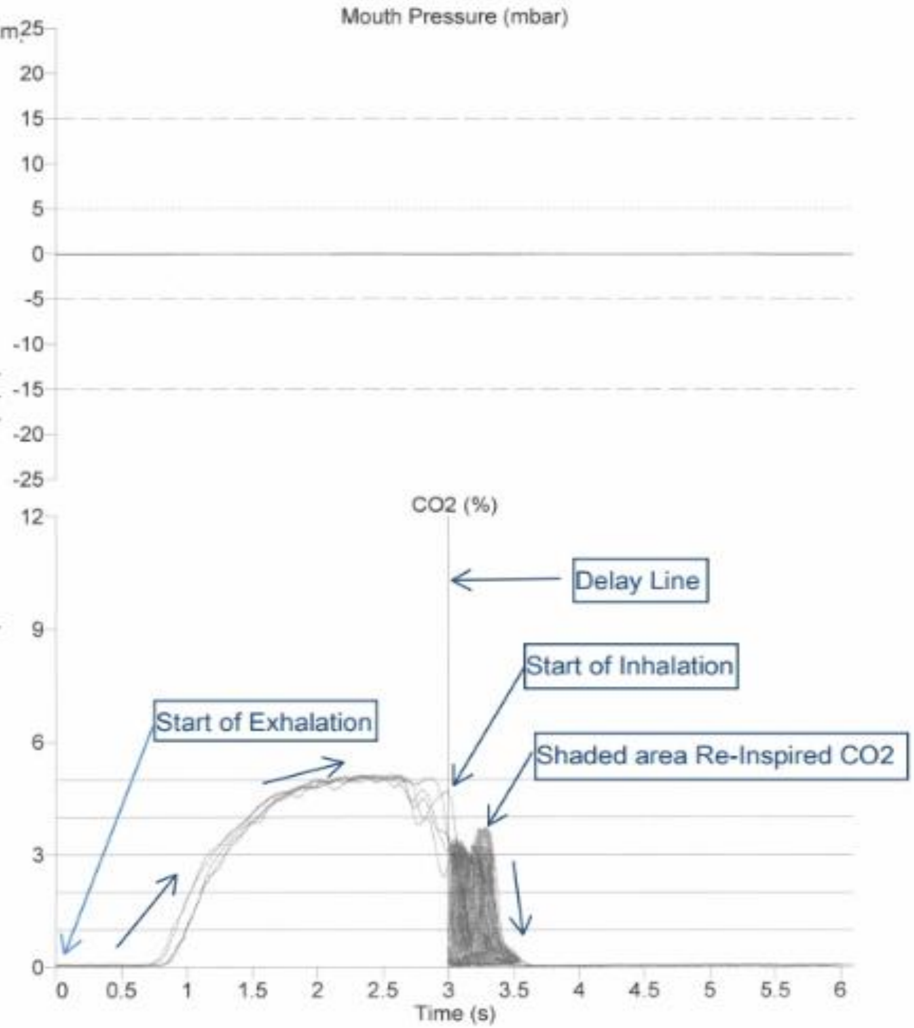
Mouth Pressure Results (5 loops)

	Mean	Min	Max
Inhale Pressure	0.11 mbar	0.10 mbar	0.13 mbar
Inhale Pos Pressure	0.00 mbar	0.00 mbar	0.00 mbar
Exhale Pressure	0.09 mbar	0.08 mbar	0.10 mbar
Ext Work of Breathing	0.01 J/l	0.01 J/l	0.01 J/l
Ext Inhale Work	0.01 J/l	0.01 J/l	0.01 J/l
Pos Inhale Work	0.00 J/l	0.00 J/l	0.00 J/l
Pos Exhale Work	0.00 J/l	0.00 J/l	0.00 J/l

CO2 (%) Results (5 loops)

	Mean	Min	Max
Offset Time	660 ms		
VWA PCO2	1.40 mbar	1.05 mbar	1.77 mbar
Equivalent Deadspace at 5% CO2	27.63 ml	20.59 ml	34.76 ml
Time average CO2	0.36 %	0.27 %	0.44 %

Head Only 10 RMV



A2

ANSTI TEST SYSTEMS - Dive Lab

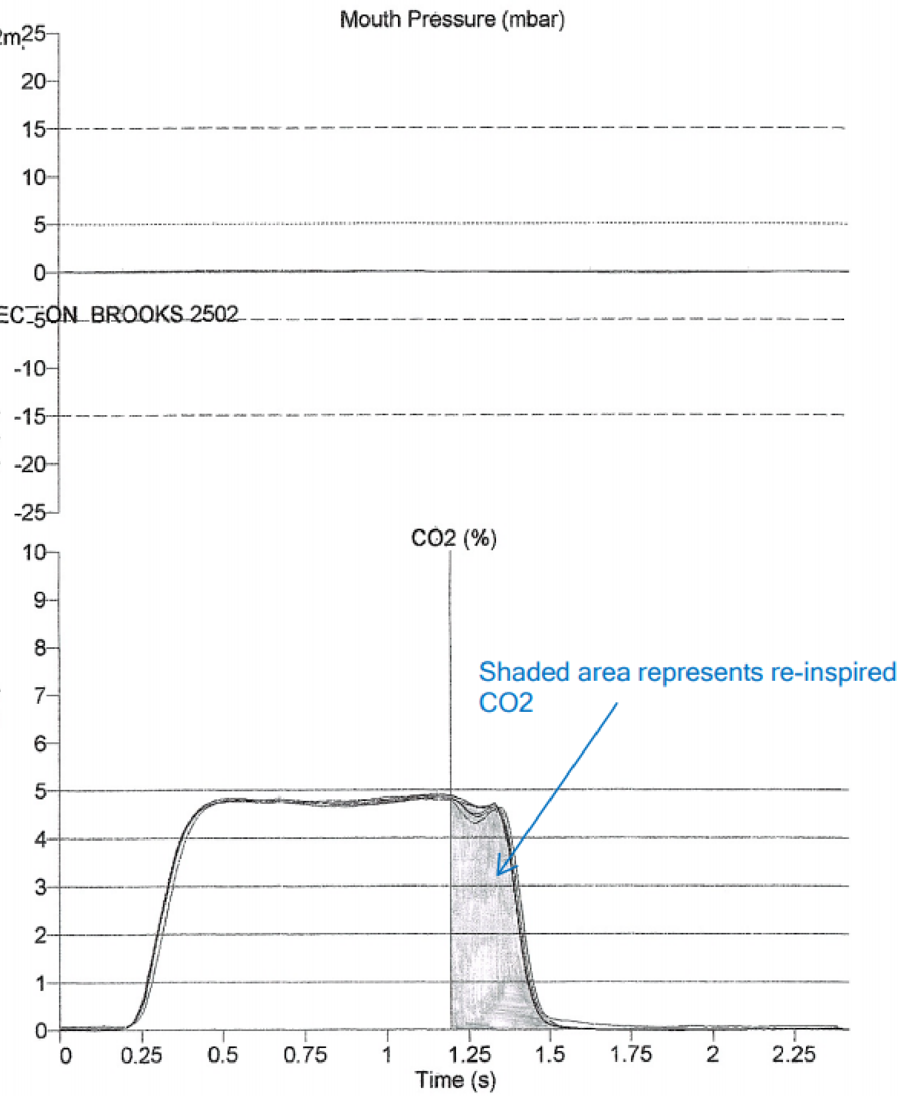
File	LSTF-0615_20220707_065109.co2m
Date: 7/7/2022	Time: 6:51:09 AM
Run Time (s)	14.387
Equipment	
Serial Number	SNORKLE MASKS
Room Temperature (C)	20
Water Temperature (C)	4
Depth (msw)	0
Tidal Volume (l)	2.50
Breathing rate (BPM)	25.02
Ventilation (l/min)	62.52
Remarks	HEAD AND CE TUBE 2.5 LPM INJECTION BROOKS 2502

Mouth Pressure Results (6 loops)

	Mean	Min	Max
Inhale Pressure	0.14 mbar	0.13 mbar	0.15 mbar
Inhale Pos Pressure	0.05 mbar	0.05 mbar	0.05 mbar
Exhale Pressure	0.14 mbar	0.14 mbar	0.16 mbar
Ext Work of Breathing	0.02 J/l	0.02 J/l	0.02 J/l
Ext Inhale Work	0.01 J/l	0.01 J/l	0.01 J/l
Pos Inhale Work	0.00 J/l	0.00 J/l	0.00 J/l
Pos Exhale Work	0.01 J/l	0.01 J/l	0.01 J/l

CO2 (%) Results (6 loops)

	Mean	Min	Max
Offset Time	480 ms		
VWA PCO2	4.02 mbar	3.81 mbar	4.49 mbar
Equivalent Deadspace at 5% CO2	198.39 ml	187.83 ml	221.45 ml
Time average CO2	0.84 %	0.81 %	0.89 %



Head & CE Tube

B1

CARBON DIOXIDE & DIVING APPARATUS

ANSTI TEST SYSTEMS - Dive Lab

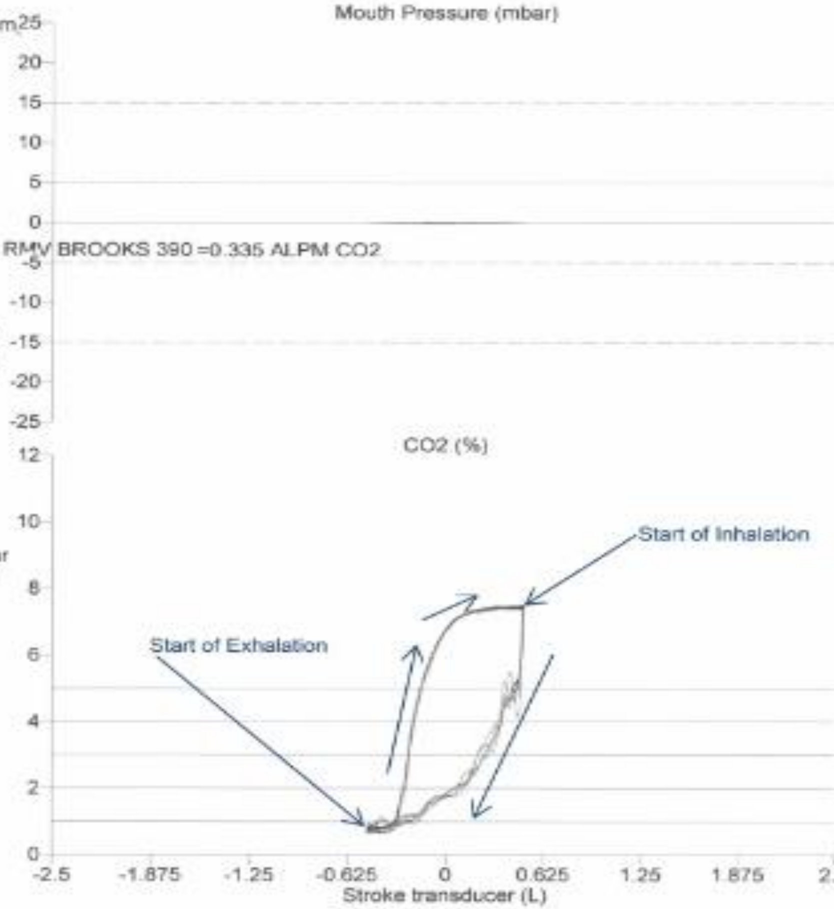
File	LSTF-0615_20200223_134914.co2m
Date: 2/23/2020	Time: 1:49:14 PM
Run Time (s)	30.035
Equipment	
Serial Number	CO2 BASE LINE
Room Temperature (C)	20
Water Temperature (C)	19C
Depth (msw)	0
Tidal Volume (l)	1.00
Breathing rate (BPM)	9.99
Ventilation (l/min)	9.97
Remarks	3 M MODEL 5200 DUST MASK 10 RMV BROOKS 390 =0.335 ALPM CO2

Mouth Pressure Results (5 loops)

	Mean	Min	Max
Inhale Pressure	0.13 mbar	0.13 mbar	0.13 mbar
Inhale Pos Pressure	0.00 mbar	0.00 mbar	0.00 mbar
Exhale Pressure	0.08 mbar	0.08 mbar	0.08 mbar
Ext Work of Breathing	0.01 J/l	0.01 J/l	0.01 J/l
Ext Inhale Work	0.01 J/l	0.01 J/l	0.01 J/l
Pos Inhale Work	0.00 J/l	0.00 J/l	0.00 J/l
Pos Exhale Work	0.00 J/l	0.00 J/l	0.00 J/l

CO2 (%) Results (5 loops)

	Mean	Min	Max
Offset Time	650 ms		
VWA PCO2	22.80 mbar	22.54 mbar	23.14 mbar
Equivalent Deadspace at 5% CO2	449.14 ml	444.08 ml	455.74 ml
Time average CO2	2.56 %	2.47 %	2.63 %



3 M Model 5200 Dust Mask

C1

CARBON DIOXIDE & DIVING APPARATUS

ANSTI TEST SYSTEMS - Dive Lab

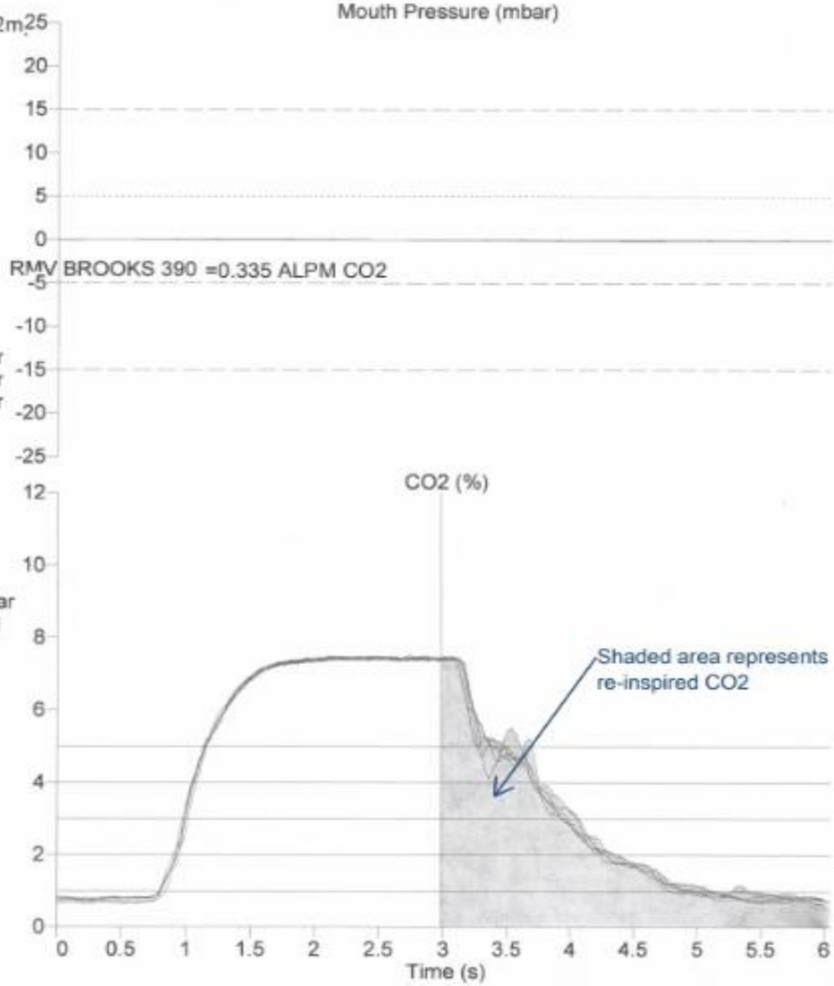
File	LSTF-0615_20200223_134914.co2m
Date: 2/23/2020	Time: 1:49:14 PM
Run Time (s)	30.035
Equipment	
Serial Number	CO2 BASE LINE
Room Temperature (C)	20
Water Temperature (C)	19C
Depth (msw)	0
Tidal Volume (l)	1.00
Breathing rate (BPM)	9.99
Ventilation (l/min)	9.97
Remarks	3 M MODEL 5200 DUST MASK 10 RMV BROOKS 390 =0.335 ALPM CO2

Mouth Pressure Results (5 loops)

	Mean	Min	Max
Inhale Pressure	0.13 mbar	0.13 mbar	0.13 mbar
Inhale Pos Pressure	0.00 mbar	0.00 mbar	0.00 mbar
Exhale Pressure	0.08 mbar	0.08 mbar	0.08 mbar
Ext Work of Breathing	0.01 J/l	0.01 J/l	0.01 J/l
Ext Inhale Work	0.01 J/l	0.01 J/l	0.01 J/l
Pos Inhale Work	0.00 J/l	0.00 J/l	0.00 J/l
Pos Exhale Work	0.00 J/l	0.00 J/l	0.00 J/l

CO2 (%) Results (5 loops)

	Mean	Min	Max
Offset Time	650 ms		
VWA PCO2	22.80 mbar	22.54 mbar	23.14 mbar
Equivalent Deadspace at 5% CO2	449.14 ml	444.08 ml	455.74 ml
Time average CO2	2.56 %	2.47 %	2.63 %



3 M Model 5200 Dust Mask

C2

2.9 EUROPEAN CE BREATH BY BREATH WASHOUT TESTING

The European standards do not give specific step by step written guidelines on exactly how re-inspired testing is to be done. The way Dive Lab has been testing re-inspired CO2 is based on what we understand the EU standards require. Basically, the standard requires breath by breath testing at the surface with the test head alone, and then the equipment. For SCUBA full face masks testing IAW EN-250 is done at 10, and 62.5 RMV at one ATA, and then repeated at a depth of 6 ATA, 50 MSW 165 fsw. If testing the same full-face mask for surface supply diving the test RMV changes and now requires testing also at 22.5, 40 as well as 62.5 RMV. Why? These test rates come from table 6, in EN 15333-1, there are other test rates as well, however it is not clear in the standard when the other rates need to be tested. The 5.7.3 states the CO2 shall not exceed 20 MBR when tested at 10 RMV, and shall not exceed 10 MBR when tested at an RMV of 40, and 62.5 according to table 6. EN-250 is used for testing SCUBA full face masks and it requires testing at only 10 RMV and 62.5 RMV, using the same 20, and 10 MBR limits. As mentioned before, it might make more sense to base the limit of reinspired CO2 on each individual work rate.
Below is the process for those capable of duplicating this type of testing.

STEP ONE - CO2 SYSTEM CALIBRATION CHECKS

Prior to testing, the CO2 system needs to be calibrated with the test head alone. A small fan set for a very light breeze is used to lightly blow at the side of the head to minimize CO2 collection around the face based on a flow of .2 ms. We start our test head base line at the highest RMV first (62.5), injecting CO2 based on the U.S. Navy 4% of RMV, and slowly adjust it until we have a steady 5% ET as required by the European CE standards. At this point, we then determine the time delay between the sample exiting the sample port at the mouth and being read in the sample cell of the analyzer. The delay is determined by adding or subtracting time in milliseconds from the start of inhalation. Once the delay is determined, we use it for each of the test RMV's which gives the delay for use with all the test RMV'S, starting at the highest RMV first and working to the lowest (62.5, 40, and 10). Each test RMV will have the same sample delay but a different injection rate. On average for 62.5 RMV we are injecting CO2 at approximately 2.85 ALPM, for 40 RMV-1.75 ALPM, for 22.5 RMV- 0.9 ALPM and for 10 RMV - 0.350 ALPM. The numbers may change slightly based on temperature barometric pressure and background CO2 however overall, they remain very close.

STEP TWO

Once the head CO2 calibration is complete, we document the CO2 injection flows from the mass flow controller for each test RMV, then we check and document the actual flow using a separate 0-5 lpm extremely accurate flow meter or Dive Lab's bubble system to verify the actual true flow corrected for temperature and pressure. Once this is done, these will be the actual flow rates used for testing the equipment.

STEP THREE - EQUIPMENT SURFACE TESTING

Next, we install the helmet, mask or equipment in the face forward position and ensure the system is sealed and secure, then we start breathing and CO2 injection. When testing at 10 RMV it can take as long as 5 to 8 minutes for the CO2 peak to settle. As the test RMV's increase, the time to stabilize decreases. At RMVS of 40 and 62.5 the loop will usually stabilize in less than two minutes. Once the CO2 loop has stabilized, record the data, and print out the loop using at least a 5-loop average. With many helmets and full-face masks, the CO2 will usually settle out with a peak between 6-8%. After printing the data, we then reduce the injection until the end tidal CO2 is once again peaking at 5% IAW the CE requirements. We then print the data again and if the test loop at 10 and 22.5 RMV is below 2% SEV, and bellow 1% SEV, at 40 and 62.5 RMV the equipment passes. It must be noted that most items can pass the 2% SEV requirement at 10 and 22.5 RMV however if they are above 15 MBR when tested at 10 or 22 RMV, very few will pass whan tested to the 1% SEV limit at the 40 and 62.5 RMV test rates. As mentioned before perhaps the limit should be based on the individual RMV.

CE UNWRITTEN PRACTICE

What is not in writing in the CE standards as far as re-inspired CO2 testing goes, or perhaps technically it is, but certainly not explained. The standard requires even though it does not specifically tell you to do it, it simply states test at 5% end tidal. This is done to represent the human bodies response to the increase in CO2. With most humans, the normal human response when the blood level CO2 rises is to increase the breathing rate, or decrease the level of exertion so the body can balance out the blood level CO2. So, to simulate this, those performing CE tests simply back off on the amount of CO2 being injected until as previous with the head only, the 5% ET line is reached, then the data is recorded, and this end tidal (ET) number is used as the final answer. However, there are doctors that will argue that some people are insensitive or tollarent to increased levels of CO2, until the level get high and causes serious problems.

PROBLEM!

There is a problem with backing off the CO2. Primarily because there is nothing written in the standards that actually explains the rational. Dive Lab has conducted tests on some equipment where the CO2 injection had to be reduced by over 50% or greater to get back to 5% end tidal. In essence, this would be the same as increasing the breathing rate 50%. As an example if at 40 RMV we had to cut back 50% on the amount of CO2 being injected to get back to to the 5% line, this would be the same as the diver having to increase ventilatory rate by 50%, which would then be 60 RMV. The question then becomes, is backing off the CO2 reasonable, and at what point does it become unreasonable.

We feel using the the 2% SEV limit like the US Navy, or using an establish limit for each RMV is the better approch. The second option for the EU testing would simply increase the breaths per minute to get the E.T. CO2 either back to the 5% E.T. line like that of a human, or simply below the limit of 10 or 20 MBR depending on RMV. However, this does not address the unreasonable 10 mbr limit at rates above 22.5 RMV. So basically at 10 RMV you would increase the breaths per minute until you get back to the 5% ET line. However, this needs to be done in a reasonable manner and there needs to be a limit as to how much you can increase the RMV. As an example, if we were testing a dust mask at 10 RMV and in initial testing it showed 22.80 MBR (2.28 % SEV), then we would slowly increase the breathing breaths per minute in hopes of coming in under the 20 MBR limit. At the 10 RMV original test RMV, even if we had to increase the RMV to 17 RMV (7 RMV increase), to get back down to the 5% ET line that would be a 70% increase in ventilation. Now comes the question, is it a reasonable to increase in RMV and is this something a user could do easily? It took a 7 RMV increase to get back to the 5% line, however it only required a 4 RMV (4 BPM) increase to get just under the 20 MBR limit. This means at a test rate of 10 RMV we may need to increase the BPM by 7 BPM which is a 70% increase. However, to get to the 20 mbr limit, it only required 4-one liter breaths resulting in a 40% increase. For 40 RMV, a maximum RMV increase of 15%, (6 bpm) and 62.5 RMV a maximum of 10% increase (6.25) = 69 RMV. The above is just a suggestion, understanding that as the test RMV breathing rate increases, the percentage of RMV to simulate the human response will decrease. Once again the most sensible choice is just to use a 20 mbr limit or determine the limit based on CO2 production for rmv. This would provide a reasonable and safe approch.

RESPIRATOR MASK EXAMPLE

Dive Lab tested a very popular high-performance respirator mask used for protecting industrial workers which has annual sales in the millions. The mask had a peak CO2 value of 7.8 MBR, and a re-inspired CO2 of 22.80 MBR, which is 2.8 MBR above the EU CE limit. We then increased the number of breaths per minute until the 5% ET line was reached which required a five breath per minute (5 BPM) increase, which lowered the CO2 from 22.8 to 14.78 MBR, well below the 20 MBR

CE limit. The 5 BPM increase was a 50% increase in RMV. We then did the same kind of test at 62.5 RMV resulting in a peak CO2 of 6% ET, and re-inspired CO2 value of 9.60 MBR just under the 1% SEV limit. Then to take it one step further, we increased the RMV to get back to 5% ET, it required an increase of 5 BPM, (70 RMV) to get to back to 5% ET, resulting in a re-inspired value of 8.65 MBR. The increase of 5 BPM represents an increase of 14 % in RMV. As a personal note, Dive Lab uses this very mask for respiratory protection, when doing fiberglas repairs, and no one has complained about CO2.

UNREASONABLE EXAMPLE

Another example, we tested a Full-Face Snorkel Mask at 10 RMV, and the re-inspired peak ET CO2 was 14 % with a re-inspired CO2 of 75.77 MBR, (7.57 % SEV), *extremely high but not uncommon*, for some of these types of masks. We then increased the breathing rate until we got back to 5% ET, which required going from 10 RMV to 25 RMV, a 150% RMV increase. And even though we got to 5%, the actual re-inspired CO2 still showed 27.27 MBR, which was still 7.27 MBR above the limit. Completely unreasonable. Next, we went back to 10 RMV, allowed the system to stabilize, then reduced the CO2 injection until the 5% ET line was reached. This required cutting the CO2 injection from 0.350 ALPM to 0.110 ALPM, which is a 75% reduction in CO2 to get back to the 5% line resulting in an ET CO2 value of 28.47 MBR. This clearly shows that decreasing the CO2 flow or increasing the RMV will accomplish the same thing, however, in this case the CO2 is so high, neither procedure would be reasonable. The problem with many of the various snorkel full face masks Dive Lab has tested is in many cases the exhaust valves did not seal, or in some cases were not present at all. We feel that the simplest way to emulate the human response to increased CO2 is to increase the ventilation rate.

TESTING AT DEPTH

After surface testing is done one ATA, we then connect the sample catheter combination for testing at depth and perform the testing again at 50 MSW (164 FSW). Prior to pressing to depth, we re-scale the computer CO2 analyzer for the test depth. At 164 FSW (50 MSW) we are at 6 ATA, therefore we are now looking for the surface SEV of 0.0833%. So we usually set the CO2 scale to 1.5 to 2% during the first test at depth, careful attention is paid to the start of inhalation, and the delay is carefully adjusted to be the same as during the surface testing at 1 ATA. The delay at depth is not adjusted using the computer, but by slowly trimming back the surface catheter so the start of inhale on the timeline matches that of the previous tests done on the surface. If the work of breathing has not changed significantly the re-inspired CO2 numbers will be be very close to those of the surface testing.

SUMMARY

It is very important that proper standardized procedures for measuring the re-inspired CO2 in man worn equipment be easily understood. We believe using 1% SEV limit for re-inspired CO2 is reasonable and feel that using the 2.0% SEV without bringing the CO2 back to 5% end tidal is a more accurate way to test. The 2% re-inspired limit has been in use since testing began and is very safe. At the very least, by doing it this way you could then also increase the BPM to identify what BPM increase is necessary to bring the ET back to 5%. Or to the 2% SEV limit.

The CE standards have done much to improve overall equipment and test procedures. There is always more that can be done especially with the advent of new technology and procedures. It is extremely important that manufactures know what to expect from their equipment and exactly how it should be tested. Notified bodies and those overseeing testing and certification must not only be knowledgeable but must constantly seek to improve the accuracy of the testing and test procedures. Dive Lab welcomes all comments, criticism and looks forward to moving forward. Feel free to email us at divelab@divelab.com Attention: Mike Ward.