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NAVY EXPERIMENTAL DIVING UNIT



TECHNICAL MANUAL NO. 15-01

U.S. NAVY UNMANNED TEST METHODS AND PERFORMANCE LIMITS
FOR UNDERWATER BREATHING APPARATUS

JUNE 2015

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WILLIAM A SCHULTZ
Commanding Officer, NEDU

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ACRONYMS

AMU	Authorized for Military Use
ATA	Atmospheres absolute
B/S	Breathing simulator
BPM	Breaths per minute
BTPS	Body temperature and pressure, saturated
°C	Degrees Celsius
CLM	Cowgill, Landstra, Mobley (verification orifice)
cm	Centimeters
cmH ₂ O	Centimeters of water pressure
CO ₂	Carbon dioxide
EDF	Experimental Diving Facility (NEDU unmanned test facility)
°F	Degrees Fahrenheit
f	Breathing frequency measured in breaths per minute (BPM)
fsw	Feet of seawater
ft	Feet
HeO ₂	Helium-oxygen gas mixture
HP	High pressure
ID	Inside diameter
in.	Inches
J/L	Joules per liter (unit of breathing effort, equivalent to 1 kPa)
kg·m/L	kilogram meters per liter of respired volume (old form for breathing effort; aka, work of breathing)
kPa	kiloPascal (unit of pressure or breathing effort = 1000 Pa)
L	Liters
L/min	Liters per minute
L·min ⁻¹	Liters per minute (scientific format)
L/sec	Liters per second
LP	Low pressure
LVDT	Linear variable differential transformer (displacement transducer)

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m	Meters
min	Minutes
mg/L	Milligrams per liter (water vapor content)
msw	Meters of seawater (a unit of pressure)
NAVSEA	Naval Sea Systems Command
NEDU	Navy Experimental Diving Unit
N.I.S.T.	National Institute of Science and Technology (formerly National Bureau of Standards)
O/B	Overbottom (pressure)
O/C	Open circuit
OD	Outside diameter
Pa	Pascal = (newton/meter ²)
PO ₂	Oxygen partial pressure
psi	Pounds per square inch
psid	Pounds per square inch differential
psig	Pounds per square inch gauge
PTC	Personnel transfer capsule
P-V	Pressure-volume
ΔP	Pressure differential
RE	Resistive effort, volume-averaged pressure, “work of breathing”
R	Gas exchange ratio; $R = \dot{V}CO_2 / \dot{V}O_2$
RMV	Respiratory minute volume; volume of breathing mixture exhaled by a diver in one minute (measured in L/min, BTPS)
resistive effort	Volume-averaged pressure (\bar{P}_V or RE), historically called work of breathing
scuba	Self-contained underwater breathing apparatus
% SEV	Percent surface equivalent volume
SLL	Static lung load
slpm	Standard liters per minute
STPD	Standard Temperature and Pressure (Dry)
suprasternal notch	An anatomical reference point for oral/nasal differential pressure
test mannequin	Semi-rigid polymer head sized to cover 93 rd percentile
UBA	Underwater breathing apparatus
USN	United States Navy

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\bar{P}_V	Volume averaged pressure (Resistive Effort)
lpm	Volumetric flow rate in liters per minute
$\dot{V}CO_2$	Metabolic carbon dioxide production measured in liters per minute (STPD)
$\dot{V}O_2$	Metabolic oxygen consumption in liters per minute (STPD)
max	Maximum flow rate
\dot{V}	Ventilation, first time derivative of volume
V_T	Tidal volume; volume of gas that a diver either inspires or expires during each breath (measured in liters, BTPS)
RE	Resistive work of breathing normalized for tidal volume (aka resistive effort), a measure of pressure averaged over volume and thus removing pressures due to UBA elastance. Consequently, RE — a volume-averaged pressure — is currently measured in kPa or J/L. Historically, NEDU reported RE with units of kg·m/L.
ρ	Gas density
\propto	Proportional to
π	Pi = 3.14159...

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CONVERSIONS

<u>To Convert From</u>	<u>To</u>	<u>Multiply By</u>
kg·m/L	J/L	9.807
psi	kPa	6.895
msw	fsw	3.2646
fsw	kPa	3.063
bar	psi	14.504
bar	kPa	100
cmH ₂ O	kPa	0.0982
J/L	kPa	1.000

SAFETY SUMMARY

The following general safety precautions are not related to any specific procedures; thus, they do not appear elsewhere in this manual. They are, however, recommended precautions that personnel must understand and apply during various phases of testing and evaluation.

STANDARD SAFETY PRECAUTIONS. Operating personnel must observe all applicable safety regulations in compliance with the Navy Occupational Safety and Health (NAVOSH) Program Manual, OPNAVINST 5100.23 Series.

Safety precautions for unmanned testing are normally associated with testing at pressures of 5000 psig or less. To minimize safety risks when UBA testing is being conducted, personnel shall adhere to the test procedures as presented in this report. Failure to perform the procedures as prescribed may result in injury to personnel or damage to equipment.

CHAPTER 1. INTRODUCTION

The Navy Experimental Diving Unit (NEDU) is the United States Navy facility for testing and evaluating underwater breathing apparatus (UBAs). Each military or commercial UBA that the Navy considers for use is sent to NEDU for an in-depth evaluation of its performance, material suitability, human factors, and systemic reliability. This technical manual supersedes NEDU TR 01-94 and presents the unmanned performance goals and test methods NEDU currently uses to evaluate UBAs.

This manual employs physiologically-based performance goals and limits — a significant departure from previous engineering-based goals. Much of the rationale for this transition is detailed in NEDU Technical Report 15-03 and various publications cited in this manual.

The instrumentation and test methods described in this manual should allow any hyperbaric test facility to reproduce the tests conducted by NEDU. Any test instrument comparable to those specified in the UBA test setup may be used, if its accuracy and response characteristics are equal to or exceed those used by NEDU — and if its calibration is traceable to National Institute of Science and Technology standards.

Minimum manning during unmanned hyperbaric testing shall be two personnel per chamber (one test supervisor and one chamber operator per test per chamber).

This manual is meant to be dynamic in nature, and the methods herein are valid as of 15 July 2015. As instrumentation technology advances and new test methods are developed, this manual will be updated to facilitate improved unmanned test simulations.

CHAPTER 2. UBA CATEGORIES

2-1 GENERAL

NEDU has classified UBAs into five categories. Each category was selected according to UBA operational characteristics. This chapter provides a general description of each category and the operation of each UBA classified within.

- Category 1. Open-circuit Demand UBA
- Category 2. Open-circuit Umbilical Supplied Demand UBA
 - A. Open-circuit Noncompliant Demand UBA
 - B. Open-circuit Compliant Demand UBA
- Category 3. Open-circuit Umbilical Supplied Free Flow UBA
- Category 4. Closed and Semi-closed-circuits, Breath Powered UBA
- Category 5. Semi-closed-circuit, Ejector or Pump-Driven UBA

2-2 CATEGORY 1. OPEN-CIRCUIT DEMAND UBA



All open-circuit scuba equipment authorized for Navy use employ a demand system that supplies breathing gas each time the diver inhales. Category 1 is comprised of a first stage regulator, hose, a second stage demand regulator, and a mouthpiece. The purpose of the first stage regulator is to reduce the tank pressure from as much as 345 bar (5000 psi) to 8.6-12 bar (125-175 psi) over ambient. This reduced pressure is constantly maintained at the second stage. The second stage regulator supplies air through the mouthpiece to the diver on demand and at a pressure slightly above the surrounding water pressure. The second stage demand regulator is the central component of the Category 1 UBA; however, the first stage regulator should never be overlooked when evaluating a Category 1 UBA.

2-3 CATEGORY 2. OPEN-CIRCUIT UMBILICAL SUPPLIED DEMAND UBA

Equipment in this category requires either a full face mask or a dry helmet. Each is assumed to have a built-in oral-nasal mask or a mouthpiece.

Category 2 consists of two types of UBA:



A. Open-circuit noncompliant demand UBA. This category covers UBAs that provide gas to the diver via a demand regulator attached to an oral-nasal mask in the face mask or helmet. An example of the UBA in this category is the MK 20.

B. Open-circuit compliant demand UBA. This category contains UBAs that supply gas to a diver's helmet via a demand regulator with an oral-nasal mask, and is fitted with a neck dam. This category includes MK 21 and the KM 37 diving helmets.

2-4 CATEGORY 3. OPEN-CIRCUIT UMBILICAL SUPPLIED FREE FLOW UBA



UBAs in this category also supply gas to the diver via an umbilical hose; however, the gas constantly flows past the diver's face (no demand required) into the helmet or mask. Excess gas is constantly dumped from the helmet or mask into the water. No oral-nasal mask or mouthpiece is used.

Free flow helmets like the MK 12 are no longer in Navy use.

2-5 CATEGORY 4. CLOSED- AND SEMI-CLOSED-CIRCUITS, BREATH POWERED UBA

Fully closed-circuit UBA are divided into two categories: 100% O₂ and constant oxygen partial pressure.



Pure oxygen UBAs have no electronics and consist of an oxygen bottle, regulator, breathing bag, and a chemical-based carbon dioxide scrubber. 100% O₂ is added to the breathing bag prior to diving. As the diver consumes oxygen, the volume in the breathing bag decreases, causing the bag to bottom out; an O₂ add valve attached to the regulator then allows O₂ to flow into the breathing bag, reinflating the bag. The diver's exhaled carbon dioxide is removed from the UBA by the chemical scrubber. The MK-25 is an example of a closed-circuit O₂ rebreather.

Closed-circuit constant O₂ partial pressure UBAs are more complex than 100% O₂ UBAs, but are also more versatile. These UBAs maintain a constant O₂ partial pressure regardless of depth or diver work rate. The UBAs consist of a chemical scrubber, electronics, oxygen sensors, breathing bag(s), O₂ bottle, electric O₂ add valve, and a mixed gas bottle. The constant O₂ partial pressure is maintained by the

electronics and the O₂ sensors. As O₂ is consumed and the O₂ partial pressure falls below the set point, O₂ is automatically added into the UBA until the set point is reestablished. This cycle is repeated during the entire dive. Carbon dioxide is removed by the chemical scrubber as the gas

flows from the diver through the scrubber and into the compliant breathing bag. Examples of these types of UBAs are the MK 16 and MK 28.



Semi-closed-circuit UBAs function by flowing a constant volume of gas (100% O₂ or O₂ mixed with nitrogen or helium) through a mass flow orifice into the inhalation side of the UBA. This provides a supply of O₂ to the diver, but the O₂ level maintained in the UBA depends upon the diver's work rate. Because gas is constantly added to the UBA, an exhaust regulator periodically dumps gas into the water to keep the UBA from overinflating. An example of a semi-closed-circuit UBA is the Viper VSW.

U.S. Navy photo by Bernie Campoli.



2-6 CATEGORY 5. SEMI-CLOSED-CIRCUIT, EJECTOR OR PUMP-DRIVEN UBA

An example of the semi-closed-circuit pump-driven UBA is the Divex Gasmizer Diver Gas Recovery System / Helium Reclaim Helmet. The Gasmizer Diver Gas Recovery system consists of four main components: a Control Console, Reprocessing Unit, Dive Bell Panel and a Gas Booster Pump. The Diver's Helmet is a Category 2B modified to recover the diver's exhaust back into the system. The Divex Ultrajewel 600 Helium Reclaim Helmet is an example of this. This system could also have Emergency Life Support System which would normally be a Category 4. An example of this is the Divex SLS MK IV Deep Diving Bailout System.





The semi-closed-circuit MK 12 mixed gas UBA (no longer in use) was an example of an ejector type UBA. It consisted of a helmet, umbilical, back pack with chemical carbon dioxide scrubber, and mass flow orifice. Gas flowed from surface gas banks through an umbilical to a backpack constant mass flow orifice, through the backpack and into the helmet. The gas then flowed from the helmet through the scrubber and back to the helmet. The mass flow ejector assisted in circulating the gas through the UBA. Excess gas was dumped from the helmet into the water through an exhaust valve located on the helmet.

CHAPTER 3. UBA TEST PROCEDURES – AN INTRODUCTION

3-1 GENERAL

3-1.1 Functional Characteristics

A UBA's suitability for diving can be described by up to seven functional characteristics, although not all characteristics apply to all UBA categories. Those characteristics of current interest to NEDU are:

- Peak inhalation and exhalation breathing pressures
- Resistive breathing effort
- Hydrostatic imbalance
- Dynamic elastance
- Intermediate pressure loss
 - First stage over bottom pressure drop (SCUBA regulators and open-circuit demand helmets)
 - Umbilical pressure drops (surface supplied or Personnel Transfer Capsule (PTC) supplied umbilical fed UBA)
 - Mask/helmet sideblock and non-return valve pressure loss CO₂ concentration Oxygen control (closed and semi-closed-circuit UBA)

This section contains a general discussion of each of the seven areas mentioned above. Where appropriate, the rationale for NEDU's use of various test methods or performance goals will be given.

3-1.2 Data Acquisition

The digital sampling of pressure and volume data must occur at a rate high enough to faithfully resolve details. At a minimum, the time-varying analog signal should be sampled at a frequency greater than twice the highest frequency present in the signal¹. Pressure and volume signals should be acquired at more than 100 Hz per channel. NEDU uses an IBM compatible personal computer with a LABVIEW interface (National Instruments, Austin) for some tests and a similar PC with proprietary software using MS Visual Basic to sample data channels at rates from 2 to 250 Hz, as appropriate, for the specific parameters being evaluated.

3-2 SIMULATOR SETTINGS

As a diver's work load varies, tidal volume (V_T) and breathing frequency (f) measured in breaths per minute (BPM) change to meet metabolic demands. These conditions are reproduced in the testing laboratory by using a breathing simulator with various tidal volume and BPM settings as shown in Table 3-1. Respiratory Minute Ventilation (RMV) is f times V_T .

Table 3-1 Breathing Simulator Standard Setting

f (BPM)	V_T (Liters)	RMV (L/min)	Diver Work Rate
15	1.5	22.5	Light
20	2.0	40.0	Moderately Heavy
25	2.5	62.5	Heavy
30	2.5	75.0	Severe
30	3.0	90.0	Extreme

3-3 VENTILATORY PRESSURES

A differential pressure transducer measures the positive and negative pressures generated during breathing. This respiratory pressure is measured at the NEDU Breathing Block where inspiratory and expiratory flow is divided during Category 1 and 4 tests (Figures 5-3 and 5-4) and in the oral cavity of the test mannequin for Category 2, 3, and 5 UBAs. The physical reference point for the ± 7 kPa (± 1 psi) differential pressure transducer is an anatomical landmark called the suprasternal notch which is approximately 17 cm (6.7 in) below the mid-oral cavity in a vertical orientation².

Three types of ventilatory pressures are routinely measured. These are routinely referred to as various mouth pressures since they are measured near the mouth or oronasal cavity of an unmanned testing mannequin.

- 1) Peak inhalation and exhalation pressure - the minimum and maximum pressures found in a P-V loop with pressure measured for zero flow defined to be 0 kPa referenced to the suprasternal notch.
- 2) Volume-averaged pressure (\bar{P}_V), commonly denoted as resistive effort (RE), or sometimes work of breathing (WOB), is an average of the pressures contributed by **resistive** components to **flowing** gas within the UBA. (Use of the term “WOB” is misleading because it does not have units of work, but rather pressure.)
- 3) Tidal volume is measured by a linear variable displacement transducer (LVDT) mounted on the breathing machine. An example time tracing of both mouth pressure and tidal volume are shown in Figure 3-1.

While it may be dimensionally correct to refer to RE in units of work of breathing per liter (WOB/L), that is not a concise physical description. Dimensionally, a six foot tall person may be

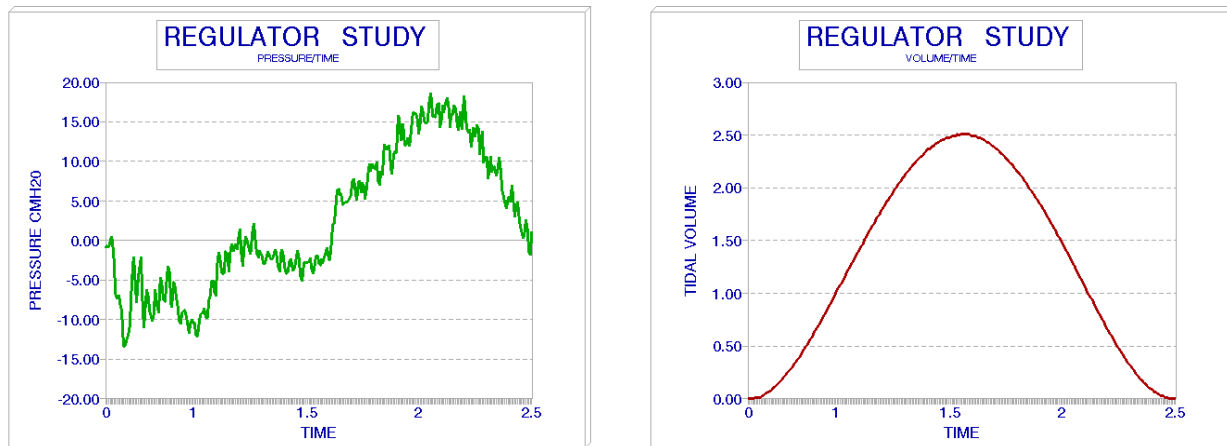


Figure 3-1 Pressure and Volume Tracings (Category 1 or 2)

1829 Liter/meter² tall, but “6 ft” or “1.83 meters” is the engineering convention.

3-4 BREATHING RESISTIVE EFFORT

It is customary to plot pressure against tidal volume, yielding a P-V loop (Figure 3-2). The P-V loop provides useful information because the area inside the loop represents the resistive effort of breathing. The larger the area enclosed within the loop, the greater the RE; i.e., the more difficult it is to breathe. Mechanical work (W) is defined as the product of force multiplied by displacement, or for fluid systems, the change in system pressure (ΔP) multiplied by the change in system volume (ΔV). Expressed³ as an integral, $W = \oint p \cdot dv$ with units of kg·m or Joules (J).

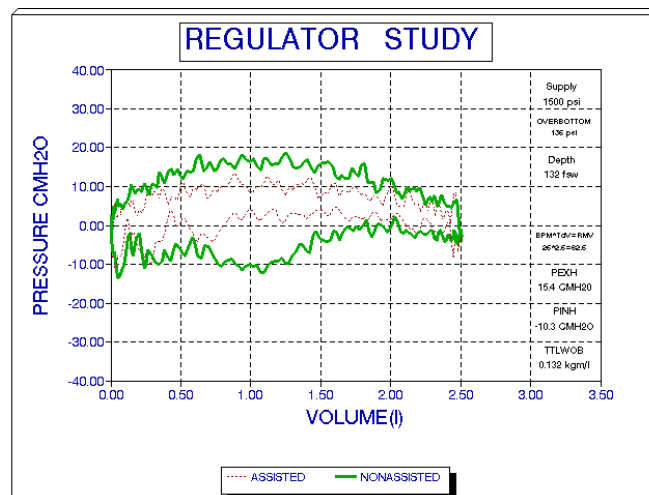


Figure 3-2 P-V Loop (Category 1 or 2 UBA)

Most modern demand regulators are assisted; i.e., they have venturi, vortex, or pilot assisted boosters to reduce second stage inhalation effort. As a result, while peak inhalation pressures for an assisted and non-assisted regulator may be similar, W and \bar{P}_V for the assisted regulator drops significantly because its peak inhalation pressure occurs for a much shorter period of time. This is illustrated in Figure 3-2 where RE is much larger for the non-assisted regulator (bold curve) than for

the assisted unit (light curve).

Resistive effort (RE) or volume-averaged pressure (\bar{P}_V), are terms that will be used interchangeably throughout this document. Those terms are not widely used outside of the U.S. Navy⁴, however they are gaining credence in the medical literature. Dr. Walter F. Boron, 72nd President of the American Physiological Society, Secretary-General of the International Union of Physiological Sciences and co-editor of the book, Medical Physiology, uses similar terminology to describe inspiratory pressure as effort, further dividing effort into elastic and resistive components⁵ (Figure 3-3).

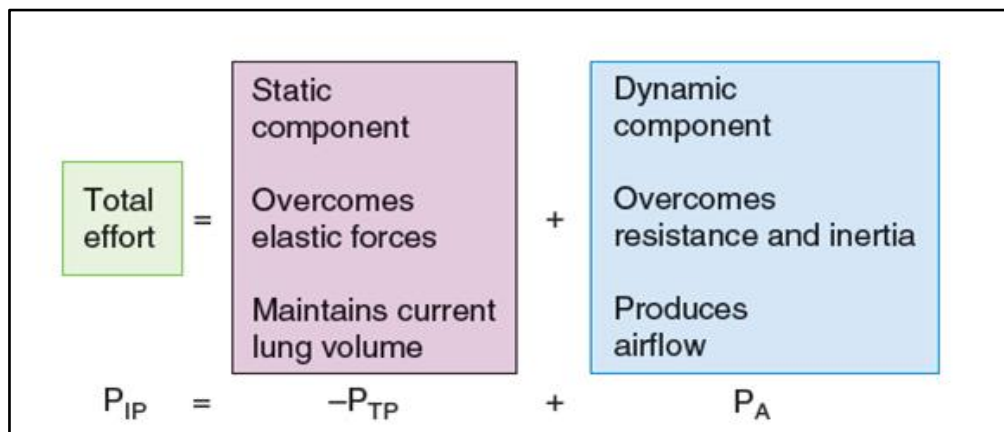


Figure 3-3 Respiratory Effort

Figure 3-3 illustrates that the pressures that a diver has to generate to breathe are perceived as a respiratory effort. Those pressures come from both resistive and elastic sources. PIP is inspiratory pressure, PTP is transthoracic pressure, and PA is alveolar pressure.

Since successive P-V loops invariably differ due to electrical or mechanical noise, a number of P-V loops are required to ensure statistical validity of the collected data. Typically, ten breathing loops are acquired, but even six iterations provide relatively noise free, average loops. Ensemble-averaging of P-V loops (Figure 3-4 and Chapter 6) reduces random noise without the distorting effects of filters. Figure 3-4 is an extreme example. In the upper portion of the figure, the underlying oscillating waveform is obscured by random noise. In the lower plot, ensemble averaging reveals the previously hidden structure (solid black curve). Likewise, the oscillating patterns in Figure 3-4 become clearly discernible only after signal averaging.

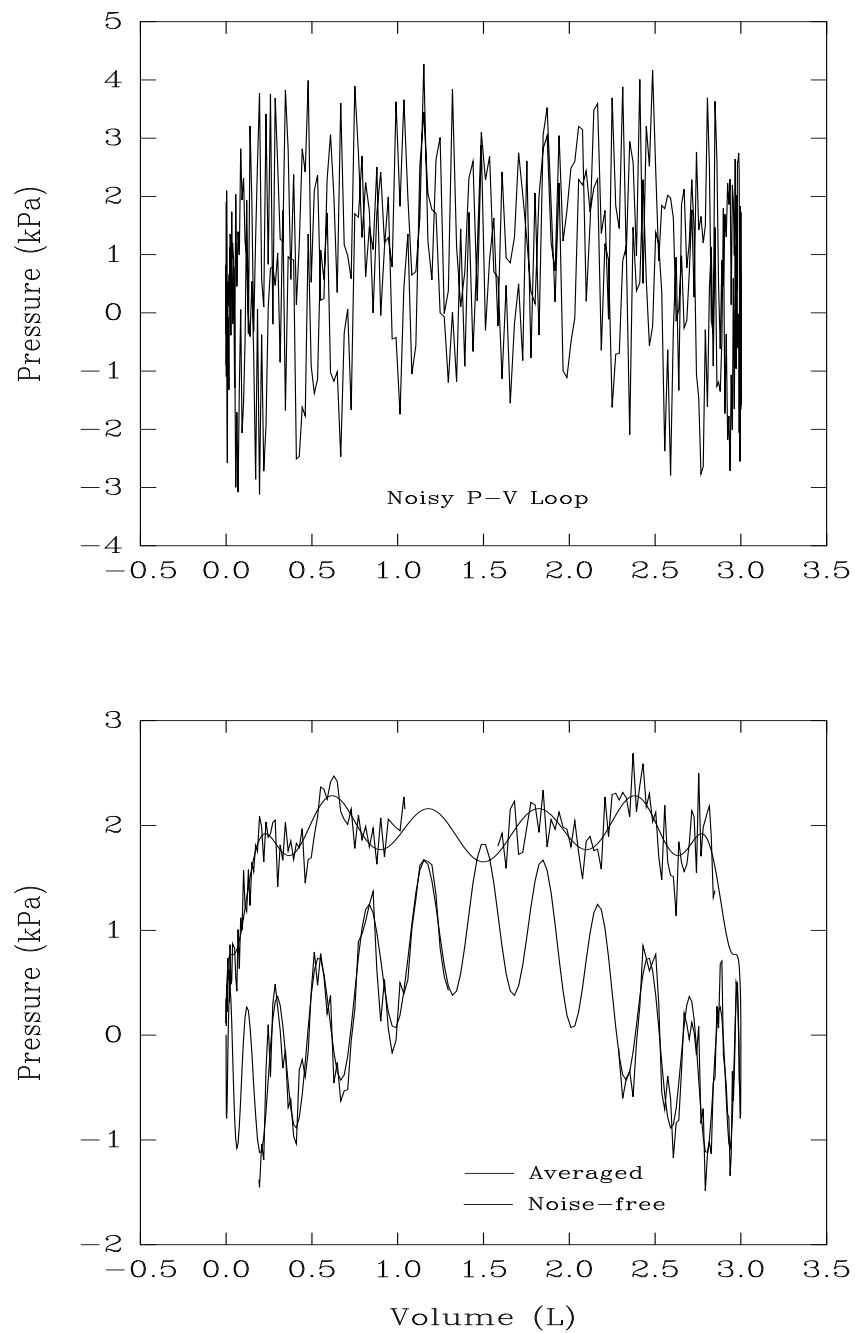


Figure 3-4 Noisy P-V Loop with and without Ensemble Averaging

3-5 HYDROSTATIC IMBALANCE

3-5.1 What Is It?

The weight of water pressing around a diver's ribcage can make it difficult for him to breathe unless that inward force is counterbalanced by the outward force of gas filling the diver's lungs. If breathing bags are placed high on the chest or back of an upright diver, a pressure imbalance will exist with the inspired gas being at a lower pressure than the mean hydrostatic pressure surrounding the lungs. Relative to the external pressure, the inspired pressure is negative in sign, and therefore a negative pressure balance is said to exist.

To inhale against a negative imbalance, a diver has to create highly negative respiratory pressures. Likewise, breathing bags low on a diver means the gas supply is at a higher, more positive pressure than the hydrostatic pressure surrounding the diver's chest. Therefore, gas flows down a pressure gradient into the diver's lungs. Unfortunately, to exhale, the respiratory muscles must contract forcefully to expel gas back to the breathing bags. Both forceful inhalation and forceful exhalation can result in diver fatigue. Excessively positive pressure can also result in off-gassing of the rig, reducing gas supply and endangering covert operations.

The effects of hydrostatic imbalances on diver comfort and performance, reviewed by Lanphier and Camporesi⁶, has been one of the most extensively researched topics in diving physiology during the last decade. The central question has been the following: What respiratory pressures are optimal for counterbalancing the inward force of the water column?

Lung centroid pressure (P_{LC}) appears to be the optimal pressure for diver comfort during immersion⁷. P_{LC} in an upright immersed man is 13.6 cm below the sternal notch, and 7 cm above the plane of the sternal notch in supine (horizontal, face down) man (Figure 3-5). More positive static pressures (up to 20 to 30 cmH₂O) benefit helmeted divers during high ventilatory rates. In tests with MK 15 closed-circuit UBA, the tolerated range of hydrostatic imbalance was relatively large⁸. Therefore, hydrostatic imbalance can range approximately 10 cmH₂O (0.98 kPa) in any direction from the P_{LC} identified in Figure 3-6. For non-helmeted diving, values between P_{LC} and P_{LC} -10 cmH₂O are favored. Lower pressures cause less inflation of the cheeks and oropharynx.

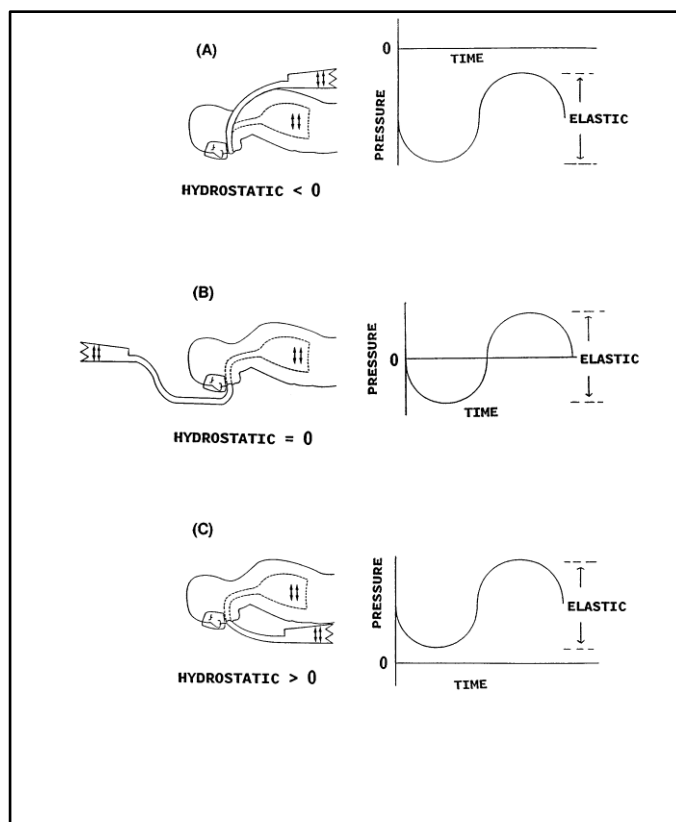


Figure 3-5. Breathing Bag Position and Hydrostatic Imbalance

For helmeted diving where the upper airways are counterbalanced by helmet pressure, pressures between P_{LC} and $P_{LC}+10 \text{ cmH}_2\text{O}$ are advantageous⁹.

3-5.2 How is it Measured?

3-5.2.1 General

From a physiology standpoint, the pertinent pressure is pressure at the lung centroid. Since most testing manikins do not provide access to a location in space comparable to the lung centroid, we use an anatomical landmark used in human research; the suprasternal (above the sternum, aka breastbone) notch. In upright man, the suprasternal notch ranges from 14 to 17 cm below the mouth opening². When a UBA is in the vertical position, the position of the mouthpiece Breathing Block is fixed relative to the support for the UBA. The mouthpiece pressure transducer with its integral reference pressure port is secured 17 cm below the Breathing Block, with a pressure line attached between the positive side of the transducer and the Breathing Block. Therefore, mouth pressure is automatically referenced to a pressure corresponding to the approximate pressure at a diver's suprasternal notch.

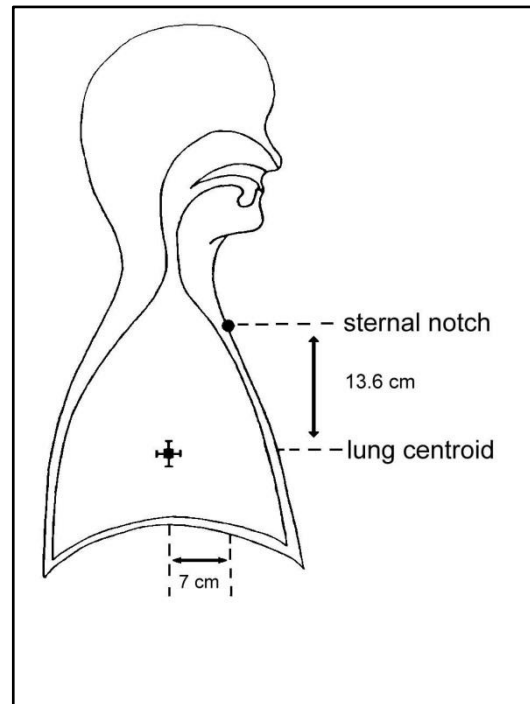


Figure 3-6 Lung Centroid and Suprasternal Notch in an Upright Diver.

Figure 3-6 provides one measurement of the vertical distance from the suprasternal notch to the lung centroid, with other sources quoting a larger value (19 cm). As long as a pressure reference port is located consistently relative to the mid-oral position, and that distance is reported, then translation from one anatomical reference system to another should be facilitated.

Hydrostatic pressure is that pressure which exists in a diver's lungs in the absence of gas flow; hence *hydrostatic*. However, in elastic UBA, mouth pressure varies with UBA volume even in static, no-flow conditions. Therefore, it is necessary to establish a reference, no-flow condition. We define that condition as end-expiration.

In divers, normal end-inspiration occurs at a volume called Functional Residual Capacity (FRC). In unmanned testing, the reference condition is simply end-expiratory volume. By present convention, "volume" means the volume contained in the breathing machine. Therefore, end-expiration is identified on a P-V loop as a volume of 0 liters.

If the UBA is upright, and the pressure transducer reference port is situated 17 cm below the submerged mouthpiece, then a reading of 0 kPa with a volume of 0 liters is interpreted as a zero hydrostatic imbalance *referenced to the suprasternal notch*. It is 13.6 cm H_2O negative (lower pressure) relative to the lung centroid.

Mouth pressure is determined by the location in the water column of the interface between

gas and water in the breathing bag. If the reference port on the mouth pressure transducer is located at the same level as the gas-water interface, then a pressure of 0 cmH₂O will be sensed.

3-5.2.2 Specific Procedures

Hydrostatic loading has a great impact on the tolerance of divers using closed-circuit UBA such as the MK 16 and LAR V. See detailed procedures for measuring hydrostatic imbalance in Chapter 10.

3-6 DYNAMIC ELASTANCE

Sloping P-V loops are indicative of UBA elastance (Figure 3-7). Due to the vertical motion of the air-water interface in UBAs with breathing bags or neck dams, a change in UBA volume is associated with a change in system pressure. Elastance presents a respiratory load to a diver¹⁰⁻¹², and is measured by the average slope, $\Delta P/\Delta V$, of the P-V loop¹⁰. By necessity, peak-to-peak pressure measurements include contributions from both the resistive and elastic components of UBA. See detailed procedures for measuring hydrostatic dynamic elastance in Chapter 10.

Peak expiratory and inspiratory pressures are identified in Figure 3-7, along with the line of elastance and peak resistive inspiratory pressure (PRIP). The line of elastance connects points of *zero flow* (maximum and minimum volume) obtained dynamically; i.e., during continuous motion of the breathing machine. The dynamic elastance line approximates the pressure that would be generated during the tidal breath in the absence of resistance. For any given UBA volume, the total mouth pressure is the sum of elastic and resistive pressure.

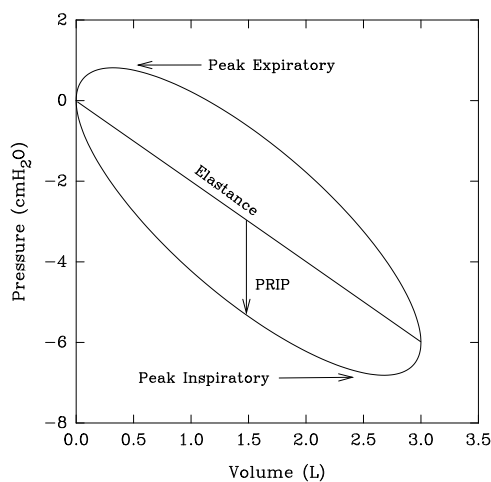


Figure 3-7 P-V Loop in Elastic UBA (Category 4).

The dynamic elastance of MK 16 UBA is typically less than 0.7 kPa/L when the UBA breathing bag is properly inflated. Over or under-inflation causes curved P-V loops which markedly elevate both respiratory pressures and the measured dynamic elastance.

3-7 INTERMEDIATE PRESSURE LOSS

3-7.1 First Stage Over-Bottom Pressure Drop

The performance of the SCUBA regulator's first stage is critical to the inhalation effort required by the diver. The first stage must supply air at a sufficiently high pressure and volume for the second stage regulator to function properly. As the diver work rate increases, regulator performance degrades mainly due to the failure of the first stage to supply sufficient gas volume to the second stage.

The spring/valve mechanism of most second stage regulators is designed to function with minimum inhalation effort when supplied with 125 to 150 psig over bottom (O/B) from the first stage. This first stage intermediate pressure is normally set at static or no-flow conditions. Upon inhalation, this pressure drops as the air flows from the first to the second stage. As a diver descends and work rate increases, the increased flow from the first to the second stage causes the pressure drop from the static setting to increase dramatically. Consequently, the second stage may no longer be receiving air at a rate that meets the diver's inhalation demands, resulting in increased inhalation effort. When the supply pressure to the first stage is below 500 psig, UBA efficiency is further reduced. For this reason, Category 1 UBAs are always evaluated with a supply pressures of 500 and 1,500 psig to the first stage.

The maximum intermediate pressure drop from the static setting is measured by attaching a differential pressure transducer to the spare low pressure (LP) port on the first stage. The reference port of the transducer is open to the chamber. By plotting the intermediate pressure drop from the static setting versus depth at each RMV tested, the design limitations of the first stage can be evaluated. Correlating this information with the P-V loop, poor regulator performance can be traced to the first stage, second stage or both. For example, a regulator with a static intermediate pressure of 9.65 bar (140 psig) O/B can usually operate efficiently with dynamic intermediate pressures as low as 7.93 bar (115 psig) O/B. Pressure losses greater than this during inhalation generally result in significantly increased inhalation effort. When pressure losses approach 40 to 50 psig less than static, the regulator ceases to function in a manner that can effectively support a diver. Conversely, when a regulator exhibits poor inhalation performance while exhibiting very small intermediate pressure drops, the problem usually exists in the second stage design.

3-7.2 Umbilical Pressure Drop

Umbilical pressure losses have an adverse impact on UBA performance as do the intermediate losses mentioned in the previous paragraph. Gas flow is directly related to supply pressure, umbilical inside diameter (ID) and any added restrictions such as hose splices and connectors. Losses incurred within the umbilical can substantially reduce gas supplied to the second stage of a Category 2 UBA. O/B supply pressures in the UBA can be reduced by 10 to 40 percent through umbilical pressure drop. For this reason the correct ID hose should be used with the

minimum length required to accomplish the mission. The inability of the pressure to return to the set point between breaths is a strong indication of impending failure.

Pressure drops generally increase linearly with depth in free flow type UBAs. However, with demand UBAs, the instantaneous flow requirements can give rise to much greater pressure drops. At high diver RMVs, umbilical pressure drops typically transition from a linear to an exponential function, sharply increasing breathing effort. While Figure 3-8 is an example of pressure loss in a mask sideblock, the same type of trace will be observed with increases in the umbilical pressure drop.

3-7.3 Mask/Helmet Sideblock and Non-return Valve Pressure Loss

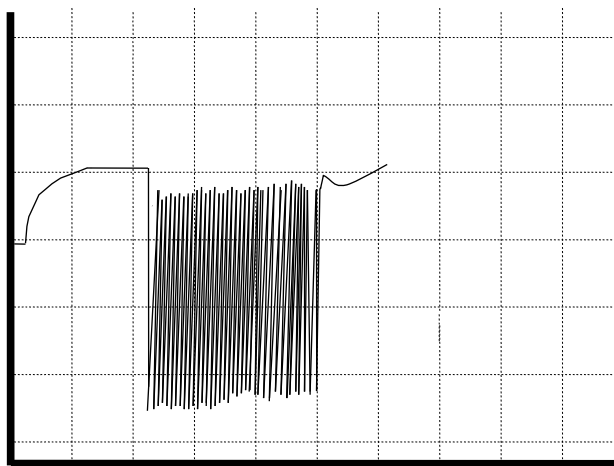


Figure 3-8 Sample intermediate pressure (ΔP vs time). Work rate = 62.5 L/min RMV, Supply Pressure = 1500 psi, Depth = 132 fsw

Pressure loss across the sideblock assembly of a UBA can adversely affect breathing resistance. This loss becomes important at or near maximum operating depths where the total intermediate pressure loss (umbilical ΔP plus sideblock ΔP) is large enough to significantly reduce supply pressure to the UBA's regulator, thereby reducing performance. By correlating this information with P-V loops, changes in breathing work performance can be traced.

3-8 CO₂ CARBON DIOXIDE

3-8.1 Ventilation Sufficiency

The amount of CO₂ inspired by a diver should be minimized to avoid signs and symptoms of hypercapnia, including loss of consciousness while submerged, by optimizing fresh gas flow to the diver (ventilation) and by minimizing dead space within the UBA. Dead space comes from two sources: 1) the diver (anatomical dead space) and 2) the diving equipment

(external dead space). Anatomical dead space is that volume in the conducting airways occupied by gas but not involved in gas exchange with blood in the pulmonary vessels; i.e., the larynx, the trachea and the oral cavity. The average anatomical dead space volume is about 150 ml for young, physically fit men. NEDU is not concerned with the influence of anatomical dead space when performing unmanned testing as it is fixed by biology and cannot be modified.

External dead space in a UBA is a volume of gas that does not circulate consistently and therefore may contain residual levels of CO₂ from the preceding expired breath. External dead space ranges from a few mL (SCUBA mouthpiece) to 400-500 mL in some full face masks to even higher in some diving helmets. The larger the dead space, the more difficult it is to eliminate all of the preceding exhalation. Due to mixing of a portion of the preceding exhalation with newly inspired breathing gas, levels of inspired CO₂ are higher than CO₂ levels in the supply breathing gas during much of a given inspiration. Inspired CO₂ levels are minimized by reducing external dead space, increasing helmet ventilation, and minimizing supply gas CO₂ levels by maintaining CO₂ scrubber efficiency or monitoring diver supply gas quality.

Ventilation sufficiency measurements determine whether or not fresh gas flow is large enough, and the dead space is small enough, to sustain a safe level of inspired CO₂ under conditions of simulated heavy or severe work (Table 3-1). The dive helmet, T-bit, or face mask is positioned on a human mannequin head and either tested in the dry at 1 atm, or immersed in a water tank inside the Bravo hyperbaric chamber. At 1 atm, testing is conducted at ambient temperature. In the water, water temperatures depend on end-use specification. Multiple tests are performed using combinations of depths and breathing gases appropriate for the test UBA. A breathing simulator (Battelle, Columbus, OH or Reimers Consulting, Springfield, VA) is used to generate a sinusoidal breathing pattern with a minute ventilation of either 22.5 or 62.5 L/min.

Carbon dioxide is injected into the breathing loop at a rate of approximately 4% of the minute ventilation volume. A small sample of gas is continuously drawn from the mannequin's mouth and analyzed for CO₂ with a fast-responding infrared absorption analyzer (Model CD-3A with a P-61B sensor, Applied Electrochemistry Ametek; Pittsburgh, PA) at a sampling frequency of 100 Hz. Breathing simulator volume is sampled simultaneously.

Inspired CO₂ Levels based on UBA Category

Category 1: Not applicable.

Category 2: End-inspired CO₂ levels at the mouth shall be no greater than .267 kPa (2 mmHg) more than the supply gas CO₂ at an RMV of 62.5 L/min at all depths from the surface to 40.4 msw (132 fsw) on air and from the surface to 306.3 msw (1000 fsw) on HeO₂.

Category 3: End-inspired CO₂ should be less than or equal to 2.03 kPa (15.2 mmHg, 2% surface equivalent) at an RMV of 75 L/min with a CO₂ injection rate of 3.0 L/min.

Category 4: End-inspired CO₂ levels at the mouth shall be no greater than 0.267 kPa (2 mmHg) more than canister effluent at an RMV of 75 L/min with a CO₂ injection rate of 3.0 L/min.

Category 5: Maximum allowable CO₂ level in the mask or helmet is to be less than 2.0% SEV 2.03 kPa (15.2 mmHg) at an RMV of 75 L/min with a CO₂ injection rate of 3.0 L/min.

3-8.2 Canister Durations

It is currently possible to monitor O₂ levels and bottle pressure, but not CO₂ levels within an operationally deployed UBA. Therefore, for safety's sake, the duration of the CO₂ absorbent canister in a closed-circuit UBA should exceed that of the O₂ bottle supply at all temperatures and depths. Regardless of work rate, the diver could monitor his O₂ consumption with the O₂ bottle gauge and have confidence that the CO₂ scrubber would still be adequate. Unfortunately, this is rarely the case. Alternative means of determining the useful life of a CO₂ canister are required. Two means now exist: one determines the time required to break through a canister (i.e., the time duration at which unacceptably high level of CO₂ exits the canister and is inhaled by the diver) for a particular condition; the other determines the amount of CO₂ the canister can absorb under any condition.

The ratio of carbon dioxide output rate to oxygen uptake rate measured at the lungs is known variously as the respiratory quotient (RQ), respiratory exchange ratio (R), or gas-exchange ratio (R). *The differences between the meanings of these terms are unimportant to this discussion and will not be further addressed except to say we use the term gas-exchange ratio (R) as given in the most authoritative source*¹³. For an exercising individual on a mixed diet of carbohydrates, fat, and protein^{14,15}, R is typically between 0.80 and 0.82. Furthermore, R does not change with hyperbaric conditions¹⁶. Unless the diver is performing maximal work, it is doubtful that the diver's R would exceed this value during extended diving operations. To be conservative, however, R will be assumed as 0.9 for diving operations. That is, CO₂ canisters will be tested with a slightly higher injection rate than is likely to be found in practice.

For each type of material from a given manufacturer, the performance of CO₂ absorbents may be affected by temperature, depth, gas mixture, and canister design. Hence, five different test temperatures (ranging from the minimum to the maximum operational limits for the UBA tested) and at least one depth (the operational maximum) are recommended to obtain a profile of the canister CO₂ absorbency characteristics. Also, to provide statistically useful numbers, at least five canisters should be tested for each combination of temperature, depth, and CO₂ injection rate.

NEDU uses a continuous CO₂ injection method for determining canister CO₂ absorbency. Breakthrough is defined as the time until the canister effluent reaches 0.51 kPa (3.8 mmHg or 0.5% SEV). A resting diver is simulated by a continuous CO₂ injection rate of 0.9 L·min⁻¹ STPD (Standard Temperature and Pressure, Dry) at an RMV of 22.5 L·min⁻¹. This represents R (0.9) times an O₂ consumption of 1.0 L·min⁻¹. A moderately heavy work rate is simulated by continuously injecting CO₂ at a rate of either 1.35 L·min⁻¹ STPD at an RMV of 40 L·min⁻¹ (in keeping with NEDU historical studies and sponsor wishes), or 1.6 L·min⁻¹ STPD at an RMV of 40 L·min⁻¹. This latter CO₂ injection rate is in keeping with European standards, but obviously results in shorter canister durations than the more moderate (1.35 L/min) historical NEDU injection rate.

To maintain conservatism, NEDU uses a 95% prediction limit applied to the measured canister durations¹⁶. NEDU TR 12-03¹⁷ describes how this approach is applied to “quick-look” or one-sample data collection efforts for UBA used in preliminary trials.

3-9 OXYGEN CONTROL

In addition to removing CO₂ from the breathing loop, closed circuit rebreather UBAs also must add oxygen to make up for the oxygen that the diver has consumed. To evaluate the ability of a UBA to maintain an acceptable level of oxygen, a procedure to simulate oxygen consumption must be used for unmanned testing.

NEDU simulates oxygen consumption as follows:

- 1) To simulate the desired O₂ consumption rate, a calibrated mass flow controller (MFC) removes a given quantity of mixed gas from the UBA breathing loop. This amount, which depends on both the oxygen concentration and the depth, is adjusted automatically and continuously via the data acquisition and control software on a computer.
- 2) To determine the PO₂, a laboratory O₂ analyzer monitors the oxygen content of the gas exiting the MFC from the inhalation side of the UBA.
- 3) To maintain the stability of the inert volumetric balance, another calibrated MFC adds the correct amount of inert gas (nitrogen) back into the loop. This depth-dependent flow also is controlled as in 2) above.

Data analysis on oxygen set point control involves simultaneously measuring both percent O₂ in breathing gas and the depth of the UBA to calculate partial pressure of O₂. Figure 3-9 provides a sample of the dynamic plots generated during testing. The oscillations result when PO₂ is under control at an equilibrium value and the oxygen automatic add valve opens and closes to maintain PO₂ near the set point.

The questions of primary interest are:

- 1) At equilibrium conditions (fixed oxygen consumption rate and depth), how close to the set point does the UBA control PO₂?
- 2) Under dynamic conditions (varying oxygen consumption rate and/or changing depth), how far above and below the set point does PO₂ range and how long does it take the UBA to return to equilibrium conditions; i.e., to bring PO₂ back within an acceptable control band around the set point?

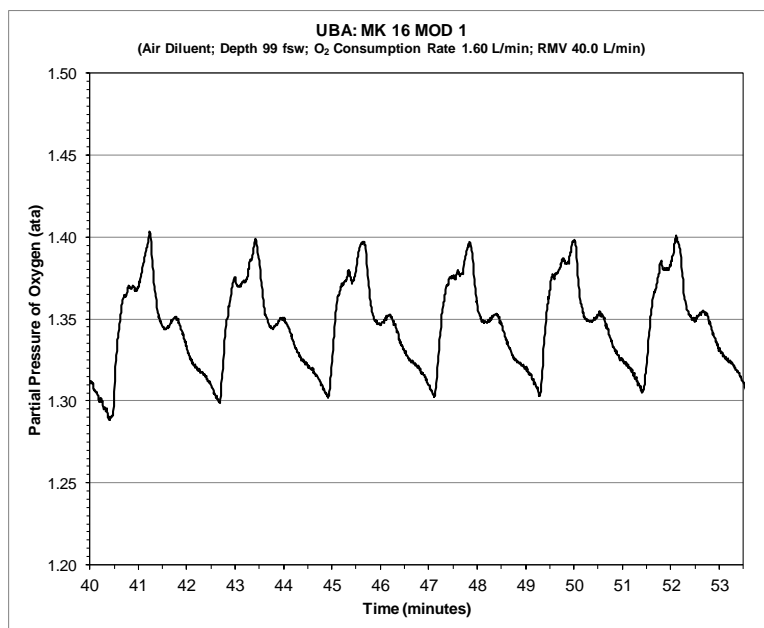


Figure 3-9 O₂ Add vs. Time.

Figure 3-9 shows a typical pattern of PO₂ control at equilibrium with large volume breathing loops. For more detailed descriptions of how oxygen consumption is simulated and how PO₂ control is measured, see chapter 9.

REFERENCES

1. Principe, J.C. and J.R. Smith, "SAMICOS- A sleep analyzing microcomputer system". IEEE Transactions on Biomedical Engineering, Vol. BME-33, NO. 10, October, 1986, pp. 935-941.
2. Knafelc, M.E., "Unmanned and manned evaluation of a prototype closed-circuit underwater breathing apparatus, the EX-19", NEDU Report 5-88. US Navy Experimental Diving Unit, Panama City, FL, 1988.
3. Otis, A.B., "The Work of Breathing", In: Handbook of Physiology: Section. 3 Respiration, Vol. 1, W. Fenn and H. Rahn, Eds., American Physiological Society, Washington, pp: 463-476, 1964.
4. NEDU Technical Manual 1-94, "U.S. Navy Unmanned Test Methods and Performance Goals for Underwater Breathing Apparatus", June 1994.
5. Boron, W. F., "Mechanics of Ventilation", In: Walter F. Boron and Emile L. Boulpaep, eds., Medical Physiology: A Cellular and Molecular Approach, 2nd edition, (Philadelphia, PA: Saunders/Elsevier, 2009), pp. 630-651.
6. Lanphier, E.H. and E.M. Camporesi, "Respiration and Exertion", In: The Physiology and Medicine of Diving, 4th Ed., P.B. Bennett and D.H. Elliott, eds, W.B. Saunders Co., London, 1993.
7. Taylor, N.A.S. and J.B. Morrison, "Lung centroid pressure in immersed man". Undersea Biomedical Research, Vol. 16, pp.3-19, 1989.
8. Clarke, J.R., "Optimal hydrostatic loading for closed-circuit underwater breathing apparatus", Naval Medical Research Institute, NMRI Report 91-08, 1991.
9. Carlson, N., J.R. Clarke, and E.T. Flynn, "The effects of hydrostatic loading during immersion on oxygen uptake and ventilatory endurance". Undersea Biomedical Research 16: Suppl., 1989.
10. Joye, D.D., J.R. Clarke, N.A. Carlson, and E.D. Thalmann, "Characterization and measurement of elastance with application to underwater breathing apparatus", Undersea and Hyperbaric Medicine 21:53-65, 199,
11. Lundgren, CEG, "Biomedical criteria for optimal elastic resistance in divers' underwater breathing apparatus", Final Report, Navy Medical Research & Development Command, NMRDC Project N0001489J1702, 1993.
12. Warkander, D. E., and C. E. G. Lundgren, "Development of Comprehensive Performance Standards for Underwater Breathing Apparatus". Final report to U.S. Navy: Naval Sea Systems Command and Office of Naval Research. Center for Research and Education in

Special Environments, University at Buffalo, Buffalo, NY, 2000.

13. Fishman, A.P., L.E. Farhi and S.M. Tenney, Eds, Handbook of Physiology, Section 3: The Respiratory System, Volume IV. Gas Exchange, American Physiological Society, Bethesda, 1987.
14. Powers, S.K., W. Riley, and E.T. Howley, "Comparison of fat metabolism between trained men and women during prolonged aerobic work". Research Quarterly for Exercise and Sport 51(2): 427-431, 1980.
15. Jansson, E., "On the significance of the respiratory exchange ratio after different diets during exercise in man", Acta Physiologica. Scandinavica., 114:103, 1982.
16. Fagraeus, L., "Cardiorespiratory and metabolic functions during exercise in the hyperbaric environment". Acta. Physiologica. Scandinavica. Suppl. 414, 1974a.
17. Clarke, J.R., "Statistically based CO₂ canister duration limits for closed-circuit underwater breathing apparatus". Navy Experimental Diving Unit, NEDU Technical Report 2-99, 1999.
18. Clarke, J.R. and V. Ferris. "The use of one-sample prediction intervals for estimating CO₂ scrubber durations". Navy Experimental Diving Unit , NEDU TR 12-03, 2012.

CHAPTER 4. PERFORMANCE GOALS AND LIMITS

NEDU is transitioning from its historical performance goals to a combination of performance *goals* and *limits*. When UBAs are tested, the measurement used to pass the equipment (recommended for certification or AMU) will be the lesser of *goals* and *limits*. Depending on depth, the *goals* may be more stringent than the *limits*, particularly at shallow depths; but, at deeper depths the *limits* may be more stringent.

New limits are required because rebreathers (category 4) rarely if ever pass the historical NEDU goals, whereas they will most likely pass the new limits under most diving conditions.

4.1 FLOW-RATE-DEPENDENT PERFORMANCE GOALS

This Technical Manual contains a modified excerpt from the original performance goals¹ as a means of preserving diver comfort and stimulating engineering excellence (Table 4.1) while adding performance limits^{2,3} to what is physiologically acceptable. This approach is akin to the methods used by Morrison and Reimers (1982) in defining separate limits for comfort and tolerance⁴. A UBA that meets the following performance goals (Table 4-1) would most likely easily meet the new NEDU performance limits except at high gas density.

Table 4-1 2015 Modification of Original NEDU Performance Goals

ALL CATEGORIES 0 to 200 fsw air 0 to 1500 fsw HeO ₂							
$\dot{V}CO_2$ (L/min)	RMV (L/min)	V_T (L)	f (BPM)	PEAK FLOW RATE (L/sec)	$\Delta P^{(1)}$ (kPa)	RESISTIVE EFFORT	
						kg·m/L	kPa (J/L)
0.90	22.5	1.5	15	1.18	1.74	0.14	1.37
1.60	40.0	2.0	20	2.09	1.74	0.14	1.37
2.50	62.5	2.5	25	3.27	1.96	0.16	1.54
3.00	75.0	2.5	30	3.93	2.75	0.22	2.16
3.60	90.0	3.0	30	4.71	3.93	0.32	3.09

Notes: ⁽¹⁾ ΔP_{max} is measured from maximum inhalation to maximum exhalation pressure. For sinusoidal breathing of a pure resistance, peak to peak pressure = 1.273 x Resistive Effort.

Table 4-1 simplifies the disparate goals presented in NEDU documents^{1,5} by applying the previous goals for Category 1 to moderate ventilation rates (RMVs of 22.5 and 40 L/min) and categories 3 and 5 at higher ventilation rates (62.5 – 90 L/min). For example: An incorrectly assembled KM 37 helmet caused a diver severe respiratory distress and near loss of consciousness near the surface. When tested, the helmet's resistive effort (RE) at 0 fsw and an

RMV of 40 L/min was 2.14 kPa. It therefore failed the NEDU goals. When properly assembled, its RE was 0.44 kPa, and the helmet easily passed the NEDU goals.

4.2 ACCEPTABLE LEVELS OF WORK OF BREATHING

4.2.1 Air Diving Acceptable levels of Work of Breathing

NEDU's limits on work of breathing on air follow the equation

$$RE_{\max} = A - B \cdot \text{depth}, \quad (4-1)$$

where $A = 2.99 \text{ kPa}$ and $B = 0.00636 \text{ kPa/fsw}$ (0.021 kPa/msw).

Figure 4-1 is an illustration showing the limits on resistive work of breathing (resistive effort) for several gas mixtures and how they change with common diving depths.

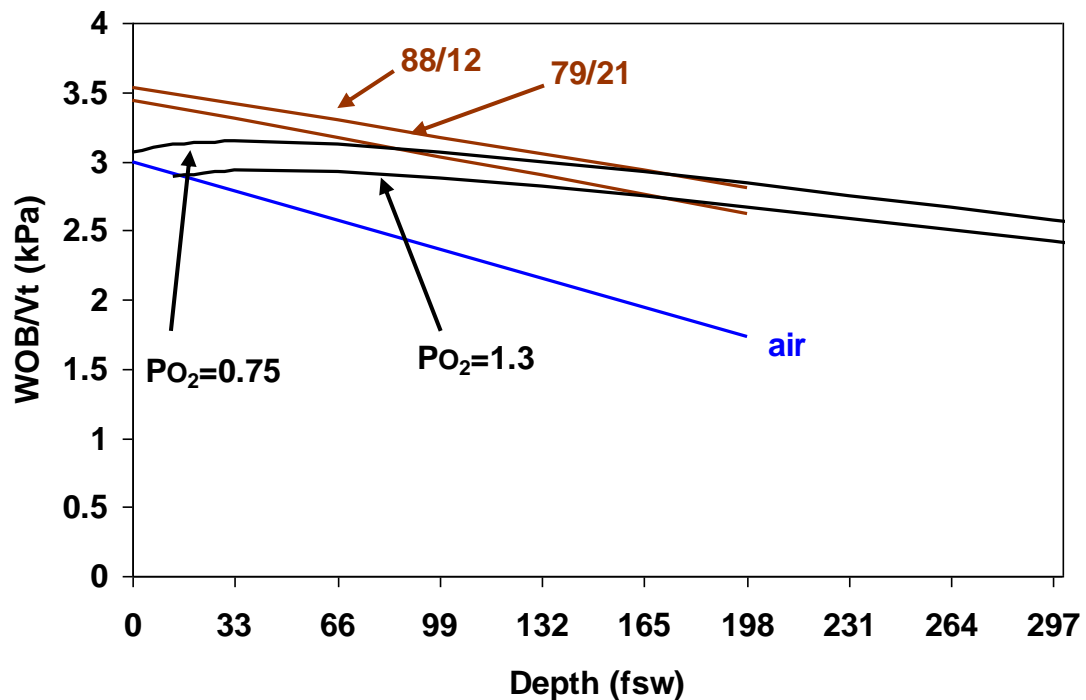


Figure 4-1 NEDU's limits on resistive effort in an air/nitrox atmosphere

4.2.2 Heliox Diving Acceptable levels of Work of Breathing

NEDU's limits on RE for heliox breathing divers are based on empirically determined changes in breathing capacity³. The changes in coefficients A and B (equation 4-1) depend on which heliox mixture is used. For details of these determinations, see Warkander (2010).

Diving with heliox with a constant O₂ concentration: Table 4-2 shows the coefficients.

Table 4-2 Coefficients for performance limits for varying oxygen percentages in heliox.

FO ₂ (%)	A (kPa)	B	
		(kPa/msw)	(kPa/fsw)
21	3.44	0.0137	0.00414
20	3.45	0.0135	0.00410
19	3.46	0.0134	0.00405
18	3.47	0.0132	0.00400
17	3.48	0.0130	0.00395
16	3.49	0.0129	0.00390
15	3.50	0.0127	0.00385
14	3.52	0.0125	0.00379
13	3.53	0.0123	0.00374
12	3.54	0.0122	0.00368
11	3.55	0.0120	0.00363
10	3.56	0.0118	0.00357
9	3.57	0.0116	0.00351
8	3.59	0.0114	0.00345
7	3.60	0.0112	0.00338
6	3.61	0.0110	0.00332
5	3.63	0.0107	0.00325
4	3.64	0.0105	0.00318
3	3.65	0.0103	0.00311
2	3.67	0.0100	0.00304
1	3.68	0.0098	0.00296

Diving with heliox with fixed partial pressure: In an UBA with a constant partial pressure of O₂, the O₂ concentration will vary with depth and coefficients A and B as well. Table 4-3 shows the limits for common diving depths.

Table 4-3 Limits in kPa (RE) for common diving depths and gas mixtures. PO₂ in atmospheres absolute (ATA).

Depth (fsw)	Depth (msw)	Breathing Gas				
		Air	He/O ₂ (79/21)	He/O ₂ (88/12)	PO ₂ = 0.75	PO ₂ = 1.3
0	0	2.99	3.44	3.54	3.06	-
33	10	2.78	3.31	3.42	3.14	2.93
66	20	2.57	3.17	3.29	3.12	2.93
99	30	2.36	3.03	3.17	3.07	2.88
132	40	2.15	2.90	3.05	3.00	2.82
165	50	1.94	2.76	2.93	2.92	2.75
190	57	1.79	2.66	2.84	2.86	2.69
198	60	-	2.62	2.81	2.84	2.67
231	70	-	2.49	2.69	2.75	2.59
264	80	-	2.35	2.57	2.67	2.50
297	90	-	2.21	2.44	2.58	2.42
300	91	-	2.20	2.43	2.57	2.41
330	100	-	1.94	2.32	2.49	2.33

4.2.3 Other UBA Acceptance Criteria

While NEDU is most commonly interested in the resistive component of impedance, measured by resistive effort (RE, or kPa), there are other respiratory loads that are important to NEDU's evaluation of UBA acceptability:

Elastance acceptable levels

Elastance should not exceed 7 cmH₂O/liter (0.69 kPa/L) independent of depth^{6,7}. These are the same values given in TM 01-94.

Hydrostatic loading (static lung load) acceptable levels

Table 4-4 shows maximum acceptable levels of hydrostatic imbalance for an upright and a horizontal diver. These values represent a change from TM 01-94¹.

Table 4-4 Maximum tolerable hydrostatic imbalances (kPa).

Diver orientation	Reference point	
	Lung centroid	Suprasternal notch
Upright (vertical)	-1.0 to +1.5 kPa	+0.4 to +2.9 kPa
Prone (swimming face down)	-1.0 to +1.0 kPa	-0.3 to +1.7 kPa

Respiratory load combinations

Even the simplest of UBAs, the snorkel, imposes at least two respiratory loads: breathing resistance (R) and hydrostatic imbalance (HI). When the respiratory loads act together, they are additive⁶. This means that the total respiratory load (Load%) can be calculated by adding the relative value for each load (when acting alone):

$$\text{Load\%} = \%R + \%E + \%HI \quad (4-2)$$

where %R is the ratio of the resistive load (RE) in a given situation to the maximum acceptable load in the same situation. Similarly, %E and %HI are the relative loads for elastance and hydrostatic imbalance.

Warkander (2007) points out that the work of breathing limits, elastance limits and the limits on hydrostatic imbalance are based on studies in which subjects worked hard (60% of their maximum) for 25 minutes². Therefore, it is possible to sustain a respiratory load higher than the proposed limit for a shorter time or a lesser load for a longer time than the proposed limit.

When a diver's Load% approaches or exceeds 100%, it is unlikely that the diver will be able to sustain that load for more than 25 minutes.

Example of judging UBA acceptability

Assume that a diver is swimming in the prone position and breathing air. The ventilation is 40 L/min and the depth is 10 msw (33 fsw). The following respiratory loads are imposed by the breathing apparatus:

Resistive Effort (RE): empirically determined to be 0.72 kPa. Table 4-3 shows that the maximum RE at this depth is 2.78 kPa. The current load is then $0.72/2.78 = 26\%$ of the limit.

Elastance: empirically determined to be 0.2 kPa/L. This is $0.2/0.7 = 29\%$ of the limit.

Hydrostatic imbalance: empirically determined to be +0.5 kPa. This load is $0.5/1.5 = 33\%$ of the maximum allowed.

These three loads add up to a total of $26\% + 29\% + 33\% = 88\%$. Since the total load is below 100% the breathing apparatus should be acceptable.

4.3 RESISTIVE EFFORT DATA JUDGMENT PROCESS

4.3.1 Rationale

The NEDU approach to respiratory comfort and tolerance takes into account both the effects of depth and ventilation rate on the ability of a diver to breathe with an UBA. A somewhat equivalent approach is obtained by simultaneously testing measured Resistive Effort data against performance goals (ventilation influence only) and performance limits (depth effect only). Performance goals are designed for long term diver comfort, and performance limits

indicate a limit for diver tolerance to respiratory loads not to exceed a duration of 25 minutes or greater. The following examples will illustrate these approaches for scuba (Category 1), MK16 and Megalodon rebreathers (Category 4), MK 21, and KM 37 helmets (Category 2).

Example 1. Scuba

Step 1. List the mean (average) result of five Resistive Effort tests in a matrix of ventilation versus depth, with each of the five tests conducted under the same conditions; e.g., five tests at 0 fsw and 22.5 L/min RMV.

Resistive effort data (units of kPa) for a scuba regulator, Table 4-5, indicates excessively high oral pressure during the test, a pressure which caused an automatic abort of the test to protect transducers. Resistive effort (RE) is expressed as the work of breathing per unit volume and calculated with the resistive effort for a respiratory load acting alone. It does not include the influence of elastance or hydrostatics.

Table 4-5 Resistive Effort Data for Scuba Regulator

Ventilation (L/min)	Depth (fsw)						
	0	33	66	99	132	165	198
22.5	0.62	0.70	0.76	0.80	0.84	0.85	0.86
40.0	0.73	0.86	0.93	0.98	1.01	1.03	1.05
62.5	0.83	0.98	1.04	1.09	1.12	1.13	1.17
75.0	0.86	1.00	1.07	1.12	1.18	1.22	1.60
90.0	0.90	1.03	1.11	1.18	1.40	2.65	XP

Step 2. Compare the data in the matrix to Table 4-6 (helium gas mixtures) or Table 4-7 (air or nitrox mixtures), the NEDU Performance Goals as a function of ventilation rate (ignoring depth) and Table 4-8, Performance Limits as a function of depth (ignoring ventilation).

Table 4-6 Performance goals (in kPa) as a function of ventilation rate (RMV).

	Ventilation (L/min)				
RMV	22.5	40	62.5	75	90
RE (kPa)	1.37	1.37	1.54*	2.16	3.09

*The original NEDU Performance Goals⁵ allowed a tolerance of $\pm 10\%$. For a goal of 1.37 kPa that translates to 1.51. The new goal at 62.5 kPa is very close to that old tolerance limit.

Table 4-7 Resistive Effort (kPa) performance limits as a function of depth and independent of ventilation rate for UBA, air or nitrox diluent.

Numbers must be calculated using equation 4.1 for the appropriate gas density.

	Depth (fsw)						
Depth (fsw)	0	33	66	99	132	165	198
RE (kPa)	2.99	2.78	2.57	2.36	2.15	1.94	1.73

Step 3. Indicate, for example by color, those Resistive Effort measurements which meet the NEDU Performance Goals and Limits (Table 4-8).

**Table 4-8 Scuba regulator recommended for Fleet use.
Limits were for air.**

Ventilation (L/min)	Depth (fsw)							Goals (kPa)
	0	33	66	99	132	165	198	
22.5	0.62	0.70	0.76	0.80	0.84	0.85	0.86	1.37
40.0	0.73	0.86	0.93	0.98	1.01	1.03	1.05	1.37
62.5	0.83	0.98	1.04	1.09	1.12	1.13	1.17	1.54
75.0	0.86	1.00	1.07	1.12	1.18	1.22	1.60	2.16
90.0	0.90	1.03	1.11	1.18	1.40	2.65	XP	---
Limits (kPa)	2.99	2.78	2.57	2.36	2.15	1.94	1.73	

Green (bold): Met both limits and goals.

Red (strikethrough): Exceeded limits.

XP: Excessively high oral pressure. No measurement possible

Note: Although the “goal” of 3.09 kPa for RMVs of 90 L/min has a historical precedent (TR 3-81, and TM 01-94), it has been removed from this and following tables since it is higher than any of the new limits. Therefore it is no longer suitable as a “goal”. That deletion is indicated in the Tables by ---.

Example 2 Scuba.

Table 4-9 Scuba regulator involved in a shallow water diving fatality.

Ventilation (L/min)	Depth (fsw)							Goals (kPa)
	0	33	66	99	132	165	198	
22.5		4.21		5.15				1.37
40.0		5.03	6.71	15.02				1.37
62.5	6.35	9.51						1.54
75.0	6.62	14.06						2.16
90.0	7.20							---
Limits (kPa)	2.99	2.78	2.57	2.36	2.15	1.94	1.73	

Limits were for air.

Red (strikethrough): Exceeded limits.

Example 3 MK 16 Rebreather in helium.

Limits for a heliox gas mixture with a PO₂ of 1.3 ATA.

Table 4-10 MK 16 Rebreather in helium

Ventilation (L/min)	Depth (fsw)					Goals (kPa)
	165	198	231	264	300	
22.5	0.26	0.27	0.34	0.39	0.42	1.37
40.0	0.42	0.52	0.70	0.70	0.94	1.37
62.5	0.75	0.95	1.14	1.14	1.77	1.54
75.0	0.89	1.26	1.59	2.05	2.55	2.16
90.0	1.15	1.68	2.39	2.97	3.35	---
Limits (kPa)	2.75	2.67	2.59	2.50	2.41	

Green (bold): Met both limits and goals.

Grey: Met limits or goals but not both.

Red (strikethrough): Exceeded limits.

Example 4 Megalodon Rebreather UBA in Helium

Table 4-11 Megalodon in 1.3 ATA PO₂ in Helium

Ventilation (L/min)	Depth (fsw)					Goals (kPa)
	165	198	231	264	300	
22.5	0.38	0.39	0.39	0.40	0.41	1.37
40.0	0.55	0.57	0.57	0.62	0.65	1.37
62.5	0.83	0.91	0.96	1.02	1.08	1.54
75.0	1.02	1.12	1.19	1.27	1.36	2.16
90.0	1.27	1.39	1.51	1.62	1.74	---
Limits (kPa)	2.75	2.67	2.59	2.50	2.41	

Green (bold): Met both limits and goals.

Example 5. Megalodon Rebreather in air/nitrox

Table 4-12 Megalodon Rebreather in air/nitrox

Ventilation (L/min)	Depth (fsw)					Goals (kPa)
	0	66	99	132	165	
22.5	0.36	0.42	0.46	0.48	0.53	1.37
40.0	0.44	0.67	0.77	0.87	0.97	1.37
62.5	0.60	1.12	1.35	1.56	1.78	1.54
75.0	0.70	1.41	1.72	2.03	2.33	2.16
90.0	0.84	1.81	2.25	2.68	3.10	---
Limits (kPa)	2.99	2.57	2.36	2.15	1.94	

Megalodon Rebreather in air/nitrox

Green (bold): Met both limits and goals.

Grey: Met limits or goals but not both.

Red (strikethrough): Exceeded limits.

Example 6. MK 21 Helmet

Table 4-13 MK 21 Helmet with Air

Ventilation (L/min)	Depth (fsw)							Goals (kPa)
	0	33	66	99	132	165	198	
22.5		0.49	0.54	0.65	0.55	0.58	0.62	1.37
40.0		0.59	0.67	0.82	0.78	0.84	0.91	1.37
62.5		0.67	0.88	1.14	1.17	1.32	1.63	1.54
75.0		0.74	1.05	1.35	1.40	1.82	2.17	2.16
90.0		0.85	1.24	1.68	1.92	2.34	2.60	---
Limits (kPa)	2.99	2.78	2.57	2.36	2.15	1.94	1.79	

Data from NEDU TR 11-93.

Green (bold): Met both limits and goals.

Grey: Met limits or goals but not both.

Red (strikethrough): Met neither limits nor goals.

XP: Excessively high oral pressure. No measurement achievable.

Example 7. KM 37 Helmet with 88/12 HeO₂

Table 4-14 KM 37 Helmet with 88/12 HeO₂

Ventilation (L/min)	Depth (fsw)								Goals (kPa)
	165	198	231	264	297	330	363	380	
22.5	0.93	0.96	1.03	1.0	0.98	1.06	1.08	1.11	1.37
40.0	1.17	1.23	1.30	1.30	1.28	1.39	1.42	1.45	1.37
62.5	1.42	1.49	1.59*	1.61*	1.58	1.73	1.80	1.88	1.54
75.0	1.51	1.61	1.73	1.76	1.72	1.97	2.14	2.31	2.16
90.0	1.65	1.76	1.96	2.07	2.21	2.98	3.46	XP	---
Limits (kPa)	2.93	2.84	2.81	2.57	2.44	2.33	2.20	2.14	

Green (bold): Met both limits and goals.

Grey: Met limits or goals but not both.

Red/strikethrough: Met neither limits nor goals.

* Does not statistically exceed closest limit or goal

XP: Excessively high oral pressure. No measurement achievable.

When a mean value lies just above a goal or limit, a simple one-sample T-test can be used to confirm whether the mean of five measurements is statistically above (or below) the corresponding goal or limit. When a mean value passes that test, then it should be marked by an asterisk indicating that the mean statistically meets the goal or limit.

REFERENCES

1. NEDU Technical Manual 01-94, U.S. Navy Unmanned Test Methods and Performance Goals for Underwater Breathing Apparatus., June 1994.
2. Warkander, D.E., “Comprehensive Performance Limits for Divers’ Underwater Breathing Gear: Consequences of Adopting Diver-focused Limits”. Navy Experimental Diving Unit Technical Report 07-02. Panama City, Florida: NEDU, 2007.
3. Warkander, D.E., “Work of Breathing Limits for Heliox Breathing”. Navy Experimental Diving Unit Technical Report 10-14. Panama City, Florida: NEDU, 2010.
4. Morrison, J.B., and S.D. Reimers. “Design Principles of Underwater Breathing Apparatus.” In *The Physiology and Medicine of Diving*, 3rd ed., edited by P. B. Bennett and D. H. Elliot, 55–98. San Pedro, Cal.: Best Publishing, 1982.
5. Middleton, J.R. and E. D. Thalmann. “Standardized NEDU Unmanned UBA Test Procedures and Performance Goals”. Navy Experimental Diving Unit Technical Report 3-81. Panama City, Florida: NEDU, 1981.
6. Warkander, D.E. and C.E.G. Lundgren. ”Development of Comprehensive Performance Standards for Underwater Breathing Apparatus”. Final report to U.S. Navy: Naval Sea Systems Command and Office of Naval Research. Center for Research and Education in Special Environments, University at Buffalo, Buffalo, NY, 2000.
7. Warkander, D.E., “Recommended Amendment to NEDU Technical Manual 01-94: U.S. Navy Unmanned Test Methods and Performance Goals for Underwater Breathing Apparatus”. Navy Experimental Diving Unit Technical Memo 08-17. Panama City, Florida: NEDU, 2008.

CHAPTER 5. CALIBRATION AND TEST METHODS

5-1 GENERAL

This chapter covers calibration procedures for instrumentation, required test equipment, setup of unmanned tests, test procedures for the five categories of UBA, and general guidelines for data collection.

5-2 DATA ACQUISITION AND ANALYSIS

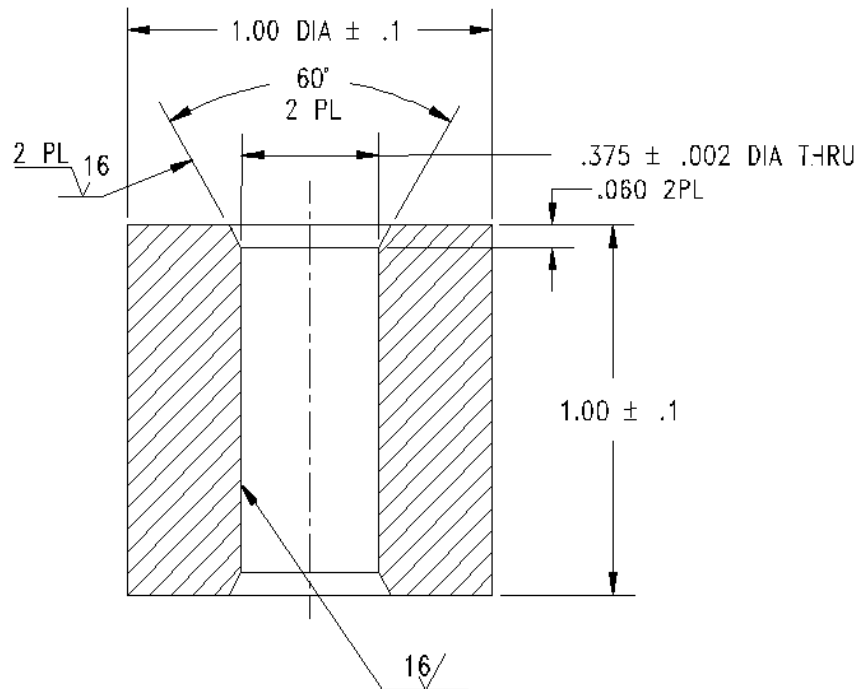
The area bounded by the P-V closed curve (P-V loop, Figure 3-2), represents work, and is calculated using the trapezoidal method of integration. The value for work is then divided by the tidal volume yielding a volume-averaged pressure with units of kPa or J/L. The software that controls the breathing simulator also collects the pressure and volume data, and calculates the resistive effort and other characteristics of the P-V loops. This software is a proprietary application developed by NEDU using Microsoft Visual Basic. More details of the software capabilities are given in Chapter 6. Pressure and volume data as a function of time are written to a spreadsheet file. Following each day's run, all test data are archived.

5-3 CALIBRATION

Before testing can begin, the results of all pertinent baseline calibrations must be written into the test log book, reviewed and approved by the test supervisor. During the course of testing, if any part of the sensing system is subjected to over-range or requires replacement, recalibration will be necessary.

5-3.1 NEDU Standard Orifice

The NEDU Standard Orifice, Figure 5-1, designed and developed by Cowgill, Landstra, and Mobley (CLM), is a performance standard to daily verify the proper functioning of the complete breathing loop, including the breathing simulator. The orifice is a highly polished cylinder with fixed physical dimensions. The purpose of the orifice is to provide a relatively fixed breathing resistance. At 1 ATA the orifice is placed where the mouthpiece of the UBA will be placed during actual UBA tests. The breathing machine is then operated, and a P-V loop recorded for each RMV to be used in testing. The calculated resistive effort is then compared against tolerance limits established for each RMV (Table 5-1). The measured resistive effort is then compared to the tolerance limits (these limits were established at 2 standard deviations above and below the mean of approved orifice checks). Example standard orifice P-V loops are found in Figure 5-2. If the standard orifice P-V loop check falls outside tolerance limits, then a problem exists, such as excess volume in the loop, high flow resistance, improper transducer calibration, or water trapped in various lines and hoses.



MATERIAL: STAINLESS STEEL 316 SERIES

Figure 5-1 Physical dimensions (inches) of the NEDU Standard Orifice.

Table 5-1 NEDU Standard Orifice Values Used for Daily P-V Loop Checks

RMV (L/min)	minimum RE (kPa)	maximum RE (kPa)	mean RE (kPa)
22.5	0.17	0.31	0.24
40.0	0.70	0.82	0.76
62.5	1.58	1.84	1.71
75.0	2.17	2.45	2.31
90.0	3.10	3.43	3.26

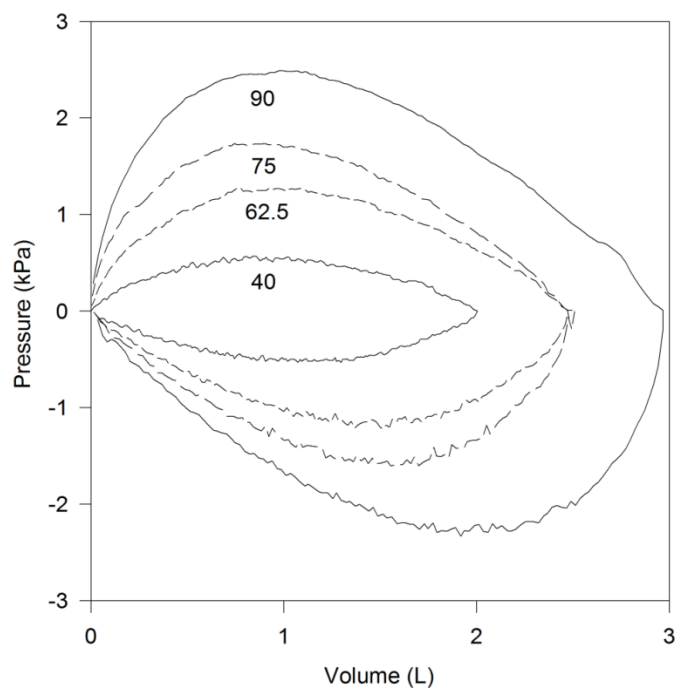


Figure 5-2 The family of typical P-V loops for the Standard Orifice at four standard RMV values in L/min (shown next to each loop).

5-3.2 NEDU STANDARD ELASTANCE

The NEDU Schlegel Elastance Verification Apparatus (SEVA) is an upright circular acrylic cylinder, 5 in. (12.7 cm) diameter, which is immersed vertically in water. Gas from the breathing machine enters the cylinder through the top hose connections. It adequately contains a 3 liter tidal volume.

The SEVA is used to confirm that measurement software is able to correctly calculate both resistive effort and UBA elastance which would be present in a closed circuit UBA (rebreather).

The elastance of this cylinder^{1,2} is by calculation 7.9 cmH₂O/L (0.8 kPa/L). This value is slightly greater than the elastance performance goal³ of 7.0 cmH₂O/L.



Elastance Test Procedure

1. Mount the SEVA submerged in water to the top plate and adjust 4 screws for level at the water's surface.
2. Connect the breathing loop routing block with a flexible coupling to the top pipe elbow.
3. Connect a low pressure air source to the top mounted metering valve.
4. With the breathing simulator at the "home" position, add air to the loop via the metering valve until a small amount of air expels from the open bottom of the SEVA.
5. Cycle the simulator at the various RMVs and record the elastance pressure.

Figure 5-3 Schlegel Elastance Verification Apparatus (SEVA).

5-4 NEDU BREATHING BLOCK

The NEDU Breathing Block (Figures 5-4 and 5-5) is a gas routing device with check valves that allow flow to and from the breathing simulator via two separate hoses. Oral pressure and inspired and expired gas temperatures are usually measured at the Breathing Block.

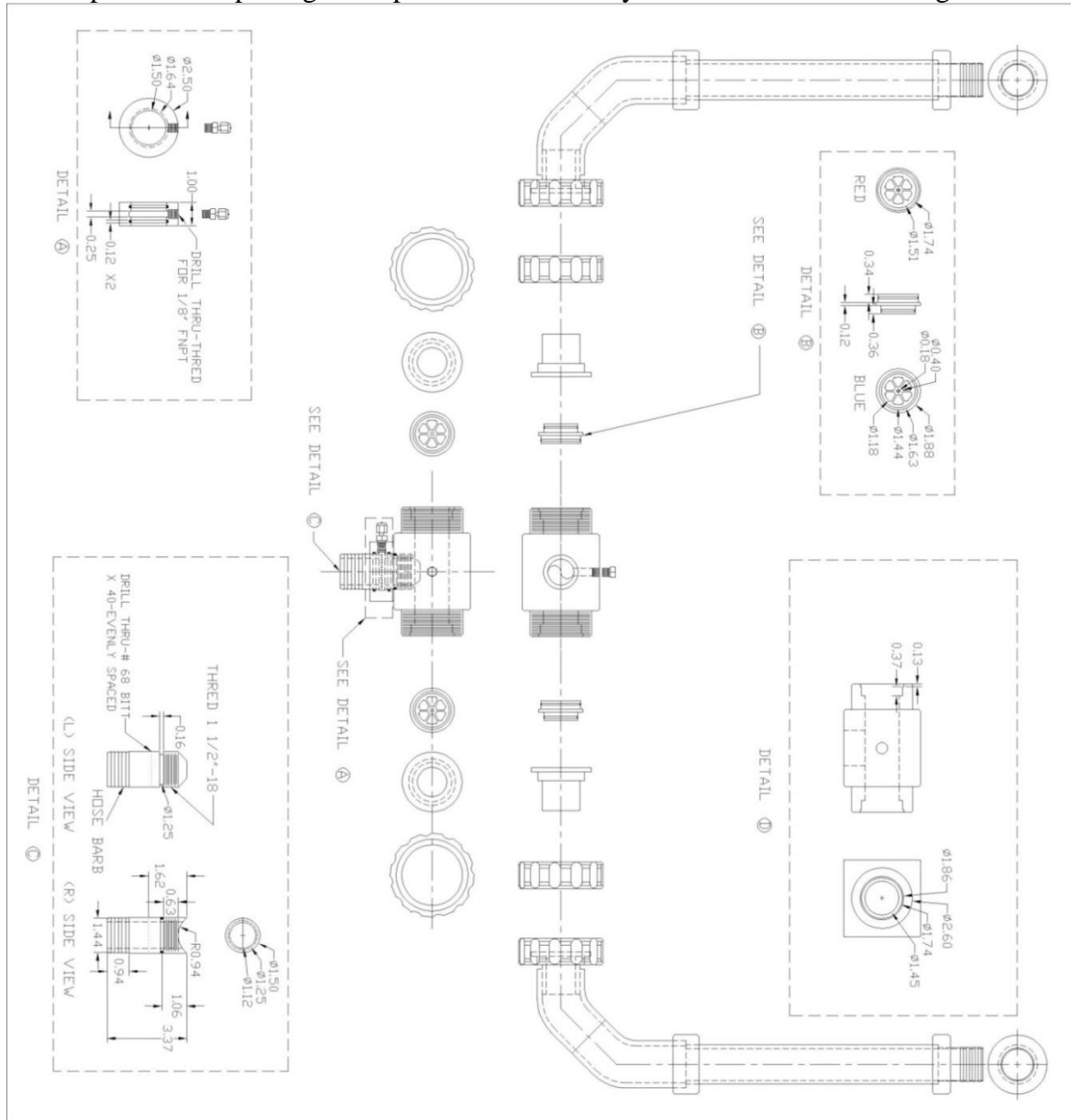


Figure 5-4 Drawing of the NEDU Breathing Block. Detail A is the pressure pickup enclosure. Detail B is the one-way valve holder, C is the pressure pickup tube, and Detail D is the routing block.

The breathing block functions as a gas routing device and also provides ports to enable measuring of characteristics of the gas in the breathing loop. Though not shown, gas sampling ports are also available to enable gas constituent concentrations (primarily oxygen and carbon dioxide) to be measured. Dewatering ports also exist.



Figure 5-5 Photograph of a typical Breathing Block used by NEDU.

The Standard Orifice is shown attached to the block with the blue flexible adapter. The white pressure pickup ring is used to measure oral pressure via a pressure transducer attached to its vertical stainless steel pressure port. Various pressure, temperature, drain and gas sample ports also are visible.

5-5 BREATHING SIMULATOR

The respiratory simulator is a noncompliant lung simulator that is calibrated to move a prescribed volume of gas at the Breathing Block of up to 3.0 liters at a controlled rate of up to 30 BPM. RMV is controllable to within ± 0.01 L/stroke. The inhalation and exhalation paths are separated by directional valves for better control of temperature, relative humidity, and constituent gas concentrations. NEDU uses four 103.4 bar (1,500 psig) breathing simulators, two built by Reimers Engineering (Model 1500, Alexandria, VA) and two built by Battelle (Columbus OH). Also available is a proprietary breathing simulator mounted internal to the chamber for tests requiring minimal loop volume (i.e., checking PO_2 overshoot in rebreathers.)

All five simulators use computer-controlled stepper motors. The simulators must be calibrated before collecting data.

5-5.1 Quarterly Integrity Evaluation

This test ensures that the total RMV flows from the outlet of the Breathing Block into the UBA, thereby identifying any system leaks or breathing simulator piston blow-by. The test normally is performed using air as the breathing gas. If testing using helium/oxygen gas mixtures is anticipated, the test may need to be performed using that specific gas mix to verify that the leak rate, which most likely will be greater than that obtained for air, is still acceptable.

The procedure conceptually is to apply a positive pressure to the process side (i.e., that side normally connected to the UBA) of the breathing simulator while collecting any gas that escapes across the piston seal into a volumetric measuring device, such as that shown in Figure 5-6. The test is conducted dynamically, with the piston moving continuously, to evaluate the leakage rate that should be representative of what will occur when testing is performed on a UBA.

5-5.1 Procedure

1. Connect the breathing simulator's inhale and exhale ports to the hyperbaric chamber and ensure they are open to the chamber atmosphere.
2. Connect the equalization port flex hose from the breathing simulator to a volumetric measurement device sufficiently large to accommodate the full tidal volume at which the test is to be conducted—typically 3.0 L.
3. With the breathing simulator able to freely draw volume from and return volume to the hyperbaric chamber, slowly pressurize the chamber to 1.0 ± 0.1 psig and maintain at that pressure.
4. Establish a starting point for the volumetric measuring device and record this volume.
5. Operate the breathing simulator at the maximum volume anticipated in the study to be performed, typically 3.0 L, and minimal BPM, typically 10.

This minimizes the inertia of the system and evaluates the piston seals at a constant



**Figure 5-5 Tissot Gasometer,
Collins 120-L**

pressure slightly greater than that typically seen during extended duration tests.

6. Upon completion of 100 breaths at 3.0 L and 10 BPM the simulator's piston is returned to its "home" position. Any increase in volume measured from the starting volume of the measuring device has resulted from piston seal leakage. This is the total volume change. Record values and depressurize chamber.
7. The leakage per stroke is calculated by dividing the total volume change measured in step 6 by the total number of strokes. If this leakage is not ≤ 0.01 L per stroke, then the breathing simulator piston seals should be replaced and the cylinder wall inspected for possible scoring.

5-5.2 Daily Calibration

Daily calibration occurs in three stages: pressure calibration, volume calibration, and system calibration check.

1. First, a two point calibration is carried out on the positive side of the oral pressure transducer (± 7 kPa range) attached to the Breathing Block. Pressure levels of 0 kPa and +4 kPa are produced and verified by a precision digital pressure gauge. Voltages produced by the transducer, which are directly proportional to pressure, are sensed by the data acquisition computer running the NEDU resistive effort software and used by the calibration part of that program.
2. A two point calibration is then performed on the breathing machine piston-position transducer. This transducer, an LVDT, measures the piston position inside the cylinder relative to the "home" position. The volume of gas moved by the simulator is a linear function of its piston position.
3. Calculated LVDT transducer coefficients are computed and stored in a file along with the pressure transducer coefficients. To minimize incorrect tidal volume readings as RMV values are varied, the volume transducer readings are checked at each tidal volume setting that will be used during testing (typically 1.5, 2.0, 2.5 and 3.0 Liters).
4. The integrity of the overall system is checked by measuring the breathing effort of the NEDU Standard Orifice and comparing the resultant RE values to the values in Table 5-1.

P-V loops generated from the standard orifice are generally asymmetrical (Figure 5-2), presumably due to the compliance of the long breathing hose between the breathing machine and the Breathing Block inside the chamber. Methods for correcting for testing system compliance have been described. Typically, the small amount of elastance present does not cause significant changes in measured resistive effort values and NEDU does not normally apply elastance corrections to reported RE data.

5-5.3 Temperature Calibration and Corrections

Temperature probes should be calibrated over the range to be measured using an appropriate temperature measuring instrument. An accuracy of $\pm 1^\circ\text{F}$ is sufficient for almost all tests performed at NEDU.

When calibrating the breathing machine, it is essential that both the breathing and the calibration device, for example a Tissot gasometer, be at the same temperature and humidity conditions, or that an appropriate correction be applied. If the breathing machine is warmer than the gasometer, then the volume measured by the gasometer will be less than that actually delivered at the outlet of the breathing machine. The volume corrections can be calculated by using Charles law as described in the next two sections.

5-5.4 Heat Exchangers and Temperature Control

Physiologists routinely express volume excursions of the lungs in terms of gas volumes at BTPS conditions. However, human upper airways are efficient heat exchangers, so that if cool gas is inhaled, that gas becomes warmed and humidified before reaching the alveolar spaces in the deepest regions of the lungs. At the same time, the upper airways become cooled. During the following exhalation warm gas from the lungs is cooled by the upper airways.

Equation 5-1 relates exhaled gas temperature to inhaled gas temperature⁴, thereby serving as a target for NEDU's conditioning of gas exhaled from breathing machines.

$$T_{ex} = 24 + 0.32 \cdot T_{in} \quad (5-1)$$

To that end, gas is heated and saturated with water by heat exchangers after it leaves the breathing machine and before it enters the SCSR.

Once saturated with moisture, recirculated gas remains saturated. However, the bulk of metal comprising the breathing machine cylinder and piston serves as a large heat sink, so that the gas within the breathing machine is returned to ambient temperature ($\sim 21^\circ\text{C}$).

5-5.5 Gas Volume Conversions

Some sponsors such as the National Institute of Occupational Safety and Health (NIOSH) require all gas volumes to be expressed at standard temperature (0°C) and pressure (760 mmHg) dry (STPD).

NEDU's breathing simulators have a fixed volume excursion based on geometry. A three-Liter tidal volume is 3-L regardless of the temperature of the gas. With moisture-saturated gas inhaled from a rebreather into the breathing machine, the gas delivered by the breathing machine is humidified, and due to the thermal mass of the breathing machine, cooled to ambient

conditions. The gas exhaled is therefore at ambient temperature, ambient (chamber) pressure, saturated conditions (ATPS).

Since ATPS conditions are not physiological, the gas exhaled at ATPS is heated, and moisture added until it approximates physiological conditions as described by Equation 5-1. This condition is T_{exPS} . T_{exPS} is not the same as BTPS since 37°C only exists deep in the human lungs.

Table 5-2 ATPS to STPD and BTPS conversions for select respiratory minute volumes (RMV).

RMV (L/min) ATPS (21°C)	RMV (L/min) STPD (0°C)	RMV (L/MIN) BTPS (37°C)
74.6	65.0	78.7
50.5	44	53.3
23.0	20	24.2
10.1	8.8	10.7

Mahler et al (1982) found in ventilatory measures in 20 non-athletic adults in the 20-30 year age range, that resting ventilation was 11 ± 4 L/min (BTPS).⁵ That RMV is half that of NEDU's normal RMV, but in some instances may be called upon by the sponsor.

A ventilator setting of 10.1 L/min ATPS corresponds to 10.7 L/min BTPS, which is close to Mahler's mean value of 11. That RMV is equivalent to 8.8 L/min STPD. (Gas coming from the breathing machine is saturated with water vapor, so no corrections other than temperature were required.)

5-6 CO₂ CANISTER DURATION CALIBRATIONS

Mass flow controllers (MFC) used for injecting CO₂ into the breathing loop should be adjusted and calibrated by the manufacturer for use with this gas. NEDU checks the calibration of each MFC before a test project is started and again at the end of the project. Additional calibration checks are performed during the duration of the project whenever there is any indication that the flow rates have altered from their calibrated values. NEDU uses a precision flow calibration standard system to check mass flow controller performance and uses 0°C for the standard temperature in STPD calculations and reporting.

If no flow calibration standard is available, the MFC output can be checked by timing the flow into a chain-compensated Collins 120 liter Tissot or other appropriate gasometer. The test should be repeated a minimum of three times. Ensure that the CO₂ regulator pressure is set as specified by the MFC manual.

Note: Unless the measurement is made quickly, CO₂ will dissolve into a water-filled spirometer, giving a falsely low reading. For example, at equilibrium 1 L of water can contain 0.872 L (STPD) of CO₂ at 1 ATA and 20 °C. If CO₂ is in contact with the water only briefly, this error

will be minor. The problem can be virtually eliminated by filling the spirometer with low viscosity fluorocarbon oil, in which CO₂ is poorly soluble.

The calibration of the CO₂ analyzer is checked each day before and after a test is performed using zero, span, and mid-range calibration gases. If necessary, the instrument is re-calibrated using these same gases.

5-7 PO₂ CONTROL CALIBRATIONS

For simulating oxygen consumption and measuring oxygen control of a UBA, NEDU uses two MFCs. One injects nitrogen into the breathing loop and the other removes gas from the breathing loop that contains the amount of oxygen to be “consumed.” Thus the latter MFC controls the flow of a gas whose relative concentrations of nitrogen and oxygen vary. MFCs use thermal conductivity of gases to accurately measure and control flow. Since both oxygen and nitrogen have similar thermal conductivity properties both MFCs can be calibrated using nitrogen only.

Breathing gases that contain oxygen and helium cannot be controlled as easily or accurately with MFCs because the thermal conductivities of these two gases are very dissimilar. Thus when NEDU tests oxygen control performance of closed circuit UBAs the diluent gas is always a nitrogen/oxygen mix. If the dive being simulated in unmanned testing would normally require a helium/oxygen diluent, then the nitrogen/oxygen mix used for that testing will have the same concentration of oxygen as contained in the helium/oxygen diluent that would be used for a manned dive.

Calibration of the MFCs and the oxygen analyzer used in UBA oxygen control testing are performed as described in Section 5-6 for CO₂ control.

5-8 HYDROSTATIC IMBALANCE CALIBRATIONS

Calibration procedures for hydrostatic pressure measurements are detailed in chapter 10.

5-9 CATEGORY 1 UBA TEST METHODS

5-9.1 Introduction

The purpose of these test procedures is to establish a standardized method to evaluate Category 1 (open circuit demand) UBA performance. The results of these tests will be compared to standards for Category 1 UBA performance and could be used in the process for obtaining "Authorized for Military Use" (AMU) status for the UBA model being tested.

5-9.2 Test Equipment

More information on required test equipment is given in Section 5-14.

1. Test Article (UBA)
2. EDF Chamber Complex
3. Water Containment Ark
4. Breathing Simulator
5. Breathing Air Supply Whip
6. Breathing Air Supply Gauge
7. EDF Chamber Depth Gauge
8. Breathing Simulator Piston Position Transducer (LVDT)
9. Oral Pressure Transducer
10. First Stage Pressure Transducer
11. SCUBA tank with a dual valve to act as a volume tank allowing gas at a constant pressure and temperature to be supplied to the first stage regulator
12. Data Acquisition and Control Computer with software capable of collecting and analyzing the data at a rate fast enough to capture peaks of any pressure spikes that occur, and display and record data from the transducers

5-9.3 Test Setup

Test equipment shall be configured within the test facility as shown in Figure 5-7. Particular attention must be paid to the hose inner diameter and number of elbows used in the breathing loop. Flow restrictions have been found to critically affect test results.

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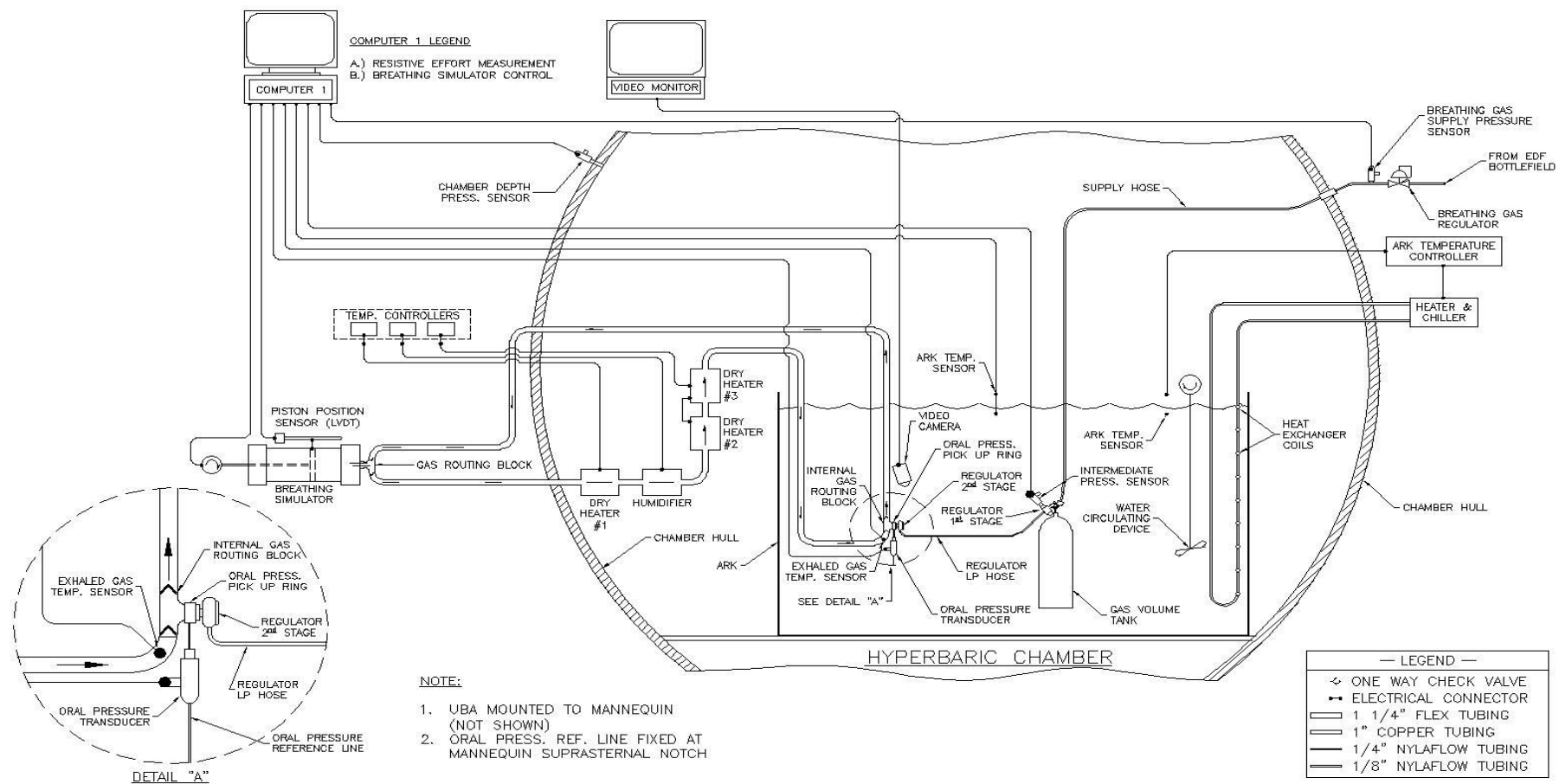


Figure 5-6 Test setup for resistive effort measurements on a Category 1 open circuit UBA

5-9.3.1 Parameters Controlled

1. Breathing simulator settings (standard values are given in Table 3.1)
2. Exhalation/inhalation time ratio: 1.00:1.00 (all tests).
3. Breathing wave form: sinusoidal (all tests)
4. First stage air supply pressure: 103.42 bar (1,500 psig) and 34.47 bar (500 psig).
5. Depth increment stops: normally 0 to 60.7 msw (0 to 198 fsw) in 10.11 msw (33 fsw) increments or per test plan
6. Ark water temperature and salinity

5-9.3.2 Parameters Measured

1. Inhalation oral peak ΔP in kPa
2. Exhalation oral peak ΔP in kPa
3. Oral ΔP vs volume data (for generating P-V loops)
4. Maximum static O/B pressure at first stage outlet (actual O/B)
5. Minimum dynamic O/B pressure at first stage outlet (first stage pressure drop)

5-9.3.3 Computations

1. Resistive Effort in kPa
2. Total Harmonic Distortion (THD) if appropriate

5-9.3.4 Parameters Compared

1. Peak Inhalation and Exhalation ΔP vs depth for each RMV and supply pressure if appropriate
2. Resistive effort at each depth, RMV and supply pressure
3. First stage pressure drop for each depth, RMV and supply pressure if appropriate

5-9.4 Test Procedures for Resistive Effort Evaluation

1.
 - a. Ensure that the test article is correctly oriented in the ark and the adjustable parameters are set, as specified in test plan, and is working properly.
 - b. Chamber on surface
 - c. Calibrate all transducers.
 - d. Perform Standard Orifice checks per 5-3.1.
 - e. Open gas supply valve to the test UBA including the valve on the scuba bottle.
 - f. Adjust breathing simulator to 22.5 L/min RMV per 5-9.4.1, and take data.

- g. Adjust breathing simulator for progressive RMVs per 5-9.4.1 until all tests at this depth are completed, UBA fails as outlined in the test plan, or testing is halted.
- h. Stop breathing simulator.



SAFETY NOTE: Breathing Simulator should be operating while increasing chamber depth to prevent flooding of, or damage to, equipment.

- 2.
 - a. Pressurize chamber to 60.7 msw (198 fsw) in 10.11 msw (33 fsw) increments or per test plan increments
 - b. Repeat steps 5-9.5.1.f through 5-9.5.1.h
 - c. NOTE: Upon completing all depths and test configurations, go to step 3
- 3.
 - a. Bring chamber to surface
 - b. Perform Standard Orifice measurements and check calibrations of transducers and instruments

5-9.5 Post Test Checks

The test supervisor will verify that all data collected are valid.

5-10 CATEGORY 2 UBA TEST METHODS

5-10.1 Introduction

The purpose of these test procedures is to establish a standardized method to evaluate Category 2 (umbilical-supplied demand) UBA performance. The results of these tests will be compared to standards for Category 2 UBA performance and could be used in the process of obtaining AMU or other authorized use status for the UBA being tested.

5-10.2 Test Equipment

More information for the required test equipment is given in Section 5-14.

- 1. Test Article (UBA)
- 2. EDF Chamber Complex
- 3. Water Containment Ark
- 4. Breathing Simulator
- 5. HeO₂ Mix or Breathing Gas Supply Whips
- 6. HeO₂ or Breathing Air Supply Gauge
- 7. EDF Chamber Depth Gauge

8. Breathing Simulator Piston Position Transducer (LVDT)
9. Oral Pressure Transducer
10. Pressure Transducer, 50 psid mounted within the test chamber to measure pressure drop across umbilical
11. Pressure Transducer, 50 psid mounted within the test chamber to measure sideblock assembly pressure drop
12. Data Acquisition and Control Computer with software installed capable of collecting and analyzing the data at a rate fast enough to capture peaks of any pressure spikes that occur, and display and record data from the transducers
13. Video monitoring, surveillance and recording equipment.

5-10.3 Test Setup

Test equipment shall be configured within the test facility as shown in Figure 5-8. Particular attention must be paid to the hose inner diameter and number of elbows used in the breathing loop. Flow restrictions have been found to critically affect test results.

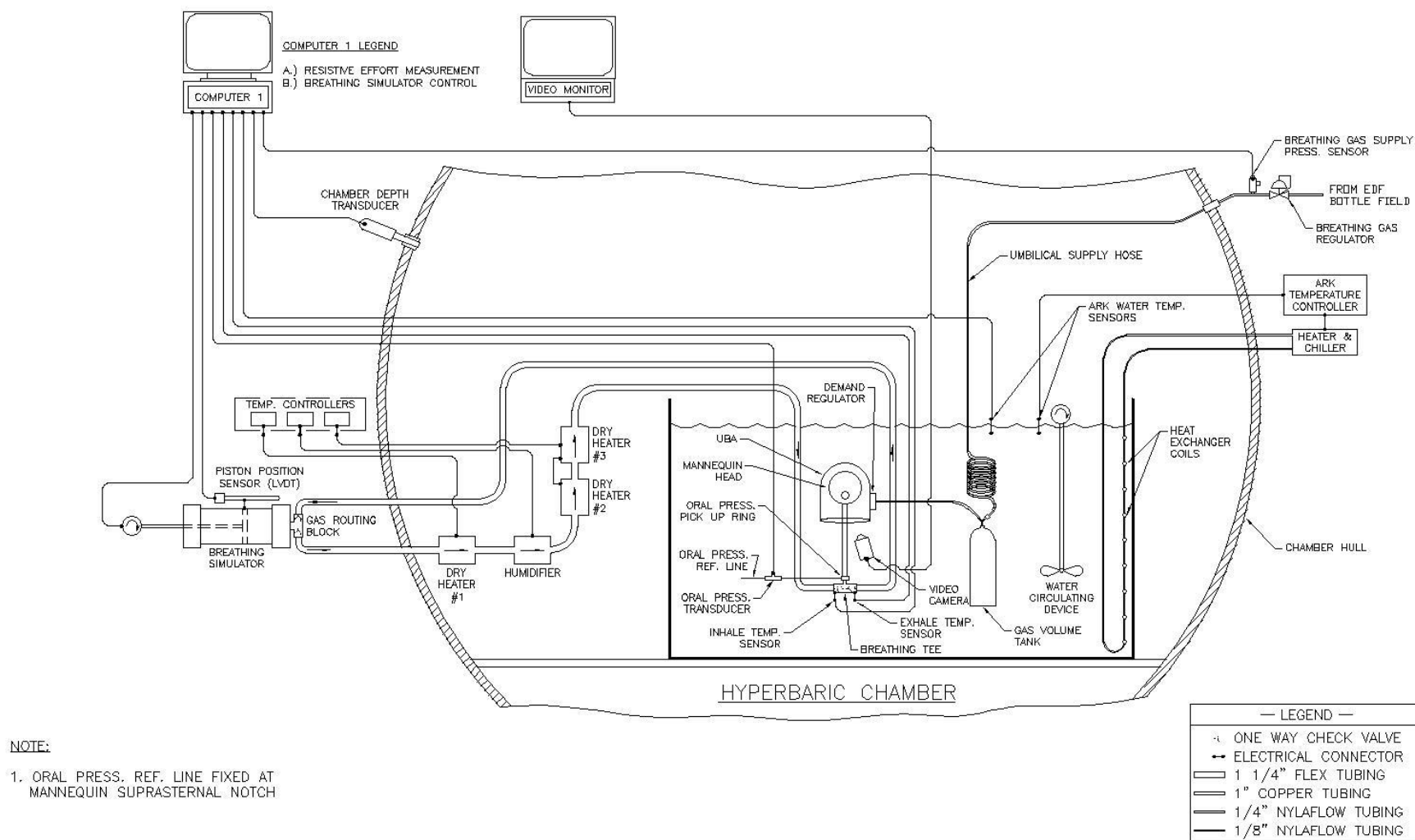
5-10.3.1 Parameters Controlled

1. Breathing simulator settings (standard values are given in Table 3-1)
2. Exhalation/inhalation time ratio: 1.00:1.00 (all tests)
3. Breathing wave form: sinusoidal (all tests)
4. Divers' gas supply pressure
5. Depth increment stops: normally 0 to 60.7 msw (0 to 198 fsw) in 10.1 msw (33 fsw) for nitrox breathing gas resistance measurements; 0 to 91.9 msw (0 to 300 fsw) in 10.1 msw (33 fsw) increments for heliox breathing gas resistance measurements; or per test plan
6. Ark water temperature

5-10.3.2 Parameters Measured

1. Inhalation oral peak ΔP (kPa)
2. Exhalation oral peak ΔP (kPa)
3. Oral ΔP vs. volume data (for generating P-V loops)
4. Umbilical pressure drop
5. Sideblock pressure drop

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5-10.3.2 Parameters Measured

1. Inhalation oral peak ΔP (kPa)
2. Exhalation oral peak ΔP (kPa)
3. Oral ΔP vs. volume data (for generating P-V loops)
4. Umbilical pressure drop
5. Sideblock pressure drop

5-10.3.3 Computations

1. Resistive effort in kPa
2. Total Harmonic Distortion (THD) if appropriate

5-10.3.4 Parameters Compared

1. Peak Inhalation and Exhalation ΔP vs. depth for each RMV if appropriate
2. Resistive effort at each depth and RMV
3. Umbilical pressure drop at each depth and RMV if appropriate
4. Dynamic pressure drop across sideblock assembly at each depth and RMV if appropriate

5-10.4 Test Procedures for Resistive Effort Evaluation

1.
 - a. Ensure that the demand regulator adjustable parameters are set per test plan (typically the middle value of manufacturer's specification), the UBA is oriented in the ark per the approved test plan, and is working properly.
 - b. Chamber on surface
 - c. Calibrate all transducers and instruments.
 - d. Perform Standard Orifice procedures per 5-3.1.
 - e. Open diver's breathing gas supply valve to regulator and set supply pressure per test plan.
 - f. Adjust breathing simulator to 22.5 L/min RMV per 5-9.4.1, and take data.
 - g. Adjust breathing simulator for progressive RMVs per 5-9.4.1 until all tests at this depth are completed, UBA fails, or testing is halted.
 - h. Stop breathing simulator.



SAFETY NOTE: **Breathing Simulator should be operating while increasing chamber depth to prevent flooding of equipment.**

2. a. Pressurize chamber from 10.1 msw (33 fsw) to max test depth in 10.1 msw (33 fsw) increments or per test plan increments.
- b. Repeat steps 5-10.4.1.f through 5-10.4.1.h.
- c. Note: upon completing all depths and test configurations, go to step 3.
3. a. Bring chamber to surface.
- b. Perform Standard Orifice measurements and check calibrations of transducers and instruments.

5-10.5 Post Test Checks

The test supervisor will verify that all data collected are valid.

5-11 CATEGORY 3 UBA TEST METHODS

5-11.1 Introduction

The purpose of these test procedures is to establish a standardized method to evaluate Category 3 (open circuit, umbilical supplied free-flow helmet) UBA performance. The results of these tests will be compared to standards for Category 3 performance and could be used in the process of obtaining AMU or other authorized status for the UBA being tested.

5-11.2 Test Equipment

More information on required test equipment is given in section 5-14.

1. Test Article (UBA)
2. EDF Chamber Complex
3. Water Containment Ark
4. Breathing Simulator
5. HeO₂ Mix or Breathing Gas Supply Whips
6. HeO₂ or Breathing Gas Supply Pressure Gauge
7. EDF Chamber Depth Gauge
8. Breathing Simulator Piston Position Transducer (LVDT)
9. Oral Pressure Transducer

10. Pressure Transducer, 50 psid mounted within the wet chamber to measure pressure drop across umbilical
11. Pressure Transducer, 50 psid mounted within the wet chamber to measure sideblock assembly pressure drop
12. Data Acquisition and Control Computer with software installed capable of collecting and analyzing the data at a rate fast enough to capture peaks of any pressure spikes that occur, and display and record data from the transducers
13. Video surveillance and recording equipment

5-11.3 Test Setup

Test equipment shall be configured within the test facility as shown in Figure 5-9. Particular attention must be paid to the hose inner diameter and number of elbows used in the breathing loop. Flow restrictions have been found to critically affect test results.

5-11.3.1 Parameters Controlled

1. Breathing simulator settings (standard values are given in Table 3-1)
2. Exhalation/inhalation time ratio: 1.00:1.00 (all tests).
3. Breathing wave form: sinusoidal (all tests)
4. Divers' gas supply pressure
5. Depth increment stops: normally 0 to 60.7 msw (0 to 198 fsw) in 10.1 msw (33 fsw) for nitrox breathing gas resistance measurements; 0 to 91.9 msw (0 to 300 fsw) in 10.1 msw (33 fsw) increments for heliox breathing gas resistance measurements; or per test plan
6. Ark water temperature and salinity

5-11.3.2 Parameters Measured

1. Inhalation oral peak ΔP (kPa)
2. Exhalation oral peak ΔP (kPa)
3. Oral ΔP vs. volume data (for generating P-V loops)
4. Umbilical pressure drop
5. Sideblock pressure drop

5-11.3.3 Computations

1. Resistive effort in kPa.
2. Total Harmonic Distortion (THD) if appropriate
3. If required, flow delivered to helmet (ACFM) from LFE data

5-11.3.4 Parameters Compared

1. Peak Inhalation and Exhalation ΔP vs. depth for each RMV if appropriate
2. Resistive effort at each depth and RMV
3. Umbilical pressure drop at each depth and RMV if appropriate
4. Dynamic pressure drop across sideblock assembly at each depth and RMV if appropriate
5. Flow at each depth and RMV if appropriate
6. Dynamic pressure drop across helmet supply valve assembly at each depth and RMV if appropriate

5-11.4 Test Procedures for Resistive Effort Evaluation

1.
 - a. Ensure that the demand regulator adjustable parameters are set according to test plan (typically to the middle value of manufacturer's specification), the UBA is oriented in the ark per the approved test plan, and is working properly
 - b. Chamber on surface
 - c. Calibrate all transducers and instruments.
 - d. Perform Standard Orifice procedures per 5-3.1.
 - e. Open diver's breathing gas supply valve to regulator and set supply pressure per test plan.
 - f. Adjust breathing simulator to 22.5 L/min RMV per 5-9.4.1, and take data.
 - g. Adjust breathing simulator for progressive RMVs per 5-9.4.1 until all tests at this depth are completed, UBA fails, or testing is halted.
 - h. Stop breathing simulator.



SAFETY NOTE: Breathing Simulator must be operating while increasing chamber depth to prevent flooding of equipment.

2.
 - a. Pressurize chamber from 10.1 msw (33 fsw) to max test depth in 10.1 msw (33 fsw) increments or per test plan increments.
 - b. Repeat steps 5-11.4.1.f through 5-11.4.1.h.
 - c. Note: upon completing all depths and test configurations, go to step 3.
3.
 - a. Bring chamber to surface.
 - b. Perform Standard Orifice measurements and check calibration of transducers and instruments.

5-11.5 Post Test Checks

The test supervisor will verify that all data collected are valid.

5-12 CATEGORY 4 UBA TEST METHODS

5-12.1 Introduction

The purpose of these test procedures is to establish a standardized method to evaluate Category 4 (rebreathers; closed and semi-closed circuit breath-powered) UBA performance. The results of these tests will be compared to standards for Category 4 UBA performance and could be used in the process for obtaining AMU or other authorized status for the UBA being tested.

In this section are described measurement techniques for resistive effort, carbon dioxide absorbent canister duration, and oxygen control on Category 4 UBAs. Another important performance characteristic of closed circuit UBAs is hydrostatic imbalance. Figures 5-10, 5-11, 5-12, and 5-13 show how to set up this evaluation; however the procedures for this measurement are given in chapter 10.

5-12.2 Test Equipment

More information on required equipment is given in section 5-14.

1. Test Article (UBA)
2. EDF Chamber Complex
3. Water Containment Ark
4. EDF Heating and Cooling System capable of controlling ark water temperature $\pm 2^{\circ}\text{F}$ during the canister duration tests ($29^{\circ} - 105^{\circ}\text{F}$)
5. Breathing Simulator
6. HeO₂ Mix and 100% O₂ Supply Whip if UBA gas bottles not used
7. HeO₂ and 100% O₂ Supply Gauge, 3D Instruments, 6-inch face and 1/4% accuracy
8. EDF Chamber Depth Gauge
9. Breathing Simulator Piston Position Transducer (LVDT)
10. Oral Pressure Transducer
11. CO₂ Gas Analyzer capable of continuous monitoring of gas sample and providing proportional input to the data acquisition computer
12. O₂ Gas Analyzer, capable of continuously monitoring O₂ levels in the breathing loop and providing proportional input to the data acquisition computer
13. Data Acquisition and Control Computer capable of collecting and analyzing the data at a rate fast enough to capture peaks of any pressure spikes that occur, and display and record data from the transducers and measurement instruments
14. Matheson model 8272-0423 mass flow controller, or equivalent, to control CO₂ injection rate during canister durations
15. Video surveillance and recording equipment

5-12.3 Test Setup

Test equipment shall be configured within the test facility as shown in Figures 5-8 through 5-11. Particular attention must be paid to the hose inner diameter and number of elbows used in the breathing loop. Flow restrictions have been found to critically affect test results.

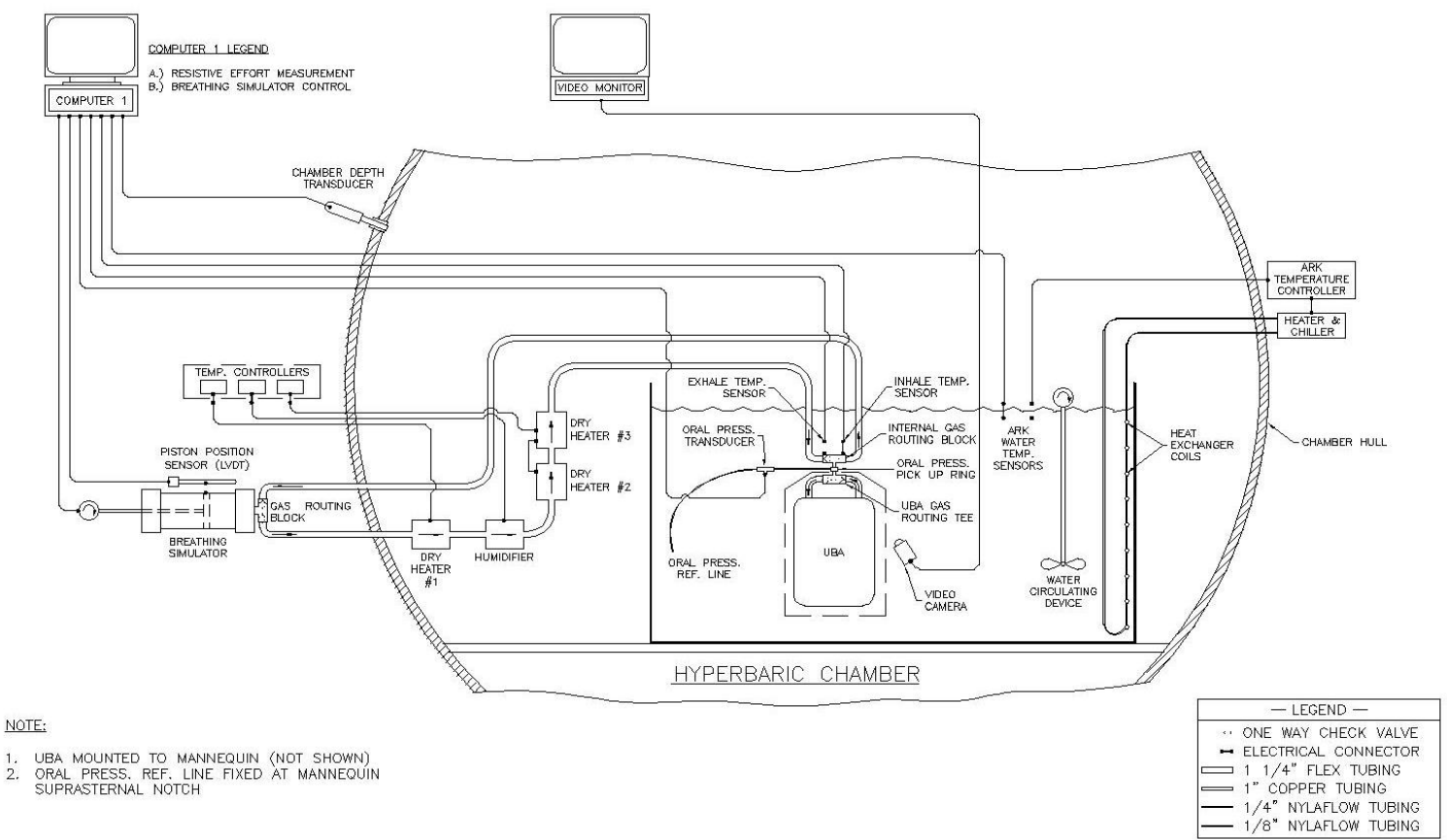


Figure 5-8 Test setup for resistive effort measurements on Category 4 UBA

S-24

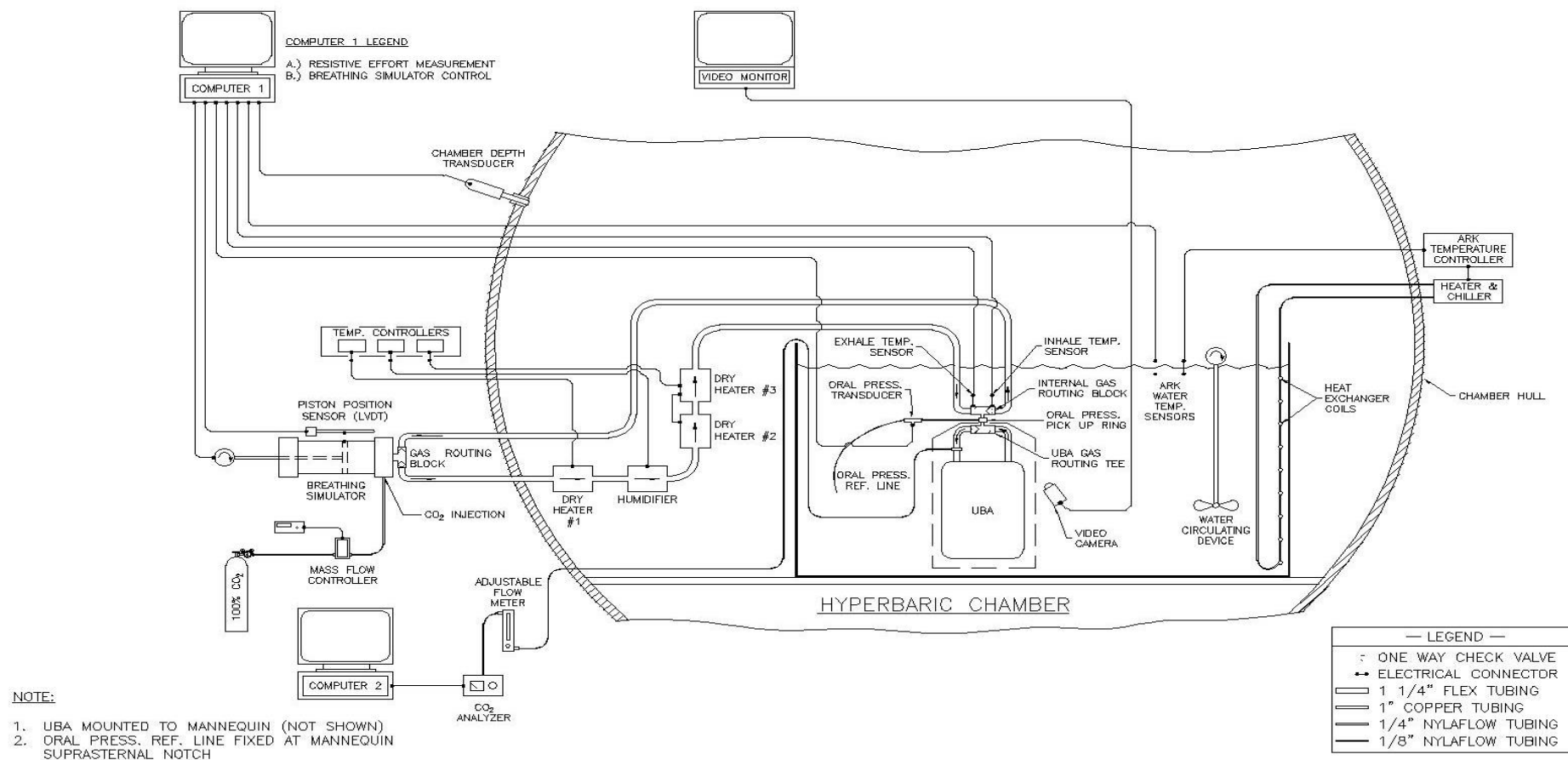
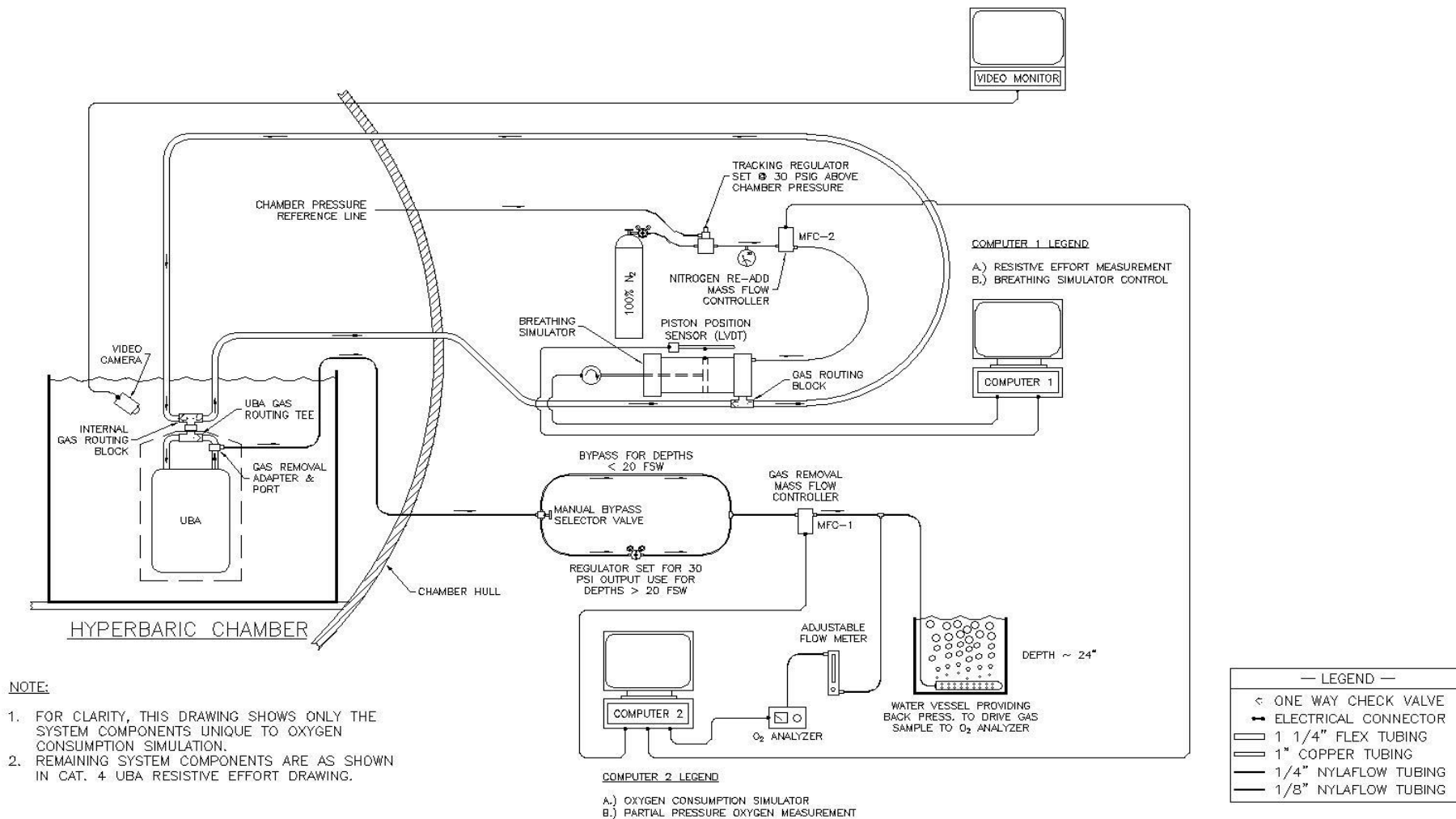


Figure 5-9 Test setup for CO₂ canister duration measurements on Category 4 UBA

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NOTE:

1. FOR CLARITY, THIS DRAWING SHOWS ONLY THE SYSTEM COMPONENTS UNIQUE TO OXYGEN CONSUMPTION SIMULATION.
2. REMAINING SYSTEM COMPONENTS ARE AS SHOWN IN CAT. 4 UBA RESISTIVE EFFORT DRAWING.

Figure 5-10 Test setup for oxygen control measurements on Category 4 UBA

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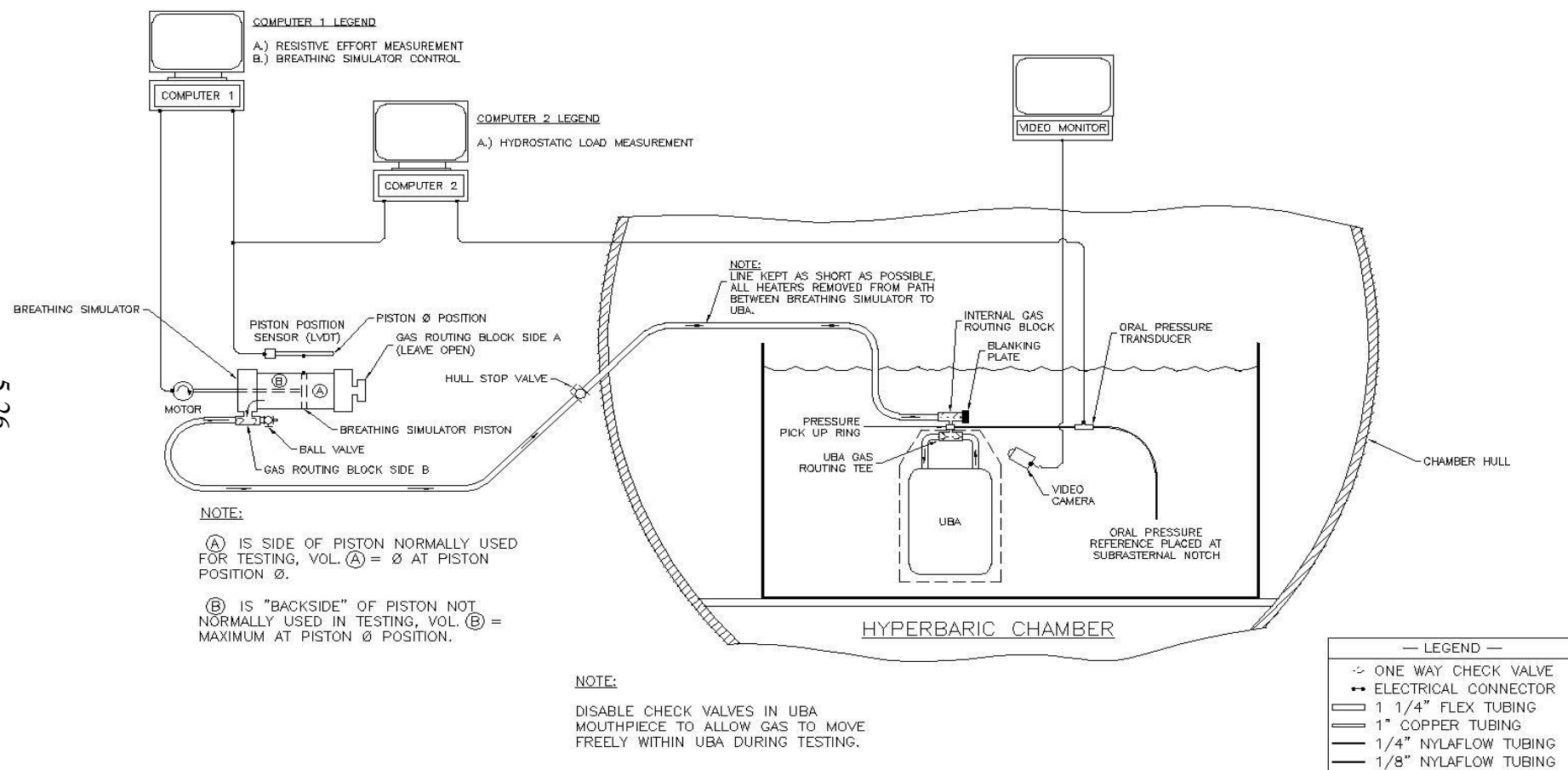


Figure 5-11 Test setup for hydrostatic imbalance measurements on Category 4 UBA

5-12.3.1 Parameters Controlled

1. Breathing simulator settings (standard values are given in Table 3-1)
2. Exhalation/inhalation time ratio: 1.00:1.00 (all tests)
3. Breathing wave form: sinusoidal (all tests)
4. Resistive effort: depth increment stops normally 0 to 60.7 msw (0 to 198 fsw) in 10.1 msw (33 fsw) for nitrox breathing gas resistance measurements; 0 to 91.9 msw (0 to 300 fsw) in 10.1 msw (33 fsw) increments for heliox breathing gas resistance measurements; or per test plan
5. Canister duration: normally tests to be conducted at maximum UBA operating depth for each absorbent material being tested, at minimum and maximum UBA operating water temperatures, and at three additional intermediate temperatures, or as per test plan. CO₂ injection normally will be at a constant rate (refer to Section 3-8), or otherwise as specified in the test plan. If UBA operationally can use both nitrox and heliox breathing gases, then canister duration must be measured separately for each gas mixture.
6. Oxygen control: normally tested at multiple depths to maximum operating depth during descent as well as ascent; at minimum and maximum operating water temperatures and at a third intermediate temperature, with constant rate of oxygen consumption of 1.60 L/min (representative of “moderate” work level), or as specified in test plan.
7. Exhaled gas temperature on canister duration and oxygen control tests
Temperature will be measured at the Breathing Block, just upstream of the routing valve.
8. Water temperature and salinity

5-12.3.2 Parameters Measured

Resistive Effort

1. Inhalation oral peak ΔP (kPa)
2. Exhalation oral peak ΔP (kPa)
3. Oral ΔP vs. volume data (for generating P-V loops)

Canister Duration

4. Visual verification of breathing simulator exhaled gas saturated relative humidity
5. Breathing simulator exhaled gas temperature
6. CO₂ concentration in gas exiting UBA absorbent canister

Oxygen Control

7. O₂ concentration in gas from inhalation hose

5-12.3.3 Computations

1. Resistive effort in kPa
2. Total Harmonic Distortion (THD) if appropriate
3. CO₂ concentration surface equivalent value (% SEV) if appropriate
4. Partial Pressure (ATA) of oxygen if appropriate

5-12.3.4 Parameters Compared

1. Peak Inhalation and Exhalation ΔP vs. depth for each RMV (RE tests) if appropriate
2. Oral pressure vs. volume at each depth and RMV (RE tests) if appropriate
3. CO₂ out of scrubber (% SEV) vs time (canister duration tests) if appropriate
4. PO₂ in inhalation gas (ata) vs time (O₂ consumption tests), if appropriate

5-12.4 Test Procedures

5-12.4.1 Test Procedure for Resistive Effort Evaluation

1.
 - a. Ensure that the demand regulator adjustable parameters are set per test plan (typically to the middle value of manufacturer's specification), the UBA is oriented in the ark per the approved test plan, and is working properly.
 - b. Chamber on surface
 - c. Calibrate all transducers and instruments.
 - d. Perform Standard Orifice procedures per 5-3.1.
 - e. Open diver's breathing gas supply valve to regulator and set supply pressure per test plan.
 - f. Adjust breathing simulator to 22.5 L/min RMV per 5-9.4.1, and take data.
 - g. Adjust breathing simulator for progressive RMVs per 5-9.4.1 until all tests at this depth are completed, UBA fails, or testing is halted.

- h. Stop breathing simulator.



SAFETY NOTE: Breathing Simulator must be operating while increasing chamber depth to prevent flooding of equipment.

- 2.
 - a. Pressurize chamber from 10.1 msw (33 fsw) to max test depth in 10.1 msw (33 fsw) increments or per test plan increments.
 - b. Repeat steps 5-12.4.1.f through 5-12.4.1.h.
 - c. Note: upon completing all depths and test configurations, go to step 3.
- 3.
 - a. Bring chamber to surface.
 - b. Perform Standard Orifice measurements and check calibration of transducers and instruments.

5-12.4.2 Test Procedure for Canister Duration Evaluation

5-12.4.2.1 Canister “Breakthrough” Time

1. Rationale

The most direct way to determine canister duration is by measuring the time to canister “breakthrough” (usually defined to be that time at which the CO₂ level in the breathing gas exiting the canister reaches 0.50% SEV) using a continuous CO₂ injection rate at a fixed RMV. Duration is primarily dependent on CO₂ injection rate, water temperature, and to a lesser extent, RMV. Canister efficiency drops at low temperatures and high RMVs.

2. Method

The CO₂ injection system at NEDU incorporates the use of a MFC for controlling the gas flow into the UBA during tests. The MFC must be calibrated prior to each dive series for the specific rate of flow using a certified flow calibration instrument. The measured volume is corrected to STPD at 0°C. Some manufacturers calibrate their flow meters at 70°F so a correction must be made to achieve the NEDU STPD standard.

- a. Fill UBA canister with absorbent (within predetermined fill volume and weight ranges). Ensure UBA is within factory specifications for operation.
- b. While chamber is on the surface with UBA immersed in water at the test temperature, ensure wet (humidifier) and dry gas heaters are on and at set temperatures.
- c. Calibrate all transducers, CO₂ analyzer, CO₂ mass flow controller, and temperature probes.
- d. Open UBA oxygen and/or diluent supply valve.
- e. Pressurize chamber and start breathing simulator per test plan.
- f. Start CO₂ addition at specified value from test plan and maintain until 2.0% SEV CO₂ is reached.

- g. Record canister effluent CO₂ level, depth, and time continuously.

5-12.4.2.2 Canister Absorption Capacity

1. **Rationale**

The volume of CO₂ gas (at STPD) absorbed by a UBA canister under a particular set of conditions can be calculated based on the CO₂ injection rate. Canister efficiency can also be reported using this volume as the percentage of the ideal maximum CO₂ volume (at STPD) that the absorbent can theoretically remove. The limitation to this approach is that canister efficiency and the amount of CO₂ absorbed are not constant. They are dependent on CO₂ injection rate, temperature and RMV.

2. **Method**

- a. Conduct canister absorption breakthrough testing per 5-12.4.2.1.
- b. Multiply the time in minutes to reach the 0.5 % SEV CO₂ level by the CO₂ injection rate (liters per minute). From this number, subtract the volume of CO₂ removed by the analyzer for sampling before the 0.5 % SEV CO₂ level was reached.
- c. Repeat above calculations following each of the tests for the water temperatures.

5-12.4.2.3 Breathing Resistive Effort Increase from CO₂ Absorption

A product of the reaction of CO₂ with the absorbent material is water. As water collects in the canister bed during extended use, an additional impedance to air flow may be introduced. This impedance may cause the overall UBA breathing resistance to increase. To determine the magnitude of this effect, periodically measure the resistive effort throughout the course of a canister duration measurement and record any significant changes.

5-12.4.4 O₂ Consumption and Control System Evaluation

Details of the system for simulating oxygen consumption and measuring PO₂ control of a UBA are given in Chapter 9.

5-13 CATEGORY 5 UBA TEST METHODS

5-13.1 Introduction

The purpose of these test procedures is to establish a standardized method to evaluate Category 5 (semi-closed circuit ejector or pump driven) UBA performance. The results of these tests will be compared to performance standards for Category 5 UBA and could be used in the

process of obtaining AMU or other authorized status for the UBA being tested.

5-13.2 Test Methods and Equipment

For measurements of resistive effort, carbon dioxide canister duration, and oxygen control for Category 5 UBAs refer to Section 5-12 for Category 4 UBAs. The techniques are common to both.

For measurement of umbilical pressure drop for Category 5 UBAs refer to Section 5-11 for Category 3 UBAs. The techniques are common to both.

In place of sideblock pressure drop measurements documented in Section 5-11 for Category 3 UBAs, measure pressure differential between inside of helmet and surrounding water pressure for Category 5 UBAs.

5-14 TEST EQUIPMENT COMPONENTS

1. NEDU Experimental Diving Facility (EDF) Complex

- a. Pressure vessels: Alpha (spherical) and Bravo (cylindrical) interlocking chambers, 740 fsw maximum operating depth, thermally insulated. Charlie (cylindrical) 1640 fsw maximum operating depth, thermally insulated.
- b. High pressure gas bottle field & piping
- c. Lighting, cameras, video surveillance & recording systems
 - i) Lighting, cameras, and positioning: Remote Ocean Systems
 - ii) Video surveillance and recording: Aver Media
- d. Chamber driving and breathing gas supply consoles
- e. High pressure breathing air compressors and filtration system

2. Test Article Submersion System

- a. Water containment ark
 - i) Alpha Chamber: 3 ft dia., 5 ft ht. cylindrical, approximately 11 ft³ (82 gal), Commercial Off-The Shelf (COTS)
 - ii) Bravo Chamber: 3 ft wide, 8 ft long, 4 ft deep rectangular parallelepiped, approximately 96 ft³ (718 gal), in-house proprietary design and construction
 - iii) Charlie Chamber: 2.5 ft wide, 4.5 ft long, 3 ft deep rectangular parallelepiped, approximately 34 ft³ (254 gal), in-house proprietary design and construction
- b. Ark water temperature control system: heaters, chillers, piping & circulation pumps, temperature range 29°F-105°F
- c. Ark water circulation motor and propeller (COTS)

- d. Configuration/orientation/positioning stand w/hoist & trolley, COTS parts and proprietary in-house design and construction

3. Gas Circulation System

- a. Breathing simulator, computer control with software
 - i) Reimers Systems, dual piston/cylinder, 5 liters, 90 L/min, external of chamber, or
 - ii) Battelle, single piston/cylinder, 5 liters, 90 L/min, external of chamber,
 - iii) Internal breathing machine mounted inside chamber for studies at depth, or for use at 1 atmosphere. Minimizes breathing loop volume compared to external breathing machine plumbing: a useful feature for measuring PO₂ overshoots in rebreathers during descent.
- b. Routing blocks (located at breathing simulators and mannequin torso), proprietary in-house design and construction
- c. Gas heating & humidifier housings and elements with controllers (wet and dry resistive elements entrained in breathing loop)
 - i) Housings: in-house proprietary design and construction
 - ii) Elements: COTS, in-house proprietary design and construction
- d. Breathing loop piping and hoses (COTS)
- e. Volume tank (as required)
- f. Breathing gas sampling and venting
- g. Glass tube flow meters, various vendors
- h. Piston position sensing (linear velocity and displacement transducers) Temposonics, L Series, magnetostrictive (Reimers & Battelle)
- i. Temperature sensing (resistive temperature detectors) Yellow Springs Instrument Co., Series 700 thermilinear temperature probes
- j. Mannequin torso, in-house design
- k. Mannequin head, in-house design, manufactured by Dive Lab, Panama City, FL.
- l. Calibration equipment
 - i) Collins, 120 liter cylindrical gasometer
 - ii) Med Science, model 720, 6 liter wedge spirometer
 - iii) Hans Rudolph 7 L and 3 L precision gas syringes

4. Pressure Sensing

- a. Chamber depth
 - i) Druck, PTX series, diaphragm-strain gage design, 4-20mA output, 0-200 psi range
 - ii) Druck, Model DPI 282, digital panel display
- b. Differential

- i) Oral pressure: Druck, PTX series, diaphragm-strain gage design, 4-20 mA output, ± 1 psi range (± 7 kPa)
- ii) Overbottom, umbilical, sideblock: Druck, PTX series, diaphragm-strain gage design; 4-20 mA output; 0-50 and 0-200 psig ranges
- c. Test article (as required)
- d. Calibration gages
 - i) Mensor, diaphragm-strain gage, digital display, ± 4 psi
 - ii) Mensor, diaphragm-strain gage, digital display, 0-500 psi

5. Gas Injection Systems (as required)

- a) Breathing gases
Divers breathing air, oxygen, nitrox and heliox blends, COTS, specialty blends, EDF and OSF bottlefields
- b) Calibration gases
Divers breathing air, COTS and specialty blends
- c) Nitrogen injection mass flow controller (oxygen consumption simulation): Sierra, transducer and controller, 1-20 L/min range
- d) Mixed gas (oxygen and nitrogen) mass flow controller (oxygen consumption simulation): Sierra, transducer and controller, 1-20 L/min range
- e) Carbon dioxide injection mass flow controller (canister duration): Matheson Gas Products, transducer and controller, 0-3.0 L/min range

6. Gas Analysis Systems

- a) Oxygen analyzer
Rosemount, NGA 2000, magnetic susceptibility sensor (paramagnetic)
- b) Carbon dioxide analyzer
Rosemount, NGA 200, non-dispersive infrared sensor (NDIR)

7. Data Acquisition (DAQ) Systems

- a) Computer hardware
Various COTS IBM compatible desktop computers
- b) Computer software
 - i) CO₂ canister duration, O₂ control: NEDU developed applications using National Instruments, LabVIEW[®]
 - ii) Resistive effort: proprietary in-house design written in Visual Basic
- c) Analog to digital conversion hardware
National Instruments, SCB-68 connector block, AMUX-64
- d) Digital to analog conversion hardware
National Instruments
- e) Signal conditioning & filtering

- i) Debane signal conditioner for thermistors
- ii) Krohn-Hite low pass filtering (50 Hz) for transducer and instrument signals
- f) Data storage & retrieval hardware, Internal and external backup hard-drives
- g) Video recording devices

REFERENCES

1. Joye, D.D., J.R. Clarke, N.A. Carlson and E.D. Thalmann, "Characterization and measurement of elastance with application to underwater breathing apparatus", *Undersea and Hyperbaric Medicine* 21:53-65, 1994.
2. Joye, D.D., J.R. Clarke, N.A. Carlson and E.T. Flynn. "Formulation of elastic loading parameters for studies of closed-circuit underwater breathing systems". NMRI 89-89.
3. Warkander, D. E. and C. E. G. Lundgren. "Development of Comprehensive Performance Standards for Underwater Breathing Apparatus". Final report to U.S. Navy; Naval Sea Systems Command and Office of Naval Research, Center for Research and Education in Special Environments, University at Buffalo, Buffalo, NY, 2000.
4. Webb, P. "Thermal Problems", in: *The Physiology and Medicine of Diving*, Bennet P. and D. Elliott (eds), 3rd edition, pp 297-318, Best Publishing Company, San Pedro, CA, 1982.
5. D. A. Mahler, E.D. Moritz and J. Loke. "Ventilatory responses at rest and during exercise in marathon runners," *Journal of Applied Physiology*. Vol. 52, No. 2, pp. 388-392, 1982.

CHAPTER 6. BREATHING RESISTANCE SOFTWARE

6-1 OVERALL DESCRIPTION

In recent years, the NEDU breathing resistance software has undergone major revision. The majority of the changes provide new information regarding tests or calibration. As always, the basic data input into the software are pressure, volume, and time. From that data are calculated work of breathing per tidal volume ($\frac{W_{OB}}{V_t}$) or volume-averaged pressure ($\overline{P_V}$). During post-processing, elastance and total harmonic distortion can be found. Only $\overline{P_V}$, peak pressures and elastance are immediately relevant to UBA performance goals. They are therefore considered *primary* measurements. The other measurements are secondary in importance, but do supply information useful in determining the validity of the primary measurements.

The primary function of the software is to perform the computations which are shown graphically in Figure 6-1. Details of the interpretation are found in Clarke (1999)¹.

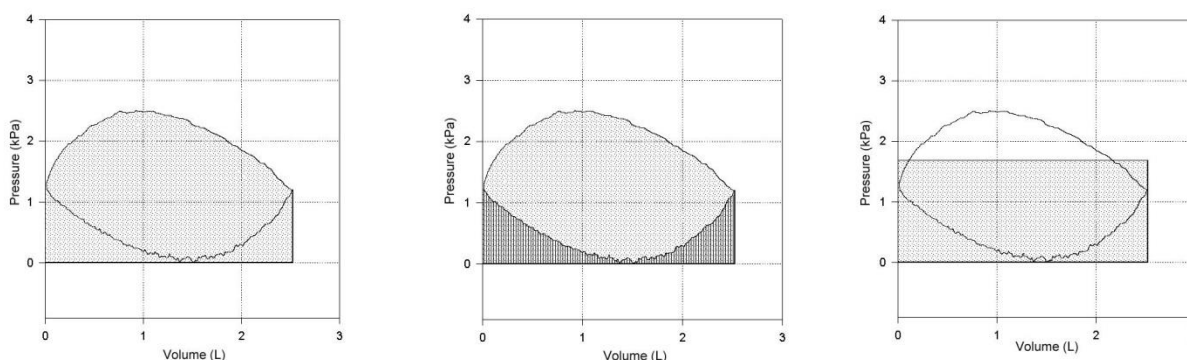


Figure 6-1 Steps in the calculation of the area inside a P-V loop (work) and its transformation into an average pressure difference (volume-averaged pressure).

The analysis program includes a single pressure-volume loop along with a variety of measured variables. The highlighted breathing loop (Figure 6-2) represents an ensemble average of 10 consecutive breathing loops. Ensemble averaging improves the signal-to-noise ratio of the data, suppressing purely random signals and thereby resolving periodic phenomena such as scuba regulator diaphragm chatter (Fig 6-3).

The methods and results for validation of the new software against mathematical functions are described in NEDU Technical Report 09-02².

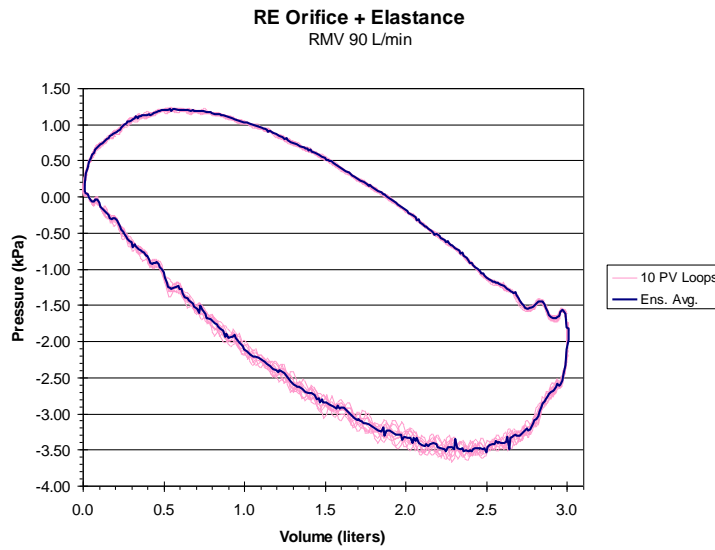


Figure 6-2 Raw superimposed data.

P-V loops with ensemble averaged

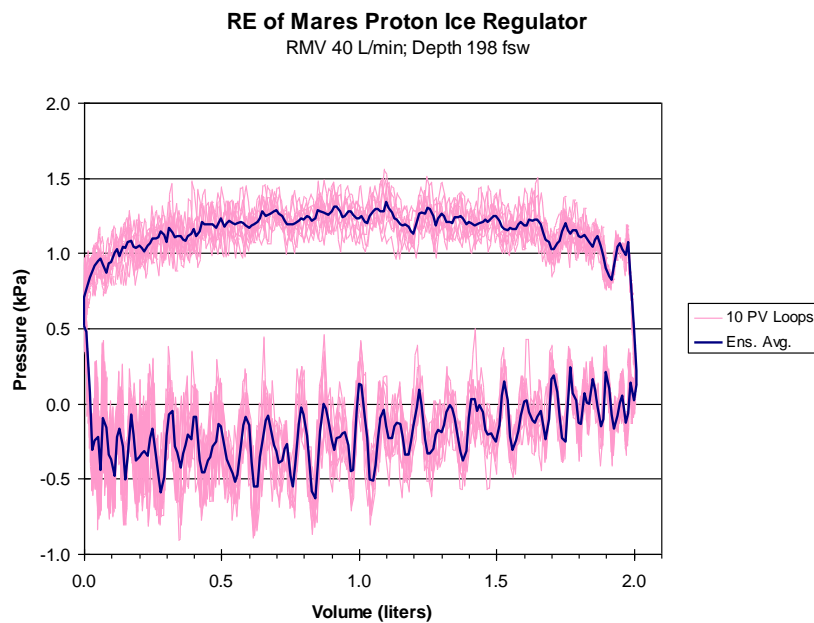


Figure 6-3 ensemble periodic

The benefit of averaging in but noisy

pressure data. The noise is caused by the regulator, not by electrical signals.

6-2 HARMONIC DISTORTION

Harmonic distortion is a measure of the purity of a waveform. This statistic is actually a ratio that compares the system response at harmonic frequencies (i.e., frequencies greater than the

fundamental or driving frequency) to the total system response. The measurement of harmonic distortion serves two purposes. In an open-circuit system it quantifies the degree of scuba regulator chattering (Figures 6-3 and 6-4), and in a closed-circuit UBA it provides information regarding the linearity of the elastance curve.

The total harmonic distortion (THD) is computed from the power spectrum of the pressure signal. The first step in the computation is the expansion of the pressure data array to be a power of 2 in length. This is required by the Fast Fourier Transform (FFT) algorithm to compute the power spectrum. This expansion is accomplished by repeating the pressure data until it fills up an array of 1024 elements.

Next a Hamming window (a standardized signal processing function) is applied to the pressure data to suppress spectral leakage, and a function is called to generate the power spectrum of the pressure signal. Since we are only interested in positive frequencies (a so-called single-sideband FFT) we double the power magnitudes that were returned by the called function.

The power data returned corresponds to harmonic frequencies 0th or fundamental frequency, 1st, 2nd, 3rd harmonics, etc. For the purposes of graphing the spectrum plot, these frequencies should be converted to Hertz (Hz). To compute the harmonic distortion, we must identify the fundamental frequency. This is done by searching the array of power spectrum values to find the largest value. This search deliberately skips the zeroth frequency, which corresponds to the steady-state component of the signal. Once the fundamental has been identified, we define a cutoff frequency to be 1.5 times the fundamental. The power contained in the spectrum above this cutoff frequency is accumulated. The power contained in the entire spectrum (except the zeroth frequency) is also accumulated. The harmonic distortion is the ratio of these two quantities.

Figure 6-4 shows the effect of increasing RMV on a chattering SCUBA regulator. Each loop is an ensemble average of 10 breathing loops. As RMV increases, the chatter increases, as evidenced by an increasing THD.

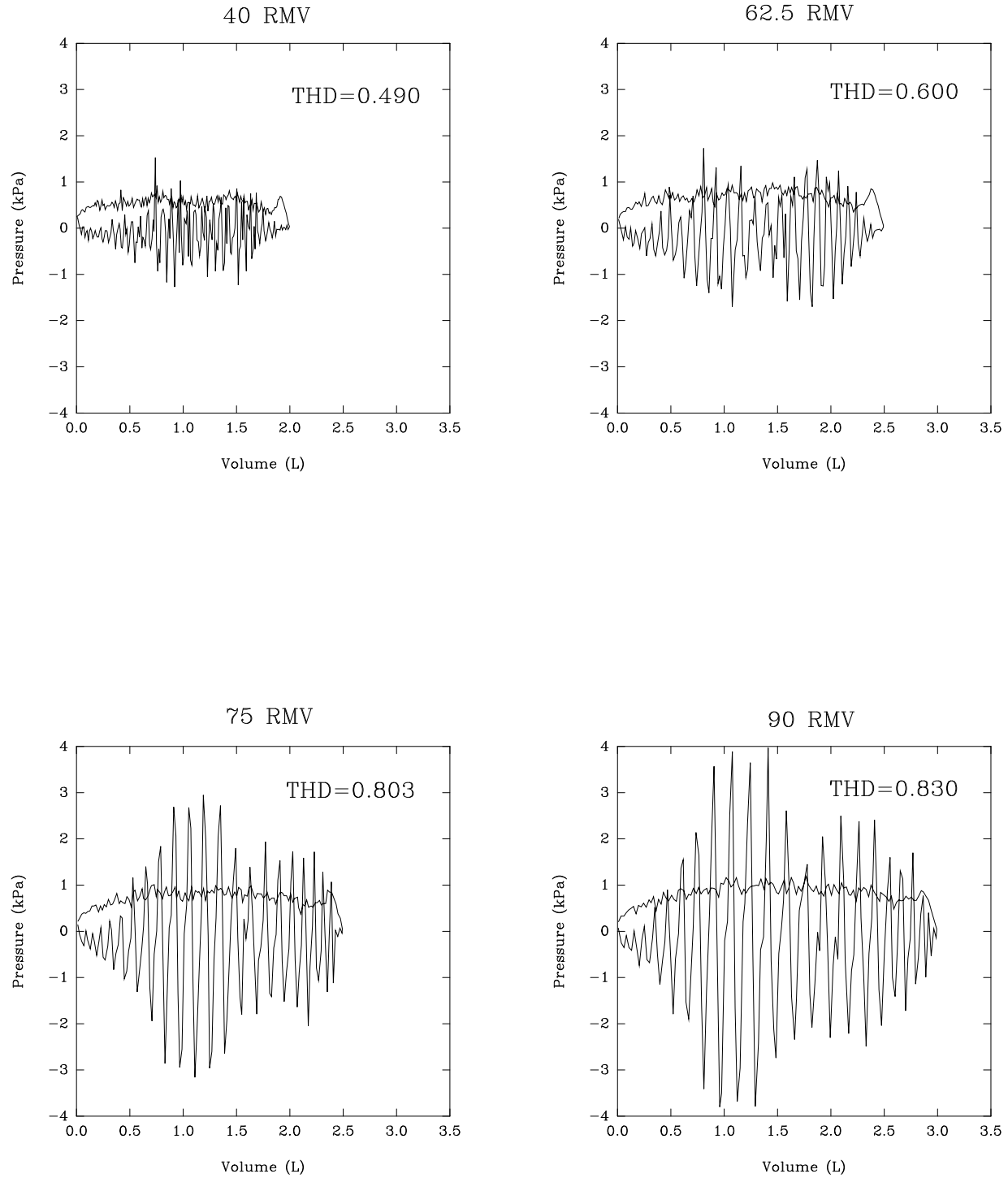


Figure 6-4 Total Harmonic Distortion (THD) and scuba regulator Chatter

REFERENCES

1. Clarke, J.R., Underwater Breathing Apparatus. The Lung at Depth, ed. CEG Lundgren and J Miller. In series, Lung Biology In Health and Disease, ed. Claude Enfant. New York, Marcel Dekker. pg.429-527, 1999.
2. Layton, R.P., "Validation of New Resistive Effort Data Acquisition and Analysis System". NEDU TR 09-02, January 2009.

CHAPTER 7. STATISTICALLY BASED DECISION MAKING

7-1 INTRODUCTION

The end result of any test of diving equipment or operating procedure is a recommendation to NAVSEA as to the suitability of the equipment or procedure for use in Navy or military diving. This chapter describes procedures for analyzing test data so that NEDU's recommendations convey a fair and accurate impression of the equipment or procedure based on valid scientific methods.

The analytical methods described in this chapter are meant to be demonstrative, not all-inclusive. The methods are available in most but not all statistical software packages. Many hand-held scientific calculators, like the Texas Instruments 83 and 84 series, have useful statistical routines available as well.

The following sections are formatted in the form of commonly asked questions, along with proposed solutions. The following examples serve only as a guide for the uninitiated. Specialized training and experience would be required before the majority of these procedures could be successfully implemented and the statistical inferences trusted.

7-2 QUESTIONS AND ANSWERS

7-2.1 Does a specific make and model regulator meet NEDU performance goals?

The statistical methods described below are standard quality control procedures. They apply whenever one wishes to determine whether a product meets legislated requirements such as air pollution standards. Examples can be found in elementary statistics textbooks.

Solution:

1. Typically, to make any inferences about the performance of a particular make and model regulator using a statistical claim, a minimum sample size of 5 is suggested.
2. Tabulate the Resistive Effort (RE or \bar{P}_V) (aka WOB) for each regulator for each combination of depth, temperature, and RMV tested.
3. Calculate the RE sample mean and standard deviation (SD) for each condition. The data should not be strongly left-skewed nor contain outliers.
4. For a specific make and model regulator, and condition, using a statistical hypothesis test, test the claim that the population parameter of the RE mean is less than or equal to the NEDU performance goal (null hypothesis). Given the stated null hypothesis, the alternate hypothesis will be that the RE mean is **greater** than the goal. Based on the stated null and alternate hypotheses, perform a right-sided, one-sample (single population) hypothesis test for the population RE mean. Under the assumptions that for the population of a given regulator make or model, the RE standard

deviation is not known, and that the probability distribution of the RE mean is normally distributed, a Student's t-distribution based hypothesis test is appropriate. (Typically, the Student's t-distribution based hypothesis test requires sample sizes greater than 30, unless the normality of the population parameter is assumed or assured). A hypothesis test routine based on the Student's t-distribution, for a single population, is available using routines available on line.

5. If the calculated probability (P value) for the hypothesis test is less than a significance level of 0.05, which corresponds to a confidence interval with a 95% confidence level, the alternate hypothesis is accepted, thereby rejecting the null hypothesis, inferring that the RE for the regulator make and model significantly exceeds the NEDU performance goal. In this case, the regulator make and model is disqualified as a candidate for use in Navy diving. Otherwise it is an acceptable candidate.

Example I

The RE for five regulators of a certain make and model tested for a selected condition was 1.22, 1.39, 1.42, 1.47, and 1.29 kPa. The mean and standard deviation (SD) was 1.36 and 0.10 kPa respectively. Since an SD of 0.10 kPa is less than 0.20 kPa, the batch of regulators is reasonably consistent and therefore qualified for further analysis (see section 3-10.2.1.2). Using the RE result for each regulator, and a RE goal of 1.37 kPa, the p-value calculated (probability for the right-sided, one-sample t-test) was 0.60 which is greater than 0.05. Therefore, the alternate hypothesis is rejected, inferring the RE for this make and model regulator is not significantly greater than the goal of 1.37 kPa and the regulator make/model is an acceptable candidate for use in Navy diving.

Example II

The RE for five regulators of a certain make and model tested for a selected condition was 1.38, 1.38, 1.90, 1.53, and 1.56 kPa. The RE mean and standard deviation was 1.55 and 0.21 kPa respectively. The mean was greater than 1.37 kPa and the standard deviation exceeded 0.20 kPa, so no further analysis should be performed since the RE variability from regulator to regulator is too large to be considered for use by the Navy.

When regulator RE is highly variable, it may be impossible to prove that the regulators do not meet the performance goal unless the standard deviation itself, were a qualifying characteristic. As an example, for this data the right-sided, one-sample T-test showed that the RE mean of the sample **was not statistically greater** than the goal of 1.37 kPa. In other words, if the manufacturer's quality control is bad enough, statistical tests for the RE parameter are meaningless. Therefore, inferences made using statistical comparisons with the goal should only be run on data that qualifies for complete analysis by having a standard deviation less than 0.20 kPa.

In NEDU Report 3-81, the goal of 1.37 J/L (kPa) was associated with $\pm 10\%$ tolerance limits. In effect, that allowed any RE up to 1.51 J/L to be accepted. By that standard, 2 of the 5 regulators approximated the target of 1.37, 2 were just above the upper tolerance limit, and 1 lay clearly above the upper tolerance limit. Logically, it would seem reasonable to condemn these regulators as candidates for use in Navy diving. By using the above statistical approach we came to the same conclusion, but more objectively.

Example III

The RE for five regulators of a certain make and model tested was 1.38, 1.48, 1.55, 1.65, and 1.72 kPa. The RE mean and standard deviation was 1.56 and 0.13 kPa respectively. The p-value for the right-sided, one-sample t-test was 0.02 which is less than the significance level of 0.05. Therefore, the null hypothesis is rejected in favor of the alternate hypothesis and the inference is made that the RE for this make and model regulator is significantly higher than the goal of 1.37 kPa, thereby making the make and model of regulator tested unacceptable for Navy use.

7-2.2 Do two make and model regulators differ in their RE?

Solution:

If at least five regulators of each make and model have been tested, a two-sided, two-sample (two populations) t-test can be used to examine RE differences between two regulator makes and models for a particular scenario (depth and RMV). The null hypothesis is that there is “no difference” in the RE parameter between the two regulators, makes and models A and B. This test is available with various statistical software packages and the TI-84 calculator. Once again, since the sample size is less than 30, the underlying assumption is that the RE parameter is normally distributed for both populations of make and model regulators.

Example I

The individual REs for five regulators of make and model A were as follows: 1.25, 1.29, 1.32, 1.45, and 1.58 kPa. The RE mean and standard deviation was 1.38 and 0.14 kPa respectively. The REs for five regulators of make and model B were 1.38, 1.48, 1.55, 1.65, and 1.72 kPa. Their mean and standard deviation was 1.56 and 0.13 kPa respectively. The 95% confidence level limits for the **difference** between the RE parameter of makes and models A and B was -0.38 to 0.02 kPa. A RE difference of 0.00 kPa lies within the boundaries of these confidence level limits. The p-value calculation for the two-sample t-test was 0.07 which is greater than the significance level of 0.05. Therefore, the inference is made that the difference between the RE for makes and models A and B **was not** statistically significant.

Example II

The RE for five regulators of a make and model tested “C” was 1.25, 1.29, 1.32, 1.39, and 1.45 kPa. The mean and standard deviation was 1.34 and 0.08 kPa respectively. The REs for five regulators of make and model B were as stated above. The 95% confidence level limits for the **difference** between the RE of makes and models C and B was -0.38 to -0.05 kPa. A difference of 0.00 kPa does **not** lie within the boundary of these confidence limits. The p-value for the two-sample t-test was 0.015 which is less than a significance level of 0.05. Therefore, the difference between the RE for these regulators makes and models **was** statistically significant.

7-2.3 Did a modification to a UBA significantly affect the RE?

This question is most pertinent when testing a single diving rig under two conditions; e.g., with and without a double exhaust valve. In this case, each regulator serves as its own control.

Solution:

Five data points are obtained for each modification of the rig at each depth. Those data are the REs for 22.5, 40, 62.5, 75 and 90 L·min⁻¹. We want to determine if the test results for the modified regulator (RE_{mod1}) are consistently different than test results for the unmodified regulator (RE_{mod0}).

The statistical modeling technique of multiple regression can be used with predictor variables, RMV and MOD 0 RE results. The response variable would be the RE results from the test of the MOD 1.

The most useful regression model is likely to be a first-order model with two predictor variables of the form:

$$RE_{mod1} = b_0 + b_1 \cdot RMV + b_2 \cdot RE_{mod0} \quad (7-1)$$

where b_0 , b_1 and b_2 are the parameters for the model with RE_{mod1} the response variable, RMV & RE_{mod0} the predictor variables. This model defines a response plane for which any point on the plane corresponds to the mean response (the expected value of the RE performance of the MOD 1 regulator) for a given combination of the predictor variables. If the MOD 1 was identical to that of the MOD 0, b_0 (vertical axis intercept point (0, b_0)) and b_1 (change in the mean response per unit increase in the RMV with RE_{mod0} held constant) & b_2 (change in the mean response per unit increase in RE_{mod0} with RMV held constant) would be 0.0, 0.0 and 1.0, respectively. The purpose of this analytical test is to determine if b_0 , b_1 and b_2 are statistically different from their expected values of 0.0, 0.0 and 1.0.

If after plotting data, the relationship between the RE and RMV is obviously nonlinear (i.e., curvilinear or exponential), the above linear model should be modified to an ordered polynomial model or exponential model as appropriate.

Example

The RE results for regulator MOD 0 are 0.25, 0.63, 1.44, 1.98, and 2.75 kPa for RMVs of 22.5, 40, 62.5, 75 and 90 L·min⁻¹, respectively (the predictor variables in the model). We wish to determine if RE results for MOD 1 (the response variable in the model) differs from MOD 0. The RE results for MOD 1 are 0.27, 0.77, 1.78, 2.43, and 3.32 kPa for the same RMVs. (We want to know if these values are dependent in a predictable fashion upon the test results of Mod 0 at any given RMV).

Multiple regression yields a model:

$$RE_{mod1} = -0.148 + 0.007 \cdot RMV + 1.039 \cdot RE_{mod0} \quad (7-2)$$

The 95% confidence level limits parameters are (-0.148 ± 0.100) , (0.007 ± 0.005) and (1.039 ± 0.124) for b_0 , b_1 and b_2 respectively. The confidence limits for b_2 include 1.0, therefore we conclude that as RE_{mod0} increases, the RE_{mod1} increases at nearly the same rate. Statistically, therefore, the RE of the modified regulator is **no different** from that of the unmodified regulator.

7-2.4 Comparing regulator freeze-up and free-flow proportions

We want to know if a regulator modification decreases the incidence of second stage freeze-ups. Suppose regulator A is the modified version and experienced 2 freeze-ups out of 40 trials; meaning 2 failures and 38 successes and regulator B, the unmodified version, experienced 5 freeze-ups out of 15 trials. Based on these results, is the modified regulator A statistically better than the unmodified regulator B?

If the number of failures for either regulator is less than 5, or the number of samples is less than 20, the use of Fisher's Exact Test for a 2 x 2 contingency table (Table 7.1) is applicable. The Fisher's Exact Test is a non-parametric (distribution independent) statistical significance test available under the category of "ratios/proportions" in SigmaStat. The resulting p-value (the hypergeometric distribution probability of obtaining such contingency table values) for a one-tailed test is 0.013, which is less than a significance level of 0.05. Therefore, it is safe to say that modified regulator A is better than unmodified regulator B.

If a small number of tests (samples) are run, differences are difficult to prove. If regulator C had 2 failures out of 6 trials, and D had 7 failures out of 10 trials, the p-value would be 0.182 which is greater than a significance level of 0.05. Thus regulator C is not significantly better (less prone to freeze-up) than regulator D.

When the number of samples is greater than 40, or between 20 and 40 with failure frequencies greater than 5, then the chi-square Test, based on the chi-square distribution, in SigmaStat is appropriate. As a hypothetical example, fleet experience yielded the following frequency of free-flow in MK 21 helmets: free-flow occurred on 11 out of 24 dives (frequency of 0.46) using an unmodified regulator, and on 10 out of 56 dives (frequency of 0.18) using a modified regulator. Do the free-flow frequencies for the two regulators differ significantly?

The 2 x 2 contingency table, Table 7.2, yields the chi-square test statistic is 5.424 with one degree of freedom, yielding a p-value of 0.02. Since this value is less than 0.05, the free-flow frequencies between the modified and unmodified regulators are significantly different.

Table 7-1 Contingency Table: Fisher's Exact Test for Regulator Freeze-Ups

	Free-Flow	No Free-Flow	Total
Unmodified	11	13	24
Modified	10	46	56
Total	21	59	80

Table 7-2 Contingency Table: Chi-Square Test for Regulator Free-Flow in MK 21 Helmets

	Freeze-Up	Freeze-Up	Total
Unmodified (B)	5	10	15
Modified (A)	2	38	40
Total	7	48	55

7-2.5 Is calculated RE correct?

Method 1: Use arbitrarily complex mathematical functions to generate simulated P-V loops. The integral of that function represents the area inside the loop. Dividing by the tidal volume (Vt) yields the "RE". Apply the computer RE analysis to the mathematically generated "data" and compare answers.

Method 2: Scan a hard copy P-V loop into a *.TIF format file. Import into SigmaScan or equivalent software and use planimetry to compute the area inside the loop. Divide that area by tidal volume. (If at all possible, scan the original P-V loop, not a copy. Copies are often slightly distorted.)

Method 3: Use a planimeter or the summation of areas of multiple hand-generated rectangles and/or trapezoids. Divide the area by Vt to yield RE.

CHAPTER 8. CARBON DIOXIDE ABSORBER PERFORMANCE

8-1 INTRODUCTION

There are two ways that carbon dioxide absorption capability is evaluated at NEDU. One is to test the absorbent quality under laboratory conditions, independent of a UBA, and the second is to test the carbon dioxide scrubbing ability of a UBA canister under the conditions of anticipated UBA use.

The first method uses a small sample of sodalime, placed in a sample tube, with CO₂ and moisture flowing through the test setup. The methodology is described in NEDU Technical Manual 02-01¹.

Prior to performing a canister duration test on any UBA, the quality of the absorbent must be checked by the above test. (This test is often called the “NATO tube test”, based in part on NATO STANAG 1411 (Standard to quantify the characteristics of carbon dioxide (CO₂) absorbent material for diving application). However, it should be noted that the NATO STANAGs are constantly changing, and NEDU procedures may diverge somewhat when the needs of the U.S. Navy differ.

Factors which have the greatest bearing on carbon dioxide scrubber performance are the amount of absorbent in the scrubber canister, the temperature of the surrounding water, the insulation of the canister, and most importantly, the rate at which CO₂ is injected into the canister.

8.1.1 The CO₂ Absorption Process

The following are images produced from NEDU’s stochastic thermokinetic modeling of the CO₂ absorption process inside a simulated rebreather scrubber canister.²

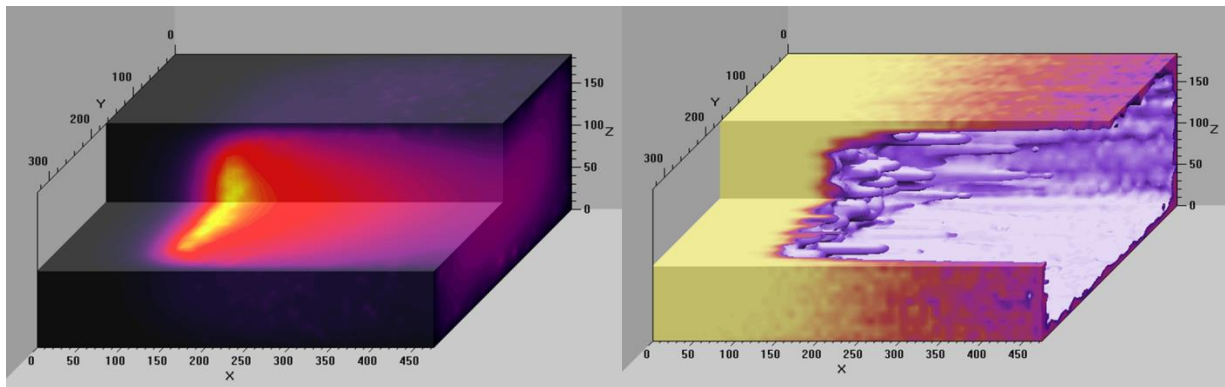


Figure 8-1 Images from an NEDU computer simulation of CO₂ absorption in rebreather scrubber canisters in cold water.

The image in the left panel of Figure 8-1 shows temperature profiles (yellow to black = hottest to coldest), and the image on the right shows simulated calcium carbonate deposition (most

to least = yellow to white.)

Once CO₂ begins to break through a scrubber canister, it usually rises exponentially because the molecules breaking through sum with the newly exhaled CO₂, adding to the overall CO₂ load on the canister.

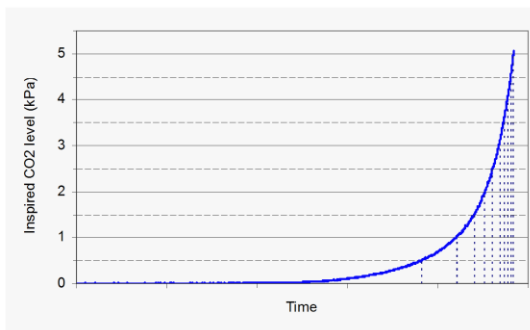


Figure 8-2 Exponential rise of carbon dioxide in canister effluent.

8.1.2 Injection rate of CO₂

NEDU uses CO₂ injection rates as requested by their sponsors. Injection rates of 0.9 L/min represent a resting diver, as during SDV (SEAL Delivery Vehicle transit). A CO₂ injection rate of 1.35 L/min has been historically used by NEDU, and a rate of 1.60 L/min is in keeping with European standards (European Standard EN 14143.)

The higher the injection and ventilation rate, the shorter the canister duration. In fact, duration is, to a first approximation, linearly and inversely proportional to both rates. Given the canister duration to a CO₂ level of 0.5% at a CO₂ injection rate of 0.9 L/min and a ventilation rate of 22.5 L/min, the duration at a 1.35 L/min injection rate and a ventilation rate of 40 L/min can be very roughly predicted by dividing the measured duration in minutes by $\left(\frac{1.35}{0.9}\right) \cdot \left(\frac{40}{22.5}\right) = 2.67$. In very cold water, that result may considerably overestimate the actual canister duration due to other inefficiencies unrelated to CO₂ flow and residence time.

For the above reasons, a CO₂ injection rate of 1.6 L/min should not be used if the purpose of the test is to ensure comparability with historical data gathered at NEDU, which routinely uses 0.9 L/min or 1.35 L/min STPD.

The CO₂ injection rate, normally controlled by calibrated mass flow controllers, can be verified by weighing the bottle of 100% CO₂ before and after each test. By knowing the weight loss and the length of time of CO₂ flow, the average mass flow rate can be calculated.

8.1.3 Oxygen consumption

Semi-closed UBAs have a continuous flow of fresh gas entering the breathing circuit. At the end of expiration, the breathing bag/bellows tends to get full and some gas will leave through a variable exhaust or over-pressurization valve. If a diver breathes on this UBA he will have

consumed oxygen and thereby reduce the volume of gas leaving the breathing circuit at the end of exhalation.

Some semiclosed UBAs have been designed so that CO₂ rich gas is exhausted, reducing the amount of CO₂ that must be removed by the CO₂ absorber. Canister endurance tests that are run on semi-closed UBAs using a breathing simulator without an oxygen consumption system that is active, would allow more CO₂ rich gas to escape than normal. Longer endurance predictions based on this data would result.

8.1.4 Data acquisition

The primary variable to record is the inspired CO₂ level. With the slow changes in the determinations of CO₂ in the absorber outlet a sampling frequency of 1 to 2 Hz is sufficient. For verification of the expired CO₂ profile, the signal from a fast responding analyzer should be sampled at a rate of at least 100 Hz.

8.1.5 Calibrations

The sensors used to measure the desired parameters must be calibrated. The rate of calibration depends on the specifications of a particular transducer.

8.1.6 Test procedure

Before any testing of an absorbent is performed in a UBA, it should be tested according to NEDU Test Manual 02-01. Material which fails the absorbent quality tests should not be used to determine UBA canister durations.

After transducers and system are calibrated, the UBA is attached to the breathing simulator. This is typically done using a mannequin head or a mouthpiece adapter. The UBA is immersed in water of the desired temperature and salinity and checked for leaks.

8.1.7 Data analysis

The time required for canister effluent to rise to 0.5% SEV (0.5 kPa) PCO₂ is plotted as a function of water temperature. That data is then fit by curve fitting software to find various estimates of canister duration versus temperature.

Curve fitting software used by NEDU can plot not only the best estimate for fitted data, but also confidence intervals on the best fit, and prediction limits for the data. One such software package is Systat's Table Curve 2D, (Systat Software Inc., Richmond, CA) formerly made by Jandel Scientific (San Rafael, CA).

For safety, NEDU publishes the lower 95% prediction limit from the best curvilinear fit to the experimental data³. That prediction limit is designed to ensure that the probability of a canister "breaking through" short of the published limits is no more than 2.5%, with all else being equal (water temperature, CO₂ injection rate, and ventilation rate).

Figure 8-3 is from NEDU TR 2-99³. It shows 1000 simulated canister durations distributed in a Gaussian (normal) fashion around mean durations. In this simulation, the mean durations were curvilinear dependent upon temperature, much as they are in the MK 25 UBA.

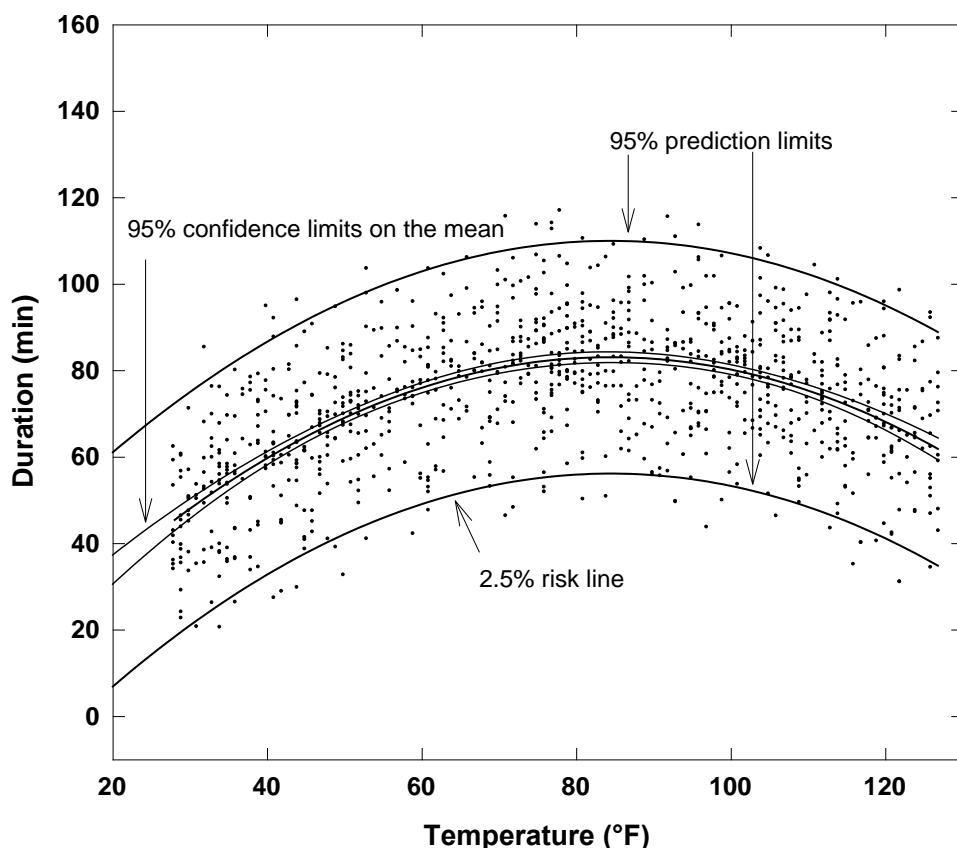


Figure 8-3 1000 simulated, normally distributed canister durations with curvilinear temperature dependencies³

The inner most line is the best estimate for the mean duration as a function of temperature. That line is surrounded closely by the 95% confidence limits on the mean. The furthestmost curved lines mark the boundary for the 95% prediction interval. As expected, about 2.5% of the data lies above the upper prediction limit line, and about 2.5% lies below the lower prediction limit.

For quick look investigations at a single water temperature⁴, a similar statistic can be found from a single sample prediction limit, as described in Clarke and Ferris, 2012.

REFERENCES

1. Long, E.T., "Test methods for Sodalime carbon dioxide absorbents". NEDU Technical Manual 02-01, 2001.
2. Clarke, J.R., Computer modeling of the kinetics of CO₂ absorption in rebreather scrubber canisters. In: *Proceedings of the Oceans 2001 MTS/IEEE Conference*, volume 3, pages 1738-1744, Honolulu, USA, November 2001.
3. Clarke, J.R., "Statistically Based CO₂ Canister Duration Limits for Closed-Circuit Underwater Breathing Apparatus", Navy Experimental Diving Unit Technical Report 2-99, 1999.
4. Clarke, J.R. and V. Ferris., "The use of one-sample prediction intervals for estimating CO₂ scrubber durations". Navy Experimental Diving Unit TR 12-03, 2012.

CHAPTER 9. OXYGEN CONSUMPTION SIMULATION

9-1 EVALUATING THE UBA O₂ CONTROL SYSTEM

Simulating human metabolic oxygen (O₂) consumption is required to test UBA O₂ control in closed- and semi-closed rebreathers. Such simulation may be accomplished by a catalytic combustion of propylene^{1,2} or by balancing a removal of mixed gas with a replenishment of inert gas.

As described in NEDU's Technical Manual 01-94, manual flow meters and metering valves were used to monitor and control gas flow as O₂ concentrations changed with changing depths. During rapid depth changes, however, the correspondingly rapid manual calculations required to adjust those gas flow values (as O₂ concentrations change with changing depth) proved to be daunting. Therefore, NEDU now uses automatically compensating mass flow controllers (MFC) to adjust flow.

Since nitrogen and oxygen have similar molecular weights and thermal properties, NEDU has selected nitrogen to be the inert background gas component in its oxygen control testing. Thus, as a diver descends and the fraction of O₂ (FO₂) changes substantially, MFCs are consistent and linear with the rapidly changing ratio of the two similar gases.

A mass flow controller combines a mass flow meter with a computer-controlled flow valve assembly capable of maintaining the flow at selected rates. The automated O₂ consumption system uses two such devices: one to control the flow of mixed gas leaving the apparatus being tested and a second to simultaneously reinject nitrogen back into the breathing loop. These two MFCs receive command signals from an algorithm within NEDU's data acquisition and control computer. A portion of the gas mixture flowing out from the UBA is routed to an O₂ analyzer, and the computer algorithm measures the FO₂ to calculate the nitrogen component to be reinjected.

Simulated metabolic consumption of O₂ is useful in evaluating both closed- and semiclosed-circuit breathing apparatus. During certain semiclosed evaluations of RE, canister duration, or oxygen control, simulation of both CO₂ production and O₂ consumption may be required to establish the proper exhaust-valve flow, heat conditions, and bag volumes.

During an O₂ control test (designed to evaluate the ability of a UBA's O₂ control system to maintain a fixed PO₂), mixed gas (nitrogen and oxygen) is removed from the UBA's inhalation hose before the mixture enters either the breathing bag or the CO₂ absorbent canister. As shown in Figure 10-1, this gas flows from the UBA through a chamber penetrator via a length of 3/8-inch (0.95 cm) OD tubing and then through the "mix out" mass flow controller located outside the chamber. A portion of this gas is analyzed by the laboratory oxygen analyzer to determine its oxygen concentration. From three parameters: 1) chamber depth, 2) concentration of oxygen in breathing gas, 3) and oxygen consumption rate to be simulated, the oxygen consumption software adjusts the flow controlled by the "mix out" MFC so that the total amount of gas removed from the breathing loop contains just the amount of oxygen that is to be "consumed." To maintain the correct inert gas (nitrogen) volume balance, the amount of nitrogen

that also is removed from the breathing loop by the mix out MFC must be added back into the loop. This is accomplished using a separate, “inert add” MFC that also is controlled by the oxygen consumption software and PC. This part of the system adds back into the breathing loop the amount of nitrogen removed by the first MFC. This amount, injected into the breathing simulator piston to improve gas mixing, is the volume of breathing gas removed by the first MFC less the volume of the oxygen that is consumed.

The following formulas provide a method to calculate the various flow rates (in STPD) for removing mixed gas and adding inert gas necessary to simulate desired O₂ consumption rates.

$$F_{O_2} = \frac{P_{O_2}}{P_{amb}} \quad (9-1)$$

where F_{O_2} is the fraction of oxygen in the rig at depth. P_{O_2} is the partial pressure of oxygen in the rig, and P_{amb} is the ambient pressure in atmospheres.

To find the flow rate of mixed gas to withdraw (\dot{V}_{out}), divide desired simulated oxygen consumption rate in (\dot{V}_{O_2}) by F_{O_2} .

$$\dot{V}_{out} = \frac{\dot{V}_{O_2}}{F_{O_2}} \quad (9-2)$$

Equation 9-3 finds the flow rate of diluent gas to inject into the rig (no oxygen) in STPD.

$$\dot{V}_{in} = \dot{V}_{out} - \dot{V}_{O_2} \quad (9-3)$$

Example:

Calculate the mix outflow and the inert addition gases for a dive depth of 60 fsw (18.3 msw or 2.82 ATA) and a 2.0 L/min desired O₂ consumption at STPD for a test UBA that has a PO₂ set point of 0.70 ATA.

$$\text{Fraction of } O_2 \text{ in rig at 18.29 msw} = \frac{0.70 \text{ set point}}{2.82 \text{ ATA}} = 0.248 \quad (24.8\%)$$

$$\text{Mix Out} = \frac{\text{desired } O_2 \text{ consumed } (L/min, STPD)}{F_{O_2 \text{ mix}}} = \frac{2.0 (SLPM)}{.248} = 8.06 \text{ L/min (STPD)}$$

As calculated for a resting diver, the inert gas added is equal to the mixed gas removed minus the O₂ consumed at 18.29 msw (60 fsw):

$$\text{Inert added} = \text{mix out} - O_2 \text{ consumed.}$$

$$\text{Inert added} = 8.06 \text{ L/min} - 2.0 \text{ L/min} = 6.06 \text{ L/min.}$$

9-3

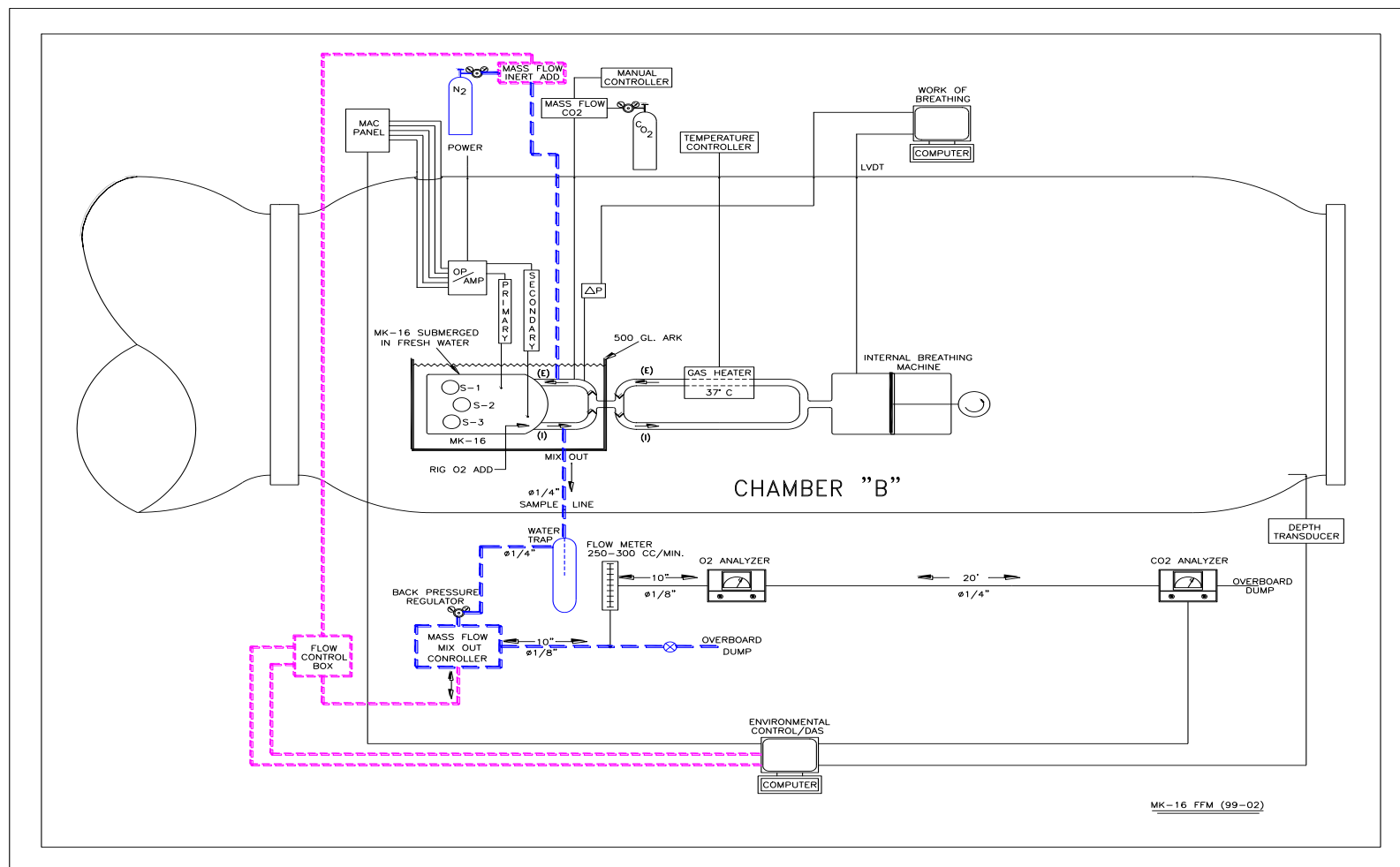


Figure 9-1 Schematic of system for simulating O₂ consumption

9-2. TEST EQUIPMENT AND PROCEDURES

9-2.1. Test Equipment

1. O₂ analyzer (model MGA; Rosemount Analytical, La Habra, CA)
2. Workstation computer systems running Windows (XP Professional; Microsoft Corporation, Redmond, WA) operating system and LabVIEW (version 7; National Instruments, Austin, TX) for data acquisition, instrument control, and data analysis
3. NEDU-developed LabVIEW programs for recording temperatures, depth, and O₂ concentrations — and for controlling MFCs during O₂ consumption simulations
4. Closed-circuit television system with continuous digital video recording capability, to monitor the UBA and in-chamber test equipment during testing
5. Calibrated 7 L gas syringe (model 4900, Series 7 L; Hans Rudolph, Kansas City, MO)
6. Two MFCs (model 840M-3-0V1-SV1-E-VI-SI; Sierra Instruments, Inc., Monterey, CA) for O₂ consumption simulation
7. Tracking regulator (model 44-4011E28-002; Tescom Corp., Elk River, MN) for use with O₂ consumption simulation system
8. Adapter inserted between the barrel valve assembly and the breathing hoses on both the inhalation and exhalation sides of the UBA, to enable gas sampling for O₂ consumption evaluations and to allow water to be drained from the UBA mouthpiece and test system hoses during testing (EDF special equipment, NEDU Design Note DN 10-01)
9. Test mannequin for mounting the UBA (EDF special equipment)
10. Stand for supporting and orienting both the mannequin and the UBA (EDF special equipment)
11. Breathing gas routing tee, to attach the UBA mouthpiece to the breathing simulator loop (EDF special equipment)
12. Oral pressure transducer (± 1 psi, differential, wet-wet, submersible; model PTX 317-9219; Druck Inc., New Fairfield, CT)
13. Hyperbaric test chamber depth transducer (0–200 psi, differential, wet-wet, submersible; model PTX 317-9219; Druck Inc., New Fairfield, CT)

9-2.2. Test Procedures

When the device to be tested has been fitted to a mannequin and placed in a hyperbaric chamber attached to the breathing simulator via hose connections, the breathing cycle is started

and the chamber complex is pressurized to 10 fsw. This minimum depth is required to generate flow to the MFC and remove the mix gas volume from the apparatus. Reinjecting the inert component is also begun, and sampled PO_2 is allowed to settle. Data recording is started, and the system, once stable, is compressed to the first evaluation depth.

A laboratory O_2 analyzer monitors the oxygen content of the gas exiting the MFC from the UBA's inhalation side. The "Mix Out" and "Inert Add" are adjusted automatically and continuously via the computer's data acquisition and control software. NEDU routinely uses nitrox rather than heliox to evaluate O_2 control which is an accepted technique to evaluate PO_2 control. To maintain the stability of the inert volumetric balance, another calibrated MFC adds the correct amount of inert gas (nitrogen) back into the loop. Table 10-2 shows an example of calculated parameters.

The test plan is then implemented via the following steps:

1. With the chamber on the surface:
 - a. Ensure that the test article is set to factory specifications and is working properly.
 - b. Calibrate all the transducers and the O_2 analyzer.
 - c. Perform the orifice verification procedures.
 - d. Open the makeup gas supply valve to the test UBA (diluent: air).
 - e. Ensure that the water temperature is 21.1 °C (70 °F), or as the test plan specifies.
 - f. Press the chamber to 3.0 msw (10 fsw), start the O_2 consumption system, and allow PO_2 to stabilize.
 - g. Press the chamber to the first data collection depth at a rate as close to 18.29 m/min (60 ft/min) as possible.
 - h. After PO_2 stabilizes collect data continuously for about 10 min or about twelve PO_2 oscillations, whichever is longer, at each set of data collection parameters as the approved test plan specifies.
2. After returning the chamber to the surface:
 - a. Verify the calibrations on the standard orifice and on all transducers.
 - b. Check O_2 analyzer accuracy with the appropriate calibration gases.

REFERENCES

1. Loncar, M., Å. Larsson and H. Örn timer. “Oxygen Consuming Unit for Tests of Breathing Apparatus.” In *European Underwater and Bromedical Society EUBS-93 Proceedings*, edited by R. Eidsmo, A.D. Brubakk and G. Bolstad. pp. 99–103. Trondheim, Norway: SINTEF UNIMED, 1993.
2. Loncar, M. and H. Örn timer, “Testing the Performance of Rebreathers.” *The Journal of the South Pacific Medicine Society* 27 (March 1997): pp. 51–57.

CHAPTER 10. ELASTANCE AND HYDROSTATIC IMBALANCE

10-1 INTRODUCTION

The impedance to breathing imposed by an underwater breathing apparatus (UBA) imposes several types of loads on the diver's respiratory muscles¹. Warkander (2007) summarizes these loads graphically in Figure 10-1. Breathing resistance is imposed by UBA hoses, narrow passages and valves, and also by airways passages within the diver's lungs³. An elastic load is imposed because the mean depth of the bag changes during breathing^{4,5}. Inertial loads due to the acceleration of water or UBA components during tidal breathing also exist, but are usually considered to be slight in comparison to the other loads⁶. (The one exception might be rebreathers that use heavy weights attached to breathing bellows to minimize hydrostatic loading. Theoretically, their inertance should be high.)

A static lung load (hydrostatic imbalance) is imposed because of the difference in depth between the lung pressure centroid and a reference point of the breathing apparatus. For an open circuit UBA, the reference point is the membrane of the demand valve in the mouthpiece while for a closed circuit UBA it is the deepest, movable part of the breathing bag. Any CO₂ in the inspired gas and the dead space in the face mask force the diver to increase his breathing, which increases the effect of the other loads.

Lundgren (1999) provides a review of the above respiratory forces and their effects encountered by divers during immersion⁷.

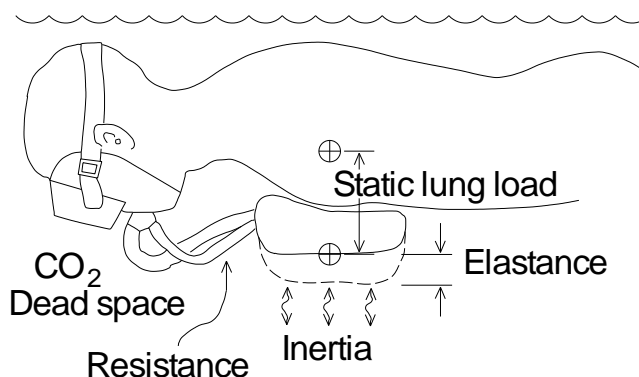


Figure 10-1 Illustration of the respiratory loads imposed on a diver who is breathing on a closed circuit UBA with the breathing bag (counter volume) on the chest.

Different tests can determine the magnitude of each of these loads. Such tests shall be made in such a way that they are accurate, performed in a standardized way and repeatable. To assure repeatability and standardization, tests are performed using a breathing simulator using a sine wave breathing pattern. The purpose of the simulator is to closely emulate the way a person breathes and interacts with the UBA. A UBA should be tested at the depths and in the attitudes where it is intended to be used.

10-2 ELASTANCE

Elastance is defined as the change in pressure when the volume changes:

$$E = dP / dV \quad (10-1)$$

For computational reasons the following equation is used:

$$E = \Delta P / \Delta V, \quad (10-2)$$

where ΔP is the change in pressure and ΔV is the change in volume between two measurements.

10-3 HYDROSTATIC IMBALANCE

The hydrostatic imbalance (static lung load) is the pressure difference caused by the vertical distance between the lung centroid and the part of the UBA that determines the pressure in the breathing loop. The lung centroid is a functional reference and is defined as the equivalent pressure point at which a person's expiratory reserve volume is the same as in the non-immersed condition (negative imbalance causes breathing at low lung volumes and positive imbalance causes breathing at high lung volumes⁸⁻¹¹). The lung centroid is typically given as being 14 cm below and 7 cm behind of the supra sternal notch, Figure 11-2.

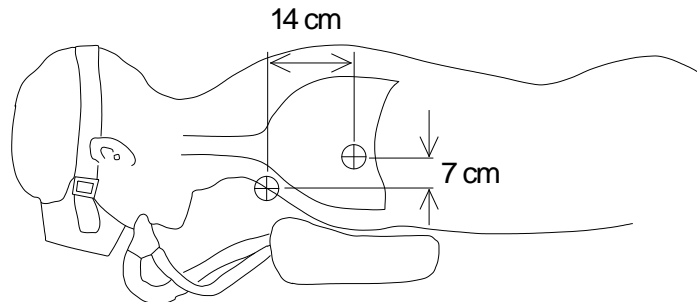


Figure 10-2 Illustration of the position of the lung pressure centroid and suprasternal notch.

One of several often confusing aspects of static hydrostatic imbalance is that it is possible to have different points of reference. Three such points come naturally: the lung centroid, but also two anatomical landmarks: the center of the mouth and the suprasternal notch. The mouth and the sternal notch are easy to identify on a person and a manikin. From a physiological function point of view, it may be preferable to have hydrostatic imbalances referenced to the lung centroid. However, during experimental set-ups and during breathing apparatus testing, a reference point that is consistent and easy to find is preferable. Figure 10-3 shows how the vertical distance between the suprasternal notch and the lung centroid changes with a diver's orientation in the water. This figure allows conversion between suprasternal notch and the lung pressure centroid.

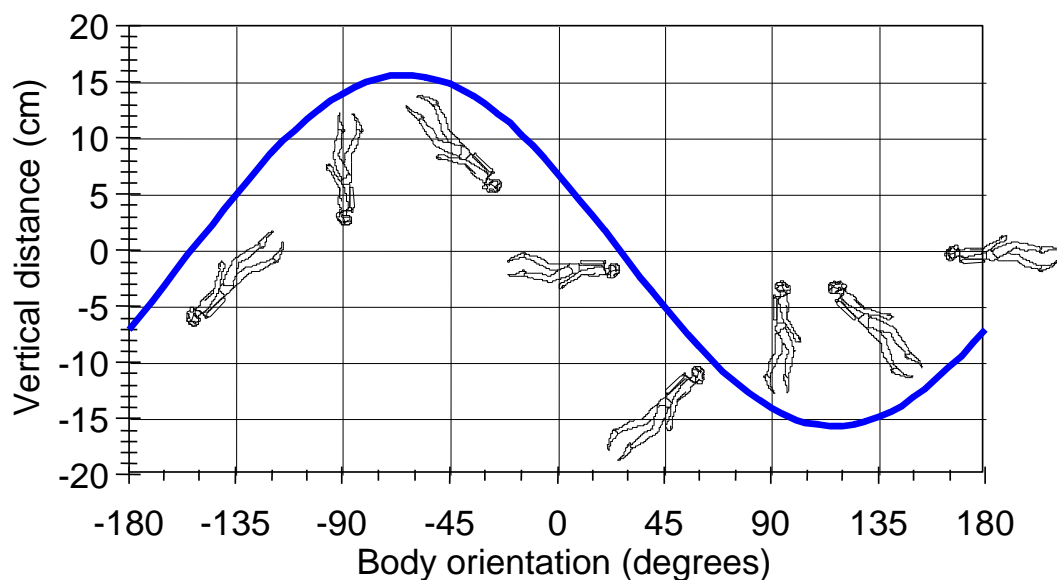


Figure 10-3 Vertical distance between the sternal notch and lung centroid for different orientations of a diver.

For instance, at 90 degrees (upright) the lung centroid is 14 cm below the suprasternal notch. This distance (in cm) follows the equation $15.6 \cdot \sin(\alpha - 26.6^\circ)$ where α is the diver's angle from a horizontal plane¹². (In a prone diver, 26.6° is the presumed angle from the horizontal pitch axis between the sternal notch and the lung centroid (Figure 10-2).

10-4 DATA ACQUISITION

The primary parameters to record are the volume of the breathing simulator and the pressure at the opening of the UBA (mouth pressure). With the slow movements in the determinations of elastance and hydrostatic imbalance a sampling frequency of 10 Hz is sufficient.

The mouth pressure should be measured as the static pressure with a static pressure pickup ring. This ring can be made from a piece of pipe with the same inside diameter as the breathing simulator plumbing. A fairly large number (10 to 20) of small holes (less than 1 mm, 0.04 in) are drilled through the pipe wall. All the holes are then connected together via a slot in the ring and then connected to the pressure transducer.

10-5 CALIBRATIONS

The sensors used to measure the desired parameters must be calibrated. The rate of calibration depends on the specifications of a particular transducer. To verify the breathing system as a whole, a check is performed daily using a standard orifice, Figure 5-1. Because the physical dimensions are fixed, resistive effort (resistive RE) values will be constant for each RMV if the temperature is stable. The purpose of the orifice is to provide a known breathing resistance. The orifice is placed where the mouthpiece of the UBA will be placed during actual UBA tests. The breathing machine is then operated at 1 ATA, and a P-V loop recorded for each RMV. The calculated resistive effort is then compared against tolerance limits established for each RMV

(Table 5-1). The tolerance limits were established at 2 standard deviations above and below the mean of approved orifice checks. If the orifice calibration check falls outside tolerance limits, then a problem exists, such as excess volume in the circuit, high flow resistance, improper transducer calibration, or water trapped in various lines and hoses.

10-6 TEST PROCEDURE

After transducers and system are calibrated, the UBA is attached to the breathing simulator. This is typically done using a mannequin head or a mouthpiece adapter. The UBA is immersed in water of the desired temperature and salinity and checked for leaks.

To provide a repeatable starting volume, air is allowed to escape from the breathing loop until the make-up valve opens. The breathing simulator is then operated in one of two ways; either the piston is moved in increments of, say, 0.5 L or it can be moved continuously at a very slow rate, say 2 breaths per minute, while volume and pressure are recorded. Ideally, the breathing bag should be fully inflated before air is withdrawn. A UBA should be tested both in a vertical and horizontal position. A UBA with over-the-shoulder bags should also be tested when rotated sideways.

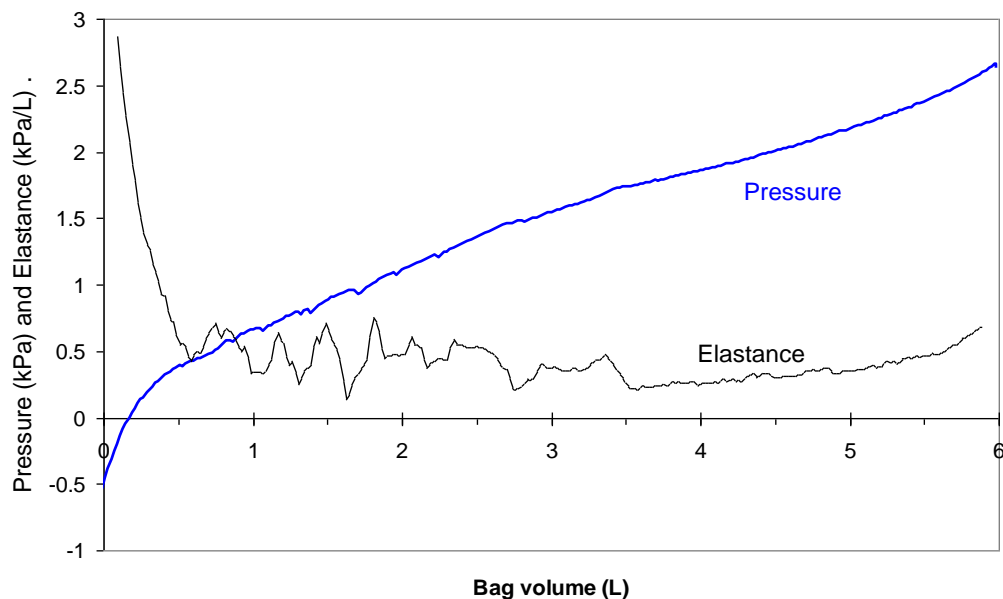


Figure 10-4 Pressure-volume plot of data from a closed circuit UBA. The breathing bag was emptied until the make-up valve opened.

10-7 DATA ANALYSIS

10-7.1 Elastance

The values of both the hydrostatic imbalance and elastance can be obtained from a pressure-volume plot, Figure 10-4. Using equation 10-2, the elastance was calculated and is also illustrated in Figure 10-4. As can be seen the elastance is high at the lowest breathing bag volume indicating that the bag was stiff making it hard to empty it. The wiggles in the calculated elastance are probably due to the expansion of folds in the bag. The average elastance between the volumes 0.5 and 5.5 L was 0.4 kPa/L. However, at lower volumes it increases drastically.

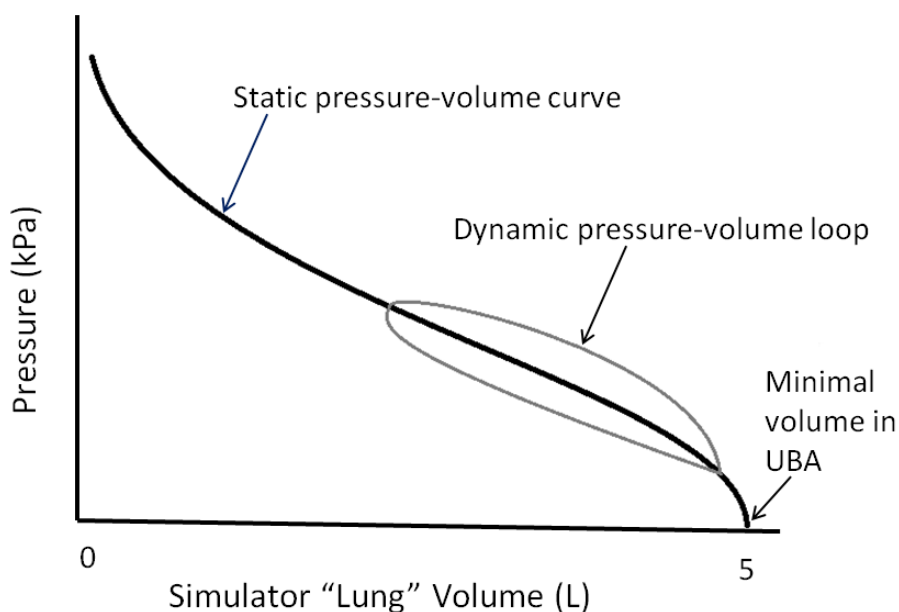


Figure 10-5 A pressure-volume loop superimposed on a static elastance curve.

The dynamic pressure-volume loop differs from the static curve due to resistive pressures generated during gas flow. As RMV (gas flow) decreases, the dynamic loop more closely approaches the static curve.

10-7.2 Hydrostatic imbalance

Hydrostatic imbalance is measured at the beginning of a breath when the respiratory muscles are relaxed. From the pressure traces in Figures 10-4 and 10-5 it can be seen that UBA internal pressure depends on the breathing bag volume. It is a summation of **hydrostatic** imbalance and **elastance**. This means that for a closed circuit UBA the hydrostatic imbalance cannot remain fixed throughout a breath. For instance, if a breath starts with 1 L in the bag the imbalance is 0.65 kPa but if the bag volume were 3 L it would be 1.5 kPa. For a Scuba regulator where the regulator is placed in a fixed position the hydrostatic imbalance is constant.

REFERENCES

1. Clarke, J.R., "Impedance and power measurements in the testing of closed circuit UBA". In: Lung Physiology and Divers' Breathing Apparatus. Eds. V. Flook and A.O. Brubakk., BPCC-AUD, Aberdeen, pp. 85-93, 1992.
2. Warkander, D.E., "Comprehensive Performance Limits for Divers' Underwater Breathing Gear: Consequences of Adopting Diver-focused Limits". Navy Experimental Diving Unit Technical Report 07-02. Panama City, Florida: NEDU, 2007.
3. Clarke, J.R., M.J. Jaeger, J.L. Zumrick, R. O'Bryan, and W.H. Spaur. "Respiratory resistance from 1 to 46 ATA measured with the interrupter technique". Journal of Applied Physiology. 52:549 555. 1982.
4. Joye, D.D., J.R. Clarke, N.A. Carlson and E.T. Flynn. Formal descriptions of elastic loads encountered in the use of underwater breathing systems. In: eds. Lundgren and Warkander, "Physiological and Human Engineering Aspects of Underwater Breathing Apparatus". Undersea and Hyperbaric Medical Society, Inc. Bethesda, Md. 1989.
5. Joye, D.D., J.R. Clarke, N. Carlson and E.T. Flynn. "Formulation of elastic loading parameters for studies of closed-circuit Underwater Breathing Systems". NMRI Tech Report, pp. 89-89, 1989.
6. Clarke, J.R., M.A. Fisher, and M.J. Jaeger. "Inertance as a factor in uneven ventilation in diving", Proceedings of the Seventh Symposium of Underwater Physiology, Undersea Medical Society, Bethesda, 1981.
7. Lundgren, C.E.G., "Immersion Effects" In: *The Lung at Depth*, ed. CEG Lundgren and J Miller. In series, *Lung Biology in Health and Disease*, ed. Claude Enfant. New York, Marcel Dekker. pp.91-128, 1999.
8. Fine, R. and E.T. Flynn. "Effects of hydrostatic loading during submersion on voluntary hyper-ventilation". *Undersea Biomedical Research* 14:24, 1987.
9. Taylor, N.A.S. and J.B. Morrison. "Lung centroid pressure in immersed man", *Undersea Biomedical Research*, 1989, vol. 16, n°1, pp. 3-19.
10. Carlson, N., J.R. Clarke, and E.T. Flynn. "The effects of hydrostatic loading during immersion on oxygen uptake and ventilatory endurance", *Undersea Biomedical Research* 16:Suppl., 1989.
11. Clarke, J.R., "Optimal hydrostatic loading for closed-circuit underwater breathing apparatus design". Naval Medical Research Institute Technical Report 91-08, March 1991.
12. Warkander, D. E., and C. E. G. Lundgren, "Development of Comprehensive Performance Standards for Underwater Breathing Apparatus". Final report to U.S. Navy: Naval Sea Systems Command and Office of Naval Research. Center for Research and Education in Special Environments, University at Buffalo, Buffalo, NY, 2000.

CHAPTER 11. COLD WATER REGULATOR TESTING

11-1 INTRODUCTION



Figure 11-1 Ice accumulation in a 2nd stage regulator after free flow.

This chapter describes the unmanned test procedures to which each candidate regulator for cold water-service will be subjected. Performance criteria of each model regulator will be the ability to provide sufficient breathing air and the absence of sustained second stage free flow and the ability to maintain intermediate pressure (IP) in a cold water environment.

For statistical purposes, a minimum of five regulators of each model will be required for testing. All regulators will be subjected to a hierarchical series of unmanned tests consisting of the following three phases:

Three different evaluations will be performed in sequential phases, on each of the UBA models:

- Phase 1: Visual inspection and dry bench evaluation
- Phase 2: Freeze-up testing
- Phase 3: Resistive effort testing

Phase 1: Visual inspection and dry bench evaluation

The over-bottom pressure, and the breathing effort required to initiate flow (negative or “cracking” pressure) will be checked to verify they are within the manufacturers’ recommended range. Should the over-bottom pressure of a regulator under test be determined to be outside the specified range, that regulator will not be tested. No attempt will be made to adjust a regulator.

Phase 2: Freeze-up testing

A mechanical breathing machine will be used to simulate the respiration process of a diver at a respiratory minute volume (RMV) of 62.5 L/min. Saline water, in the range of 35-40 parts per thousands (ppt) and temperature range of $29 \pm 1^{\circ}\text{F}$ and fresh water at $34 \pm 1^{\circ}\text{F}$ (-1.7 and $1.1 \pm 0.6^{\circ}\text{C}$, respectively), will simulate the ocean and inland environment. The possible development of a “freeze up” of the regulator 2nd stage, indicated by a sustained flow of bubbles from the exhaust port, will be determined visually using real time video monitors. At various time intervals, the over-bottom pressure and resistive effort (analysis of pressure and volume [PV] variables) will be monitored and recorded. Also, the development of instability in intermediate pressure with time or depth will be tracked.

Phase 3: Resistive effort testing

A mechanical breathing machine will be used to simulate the ventilation of a diver at various RMVs. Testing will occur in fresh water and a temperature of 50 ± 1 °F (10 ± 0.6 °C). That temperature should be warm enough to preclude internal ice accumulation and yet cool enough to stiffen soft goods that might affect RE. RE will be monitored and recorded for various depth and breathing rate combinations.

11- 2 EXPERIMENTAL DESIGN AND ANALYSIS

The first phase of testing is conducted on a platform designed for testing open circuit scuba regulators at atmospheric pressure. As part of this dry bench evaluation the ability of each regulator to hold intermediate pressure will be determined and recorded. In addition, the cracking pressure will be observed and recorded.

For RE measurement phases 2 and 3 use the test configurations shown in Figures 5-6 or 5-7. The expired gas from the breathing machine is heated and humidified to maintain 100% water saturation at an appropriate temperature (dependent on the water temperature) at the mouthpiece of the UBA. The following equation is used to calculate the appropriate expired gas target temperature:

$$T_{\text{expired}} = 24^{\circ}\text{C} + 0.32 \cdot T_{\text{inspired}} \quad (11-1)$$

where the temperatures, T_{expired} and T_{inspired} , are expressed in °C, and T_{inspired} is defined to be equal to the surrounding water temperature.¹

Due to the technique used to heat and humidify the expired gas, it may not be possible to achieve the desired temperature for all water temperature and ventilation rate combinations at target depths. Any deviations from the stated expired gas temperature intervals in Phase 2 and Phase 3 will be noted in the technical report.

The following parameters will be controlled, varied or recorded for each phase of testing:

Phase 1:

Visual inspection and dry bench evaluation

- a) Testing supply pressure: 3000 ± 25 psig
 1500 ± 25 psig
 500 ± 25 psig
- b) **Record** ability to hold intermediate pressure within manufacturer's specified range
- c) **Record** cracking pressure
- d) Test depth: surface
- e) Breathing and testing medium: diver's breathing air

Phase 2:

Freeze-up testing

- a) Testing supply pressure: 2500 ± 25 psig
- b) Water temperature 29 ± 1 °F (-1.7 ± 0.6 °C)
- c) Test depth: 198 fsw (60.4 msw)

- d) Breathing and testing medium: diver's breathing air
- e) Breathing rate: Computer controlled respiratory minute volume (RMV) of 62.5 liters per minute (L/min), 2.5 L at 25 breaths/min.
- f) Exhalation gas humidity: saturated, as confirmed visually through the exhalation hose of the routing block
- g) Expired gas temperature: $74 \pm 10^{\circ}\text{F}$ ($23.3 \pm 5.6^{\circ}\text{C}$) at 198 fsw, measured at the exhaust side of the routing valve
- h) **Record** onset of sustained free flow, if it occurs, determined visually using closed circuit video monitors, intermediate pressure and supply pressure via pressure transducers and a computer controlled data acquisition system
- i) First stage IP less than 200 psi over bottom.
- j) Supply gas temperature at inlet to the 1st stage $\pm 5^{\circ}\text{F}$ of ark temperature.



Figure 11-2 Normal salt water ice accumulation encrusting a regulator 1st stage.

Phase 3:

Resistive effort testing

- a) Test supply pressure: 1500 ± 25 psig, downward excursion; 500 ± 25 psig, upward excursion
- b) Water temperature of $50 \pm 1^{\circ}\text{F}$ ($10 \pm 0.6^{\circ}\text{C}$)
- c) Test depths: 0 feet of seawater (fsw [0 meters of seawater {msw}]) to 198 fsw (60.4 msw) in 33 fsw (10.1 msw) increments.
- d) Breathing and testing medium: diver's breathing air
- e) Breathing rates: Computer controlled, respiratory minute volumes (RMVs) of 22.5, 40.0, 62.5, 75.0, and 90 liters per minute (L/min). RMV parameters are as given in Table 3-1.
- f) Exhalation gas humidity: saturated, as confirmed visually

- g) Expired gas temperature: 77 ± 10 °F (25.1 ± 5.6 °C), measured at the exhaust side of the routing valve
- h) **Record** resistive effort, intermediate pressure and supply pressure via pressure transducers and computer controlled data acquisition system

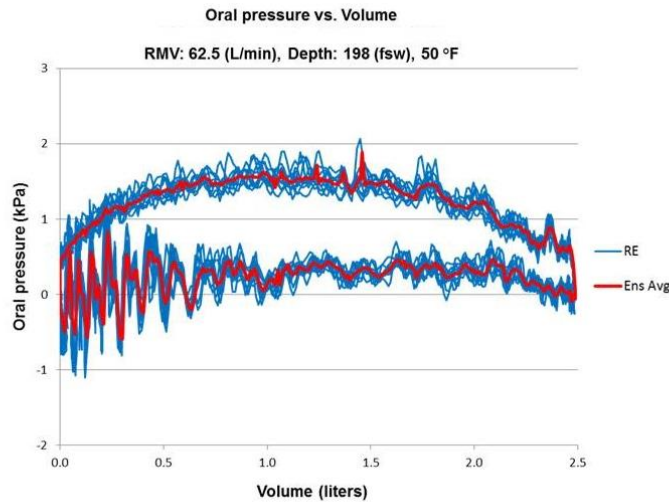


Figure 11-3 Typical P-V loop with 10-loop ensemble average

11-3 EQUIPMENT AND INSTRUMENTATION

Equipment comparable to the following shall be used:

- a. Breathing gas routing tee to attach UBA mouthpiece to breathing simulator loop (EDF special equipment)
- b. Stand for supporting and orienting UBA and routing tee (EDF special equipment)
- c. Oral pressure transducer (± 1 psi, differential, wet-wet, submersible; model PTX 317-9219; Druck Inc., New Fairfield, CT)
- d. Depth pressure transducer (0-200 psi, differential, wet-wet, submersible; model PTX 317-9219; Druck Inc., New Fairfield, CT)
- e. Linearized thermistor temperature sensors (700 series; Yellow Springs Instruments, Yellow Springs, OH)
- f. Two-channel thermilinear thermistor signal conditioner (DEI model 1442; Deban Enterprises, Inc., Yellow Springs, OH)
- g. Sinusoidal mechanical breathing simulator (BM2B; Reimers Engineering, Springfield, VA)
- h. Workstation computer systems running Windows XP Professional or later operating system; Microsoft Corporation, Redmond, WA, for data acquisition, instrument control and data analysis. **(Changes in operating system require extensive testing and**

validation of compatibility with purpose-made test and evaluation software prior to implementation.)

- i. NEDU developed software for recording and analyzing parameters of pressure-volume breathing loops as described and validated in NEDU Technical Report TR 09-02.²
- j. Closed circuit video system to monitor UBA and in-chamber test equipment during testing
- k. Standard scuba adapter, attaching the UBA 1st stage assembly to the pressure sensor for measurement of intermediate pressure. Global Manufacturing, part no: 57315
- l. Bubble deflector and diffuser (EDF special equipment)
- m. Standard orifice (EDF special equipment)
- n. Approximately 30 feet of umbilical hose attached to scuba cylinder (EDF special equipment) to allow for chilling of inspired gas.
- o. Regulator Test Bench (Global Manufacturing Corp.; Milwaukee, WI)
- p. Salinometer, (Model 30-10FT YSI Inc.)
- q. The EDF ark heater/chiller system and associated support systems will be used.
- r. High pressure (≥ 3000 psi) scuba cylinder, 40 cf or larger capacity, with attached dual outlet valve
- s. Closed-circuit video systems will provide monitoring capabilities of regulators during testing.
- t. The "Alpha" and/or "Bravo" chamber, ark and data acquisition computer system consisting of a Microsoft NT Workstation computer system, National Instruments (Austin, TX) data acquisition system, and NEDU-developed software used to process resistive effort data

11-4 TEST PROCEDURES

Each phase of testing is conducted per the following procedures:

Phase 1:

Visual inspection and dry bench evaluation

The regulator test stand will be used to perform regulator tests of intermediate pressure and cracking pressure, in accordance with EDF OP-19, with test results documented. Removal of the 2nd stage mouthpiece is required prior to Phase 1 tests. Once removed, leave unattached for subsequent use in Phases 2 and 3.

1. Parameters Controlled:

- a. Supply pressure 500, 1500, and 3000 psig
- b. Breathing gas: Diver's breathing air
- c. Regulator adjustment knob (Dial-A-Breath) setting: Set to midrange of travel or per test plan (if configured).
- d. Venturi assist vane: Set to midrange of travel or per test plan (if configured).

2. Parameters Measured:

- a. Time and date
- b. UBA manufacturer, model, serial number and NEDU tracking code

- c. Cracking pressure
- d. Ability to maintain intermediate pressure recommended by manufacturer.
- e. Confirm absence of free flow.

Phase 2:

Freeze-up testing

IMPORTANT: Strict adherence to submersion times, breathing times, bottom times and travel rates is required to simulate actual dive profiles, ensure repeatability and to control the total exposure time of the apparatus being tested.

1. Pre-Test Dive:

- a. Record regulator NEDU code and serial number on dive worksheet.
- b. Confirm regulator has been stored in a dry, room temperature area.
- c. Perform all pre-test instrument calibrations and checks.
- d. Ensure all test parameters to be controlled are within acceptable range.
- e. Attach mouthpiece adapter to 2nd stage with spacers as needed.
- f. Attach intermediate pressure IP monitoring adaptor onto 1st stage assembly.
- g. If configured, set regulator adjustment knob.
- h. If configured, set venturi assist lever.

2. Test Dive:

- a. DO NOT BREATHE regulator above the water.
- b. DO NOT PURGE regulator.
- c. Blow any residual moisture from cylinder outlet valve using dry air nozzle.
- d. Assure breathing hoses are void of trapped water.
- e. Attach 1st stage assembly to scuba cylinder outlet valve.
- f. Attach 2nd stage mouthpiece to gas routing block.
- g. Attach IP sensor to 1st stage adaptor.
- h. Confirm oral pressure transducer, drain and thermistor are attached to breathing block.
- i. Connect ~ 30 foot long umbilical from breathing gas chamber inlet to scuba cylinder outlet valve. Keep umbilical submerged to help maintain inlet gas at water temperature.
- j. Set console breathing gas to 2500 psig. (DIN models may be higher; see Test Plan.)
- k. Confirm scuba cylinder outlet valve to console breathing gas supply is OPEN.
- l. OPEN scuba cylinder outlet valve to regulator.
- m. Record time as regulator and test rig are lowered underwater. Assure test article and cylinder valve are completely submerged.
- n. Confirm the absence of bubbles from both the 1st and 2nd stages of the regulator unless expected due to regulator design. Once submerged, prior to the start of breathing, the test apparatus should be checked for leaks. If within 30 seconds of being submerged the determination is made to raise the test apparatus for any

reason, the test apparatus will remain above the water line for 5 minutes. If within 5 minutes the test apparatus is readied for test then the test apparatus will be submerged **at the 5 minute mark**. If the test apparatus cannot be readied within 5 minutes then the regulator under test will be terminated from diving for that day and so logged. Only one such iteration shall be allowed per regulator per day

- o. Start breathing machine.
- p. Descend at a rate of 60 ft/min, to a depth of 198 fsw. Record descent start time.
- q. Start 30 minute bottom timer once on the bottom.
- r. Breathing will be stopped at ten-minute run time intervals for 30-second duration to check for sustained free flow. Should a minor free flow condition exist, at the test supervisor's discretion, the dive may continue with the free flow condition monitored at intervals less than 10 minutes.
- s. Following observations at 198 fsw, regulators will travel to the surface at a rate of 30 ft/min.

3. Post Test Dive:

- a. **STOP BREATHING MACHINE PRIOR TO REMOVING UBA FROM ARK.**
- b. Record time as UBA and test rig are raised above water level.
- c. With the UBA still attached, blow residual moisture from 1st stage assembly.
- d. Detach UBA from test stand.
- e. Pressurize regulator with supply pressure (between 500 and 3000 psi) at the rinsing station.
- f. RINSE regulator in fresh water, being careful not to depress the 2nd stage diaphragm.
- g. Cap 1st stage assembly HP air inlet and IP sensor port.
- h. Store regulator in dry area at room temperature.
- i. Perform appropriate post-test calibrations and checks.

4. Parameters Controlled:

- a. Ark water temperature: $29 \pm 1^{\circ}\text{F}$
- b. Saline water in ark: 35-40 ppt
- c. Fresh water: $34 \pm 1^{\circ}\text{F}$.
- d. Breathing gas: Diver's quality air
- e. Maximum Test depth: 198 fsw
- f. RMV: 62.5 L/min
- g. Expired gas temperature: $74 \pm 10^{\circ}\text{F}$ ($23.3 \pm 5.6^{\circ}\text{C}$)
- h. Data acquisition sample rate for resistive effort measurements: 250 samples/sec
- i. Orientation of UBA: upright

5. Parameters Measured:

- a. Time and date
- b. UBA model and serial number
- c. Oral pressure

- d. Intermediate pressure
- e. Observed sustained free-flow condition
- f. Ten (10) pressure volume loops periodically during dive to electronically capture resistive effort and other measured & controlled parameters
- g. Breathing gas supply temperature measured at first stage

Phase 3:

Resistive effort testing

1. Pre-Test Dive:

Same procedures as in the freeze-up testing.

2. Test Dive:

- a. DO NOT BREATHE regulator above the water.
- b. DO NOT PURGE regulator.
- c. Blow any residual moisture from cylinder outlet valve using dry air nozzle.
- d. Assure breathing hoses are void of trapped water.
- e. Attach 1st stage assembly to scuba cylinder outlet valve.
- f. Attach 2nd stage mouthpiece to breathing Tee.
- g. Attach IP sensor to 1st stage adaptor.
- h. Confirm oral pressure transducer, drain and thermistor are attached to breathing block.
- i. Connect ~ 30 foot long umbilical from breathing gas chamber inlet to scuba cylinder outlet valve. Keep umbilical submerged to help maintain inlet gas at water temperature.
- j. Set console breathing gas to 1500 psig.
- k. Confirm scuba cylinder outlet valve to console breathing gas supply is OPEN.
- l. OPEN scuba cylinder outlet valve to regulator.
- m. Record time as regulator and test rig are lowered underwater.
- n. Confirm the absence of bubbles from both the 1st and 2nd stages of the regulator unless expected due to regulator design. Once submerged, prior to the start of breathing, the test apparatus should be checked for leaks.
- o. Seal the chamber.
- p. Set the RMV to 22.5 L/min; (Same breathing machine parameters as in Table 3-1.)
- q. Collect 10 PV loops; record them in the computer data file and manually record the displayed ensemble average value of the RE.
- r. Repeat the procedure for RMVs of 40.0, 62.5, 75.0 and 90.0 L/min; (Same breathing machine parameters as in Table 3-1.)
- s. Descend 33 fsw to next test depth.
- t. Repeat steps (p), (q), (r) and (s) until maximum depth (typically 198 fsw).
- u. Change supply pressure to 500 psig (or as per test plan).
- v. Repeat steps (p), (q) and (r) at the maximum depth.
- w. Ascend 33 fsw to next shallower test depth until reaching the surface

repeating steps (p), (q) and (r).

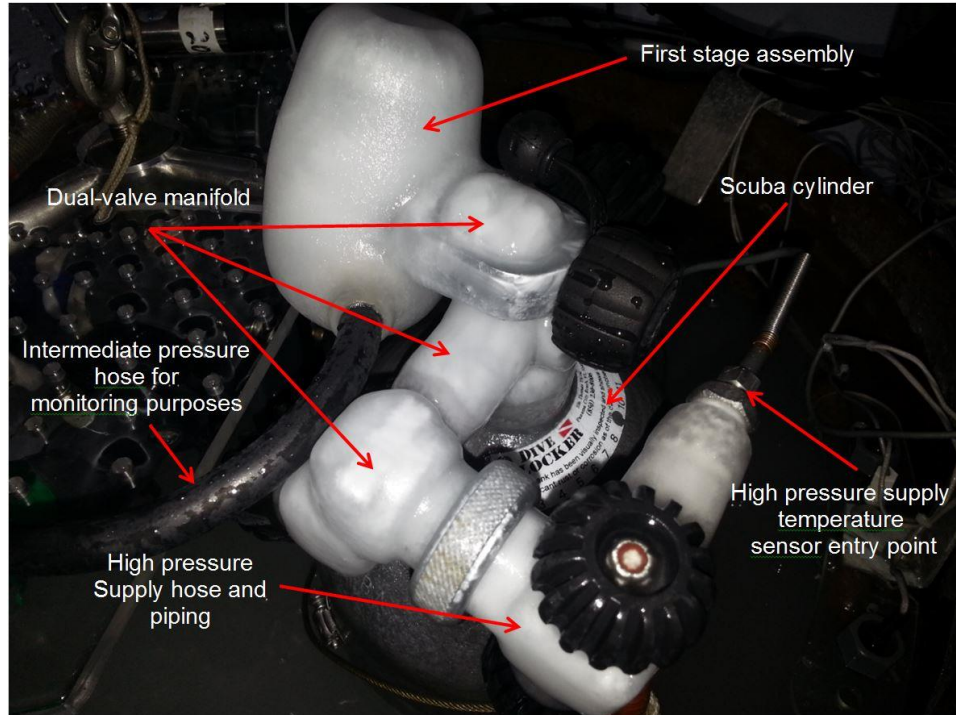


Figure 11-4 Normal external ice accumulation.

3. Post Test Dive:

Same procedures as in the Freeze-Up testing.

4. Parameters Controlled:

- a. Ark water temperature: $50 \pm 1^{\circ}\text{F}$
- b. Breathing gas: Diver's breathing air at 1500 or 500 psig supply pressure
- c. Test depths: 0, 33, 66, 99, 132, 165 and 198 fsw
- d. RMV: 22.5, 40.0, 62.5, 75.0 or 90.0 L/min
- e. Expired gas temperature: $77 \pm 10^{\circ}\text{F}$ ($25.1 \pm 5.6^{\circ}\text{C}$)
- f. Data acquisition sample rate for resistive effort measurements: 250 samples/sec
- g. Orientation of UBA: upright

5. Parameters Measured:

- a. Time and date
- b. UBA manufacturer, model, serial number and NEDU tracking number
- c. Oral pressure
- d. Intermediate pressure
- e. 10 Pressure volume loops at each depth and RMV combination

11-5 TERMINATION CRITERIA

(a) INDIVIDUAL REGULATOR BENCH TEST OR DIVE TERMINATION

Any regulator unit not meeting all criteria within each phase is said to have *failed* that phase, otherwise the individual unit *passes*.

Phase 1:

- Inability to set or maintain manufacturer specified intermediate pressure
- Sustained free flow or failure to deliver gas
- IP equal to or greater than 200 psi over bottom
- Any event for which the EDF Supervisor or the Task Leader so directs

Phase 2:

- Inhalation or exhalation oral pressure exceeding 7 kPa referenced to the suprasternal notch
- Sustained free flow or failure to deliver gas
- IP equal to or greater than 200 psi over bottom
- Any event for which the EDF Supervisor or the Task Leader so directs

Phase 3:

- Inhalation or exhalation pressure exceeding 7 kPa at a specific RMV and depth will terminate that set of test conditions only. The remaining battery of tests will be attempted.
- Sustained free flow or failure to deliver gas
- Any event for which the EDF Supervisor or the Task Leader so directs

(b) MAKE AND MODE TERMINATION

Phase 1:

- If 2 out of 5 regulators of any make and model fail the Phase 1 bench test, testing of that make and model will be terminated and that regulator model will be excluded from Phase 2 tests.

Phase 2:

- If a specific make and model has 3 failures, the cumulative failure rate will be determined. If the cumulative failure rate is greater than 33%, testing of all regulators of that make and model will be terminated and excluded from Phase 3 tests, otherwise testing of that make and model shall continue and the cumulative failure rate recalculated and the termination criteria reevaluated at the end of each dive.

Phase 3:

- No failure criteria
- All 5 regulators, of any make and model, having successfully passed Phase 2, will be subjected to resistive effort (work of breathing) tests in this phase.

REFERENCES

1. P. B. Bennett and D. H. Elliott, *The Physiology and Medicine of Diving, Third Edition* (San Pedro, CA: Best Publishing Co., 1982), p.308.
2. R. P. Layton, *Validation of New Resistive Effort Data Acquisition and Analysis System*, NEDU TR 09-02, Navy Experimental Diving Unit, Jan 2009.

CHAPTER 12. BREATHING EFFORT CALCULATION

The following pages are from a document created by MathCad (Version 8, MathSoft, Inc.) rigorously defining the procedures whereby Work of Breathing and breathing effort are determined.

Respiratory frequency (Hz)	Period (sec)	Sample rate	Sample interval
$f := 0.5 \text{ sec}^{-1}$	$T := \frac{1}{f}$	$s := 1000 \text{ sec}^{-1}$	$\Delta T := \frac{1}{s} \quad \Delta T = 1 \cdot 10^{-3} \text{ sec}$

Number of samples

$$n := T \cdot s \quad n = 2 \cdot 10^3$$

Angular frequency

$$\omega := 2 \cdot \pi \cdot f \quad \omega = 3.142 \text{ sec}^{-1}$$

Sample sequence

$$i := 1..(n - 1)$$

$$t_i := i \cdot \Delta T \quad \dots \text{time at each sampling period}$$

kPa \equiv 1000 Pa ... definition

$$\text{tnd}_i := t_i \cdot \text{sec}^{-1} \quad \dots \text{non-dimensional form for time graphing purposes)$$

UBA Resistance

$$R := 0.5 \text{ kPa} \cdot \frac{\text{sec}}{\text{liter}}$$

UBA Elastance

$$E := 0 \cdot \frac{\text{kPa}}{\text{liter}}$$

Tidal Volume

$$V_t := 3 \cdot \text{liter} \quad V_{\text{tnd}} := V_t \cdot \text{liter}^{-1}$$

Volume - as a function of time

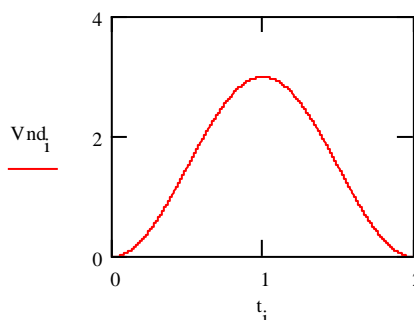
$$V(t) := V_t \cdot \sin\left(\frac{\omega}{2} \cdot t\right)^2$$

$$V_i := V_t \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2$$

... Volume at each sampling period

$$V_{\text{nd}_i} := V_i \cdot \text{liter}^{-1}$$

Volume tracing



Flow - the time derivative of volume:

$$F(t) := \frac{d}{dt} V_t$$

$$F(t) := \omega \cdot V_t \cdot \sin\left(\frac{1}{2} \cdot \omega \cdot t\right) \cdot \cos\left(\frac{1}{2} \cdot \omega \cdot t\right)$$

From a trigonometric identity this is equivalent to:

$$F(t) := \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t) \quad F_i := \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t_i) \quad \dots \text{discrete samples of flow at various sampling intervals}$$

$$Fnd_i := F_i \cdot \text{liter}^{-1} \cdot \text{sec} \quad \dots \text{non-dimensional form}$$

Pressure

$$Pm(t) := R \cdot \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t) + E \cdot \left(Vt \cdot \sin\left(\frac{\omega}{2} \cdot t\right) \right)^2$$

$$P_i := R \cdot F_i + E \cdot V_i$$

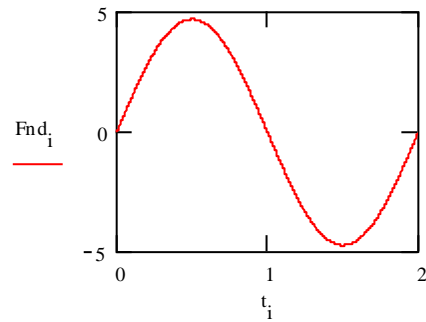
$$Pnd_i := P_i \cdot \text{kPa}^{-1}$$

$$\max(P) = 2.356 \text{ kPa} \quad \dots \text{maximum pressure}$$

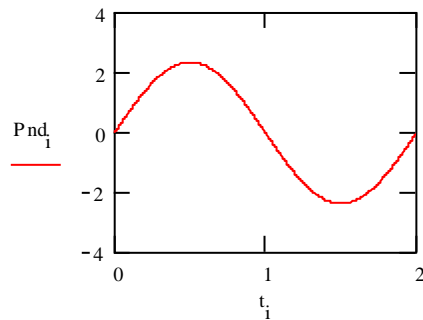
$$\text{mean}(P) = 0 \text{ kPa} \quad \dots \text{average pressure}$$

$$\min(P) = -2.356 \text{ kPa} \quad \dots \text{minimum pressure}$$

Flow Tracing



Pressure Tracing



Time-Averaged Pressure - Full Cycle

To integrate we must non-dimensionalize (a peculiarity of MathCad):

$$T := T \cdot \text{sec}^{-1} \quad \omega := \omega \cdot \text{sec} \quad Vt := Vt \cdot \text{liter}^{-1}$$

$$R := R \cdot \text{liter} \cdot (\text{kPa} \cdot \text{sec})^{-1}$$

$$Pm(t) := R \cdot \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t) \quad F(t) := \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t)$$

$$\frac{1}{T} \cdot \int_0^T Pm(t) dt = 0 \quad \dots \text{time-averaged pressure for a full cycle}$$

$$\frac{2}{T} \cdot \int_0^{\frac{T}{2}} Pm(t) dt = 1.5 \quad \dots \text{time-averaged pressure for one-half cycle}$$

Another type of time-averaged pressure is called:

Root Mean Square pressure(Prms) or Effective Pressure

$$Prms := \sqrt{\frac{1}{T} \cdot \int_0^T Pm(t)^2 dt} \quad Prms = 1.666 \quad \dots \text{ for a full breathing cycle}$$

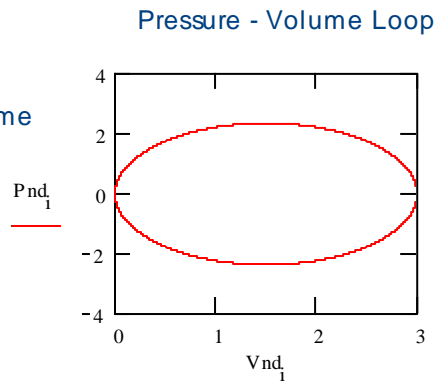
Another way of expressing Prms is:

$$Prms := \sqrt{\frac{1}{n} \cdot \sum_i (P_i)^2} \quad Prms = 1.666 \text{ kPa}$$

Periodically oscillating waveforms are typically described in terms of their RMS values. For example, 110 v is an RMS value for household voltage.

Pressure-Volume Loops

The area inside the pressure-volume loop is defined as the **Work of Breathing**, with units of Joules (J).



Work of Breathing

$$W := \int_0^T Pm(t) \cdot F(t) dt \quad W = 11.103 \quad \text{Note: } F(t) = dV/dt$$

In diving it has become customary to divide W by tidal volume. This results in a volume - a pressure (Pva). We refer to this average pressure as a measure of resistive breathing effort.

Resistive Effort

$$Pva := \frac{1}{Vt} \cdot \int_0^T Pm(t) \cdot F(t) dt \quad Pva = 3.701$$

Closed-Circuit UBA have ELASTANCE

Respiratory frequency (Hz)	Period (sec)	Sample rate	Sample interval
$f := 0.5 \text{sec}^{-1}$	$T := \frac{1}{f}$	$s := 1000 \text{sec}^{-1}$	$\Delta T := \frac{1}{s} \quad \Delta T = 1 \cdot 10^{-3} \text{sec}$

Angular frequency

$$\omega := 2 \cdot \pi \cdot f \quad \omega = 3.142 \text{sec}^{-1}$$

Sample sequence

$$i := 1..(n - 1)$$

$$t_i := i \cdot \Delta T \quad \dots \text{time at each sampling period}$$

$$\text{tnd}_i := t_i \cdot \text{sec}^{-1} \quad \dots \text{non-dimensional form for time graphing purposes}$$

UBA Resistance

$$R := 0.5 \text{kPa} \cdot \frac{\text{sec}}{\text{liter}}$$

UBA Elastance

$$E := 1 \cdot \frac{\text{kPa}}{\text{liter}}$$

Tidal Volume

$$V_t := 3 \cdot \text{liter} \quad V_{\text{tnd}} := V_t \cdot \text{liter}^{-1}$$

Volume - as a function of time

$$V(t) := V_t \cdot \sin\left(\frac{\omega}{2} \cdot t\right)^2$$

$$V_i := V_t \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2$$

... Volume at each sampling period

$$V_{\text{nd}_i} := V_i \cdot \text{liter}^{-1}$$

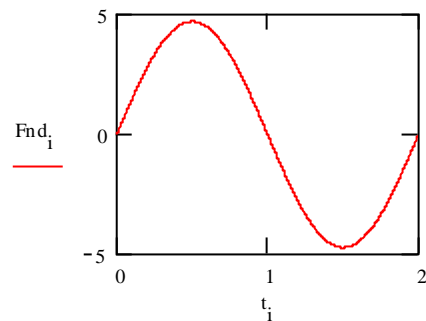
Flow - the time derivative of volume:

$$F(t) := \frac{\omega}{2} \cdot V_t \cdot \sin(\omega \cdot t)$$

$$F_i := \frac{\omega}{2} \cdot V_t \cdot \sin(\omega \cdot t_i)$$

$$F_{\text{nd}_i} := F_i \cdot \text{liter}^{-1} \cdot \text{sec} \quad \dots \text{non-dimensional form}$$

Flow Tracing



Pressure

$$P_m(t) := R \cdot \frac{\omega}{2} \cdot V_t \cdot \sin(\omega \cdot t) + E \cdot \left(V_t \cdot \sin\left(\frac{\omega}{2} \cdot t\right)^2\right)$$

$$P_i := R \cdot F_i + E \cdot V_i$$

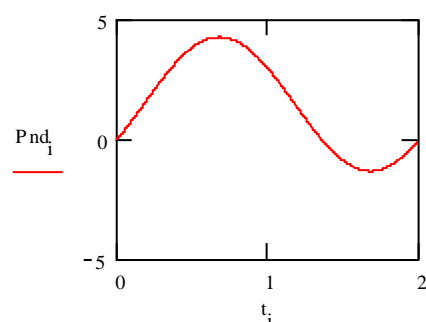
$$P_{\text{nd}_i} := P_i \cdot \text{kPa}^{-1}$$

$$\max(P) = 4.293 \text{kPa} \quad \dots \text{maximum pressure}$$

$$\text{mean}(P) = 1.5 \text{kPa} \quad \dots \text{average pressure}$$

$$\min(P) = -1.293 \text{kPa} \quad \dots \text{minimum pressure}$$

Pressure Tracing



Time-Averaged Pressure - Full Cycle

$$T := T \cdot \text{sec}^{-1} \quad \omega := \omega \cdot \text{sec} \quad V_t := V_t \cdot \text{liter}^{-1}$$

$$R := R \cdot \text{liter} \cdot (\text{kPa} \cdot \text{sec})^{-1} \quad E := E \cdot \text{kPa}^{-1} \cdot \text{liter}$$

$$P_m(t) := R \cdot \frac{\omega}{2} \cdot V_t \cdot \sin(\omega \cdot t) + E \cdot \left(V_t \cdot \sin\left(\frac{\omega}{2} \cdot t\right) \right)^2 \quad F(t) := \frac{\omega}{2} \cdot V_t \cdot \sin(\omega \cdot t)$$

$$\frac{1}{T} \cdot \int_0^T P_m(t) dt = 1.5 \quad \dots \text{time-averaged pressure for a full cycle}$$

$$\frac{2}{T} \cdot \int_0^{\frac{T}{2}} P_m(t) dt = 3 \quad \dots \text{time-averaged pressure for one-half cycle}$$

RMS Pressure

$$P_{rms} := \sqrt{\frac{1}{T} \cdot \int_0^T P_m(t)^2 dt} \quad P_{rms} = 2.48 \quad \dots \text{for a full breathing cycle}$$

Or ...

$$P_{rms} := \sqrt{\frac{1}{n} \cdot \sum_i (P_i)^2} \quad P_{rms} = 2.48 \text{ kPa}$$

All time-based pressures are **changed** by elastance (see previous example)

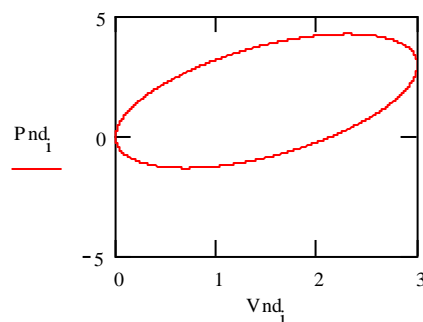
Work of Breathing

$$W := \int_0^T P_m(t) \cdot F(t) dt \quad W = 11.103$$

Resistive Effort

$$P_{va} := \frac{1}{V_t} \cdot \int_0^T P_m(t) \cdot F(t) dt \quad P_{va} = 3.701$$

Pressure - Volume Loop



Work of Breathing and Resistive Effort (a volume-averaged pressure) **unchanged** by simple elastance

If **resistance is minimal** but elastance is still present, then:

Respiratory frequency (Hz)	Period (sec)	Sample rate	Sample interval
$f := 0.5 \cdot \text{sec}^{-1}$	$T := \frac{1}{f}$	$s := 1000 \cdot \text{sec}^{-1}$	$\Delta T := \frac{1}{s} \quad \Delta T = 1 \cdot 10^{-3} \cdot \text{sec}$

Angular frequency

$$\omega := 2 \cdot \pi \cdot f \quad \omega = 3.142 \cdot \text{sec}^{-1}$$

Sample sequence

$$i := 1..(n - 1)$$

$$t_i := i \cdot \Delta T \quad \dots \text{time at each sampling period}$$

$$\text{tnd}_i := t_i \cdot \text{sec}^{-1} \quad \dots \text{non-dimensional form for time (for graphing purposes)}$$

UBA Resistance

$$R := 0 \cdot \text{kPa} \cdot \frac{\text{sec}}{\text{liter}}$$

UBA Elastance

$$E := 1 \cdot \frac{\text{kPa}}{\text{liter}}$$

Tidal Volume

$$V_t := 3 \cdot \text{liter} \quad V_{\text{tnd}} := V_t \cdot \text{liter}^{-1}$$

Volume - as a function of time

$$V(t) := V_t \cdot \sin\left(\frac{\omega}{2} \cdot t\right)^2$$

$$V_i := V_t \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad \dots \text{Volume at each sampling period}$$

$$V_{\text{nd}_i} := V_i \cdot \text{liter}^{-1}$$

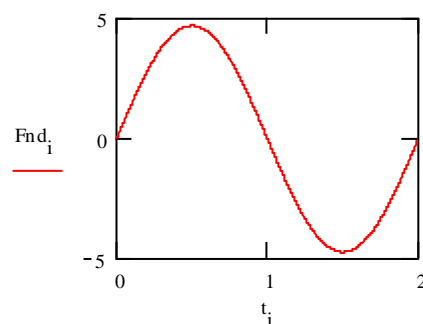
Flow Tracing

Flow - the time derivative of volume:

$$F(t) := \frac{\omega}{2} \cdot V_t \cdot \sin(\omega \cdot t)$$

$$F_i := \frac{\omega}{2} \cdot V_t \cdot \sin(\omega \cdot t_i)$$

$$F_{\text{nd}_i} := F_i \cdot \text{liter}^{-1} \cdot \text{sec} \quad \dots \text{non-dimensional form}$$



Pressure

$$P_{\text{nd}}(t) := R \cdot \frac{\omega}{2} \cdot V_t \cdot \sin(\omega \cdot t) + E \cdot \left(V_t \cdot \sin\left(\frac{\omega}{2} \cdot t\right)^2 \right)$$

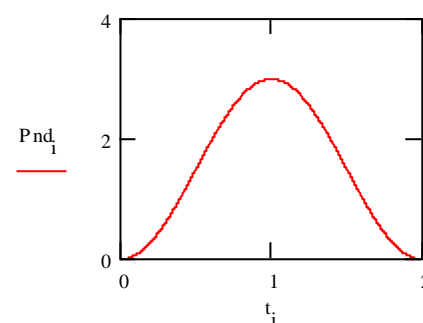
$$P_i := R \cdot F_i + E \cdot V_i \quad P_{\text{nd}_i} := P_i \cdot \text{kPa}^{-1}$$

$$\max(P) = 3 \cdot \text{kPa} \quad \dots \text{maximum pressure}$$

$$\text{mean}(P) = 1.5 \cdot \text{kPa} \quad \dots \text{average pressure}$$

$$\min(P) = 0 \cdot \text{kPa} \quad \dots \text{minimum pressure}$$

Pressure Tracing



Time-Averaged Pressure - Full Cycle

$$T := T \cdot \text{sec}^{-1} \quad \omega := \omega \cdot \text{sec} \quad V_t := V_t \cdot \text{liter}^{-1}$$

$$R := R \cdot \text{liter} \cdot (\text{kPa} \cdot \text{sec})^{-1} \quad E := E \cdot \text{kPa}^{-1} \cdot \text{liter}$$

$$P_m(t) := R \cdot \frac{\omega}{2} \cdot V_t \cdot \sin(\omega \cdot t) + E \cdot \left(V_t \cdot \sin\left(\frac{\omega}{2} \cdot t\right) \right)^2 \quad F(t) := \frac{\omega}{2} \cdot V_t \cdot \sin(\omega \cdot t)$$

$$\frac{1}{T} \cdot \int_0^T P_m(t) dt = 1.5 \quad \dots \text{time-averaged pressure for a full cycle}$$

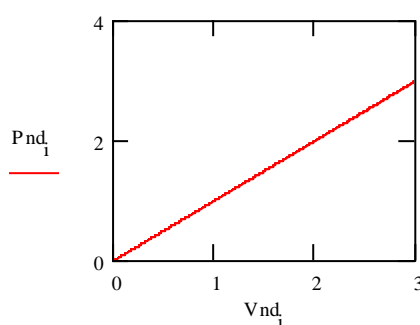
$$\frac{2}{T} \cdot \int_0^{\frac{T}{2}} P_m(t) dt = 1.5 \quad \dots \text{time-averaged pressure for one-half cycle}$$

RMS Pressure

$$P_{rms} := \sqrt{\frac{1}{T} \cdot \int_0^T P_m(t)^2 dt} \quad P_{rms} = 1.837 \quad \dots \text{for a full breathing cycle}$$

Pressures are considerable. However, as seen below, conventional measures of work and volume-averaged pressure (resistive effort) are negligibly small.

Pressure - Volume Loop



Work of Breathing

$$W := \int_0^T P_m(t) \cdot F(t) dt \quad W = 0$$

Resistive Effort

$$P_{va} := \frac{1}{V_t} \cdot \int_0^T P_m(t) \cdot F(t) dt \quad P_{va} = 0$$

Does this mean that no work or effort is required to repeatedly inflate and deflate an elastic balloon, or a breathing bag immersed in water? Experience tells us otherwise! For that reason, **P_{rms} is a physiologically relevant characteristic of UBA.**

The Summation Approximation

To simulate complex regulator function, we have to use non-integrable logical functions; these we use summations instead of integrals.

To express work as a summation we must define the inspiratory and expiratory phases; respiration, and determine the change in volume occurring during each sampling interval. We use as an example the original resistive UBA without elastance.

$$T := T \cdot \text{sec} \quad V_t := V_t \cdot \text{liter} \quad \omega := \omega \cdot \text{sec}^{-1} \quad \dots \text{ this reestablishes dimensions}$$

$$R := 0.5 \frac{\text{kPa}}{\text{liter}} \cdot \text{sec} \quad E := 0 \frac{\text{kPa}}{\text{liter}} \quad \dots \text{ resistive UBA without elastance}$$

$$F_i := \frac{\omega}{2} \cdot V_t \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right) \quad V_i := V_t \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad P_i := R \cdot F_i + E \cdot V_i$$

$$P_{\min} := \left| \min(P) \right| \quad P_{\min} = 2.356 \text{ kPa} \quad \dots \text{ definition of minimum pressure}$$

$$P_{\text{rms}} := \sqrt{\frac{1}{n} \sum_i (P_i)^2} \quad P_{\text{rms}} = 1.666 \text{ kPa}$$

Expiratory Work

$$i := 1 \dots \frac{n}{2} \quad t_i := i \cdot \Delta T$$

$$V_i := V_t \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad \dots \text{ Volume at each sampling interval}$$

$$\Delta V_i := V_i - V_{(i-1)} \quad \dots \text{ Volume increment for each sampling interval}$$

The work of breathing for the expiratory side of the loop is found by the trapezoidal rule

$$A1 := \sum_i \left[(P_i + P_{\min}) \cdot \Delta V_i \right] \quad A1 = 12.62 \text{ joule}$$

Inspiratory Work - the above is repeated except that $i := \left(\frac{n}{2} + 1\right) \dots (n - 1)$

$$t_i := i \cdot \Delta T$$

$$V_i := V_t \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad \dots \text{ Volume at each sampling interval}$$

$$\Delta V_i := V_{(i-1)} - V_i \quad \dots \text{ Volume increment for each sampling interval}$$

The work of breathing for the inspiratory side of the loop is:

$$A2 := \sum_i [(P_i + P_{min}) \cdot \Delta V_i] \quad A2 = 1.517 \text{ joule}$$

Total Work of Breathing is thus equal to $A1 - A2$ $W := A1 - A2$

$$W = 11.103 \text{ joule}$$

... This application of the trapezoidal rule yields a result which differs slightly from the previous integration. The result can be made more exact by increasing the sampling rate; i.e. by taking more data points per breath.

If we follow the diving convention of dividing W by V_t , we obtain a pressure.

$$\frac{W}{V_t} = 3.701 \text{ kPa}$$

Although there is no advantage in doing so, we can also express this quotient as:

$$\frac{W}{V_t} = 3.701 \frac{\text{joule}}{\text{liter}} \quad \dots \text{ joule/liter and kPa are equivalent units}$$

For that reason we refer to W/V_t as P_{va} (Pressure, volume-averaged) $P_{va} := \frac{W}{V_t}$

*For a **resistive UBA without elastance** P_{rms} is mathematically related to P_{va} and true W of Breathing (W) by:*

$$P_{va} := \frac{P_{rms}^2 \cdot T}{R \cdot V_t} \quad P_{va} = 3.701 \text{ kPa}$$

$$W := \frac{P_{rms}^2 \cdot T}{R} \quad W = 11.103 \text{ joule}$$

Fourier Superposition- a method for defining complicated waveforms:

$$i := 1..(n - 1)$$

$$P_i := 1.1R \cdot \frac{\omega}{2} \cdot Vt \cdot \left(\sin(\omega \cdot t_i) + 0.28 \sin(3 \cdot \omega \cdot t_i) + 0.1 \sin(5 \cdot \omega \cdot t_i) \right)$$

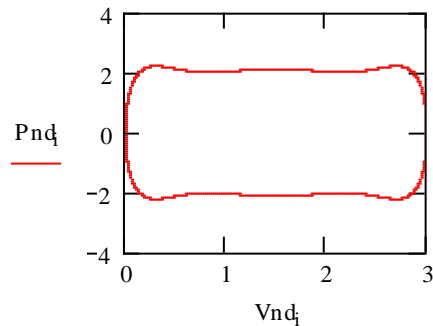
$$Pnd_i := P_i \cdot kPa^{-1}$$

$$\max(P) = 2.215kPa$$

$$\text{mean}(P) = 0kPa$$

$$\min(P) = -2.215kPa$$

$$Prms := \sqrt{\frac{1}{n} \sum_i (P_i)^2} \quad Prms = 1.912kPa$$



Expiratory Work of Breathing

$$i := 1.. \frac{n}{2} \quad t_i := i \cdot \Delta T$$

$$V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad \dots \text{Volume at each sampling interval}$$

$$\Delta V_i := V_i - V_{(i-1)} \quad \dots \text{Volume increment for each sampling interval}$$

$$A1 := \sum_i [(P_i + Pmin) \cdot \Delta V_i] \quad A1 = 13.175joule$$

Inspiratory Work

$$i := \left(\frac{n}{2} + 1\right) .. (n - 1) \quad t_i := i \cdot \Delta T$$

$$V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad \dots \text{Volume at each sampling interval}$$

$$\Delta V_i := V_{(i-1)} - V_i \quad \dots \text{Volume increment for each sampling interval}$$

$$A2 := \sum_i [(P_i + Pmin) \cdot \Delta V_i] \quad A2 = 0.962joule$$

Total Work of Breathing

$$W := A1 - A2 \quad W = 12.214joule$$

Resistiv eEffort

$$Pva := \frac{W}{Vt} \quad Pva = 4.071kPa$$

For this wave form, maximum and minimum pressures are slightly lower than the sinusoidal case but work and resistance is higher.

Inspiratory Work

$$i := \left(\frac{n}{2} + 1\right) .. (n - 1) \quad t_i := i \cdot \Delta T$$

$$V_i := V_t \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad \dots \text{Volume at each sampling interval}$$

$$\Delta V_i := V_{(i-1)} - V_i \quad \dots \text{Volume increment for each sampling interval}$$

$$A2 := \sum_i \left[(P_i + P_{min}) \cdot \Delta V_i \right] \quad A2 = 0.962 \text{ joule}$$

Total Work of Breathing

$$W := A1 - A2 \quad W = 12.214 \text{ joule}$$

Resistive Effort

$$P_{va} := \frac{W}{V_t} \quad P_{va} = 4.07 \text{ kPa}$$

For this wave form, maximum and min pressures are slightly lower than the sin but work and resistance is higher.

We can also simulate a Venturi-assisted Regulator

$$i := 0 .. (n - 1)$$

$$E_i := R \cdot \frac{\omega}{2} \cdot V_t \cdot \left(\sin(\omega \cdot t_i) + 0.2 \sin(3 \cdot \omega \cdot t_i) + 0.1 \sin(5 \cdot \omega \cdot t_i) + 0.1 \sin(27 \cdot \omega \cdot t_i) + 0.1 \text{rnd}(2) \right)$$

$$I_i := E_i - R \cdot \frac{\omega}{2} \cdot V_t \cdot \left(1.2 \sin(\omega \cdot t_i) - 0.35 \sin(3 \cdot \omega \cdot t_i) - .02 \text{rnd}(3) \right)$$

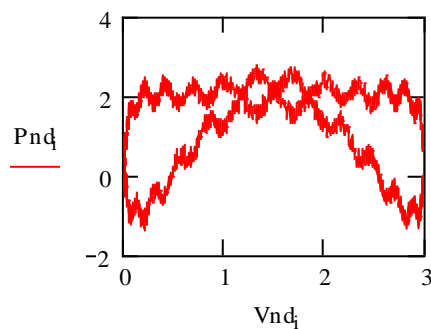
$$P_i := \text{if} \left(i < \frac{n}{2}, E_i, I_i \right) \quad P_{nd_i} := P_i \cdot \text{kPa}^{-1}$$

$$\max(P) = 2.788 \text{ kPa}$$

$$\text{mean}(P) = 1.08 \text{ kPa}$$

$$\min(P) = -1.38 \text{ kPa}$$

$$\text{Prms} := \sqrt{\frac{1}{n} \cdot \sum_i (P_i)^2} \quad \text{Prms} = 1.563 \text{ kPa}$$



Expiratory Work of Breathing

$$i := 1 .. \frac{n}{2} \quad t_i := i \cdot \Delta T$$

$$V_i := V_t \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad \dots \text{Volume at each sampling interval}$$

Chattering Regulator

$$i := 0..(n - 1)$$

$$E_i := R \cdot \frac{\omega}{2} \cdot Vt \cdot \left(\sin(\omega \cdot t_i) + 0.2 \sin(3 \cdot \omega \cdot t_i) + 0.001 \sin(5 \cdot \omega \cdot t_i) + 0.05 \sin(27 \cdot \omega \cdot t_i) + 0.001 \text{rnd}(2) \right)$$

$$I_i := E_i - R \cdot \frac{\omega}{2} \cdot Vt \cdot \left(0.1 \sin(\omega \cdot t_i) + 0.8 \sin(49 \cdot \omega \cdot t_i) - .0002 \text{rnd}(3) \right)$$

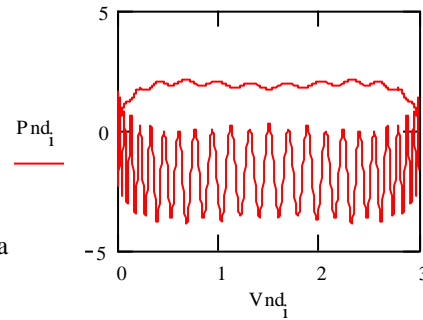
$$P_i := \text{if} \left(i < \frac{n}{2}, E_i, I_i \right) \quad P_{nd_i} := P_i \cdot \text{kPa}^{-1}$$

$$\max(P) = 2.17 \text{ kPa}$$

$$\text{mean}(P) = 0.09 \text{ kPa}$$

$$\min(P) = -3.849 \text{ kPa}$$

$$\text{Prms} := \sqrt{\frac{1}{n} \sum_i (P_i)^2} \quad \text{Prms} = 1.876 \text{ kPa}$$



Expiratory Work of Breathing

$$i := 1.. \frac{n}{2} \quad t_i := i \cdot \Delta T$$

$$V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad \dots \text{ Volume at each sampling interval}$$

$$\Delta V_i := V_i - V_{(i-1)} \quad \dots \text{ Volume increment for each sampling interval}$$

$$A1 := \sum_i \left[(P_i + P_{\min}) \cdot \Delta V_i \right] \quad A1 = 12.627 \text{ joule}$$

Inspiratory Work

$$i := \left(\frac{n}{2} + 1 \right) .. (n - 1) \quad t_i := i \cdot \Delta T$$

$$V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad \dots \text{ Volume at each sampling interval}$$

$$\Delta V_i := V_{(i-1)} - V_i \quad \dots \text{ Volume increment for each sampling interval}$$

$$A2 := \sum_i \left[(P_i + P_{\min}) \cdot \Delta V_i \right] \quad A2 = 2.081 \text{ joule}$$

Total Work of Breathing

$$W := A1 - A2 \quad W = 10.546 \text{ joule}$$

Resistive Effort

$$P_{va} := \frac{W}{Vt} \quad P_{va} = 3.515 \text{ kPa}$$

Super-Venturi Regulator

$$i := 0..(n - 1)$$

$$E_i := R \cdot \frac{\omega}{2} \cdot Vt \left(\sin(\omega \cdot t_i) + 0.2 \sin(3 \cdot \omega \cdot t_i) + 0.1 \sin(5 \cdot \omega \cdot t_i) + 0.1 \sin(27 \cdot \omega \cdot t_i) + 0.1 \cdot \text{rnd}(2) \right)$$

$$I_i := E_i - R \cdot \frac{\omega}{2} \cdot Vt \left(1.2 \sin(\omega \cdot t_i) - 1.0 \sin(3 \cdot \omega \cdot t_i) - .0002 \text{rnd}(3) \right)$$

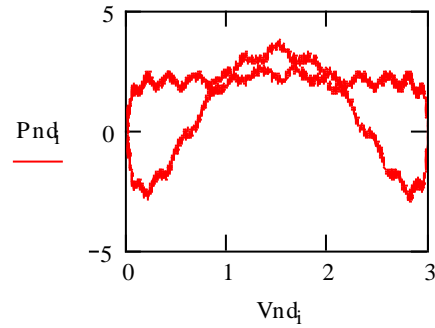
$$P_i := \text{if} \left(i < \frac{n}{2}, E_i, I_i \right) \quad Pnd_i := P_i \cdot kPa^{-1}$$

$$\max(P) = 3.756kPa$$

$$\text{mean}(P) = 0.89kPa$$

$$\min(P) = -2.923kPa$$

$$Prms := \sqrt{\frac{1}{n} \cdot \sum_i (P_i)^2} \quad Prms = 1.985kPa$$



Expiratory Work of Breathing

$$i := 1.. \frac{n}{2} \quad t_i := i \cdot \Delta T$$

$$V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad \dots \text{Volume at each sampling interval}$$

$$\Delta V_i := V_i - V_{(i-1)} \quad \dots \text{Volume increment for each sampling interval}$$

$$A1 := \sum_i \left[(P_i + Pmin) \cdot \Delta V_i \right] \quad A1 = 13.366 \text{joule}$$

Inspiratory Work

$$i := \left(\frac{n}{2} + 1 \right) .. (n - 1) \quad t_i := i \cdot \Delta T$$

$$V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \quad \dots \text{Volume at each sampling interval}$$

$$\Delta V_i := V_{(i-1)} - V_i \quad \dots \text{Volume increment for each sampling interval}$$

$$A2 := \sum_i \left[(P_i + Pmin) \cdot \Delta V_i \right] \quad A2 = 8.877 \text{joule}$$

Total Work of Breathing

$$W := A1 - A2 \quad W = 4.489 \text{joule}$$

Resistive Effort

$$Pva := \frac{W}{Vt} \quad Pva = 1.496kPa$$

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