(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 Ideally, the breathing bag should be fully inflated before air is withdrawn.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.

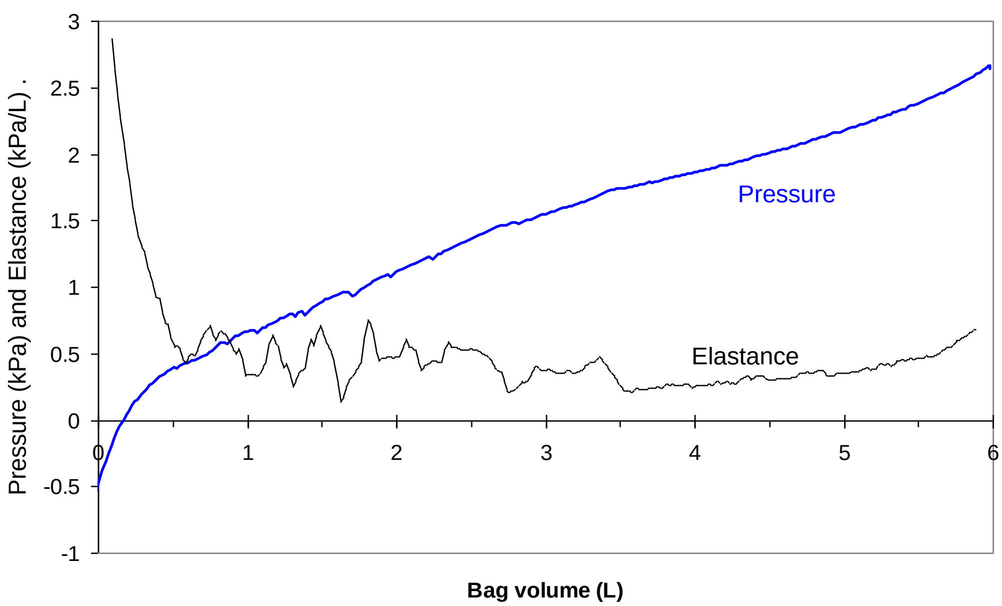

Figure 10-4 Pressure-volume plot of data from a closed circuit UBA. The breathing bag was emptied until the make-up valve opened.

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, Figure10-4. Using equation 10-2, the elastance was calculated and is also illustrated in Figure10-4. 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.

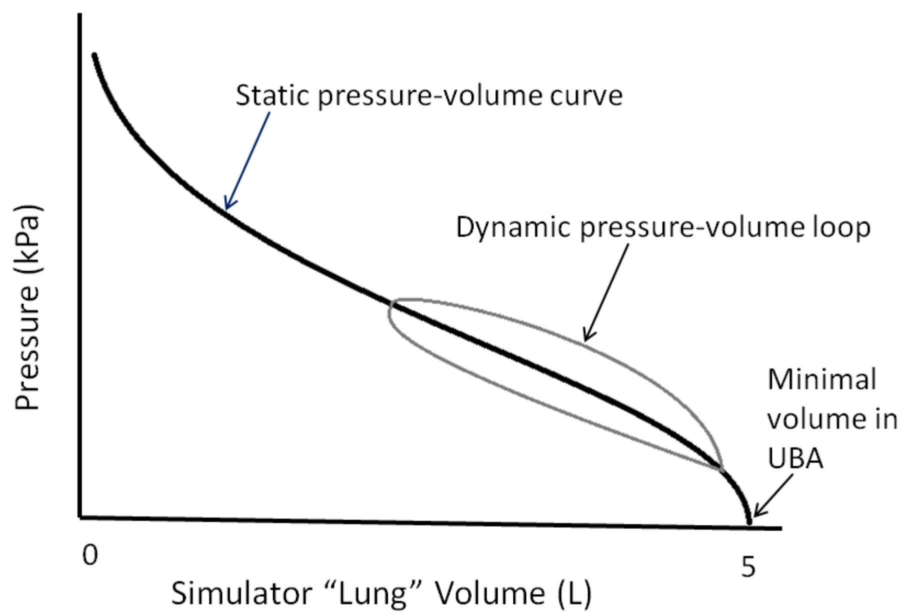

Figure 10-5 A pressure-volume loop superimposed on a static elastance curve.

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.

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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 ± 1°F and fresh water at 34 ± 1°F (-1.7 and 1.1 ± 0.6°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:

$$T_{expired} = 24°C + 0.32 \cdot T_{inspired} \qquad (11\text{-}1)$$

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 ± 10°F (23.3 ± 5.6°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 ± 5°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 ± 1 °F (10 ± 0.6 °C)
c) Test depths: 0 feet of seawater (fsw [0 meters of seawater {msw}]) to198 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

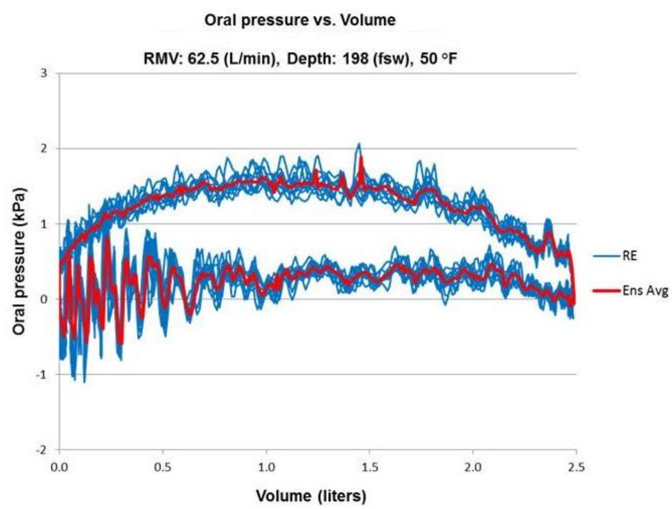


Figure 11-3 Typical P-V loop with 10-loop ensemble average

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 ± 1°F
b. Saline water in ark: 35-40 ppt
c. Fresh water: 34 ± 1°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 ± 10°F (23.3 ± 5.6°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).

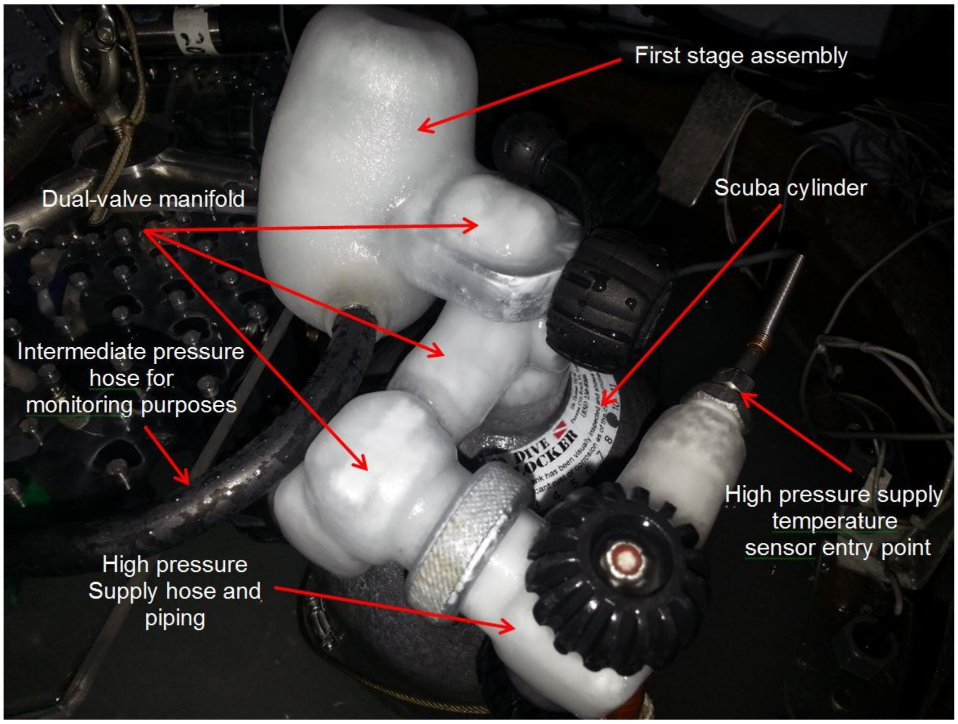


Figure 11-4 Normal external ice accumulation.

3. Post Test Dive:

Same procedures as in the Freeze-Up testing.

4. Parameters Controlled:

a. Ark water temperature: 50 ± 1°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 ± 10°F (25.1 ± 5.6°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)

$f := 0.5 \cdot sec^{-1}$

Period (sec)

$T := \frac{1}{f}$

Sample rate

$s := 1000 \cdot sec^{-1}$

Sample interval

$\Delta T := \frac{1}{s}$ $\Delta T = 1 \cdot 10^{-3} \cdot sec$

Number of samples

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

Angular frequency

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

$kPa \equiv 1000 \cdot Pa$ ... definition

Sample sequence

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

$t_i := i \cdot \Delta T$ ... time at each sampling period

$tnd_i := t_i \cdot sec^{-1}$ ... non-dimensional form for time graphing purposes)

UBA Resistance

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

UBA Elastance

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

Tidal Volume

$Vt := 3 \cdot liter$ $Vtnd := Vt \cdot liter^{-1}$

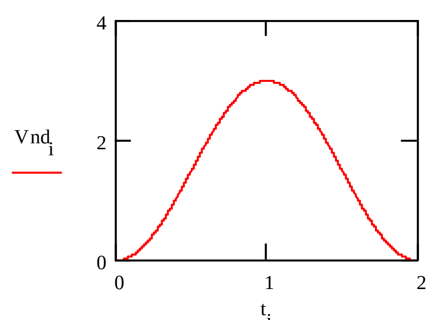
Volume - as a function of time

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

$V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2$ ... Volume at each sampling peric

$Vnd_i := V_i \cdot liter^{-1}$

Volume tracing



Flow - the time derivative of volume:

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

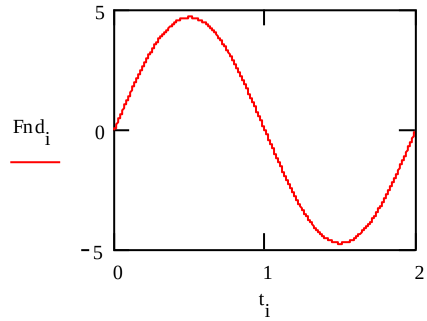
$F(t) := \omega \cdot Vt \cdot \sin\left(\frac{1}{2} \cdot \omega \cdot t\right) \cdot \cos\left(\frac{1}{2} \cdot \omega \cdot t\right)$

From a trigonometric identity this is equivalent to:

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

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

Flow Tracing



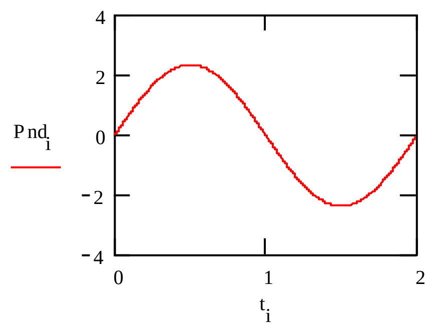
Pressure

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

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

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

Pressure Tracing



$\max(P) = 2.356 \cdot kPa$ ... maximum pressure

$\text{mean}(P) = 0 \cdot kPa$ ... average pressure

$\min(P) = -2.356 \cdot kPa$ ... minimum pressure

Time-Averaged Pressure - Full Cycle

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

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

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

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

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

$\frac{2}{T} \cdot \int_0^{\frac{T}{2}} Pm(t)\,dt = 1.5$ ... time-averaged pressure for one-half cy

Another type of time-averaged pressure is called:

Root Mean Square pressure(Prms) or Effective Pressure

$$Prms := \sqrt{\frac{1}{T}\cdot\int_0^T Pm(t)^2\,dt} \qquad Prms = 1.666$$

... for a full breathing cycle

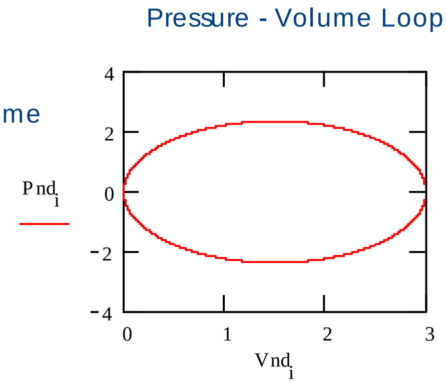
Another way of expressing Prms is:

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

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

$$W := \int_0^T Pm(t)\cdot F(t)\,dt \qquad W = 11.103$$

Note:F(t) = dV/dt

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

Resistiv e Effort

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

Closed-Circuit UBA have ELASTANCE

Respiratory frequency (Hz) — Period (sec) — Sample rate — Sample interval

$f := 0.5 \cdot sec^{-1}$ $\quad T := \frac{1}{f}$ $\quad s := 1000 \cdot sec^{-1}$ $\quad \Delta T := \frac{1}{s}$ $\quad \Delta T = 1 \cdot 10^{-3} \cdot sec$

Angular frequency

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

Sample sequence

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

$t_i := i \cdot \Delta T$ ... time at each sampling period

$tnd_i := t_i \cdot sec^{-1}$ ... non-dimensional form for time graphing purposes)

UBA Resistance

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

UBA Elastance

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

Tidal Volume

$Vt := 3 \cdot liter \qquad Vtnd := Vt \cdot liter^{-1}$

Volume - as a function of time

$V(t) := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t\right)^2$ $\qquad V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2$ ... Volume at each sampling peric

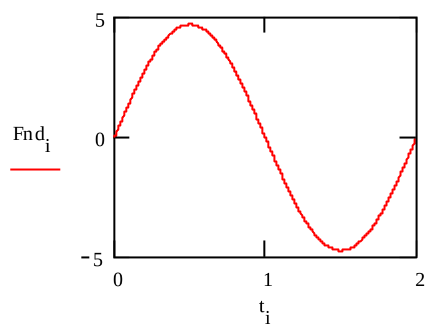
$Vnd_i := V_i \cdot liter^{-1}$

Flow - the time derivative of volume:

$F(t) := \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t)$ $\qquad F_i := \frac{\omega}{2} \cdot Vt \cdot \sin\left(\omega \cdot t_i\right)$

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

Flow Tracing



Pressure

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

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

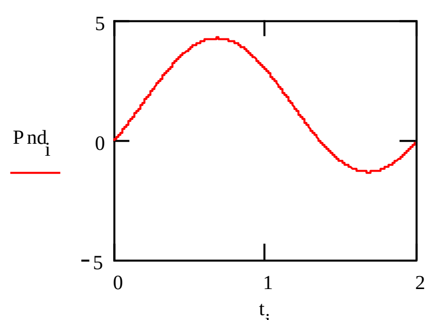
$Pnd_i := P_i \cdot kPa^{-1}$

$\max(P) = 4.293 \cdot kPa$ ... maximum pressure

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

$\min(P) = -1.293 \cdot kPa$ ... minimum pressure

Pressure Tracing



Time-Averaged Pressure - Full Cycle

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

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

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

$\frac{1}{T} \cdot \int_0^T Pm(t)\,dt = 1.5$ ... time-averaged pressure for a full cycle

$\frac{2}{T} \cdot \int_0^{\frac{T}{2}} Pm(t)\,dt = 3$ ... time-averaged pressure for one-half cycle

RMS Pressure

$Prms := \sqrt{\frac{1}{T} \cdot \int_0^T Pm(t)^2\,dt}$ $Prms = 2.48$ ... for a full breathing cycle

Or ...

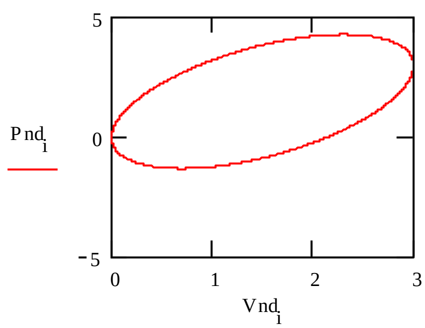
$Prms := \sqrt{\frac{1}{n} \cdot \sum_i (P_i)^2}$ $Prms = 2.48 \cdot kPa$

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

Work of Breathing

$W := \int_0^T Pm(t) \cdot F(t)\,dt$ $W = 11.103$

Pressure - Volume Loop



Resistive Effort

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

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

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

Respiratory frequency (Hz) — Period (sec) — Sample rate — Sample interval

$f := 0.5 \cdot sec^{-1}$ $\quad T := \frac{1}{f}$ $\quad s := 1000 \cdot sec^{-1}$ $\quad \Delta T := \frac{1}{s}$ $\quad \Delta T = 1 \cdot 10^{-3} \cdot sec$

Angular frequency

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

Sample sequence

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

$t_i := i \cdot \Delta T$ ... time at each sampling period

$tnd_i := t_i \cdot sec^{-1}$ ... non-dimensional form for time (for graphing purposes)

UBA Resistance

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

UBA Elastance

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

Tidal Volume

$Vt := 3 \cdot liter$ $\qquad Vtnd := Vt \cdot liter^{-1}$

Volume - as a function of time

$V(t) := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t\right)^2$ $\qquad V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2$ ... Volume at each sampling peric

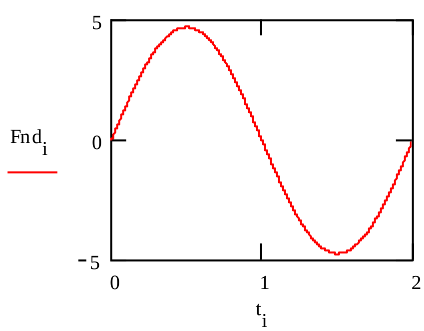
$Vnd_i := V_i \cdot liter^{-1}$

Flow - the time derivative of volume:

$F(t) := \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t)$ $\qquad F_i := \frac{\omega}{2} \cdot Vt \cdot \sin\left(\omega \cdot t_i\right)$

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

Flow Tracing



Pressure

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

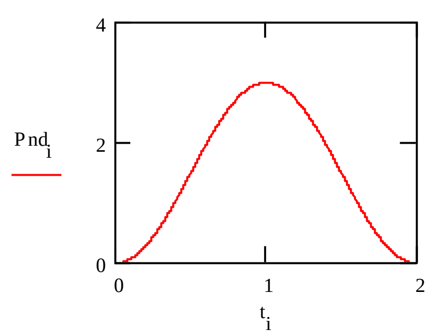
$P_i := R \cdot F_i + E \cdot V_i$ $\qquad Pnd_i := P_i \cdot kPa^{-1}$

$\max(P) = 3 \cdot kPa$ ... maximum pressure

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

$\min(P) = 0 \cdot kPa$ ... minimum pressure

Pressure Tracing



Time-Averaged Pressure - Full Cycle

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

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

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

$$\frac{1}{T} \cdot \int_0^T Pm(t)\,dt = 1.5$$ ... time-averaged pressure for a full cycle

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

RMS Pressure

$$Prms := \sqrt{\frac{1}{T} \cdot \int_0^T Pm(t)^2\,dt} \qquad Prms = 1.837$$ ... 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.

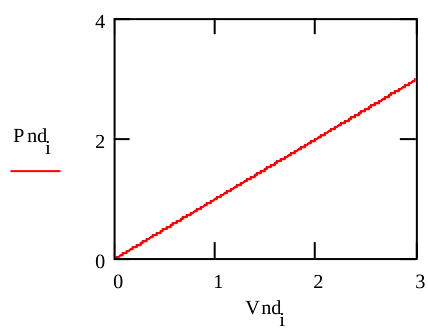
Work of Breathing

$$W := \int_0^T Pm(t) \cdot F(t)\,dt \qquad W = 0$$

Resistive Effort

$$Pva := \frac{1}{Vt} \cdot \int_0^T Pm(t) \cdot F(t)\,dt \qquad Pva = 0$$

Pressure - Volume Loop



Does this mean that no work or effort is required to repeatibly inflate and deflate an elasti balloon, or a breathing bag immersed in water? Experience tells us otherwise! For that re **Prms is a physiologically relevant characteristic of UBA.**

The Summation Approximation

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

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

$T := T \cdot sec \quad Vt := Vt \cdot liter \quad \omega := \omega \cdot sec^{-1}$ ... this reestablishes dimensions

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

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

$Pmin := |\min(P)| \quad Pmin = 2.356 \cdot kPa$ ... definition of minimum pressure

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

Expiratory Work

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

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

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

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

$$A1 := \sum_i \left[(P_i + Pmin) \cdot \Delta V_i \right] \qquad A1 = 12.62 \cdot joule$$

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

$t_i := i \cdot \Delta T$

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

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

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

$$A2 := \sum_i \left[\left(P_i + Pmin\right) \cdot \Delta V_i \right] \qquad A2 = 1.517 \cdot joule$$

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

$W = 11.103 \cdot joule$ ... 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 Vt, we obtain a pressure.

$$\frac{W}{Vt} = 3.701 \cdot kPa$$

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

$$\frac{W}{Vt} = 3.701 \cdot \frac{joule}{liter}$$

... **joule/liter and kPa are equivalent units**

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

*For a **resistive UBA without elastance**, Prms is mathematically related to Pva and true Wo of Breathing (W) by:*

$$Pva := \frac{Prms^2 \cdot T}{R \cdot Vt} \qquad Pva = 3.701 \cdot kPa$$

$$W := \frac{Prms^2 \cdot T}{R} \qquad W = 11.103 \cdot joule$$

Fourier Superposition - a method for defining complicated waveforms:

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

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

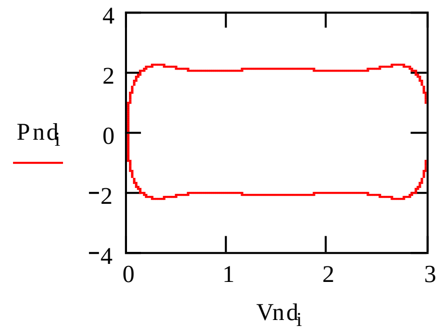
$$Pnd_i := P_i \cdot kPa^{-1}$$

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

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

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

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



Expiratory Work of Breathing

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

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

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

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

Inspiratory Work

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

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

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

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

Total Work of Breathing

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

Resistive Effort

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

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

Inspiratory Work

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

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

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

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

Total Work of Breathing

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

Resistive Effort

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

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

We can also simulate a
Venturi-assisted Regulator

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

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

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

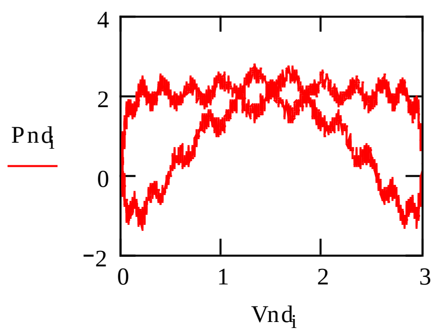
$P_i := \text{if}\left(i < \frac{n}{2}, E_i, I_i\right)$ $\qquad Pnd_i := P_i \cdot kPa^{-1}$

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

$\text{mean}(P) = 1.081 \text{kPa}$

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

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



Expiratory Work of Breathing

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

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

Chattering Regulator

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

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

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

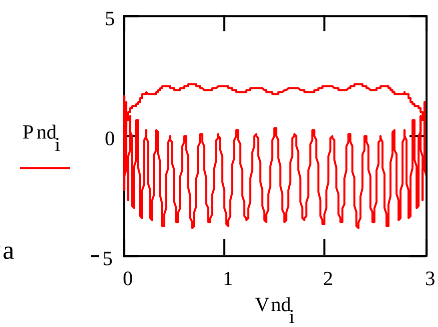
$$P_i := if\left(i<\frac{n}{2}, E_i, I_i\right) \qquad Pnd_i := P_i\cdot kPa^{-1}$$

$max(P) = 2.17\,kPa$

$mean(P) = 0.09\,kPa$

$min(P) = -3.849\,kPa$

$$Prms := \sqrt{\frac{1}{n}\cdot\sum_i \left(P_i\right)^2} \qquad Prms = 1.876\,kPa$$



Expiratory Work of Breathing

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

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

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

$$A1 := \sum_i \left[\left(P_i + Pmin\right)\cdot\Delta V_i\right] \qquad A1 = 12.627\,joule$$

Inspiratory Work

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

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

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

$$A2 := \sum_i \left[\left(P_i + Pmin\right)\cdot\Delta V_i\right] \qquad A2 = 2.081\,joule$$

Total Work of Breathing $\quad W := A1 - A2 \qquad W = 10.546\,joule$

Resistive Effort $\quad Pva := \frac{W}{Vt} \qquad Pva = 3.515\,kPa$

Super-Venturi Regulator

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

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

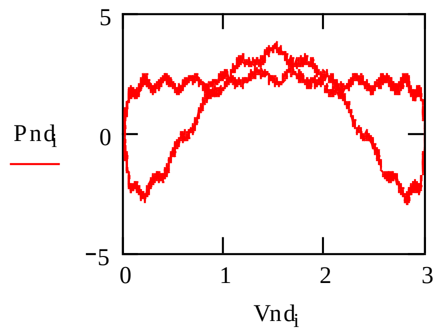
$$I_i := E_i - R\cdot\frac{\omega}{2}\cdot Vt\cdot\left(1.2\sin\left(\omega\cdot t_i\right) - 1.0\sin\left(3\cdot\omega\cdot t_i\right) - .0002\text{rnd}(3)\right)$$

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

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

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

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



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

Expiratory Work of Breathing

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

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

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

$$A1 := \sum_i \left[\left(P_i + Pmin\right)\cdot\Delta V_i\right] \qquad A1 = 13.366\,joule$$

Inspiratory Work

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

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

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

$$A2 := \sum_i \left[\left(P_i + Pmin\right)\cdot\Delta V_i\right] \qquad A2 = 8.877\,joule$$

Total Work of Breathing

$W := A1 - A2 \qquad W = 4.489\,joule$

Resistive Effort

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

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