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PROPOSED STANDARDS FOR THE EVALUATION OF THE BREATHING RESISTANCE OF UNDER-WATER BREATHING APPARATUS

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13. ABSTRACT

Respiratory impedance is a parameter that has often suffered from less than adequate attention in the development of present day underwater breathing apparatus. The result has been a number of unpleasant surprises when the apparatus have been tested or used in the deeper portions of their operating ranges. A principal factor in the lack of engineering attention to respiratory impedance has been the lack of definitive design standards. A set of definitive engineering-oriented respiratory impedance standards are proposed for use in the depth range 0 to 1000 fsw. The standards are consistent with current medical knowledge and are simply stated so that they may be easily applied. The test conditions under which the standards are to be applied are also specified in detail. Basically, the prepared standards require that the external respiratory work which a diver can be required to do on his breathing apparatus, as measured by mouthpiece conditions, must be less than 0.17 kilogram-meter of work per liter ventilation. The reference pressure to be used in calculating the external respiratory work is identified as the hydrostatic pressure at the level of the 7th cervical vertebra for all types of diving equipment except open circuit SCUBA regulators. For open circuit SCUBA regulators, the reference pressure is identified as the hydrostatic pressure at the center-line level of the second stage diaphragm.

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ABSTRACT

Respiratory impedance is a parameter that has often suffered from less than adequate attention in the development of present day underwater breathing apparatus. The result has been a number of unpleasant surprises when the apparatus have been tested or used in the deeper portions of their operating ranges. A principal factor in the lack of engineering attention to respiratory impedance has been the lack of definitive design standards. A set of definitive engineering-oriented respiratory impedance standards are proposed for use in the depth range 0 to 1000 fsw. The standards are consistent with current medical knowledge and are simply stated so that they may be easily applied. The test conditions under which the standards are to be applied are also described in detail. Basically, the prepared standards require that the external respiratory work which a diver can be required to do on his breathing apparatus, as measured by mouthpiece conditions, must be less than 0.17 kilogram-meter of work per liter ventilation. The reference pressure to be used in calculating the external respiratory work is identified as the hydrostatic pressure at the level of the 7th cervical vertebra for all types of diving equipment except open circuit SCUBA regulators. For open circuit SCUBA regulators, the reference pressure is identified as the hydrostatic pressure at the center-line level of the second stage diaphragm.

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$\dot{V}_e$	Respiratory Minute Ventilation (*L/min, BTPS*)
V_t	Tidal Volume (liters,*BTPS*)
f	Respiratory Frequency (breaths per minute)
$\dot{V}_{O2}$	Oxygen Consumption (*L/min, STPD*)
PCO_2	Partial Pressure, CO_2 (*ata*)
PO_2	Partial Pressure, O_2 (*ata*)
ata	Atmospheres Absolute
Kg-m	Kilogram-meters
cm H_2O	Pressure in Centimeters of Water
Q	Respiratory waveform shape factor, equals ratio of peak flow rate to minute volume
gm/L	Grams per Liter
L/min	Liters per Minute
BTPS	Body Temperature and Pressure, Saturated, i.e. 37°C. and ambient pressure, saturated
STPD	Standard Temperature and Pressure, Dry; 0°C, 14.7 *psia*
psia	Pounds per Square Inch, Absolute 14.7 *psia*= 1 *ata*
slpm	Standard Liters per Minute. One standard liter = 1 liter *STPD*
fsw	Feet of Sea Water, 1 *fsw* = .445 *psi*

INTRODUCTION

Respiratory impedance is a parameter that has often suffered from less than adequate attention in the development of present day underwater breathing systems as design resources have tended to be focused on the assumed more critical problems of O_2 and CO_2 level control. This has led to a number of unpleasant surprises when these systems have been tested at heavy diver work rates in the deeper parts of their operating ranges (3,6,15-18). A major contributing factor to this situation has been the relative absence of accepted respiratory impedance standards.

This paper is an attempt to formulate a set of definitive engineering-oriented respiratory impedance standards consistent with current knowledge and stated so that they can be easily applied to the design and engineering testing of underwater breathing systems. In formulating the standards proposed herein, the following rules were observed:

1. The standards must be relatively simple and expressed in normal engineering terms.
2. They must be physiologically reasonable and consistent with existing knowledge.
3. They must be adaptable to normal engineering test procedures that can be performed without requiring manned diving operations.
4. They must give reproducible results.
5. If so desired, they must be contractually enforceable.

Physiologic testing of underwater breathing systems (testing the man and breathing system as a unit and measuring the diver's physiologic responses: ventilation parameters, arterial PCO_2 and PO_2, etc.) is almost a science unto itself, and it is not intended here to propose standards for those tests. It is presumed at this time that a breathing system which meets the engineering standards proposed herein will not demonstrate any serious deficiencies related to breathing impedance in physiologic tests or in service. It is also assumed, however, that with time the standards proposed herein will be refined based on the results of physiologic tests and service experience.

BACKGROUND

The only currently accepted engineering standards for breathing impedance are those specified in the U.S. Military Specifications for open circuit SCUBA regulators used on air in the depth range 0 to 200 fsw. (29)(30). These standards place limits on the peak inspiratory and expiratory pressures that a regulator can induce in a standard breathing machine test (See Figure 1). They also place the same peak pressure limits on the regulator when it is used by a diver swimming against a trapeze ergometer set to deliver a static force of 12 pounds (roughly equivalent to force swimming at a speed of 1.3 knots)(10). The reference pressure in both cases is taken as ambient pressure at the mouthpiece level of the regulator.

Being the only existing yardsticks, the Mil-Spec standards are often applied on a general basis to other types of divers breathing apparatus, a use for which they are neither intended nor well suited. Indeed the Mil-Spec standards possess a number of limitations even for the purpose for which they are intended.

From an operational point of view the breathing machine test has proven quite satisfactory, and successful passage of it is required for all regulators approved for U.S. Navy use. The ergometer test on the other hand has been used only very rarely since it represents severe exercise ($\dot{V}_{O2} \approx 2.9$ L/min, STPD $\dot{V}_e \approx 70$ L/min BTPS (28), is difficult to implement and cannot be relied upon to give reproducible results.

The performance limits themselves are also subject to some criticism. The standards were initially developed in the mid-1950's (36)

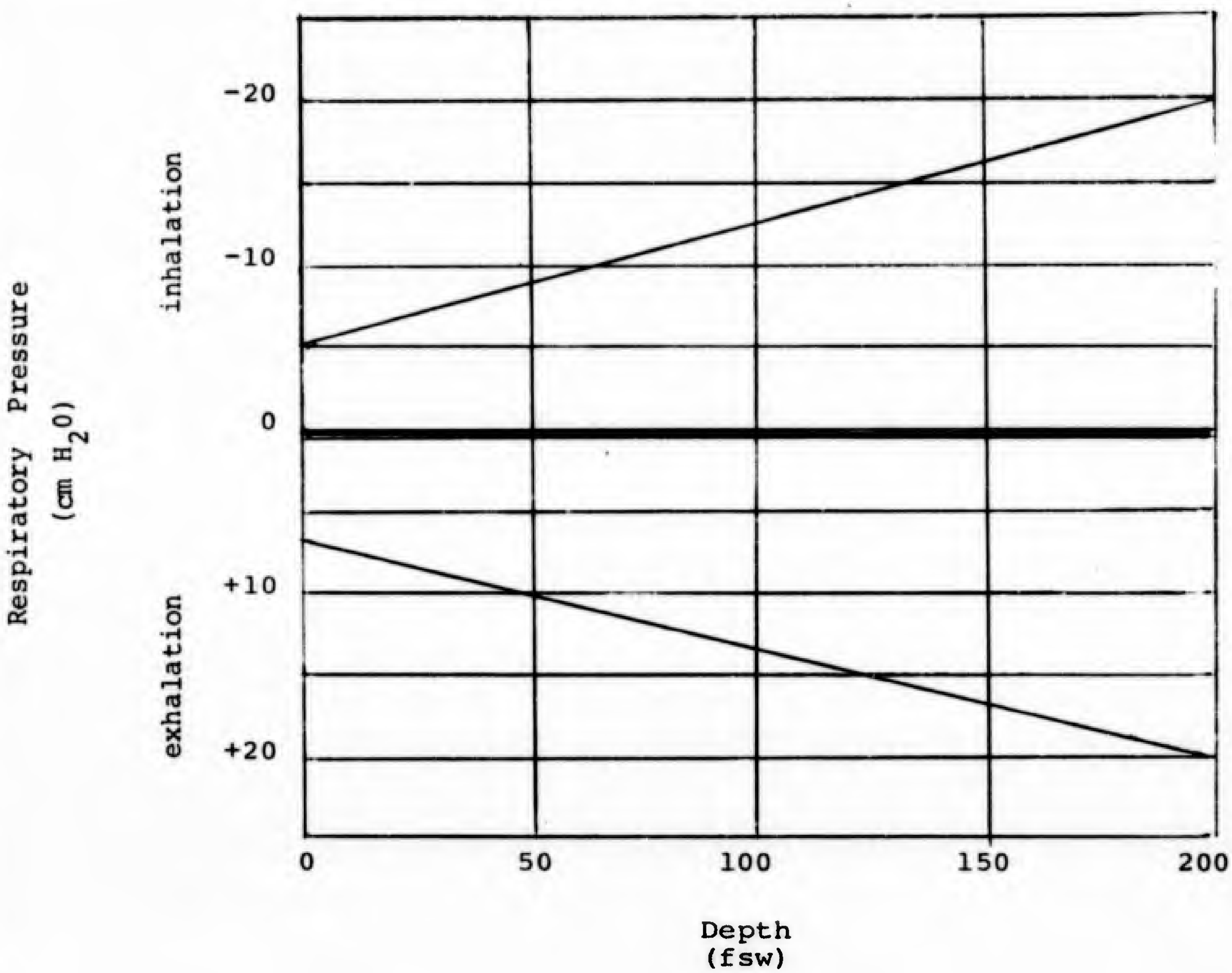


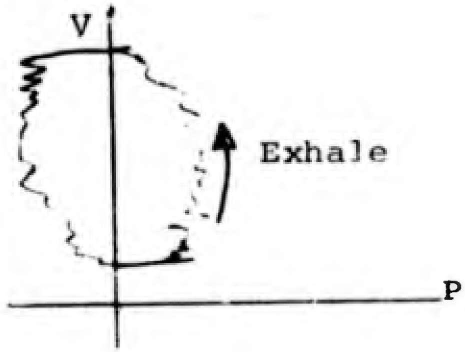
Figure 1

Allowable Peak Pressures In a Standard U.S.N. Open Circuit SCUBA Regulator Test with The Regulator Tested at a Minute Volume of 40 liters per minute (V_t=2.0 liters per breath, Waveform equals That of a Sinusoid with an Exhalation/Inhalation Time Ratio of 1.1 to 1.0).

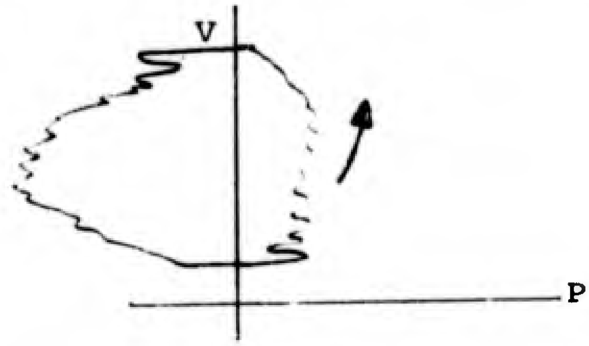
around the best regulators available at that time, and they have remained essentially unchanged ever since. Subsequent information, however, indicates that the peak pressures in open circuit SCUBA should be considerably lower, possibly no more than 10-15 cm H_2O (3)(9). This will be discussed in more detail in the succeeding sections.

Peak inhalation and exhalation pressures are an easy and convenient parameter to measure. However, their significance in both engineering and physiological terms is often obscure. On the basis of a pressure-time trace alone it is difficult to distinguish where in the breathing cycle the peak pressures are occurring. It is also difficult to distinguish the relative contributions to the total measured pressures made by elastic, flow-resistive and hydrostatic forces. Figure 2 shows typical pressure-volume (P-V) loops for several common types of underwater breathing apparatus. Under the right conditions the pressure-time traces for many of the P-V loops shown in Figure 2 can appear almost identical.

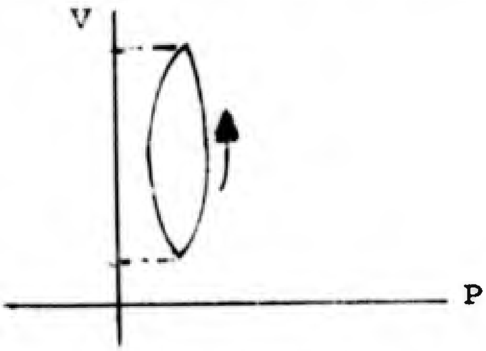
The respiratory pressure variations in an open circuit SCUBA regulator are almost all resistive with only a small hydrostatic component. This results in the pressure and flow variations being in phase (peak pressure occurs simultaneously with peak flow rate) and the rectangular P-V loop shown in Figure 2A. Since the area of a P-V loop is a measure of the respiratory work done on the apparatus by the diver it can be seen that in the case of an open circuit SCUBA regulator that relatively small pressure variations can result in quite substantial respiratory work rates. The respiratory pressure variations in a neckseal type helmet



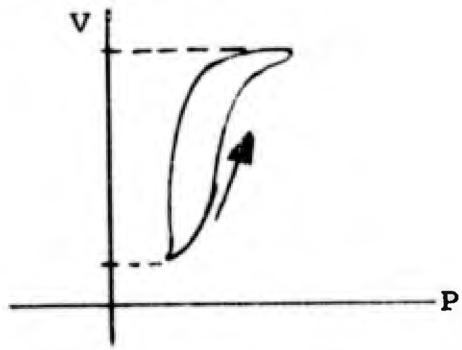
A. Open Circuit SCUBA Regulator Within Its Operating Range



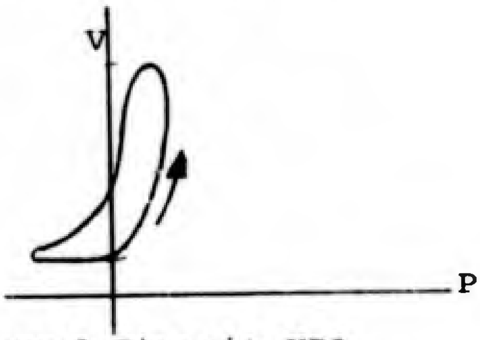
B. Open Circuit SCUBA Regulator Overbreathed



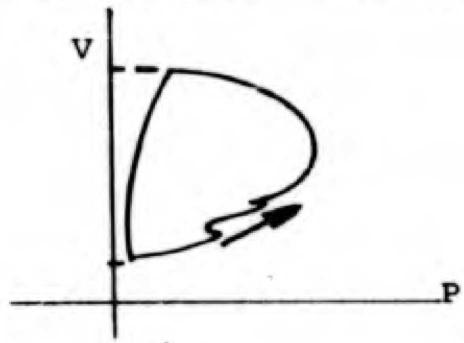
C. Closed Circuit UBA in Proper Trim



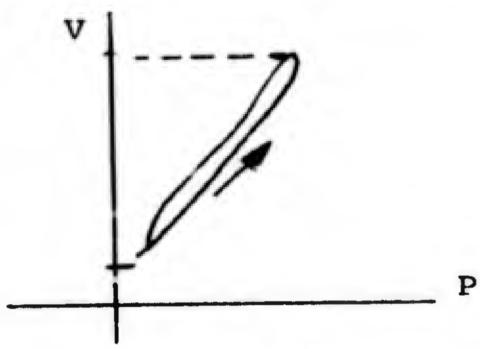
D. Closed Circuit UBA Breathing Bags Overfilled



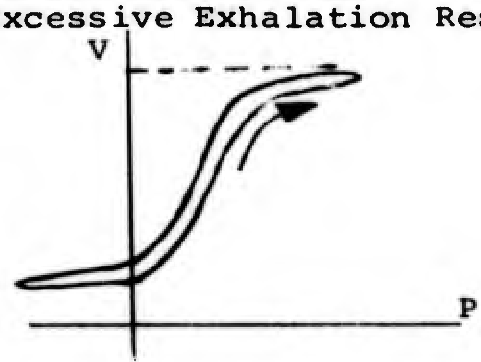
E. Closed Circuit UBA Breathing Bags Underfilled



F. Closed Circuit UBA Excessive Exhalation Resistance



G. Neckseal Type Helmet In Proper Trim



H. Neckseal Type Helmet Overbreathed

Figure 2

Typical Pressure-Volume Diagrams for Several Types of Underwater Breathing Apparatus.

on the other hand are almost all hydrostatic and elastic. This results in the helmet pressure and diver respiratory flow rates being almost perfectly out of phase (peak helmet pressures occur at end-inspiration and end-expiration, ie at conditions of zero respiratory flow) and results in the thin sloping P-V loop shown in Figure 2G. Consequently in a neckseal helmet a diver can generate quite large respiratory pressures but do relatively little respiratory work. Experience has shown that although peak pressures of 20 cm H_2O in open circuit SCUBA can become intolerable at heavy work rates (9)(33), peak pressures of up to 60 cm H_2O have been tolerated at moderate work in neckseal helmets with no complaints or signs of distress on the part of the subject (17)(18). Despite these wide differences in effects, the pressure time traces for open circuit SCUBA regulators and neckseal type helmets usually look quite similar, the only major difference normally being a shift in the time axis not usually detectable on a straight pressure-time trace.

The respiratory pressure variations in semi-closed and closed circuit SCUBA can contain significant flow-resistive, hydrostatic and elastic components. For them both P-V loops and pressure-time traces can take on many forms (See Figures 2C through 2F).

For open circuit SCUBA regulators within their normal operating range (Figure 2A) the peak pressures, time-average pressures and volume average pressures tend to be very nearly equal. This is not surprising since open circuit SCUBA regulators are essentially pressure regulators and the function of a pressure regulator is to maintain a given pressure as nearly independent of flow rate as possible. Consequently for such regulators, peak pressures are a reasonable performance yardstick to use.

However, for other types of breathing systems a different yardstick must be used. The respiratory work that the diver (or simulation test machine) must do on his breathing system in order to satisfy his respiratory needs is suggested as this yardstick.

From an engineering standpoint the work of breathing is a much more readily interpreted parameter than is peak pressure. The P-V loops required to calculate the work of breathing contain much more information than the pressure-time traces usually taken when only peak pressure information is desired. The area of the P-V provides an automatic method of weighting any pressure peaks that occur whereas on a pressure-time trace such peaks usually must be weighted (assigned importance) by the investigator's judgement. Peak pressure information is of course still available if it is needed due to physiological or equipment considerations (for instance, the pressure differential at which a helmet neck-seal can be expected to leak). P-V loops also allow a much easier judgement of instrument noise and a much easier determination of the quiescent (no flow) system pressure than do pressure-time traces.

From a phsiologic point of view the work of breathing is widely accepted as being a critical respiratory parameter, much more so than peak pressures, and it has been the subject of numerous investigations. The work of breathing is divided between internal work consumed by the movement of gas into and out of the lungs and external work consumed by the movement of gas through whatever breathing apparatus is being used. Positive and negative pressure breathing also affect both the internal and external work of breathing.

It is widely held that the total amount of power (work per unit time) that can be comfortably devoted to respiratory purposes is related to the overall body work rate (2)(3)(6)(21)(24). As the density of the respired gas is increased, the power required to ventilate the lungs is also increased (3)(24)(26) leaving less power available for moving gas into and out of the breathing apparatus. Most of the work done to date that has specifically addressed external work of breathing has been done dry in air at 1 atm, usually with mine safety and fire fighting appliances in mind (2)(3)(20)(21). Only Bradley et al (3) have specifically addressed the external work of breathing in divers breathing apparatus. However, there appears to be enough information available, primarily from the work of Bradley et al (3), Sterk (22), Uhl et al (24) and Wright et al (26) to permit the formulation of tentative. standards for external work of breathing in the depth range 0 to 1000 fsw, provided certain assumptions can be made.

DETERMINING THE EXTERNAL WORK OF BREATHING

Definitions

Figure 3 shows a typical pressure volume loop that might be obtained from a closed circuit UBA. For the purposes of this example the UBA is considered to be tested dry so that hydrostatic forces are not present. It is also considered to have no mechanical hysteresis so that its quiescent (negligable flow) pressure-volume curve is the same on inhalation as it is on exhalation. The effects of hydrostatic forces and mechanical hysteresis are discussed separately later.

In Figure 3 the vertical axis represents volume with the end-inspiratory volume in the UBA represented by A and the end-expiratory volume by E. Mouthpiece pressure relative to outside ambient pressure is represented by the horizontal axis. Lines AB and ED therefore represent the elastic pressure in the apparatus at the end of inspiration and expiration respectively. Line BD represents the elastic pressure-volume characteristic of the apparatus, which may not be linear.

Pressure times a volume change equals work. Consequently the area enclosed by ABCDEA represents the total work done by the power source on the apparatus during the expiratory cycle. The power source can be considered either a breathing machine or a diver. Of the total expiratory work an amount equal to the area at BCDB was done against flow-resistive forces and is lost and amount equal to the area of ABDEA was done against elastic forces. This latter amount of work is stored in the apparatus and is recoverable for re-use during inspiration.

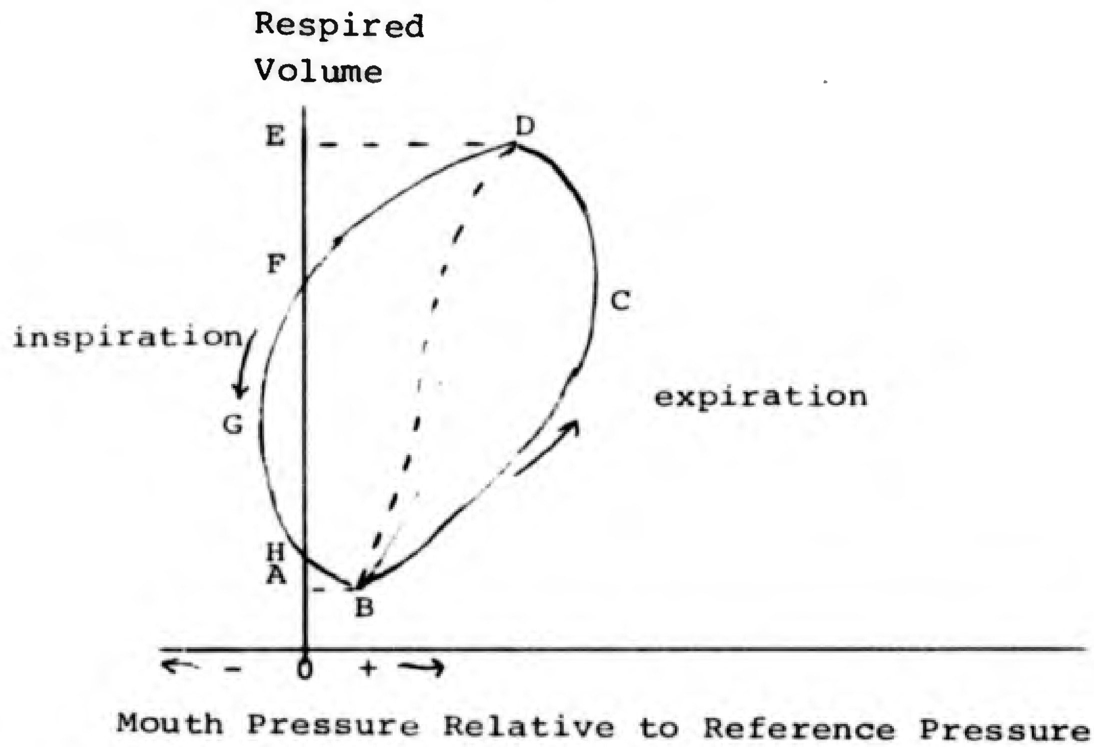


Figure 3: Normal Resistive Breathing P-V Loop

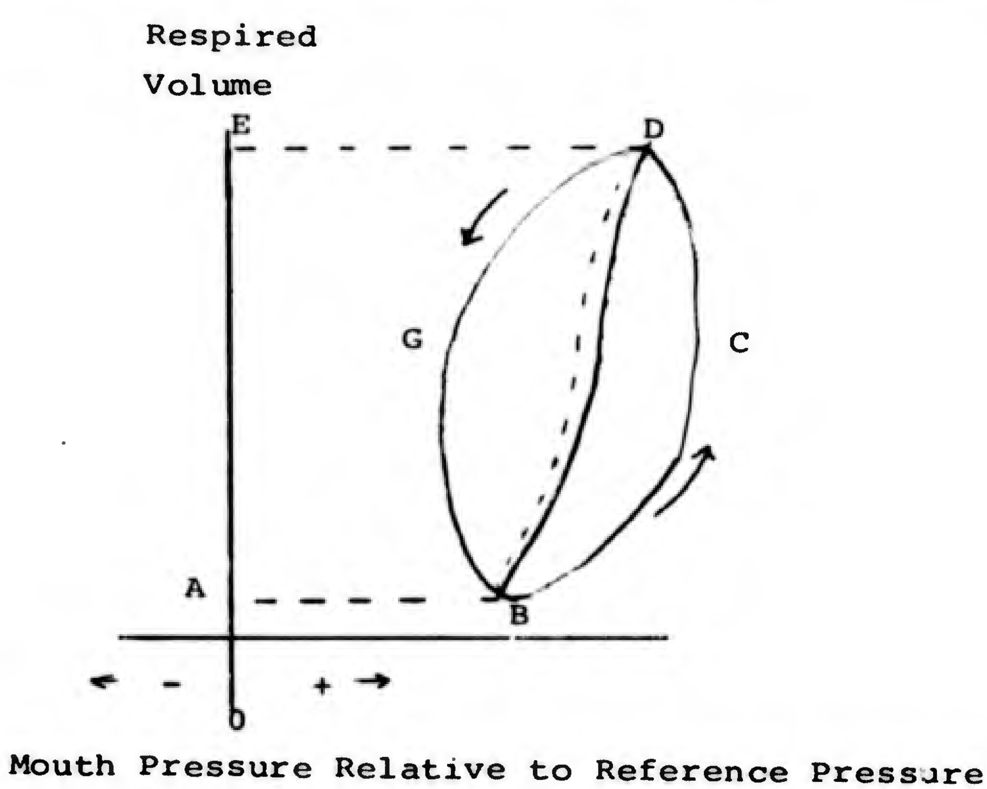


Figure 4: Positive Pressure Breathing P-V Loop

In both Figures, the area enclosed by the loop represents flow-resistive work done. The area (s) between the loop and the vertical axis represents wasted elastic or "negative" work.

Inspiration requires an amount of energy equal to the area of DGBD to overcome the flow resistive forces. In this case that energy is supplied from 2 sources. An amount equal to the area of DFHBD is recovered from the elastic energy stored in the apparatus during exhalation and an amount equal to the area of HFGH is supplied by the power source. In a purely mechanical system the un-used stored elastic energy represented by the areas DEFD and ABHA would be returned to the power source for re-use on the next exhalation. In a mechanical system, therefore, the net work expended by the power source during each cycle would be represented by the area enclosed by BCDGB.

In a physiological system, however, once muscular energy has been expended, it cannot be recovered. Consequently the energy represented by the areas of DEFD and ABHA cannot be returned to the power source, and it is lost from the system during each cycle. This lost energy is usually referred to as "wasted elastic work" (6) or negative work (14). The total physiological work expended each cycle by the power source is therefore equal to the area enclosed by BCDGB plus the areas enclosed by DEFD and ABHA.

In Figures 2A through 2H the total mechanical work of breathing is in each case represented by the area enclosed within the P-V loop. The total physiologic work in each case equals the total mechanical work plus the area(s) enclosed between the P-V loop and the vertical volume axis (indicated by the dashed lines).

Total repiratory work (internal plus external, if any) is usually calculated in a similar fashion. The major difference is that the differential pressure that is usually used is the pressure difference between the thoracic cavity pressure as measured by the esophageal balloon technique and the external ambient pressure (14).

When computing the total work of respiration (internal plus external) several investigators feel that "wasted elastic work" or "negative work" that occurred during one respiratory half-cycle (inspiration or expiration) must be counted again on the succeeding half-cycle (14). If Figure 3 were taken to represent the total work of breathing, then the total work per cycle would be equal to the area of ABCDEFGHA plus DEFD and ABHA. This is said to be so because in the case of "negative work" occurring during the expiratory cycle (as in Figure 3) an equal amount of work must be expended by the expiratory muscles during inspiration to prevent undesirably rapid inspiration.

This is somewhat a dubious point since the problem is not one of generating energy, but rather one of dissipating it, and there are many ways of dissipating energy besides by active muscular resistance. Indeed Otis (14) pointed out that esophageal pressure measurements do not take into account inertial or flow resistive work done on the tissues of the thorax and abdomen. The inertial work is said to be small, but Otis reported some investigators had found thorax and abdomen flow-resistive work to be as much as 28 to 36 per cent of the total internal mechanical work of breathing. Further, the importance of how this "negative work" is handled can be expected to diminish rapidly as minute volumes are increased. Increased minute volumes mean a greatly increased proportion of flow resistive work, and an inspection of Figure 3 will quickly reveal that as the proportion of flow resistive work increases the proportion of "negative work" can be expected to diminish rapidly.

When measuring the external work of breathing, the adding of "negative work" from one respiratory half-cycle to the following half-cycle is probably even less important. Cooper (6) found that in six different types of closed circuit breathing apparatus (tested dry) the proportion of "wasted elastic work" decreased rapidly as the minute volume was increased, decreasing from 30% of the total at $\dot{V}_e$=20 L/min, BTPS to 5% of the total at $\dot{V}_e$=40 L/min. Also the number of ways this excess elastic energy can be dissipated is increased since the diver can add flow resistance in his mouth and upper airways at will. Consequently for the standards proposed herein, wasted elastic work is considered to be just that. It is not considered work that must be added again to the next respiratory half-cycle.

The only situations in which this approach may not be valid are in extreme positive and negative pressure breathing where the "negative work" contributions can become quite large (See Figure 4). However the standards proposed herein should be sufficiently severe in those situations. Continuous positive breathing at altitude without the aid of a pressure suit is limited to 20 cm H_2O (3)(31). Bradley et al (3) have recommended that continuous positive or negative pressure breathing in a diving situation be limited respectively to + and -15 cm H_2O. The standards as proposed herein will have the effect of limiting pressure breathing to a maximum of about + or -15 cm H_2O.

Mechanical Hysteresis

Some types of UBA, particularily semi-closed types, can be expected to exhibit some mechanical hysteresis. That is to say that in Figure 3 if the exhalation elastic pressure-volume relationship is represented by the solid line BD, then the inhalation elastic pressure-volume relationship would be represented by the dashed line BD. The presence of such a hysteresis would not affect the overall measured work of breathing. However, it would be important if the relative contributions of elastic, hydrostatic, and flow-resistive work were to be determined. The net effect of hysteresis is to make part of the elastic work done on the apparatus non-recoverable.

Mechanical Hysteresis has also been observed to occur in the lungs with more energy being required to expand them than is released during subsequent contraction (22)(25)(37).

Hydrostatic Forces

Hydrostatic forces manifest themselves in two ways. First the presence of water outside of any UBA that uses breathing bags or a neckseal will cause a change in the elastic pressure-volume relationship. The total elastic forces resisting the flow of gas into the apparatus will now be the mechanical elastic forces that exist when the apparatus is dry plus the hydrostatic forces resisting bag or neckseal displacement. The mechanical elastic forces can be expected to be reasonably independent of apparatus orientation whereas the hydrostatic forces will change with a change in apparatus orientation with respect to either the vertical axis or the vertical level at the pressure reference point. These effects require nothing more than the apparatus be tested in working trim in all orientations in which it is expected to be used under normal diving conditions.

The other, much more troublesome effect of hydrostatic forces is to make the choice of the pressure to which the mouthpiece pressure is to be referenced (See Figure 3 and 4) much more difficult.

Sterk (22), after a considerable review of the literature for his work in 1970, chose to use as his reference pressure the hydrostatic pressure at the mouthpiece level. His comments on the subject were as follow:

> "In order to discover the optimum position of the breathing bag, Paton and Sand (13) have introduced the term "eupnoic pressure", that is, the pressure of respired gas at which breathing is most comfortable, relative to the pressure exerted by the surrounding water on the chest.

They found the eupnoic pressure to be at the suprasternal notch in all positions of their submerged subjects, except in head-up vertical posture.

Here, eupnoic pressure was above the notch at rest, and approached the notch during hyperpnea. However, it seems illogical to find the center of pressure, or centroid of the chest, somewhere in the neck regions.

Jarret (7) found the centroid where it should be expected, at about 19 cm inferior and 7 cm posterior to the sternal notch. The apparent contrast of these finds can be explained by the work of Thompson and Md-Cally (32) who have demonstrated that the subjective choice of the comfortable pressure of respired gas is influenced by pressure sensations in the upper airways.

Since the balance point of pressure is not accurately known, we have referred all the pressure measurements in our prototype to the hydrostatic pressure at the mouthpiece."

Flynn, et al (34), as a result of a recent set of experiments with trained subjects positive and negative pressure breathing while in a head-out immersion status, have suggested the hydrostatic pressure at the level of the 7th cervical vertebra as the reference pressure. Bradley (35) has agreed that the choice of the 7th cervical vertebra level is as reasonable as any at this time, and that is reference pressure proposed for use with these standards. (The 7th cervical vertebra is located at the junction of the neck and shoulders, and it can be readily located by feeling for the large bump usually found at that location.) The reasons for the choice of the 7th cervical vertebra level are as follows:

Agostini et al (1) in 1966 found that in their trained subjects the principal effect of immersion in water up to the neck level was a downward shift in the resting (end-expiratory) lung volume. Most of the other characteristics of normal respiration remained unchanged. Inspiration remained fully active. Expiration remained fully passive. Their subjects were observed to adjust to the applied hydrostatic pressure by simply permitting their lungs to deflate during expiration until the additional recoil (spring effect) of their respiratory system (lungs and chest walls) balanced the applied hydrostatic load. They were then observed to breathe "normally" about their new vesting lung volumes. This effect can be seen in Figure 5, which shows the effect that immersion to the neck had on the mean respiratory system static (i.e. elastic) volume-pressure curves for Agostini's subjects. Resting lung volumes were reduced from 35.8% of vital capacity to 10.8%, and an increase in airway pressure of about 20 cm H_2O was required to maintain lung volumes equal to those which occurred when the hydrostatic force was not present.

When their subjects were breathing against normal atmospheric pressure, Flynn et al obtained results very similar to those of Agostini's group. If, however, a positive pressure were applied to their subject's inspired air (as it would be, for instance, were the subject upright in an underwater breathing apparatus designed to maintain lung centroid pressure at the mouth), their end-expiratory lung volumes fell below the levels predicted by their respective respiratory static volume-pressure curves. Expiration became partly active; fully active if sufficient positive pressure were applied. Negative pressure applied to their subject's respired air produced an opposite effect, although to a lesser extent. Only when their subjects breathed air at a pressure approximately equal to hydrostatic pressure at the level

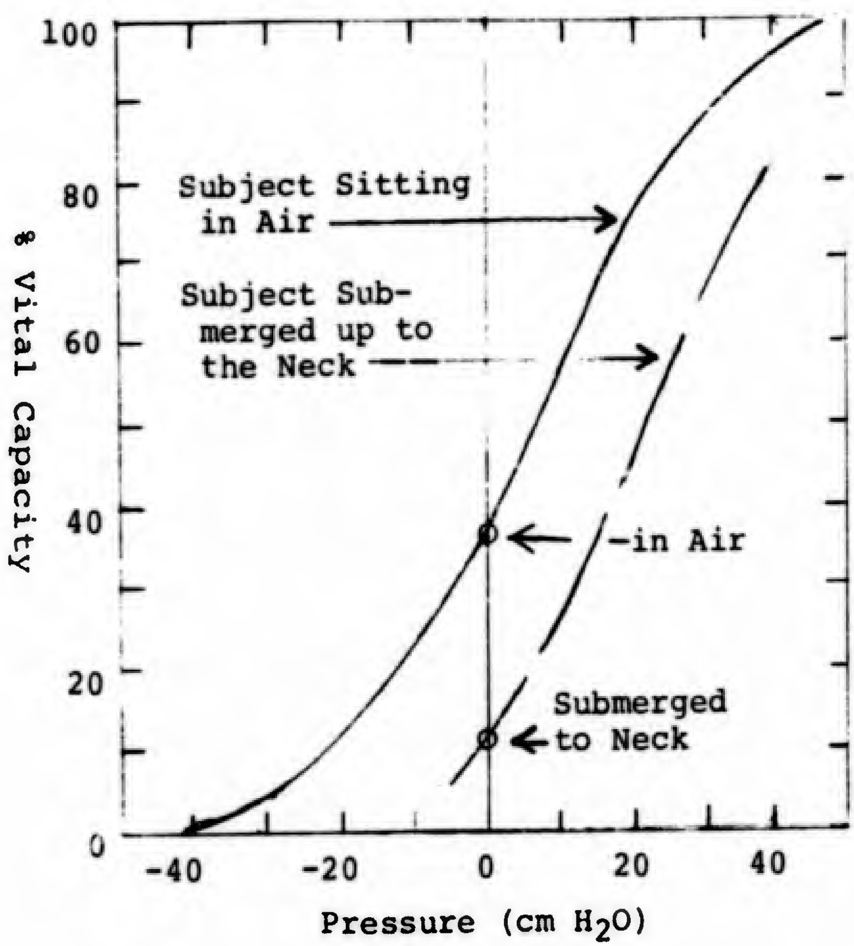


Figure 5

Static (Elastic) Volume-Pressure Curves of the Relaxed Respiratory System. The Circles Indicate the Points Corresponding to the End of Spontaneous Expirations Under the Conditions Indicated.

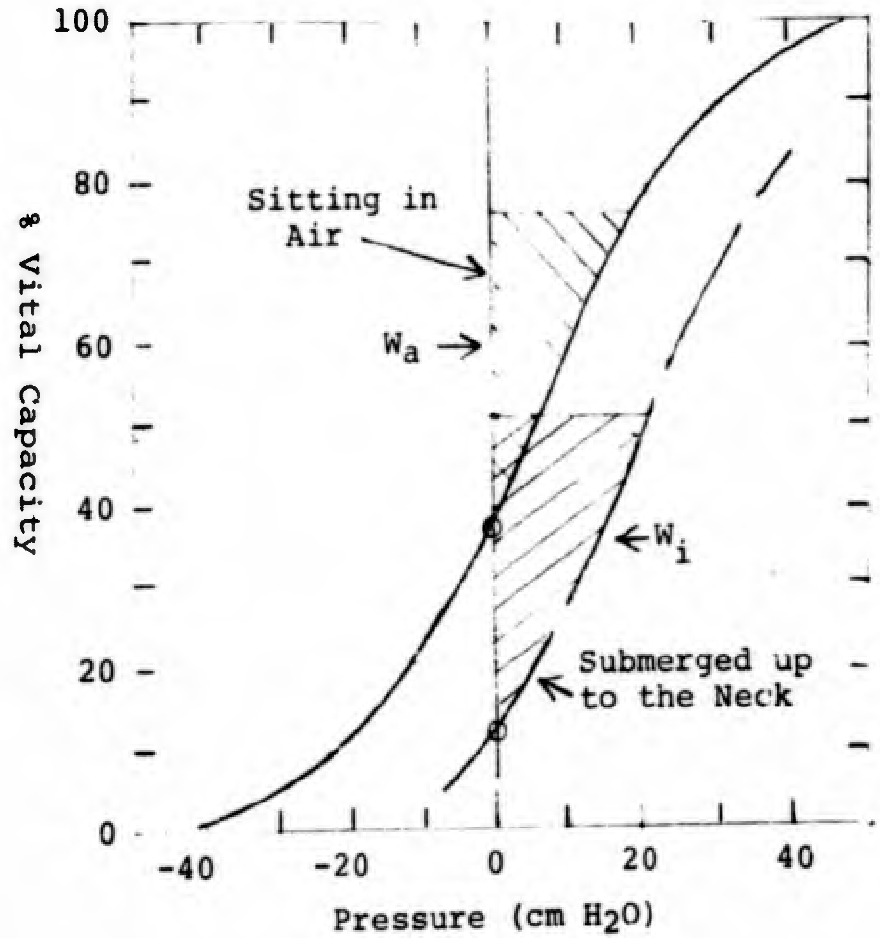


Figure 6

Total Elastic Work Done During Spontaneous Respiration at a Tidal Volume of 2.0 Liters.

of the 7th cervical vertebra, were "normal" breathing patterns, characterized by active inspiration and passive expiration, observed. Any deviation from this pressure produced a breathing pattern in which the respiratory muscles were not relaxed at the end of the expiratory cycle.

Since the respiratory system in most normal situations selects a breathing pattern whereby the respiratory muscles are relaxed at end-expiration (1)(37), it is logical to assume that that pattern normally requires the least work. Consequently, any standards proposed for external work of breathing, should logically impose a work penalty on any apparatus which forces the respiratory system into any other kind of breathing pattern. Using the pressure differential between the airway (mouth) pressure and the hydrostatic pressure at the level of the 7th cervical vertebra performs that function. Consequently, 7th cervical vertebra pressure is considered the most logical reference pressure for use with these standards.

The other pressure frequently discussed as a candidate for the reference pressure is the hydrostatic pressure at the location of the lung centroid. Use of that reference pressure can readily be shown to be incorrect. Consider, for example, a subject for whom the respiratory static volume-pressure curves of Fig.5 apply. Consider further that this subject is breathing spontaneously with a tidal volume of 2.0 liters (38% of vital capacity for this hypothetical subject). The total elastic work expended per breath by this subject when he is breathing in air is indicated by the shaded area W_a in Figure 6. His total elastic work when breathing immersed is indicated by the shaded area W_i. The two areas indicate, respectively, total elastic works of 0.20 and 0.24 Kg-m per breath, or in specific terms, 0.10 and 0.12 Kg-m per liter ventilation.

In both cases the hypothetical subject would be breathing with a "normal" pattern of active inspiration and passive expiration. In both cases the external work of breathing, calculated by use of the 7th cervical vertebra reference pressure, would be zero, there being no pressure differential between the airway (mouth) pressure and the reference pressure. If the lung centroid pressure were used as the reference pressure, the external work in the in-air case would also be zero. However, in the immersion case, the external work would be about 0.40 Kg-m per breath or about 0.20 Kg-m per liter ventilation (assuming the lung centroid to be 20 cm below the 7th cervical vertebra). This is almost double the total elastic work indicated by the lung volume-elastic curve! This situation is obviously incorrect.

Recalling the original goal of these proposed standards (see Introduction), the following pressures are suggested as the reference pressures to be used. They are suggested as a compromise between technical convenience and physiological significance.

TYPE OF APPARATUS	REFERENCE PRESSURE
Helmets, Semi-closed and Closed Circuit UBA	Hydrostatic pressure at the level of the 7th cervical vertebra.
Open Circuit SCUBA and Other Demand Apparatus	Hydrostatic pressure at the level of the center-line of the 2nd state diaphragm.

The performance of demand type breathing systems is determined by the pressure differential between the mouthpiece interior and hydrostatic pressure at the centerline level of the 2nd stage diaphragm. Consequently, the latter pressure has been chosen as the reference pressure for those systems. Use of any other reference pressure, from an engineering point of view, simply makes very little sense. Also, as most demand systems are currently designed, the 2nd stage diaphragm is at or near the level of the 7th cervical vertebra during most swimming and standing maneuvers anyhow. Consequently in this situation the selection of the reference pressure to gain engineering significance at the expense of some physiological significance is considered reasonable.

In the cases of helmets, closed circuit and semi-closed circuit UBA's, the physiological significance gained by use of the hydrostatic pressure at the level of the 7th cervical vertebra is considered to merit the extra engineering difficulties it creates.

PROPOSED STANDARDS

Internal Work of Breathing

The physiologic parameter most relevant to the work of breathing appears to be the total amount of respiratory work, internal plus external, that must be expended per liter of ventilation in order to ventilate the lungs (2)(24). To be physiologically valid, standards which address only the external work of breathing must therefore either take into account the corresponding amounts of internal work or the internal work of breathing must be shown sufficiently stable so that it can be assumed constant over the range of conditions of interest.

A number of investigators have investigated the effects of imposed external breathing resistances on the ability of test subjects to perform work in a dry environment when breathing air at one atmosphere. However as one might infer from the stated test conditions, most of the external work of breathing investigations that have been conducted to date have been concerned primarily with mine safety and fire fighter's breathing appliances. Very few have addressed diving apparatus either directly or indirectly. In a diving situation the person is breathing while submerged and at an elevated pressure. Consequently both the internal and external work of breathing may be affected by both hydrostatic forces and by increased flow-resistive forces due to the increased density of the respired gas. The applicability of most of the proposed external work of breathing standards to a diving situation then depends largely on how much the internal work of breathing is affected by the presence of hydrostatic forces and the increased density of the respired gas.

Influence of Hydrostatic Forces

In the horizontal position where both mouth and lung centroid are at the same level, the effect of hydrostatic forces can be expected to be negligible.

Agostini et al (1) have reported an increase in airway resistance of 58% during submersion up to the neck. That, of course, would result in an increase in flow-resistive internal work of breathing. However, since the absolute amount of internal flow-resistive work is usually small (Sterk (23): 0.01 Kg-m/L, subject dry in air at 1 ata and $\dot{V}$ =10 L/min, BTPS; .026 Kg-m/L in 6 ata air, $\dot{V}_e$=10 L/min, BTPS; see also Table 1), the actual significance of this increase can be expected to be small.

Referring back to Figure 6, it is seen that immersion up to the neck can also be expected to cause some increase in the internal elastic work of breathing. (For the purposes of these standards, all elastic work done by the respiratory muscles which is not accounted for in the calculated external work is considered to be internal elastic work). Although the increase in internal elastic work in Agostini's subjects brought about by immersion was small, about 0.02 Kg-m per liter ventilation at a 2 liter tidal volume (.016 Kg-m per liter ventilation at a 1.0 liter tidal volume), it cannot be dismissed out-of-hand. It is, however, an increase that can reasonably be considered independent of depth. It can also be expected to disappear if the diver assumes a horizontal position. For these reasons, the increases in elastic work brought about by immersion are considered safely negligible as far as these proposed standards are concerned.

Effect of Increasing Gas Density

That the changes in internal work of breathing brought about by an increase in the respired gas density can be safely neglected is not so easily shown. Assuming $\dot{V}_e$ constant, as the respired gas density is increased, the elastic component of the internal work of breathing (the work required to overcome the spring constant of the lungs and chest) can be expected to remain constant; the flow-resistive component can be expected to increase; and the "negative work" component can be expected to decrease. The question is are the changes sufficiently small that they may be neglected or assumed less than some fixed value.

Bradley et al (3), Sterk (22), Uhl et al (24) and Wright et al (26) have investigated the effect of increased gas density on the total work of breathing in a number of situations directly related to diving applications. Bradley et al measured both the internal and external work of breathing in 6 subjects breathing through a low resistance mouthpiece and also using standard USN MK VIII and MK XI UBA's. Their tests were all performed dry at 1 ata with the subjects working against a bicycle ergometer at rates of rest, 500 and 1000 Kg-m/minute. Breathing gas mixtures of 70/30 N_2O_2 (70% Nitrogen, 30% Oxygen) and 70/30 SF_6O_2 were used to simulate respectively shallow and very deep diving. The 4.7 gm/L density of 70/30 SF_6O_2 at 1 ata is roughly equal to the density of 97/3 HeO_2 at 695 fsw (.66 ata PO_2). Sterk measured the total work of breathing expended by 6 divers at rest at pressures of 1 and 6 atmospheres when breathing chamber air and also when submerged using a semi-closed circuit breathing apparatus. Uhl et al measured the total work of breathing in 5 subjects when working against a bicycle ergometer at work rates of rest and 500 Kg-m/minute and while breathing through graded resistances. Only Bradley et al reported the measured internal work of breathing separately. However an estimation of the internal work of breathing appropriate to the data of Sterk and Uhl et al can be obtained from their no external resistance controls. Wright et al measured the internal flow-resistive work in a group of 6 subjects during tidal breathing at 1 and 4 atm on normoxic N_2O_2 mixtures (PO_2=.21 ata). The results are shown in Table 1.

The data in Table 1 shows a significant variation between investigators, probably due to differences in experimental technique. However, for each investigator under comparable work rate conditions there is relatively little absolute variation in the work per liter values over quite large density variations, even though the percentage changes in some cases are quite large. Bradley et al in some cases actually reported less internal work with the heavier SF_6O_2 mixtures than they did with the lighter N_2O_2 mixtures.

The internal work expended per liter of ventilation is dependent on the interplay between many variables, only a few of which are represented in Table 1. Respiratory waveform, tidal volume, respiratory frequency, lung inflation level and several other factors are also important (14). All of the factors except gas density, however, can be reasonably assumed to exert similar influences in diving situations as they do in dry one atmosphere situations (excepting, of course, external hydrostatic forces which were discussed previously).

Investigator	imposed work rate (Kg-m/min)	gas	ambient pressure	gas density (gm/L)	average minute volume (L/min, BTPS)	average internal work per liter (Kg-m)
Bradley et al (3)	0	70/30N_2O_2	1 ata	1.2	13.6	.103
	500	"	"	1.2	27.3	.123
	1000	"	"	1.2	53.1	.179
	0	70/30SF_6O_2	"	4.7	8.8	.091
	500	"	"	4.7	25.4	.116
	1000	"	"	4.7	46.7	.239
Uhl et al (24)	0	Air	"	1.2	20.0	.026
	500	Air	"	1.2	43.2	.064
	0	80/20SF_6O_2	"	5.2	13.7	.033
	500	"	"	5.2	45.6	.113
Sterk (22)	0	Air	"	1.2	10.0	.030
	0	Air	6 ata	7.2	10.0	.046
Wright et al (26)	0	Air	1 ata	1.2	-	.028*
	0	94.8/5.2 N_2O_2	4 ata	5.0	-	.045*

* flow-resistive work only

Table 1

Average Internal Work per Liter Ventilation Report by Several Investigators. External Resistance to Breathing Was Essentially Zero in All Cases. All Subjects Were in a Dry Environment.

Variations in Internal Work Neglected

The maximum external work per liter ventilation recommended herein will be seen to be .17 Kg-m/liter. The densities of the gases normally used for diving purposes in the depth range 0 to 1000 fsw vary from 1.2 gm/L to 8.4 gm/L for air and from .5 to 7.8 gm/L for HeO_2 mixtures. The influence of density changes over that range on the internal work per liter appear to be not more than about .02 to .05 Kg-m/liter at most normal minute ventilations (0 to 40 L/min). The influence of immersion on the internal work per liter over the same range of minute ventilations appears to be .015 to about .02 Kg-m/liter. It is therefore possible, but considered unlikely, that all of the factors discussed could produce a variation in the internal work of breathing of as much as .07 Kg-m/liter. The proposed .17 Kg-m/L limit on the external work at breathing will be seen to allow a considerable margin for error (something on the order of 0.05 Kg-m/L). Consequently, it seems justifiable, for the purpose at hand, the formulation of workable standards for the external work at breathing in the depth range 0 to 1000 fsw, to neglect changes in the diver's internal work of breathing caused by gas density variations, immersion and related factors. That some error is introduced by this procedure is not denied, and it is expected that the standards proposed will be refined with time. However, at the present time, the advantages to be gained from a simple, easily workable standard are considered to far outweight the potential hazards involved.

Standards Previously Recommended

Since the effects of hydrostatic forces and the effects of increasing gas densities due to increasing depth have been assumed to be negligible, all of the work done previously on external work of breathing in dry one atmosphere situations can now be considered applicable. Table 2 lists the essential features of several of the standards that have been proposed. Figure 7 shows them related, as best as is possible, to minute ventilation and oxygen consumption. Oxygen consumption is shown along with minute ventilation since there is some evidence that as resistance to breathing is increased, that minute ventilation may fall with respect to oxygen consumption (2)(3)(4)(23)(27). That would allow an increase in external work per liter under standards which recommend that the total external work of breathing not exceed a fixed fraction of the total body work rate. The relation between $\dot{V}O_2$ and $\dot{V}_e$ is taken from references (9) and (28).

Silverman et al (20)(21) conducted the first major study on the physiological effects of resistive breathing. In all they tested 75 healthy, young, adult males. On the basis of the physiologic effects and subjective sensations of their subjects they recommended that the total rate of external respiratory work should not exceed 0.6% of the total external body work and that the expiratory work load should not exceed 40% of the total external respiratory work load. Cooper (6) and Senneck (19) reviewed the work of Silverman and his group. Cooper stressed that Silverman's subjects were not accustomed to resistance breathing and only

Investigator and Date	Recommended Maximum Values for External Work of Breathing
Silverman et al, 1945 (22)	0.6% of total external work rate. Expiratory work to be less than 40% of the total external work of breathing.
Lamphier, 1951 (9)	Peak Pressures in SCUBA should not exceed 10-15 cm H_2O.
Cooper, 1960 (5)	Maximum, 0.25 Kg-m per liter ventilation, or 1.5% of total external body work rate. 0.125 Kg-m per liter (0.74% of total external body work rate) desirable. Expiratory work not greater than inspiratory work at high minute volumes.
Senneck, 1962 (21)	Variable with $\dot{V}_e$, See Figure 7.
Bradley et al, 1970 (2)	0.6% of total external work rate. Positive and negative pressure breathing to be limited to + and -15 cm H_2O respectively.
Bentley, et al, 1971 (1)	.17 Kg-m per liter ventilation
Uhl, et al, 1972 (25)	Total work of breathing less than .350 Kg-m/liter alveolar ventilation and less than 11.0 Kg-m/minute in aggregate. Total system resistance less than 10 cm H_2O/liter/second.

Table 2

Essential Features of the Standards for External Work at Breathing Proposed by Several Investigators.

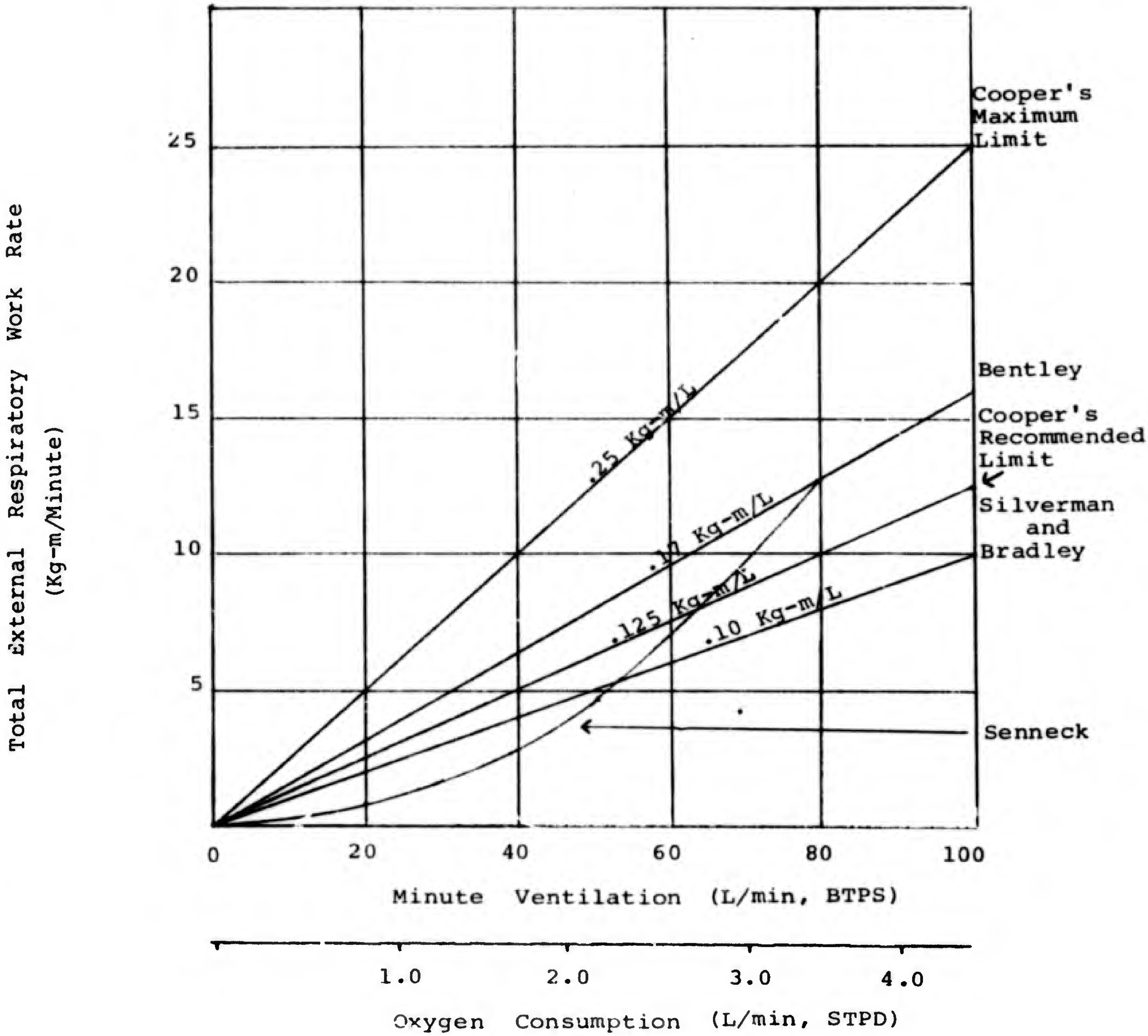


Figure 7

Recommended Limits on the External Work of Breathing Proposed By Several Investigators. Lines of Constant Slope Represent Constant Work Expenditure per Liter Ventilation exercised for 15 minutes at a time,whereas men likely to wear respiratory apparatus would be trained in their use and would probably have to wear them for a much longer time. After modifying slightly the calculation methods used by Silverman and his group and including data from his own work, Cooper recommended that the external work of breathing not exceed 1.5% of the total external body work with a limit of .74% being highly desirable. For his data 1.5% of total body work represented .25 Kg-m work per liter ventilation. Senneck (19) reviewing also the work of Silverman, proposed much lower limits, see Figure 7. Bradley reported that Hart (8) in 1945 proposed resistance limits that agree with the standards proposed by Silverman. Cooper reported agreement with his desirable 0.74% of body work rate standard by data reported by Mead (11). Bradley et al (3) in 1970 in reviewing Silverman's work and their own recommended again that the total external work of breathing not exceed 0.6% of the total external body work rate.

Bentley et al (1971)(2) conducted a comprehensive study involving 158 men aged 21 to 48 years walking on a treadmill while being exposed to a series of 10 graded inspiratory resistances. Expiratory resistance in all cases was kept low as they were evaluating the physiologic costs of "self-rescue" units for coal mine use and the units had substantial resistance only on the inspiratory side. Bentley et al used as their criterion of acceptable resistance, the point at which 10% of their subjects experienced subjective discomfort. This point they found to be closely related to the work done per liter (which has units of pressure) and to the peak pressure swings. Their data exhibited relatively little scatter. Applying their 10% incidence of discomfort criteria they recommended an external work limit on inspiration of 0.14 Kg-m/L and a total respiratory external work limit of 0.17 Kg-m/L. These limits are not however especially rigid as nothing cataclysmic happened when they were exceeded. As the external workload was increased, the proportion of subjects experiencing discomfort showed a steady, but rather uniform increase. The 50% incidence of discomfort levels were not reached until the external inspiratory and total work rates reached respectively .23 and .27 Kg-m/liter.

As in Silverman's work Bentley's subjects were not trained in resistance breathing as each subject took part in only 1 experimental run. There is considerable opinion to the end that practice improves a subjects tolerance to resistance breathing (3)(6)(21). Consequently Bentley's limits may be somewhat conservative when applied to diving applications.

This hypothesis is further supported by the semi-quantitative standards for peak pressures in SCUBA's of not more than 10-15 cm H_2O proposed on the basis of many operational observations by Lamphier (9). Reimers (15) has recently shown by actual measurement that in open circuit SCUBA regulators peak breathing pressures of 10 to 15 cm H_2O represent total external work rates of 0.17 to 0.23 Kg-m per liter minute ventilation. Peak pressures of 10-15 cm H_2O are common to most open circuit SCUBA regulators, and are widely tolerated without complaints.

It would seem logical that the presence of an expiratory resistance in Bentley's work would increase somewhat the maximum tolerable external work rate. This hypothesis is not supported by the work of Silverman, Cooper, Senneck or Bradley. It is, however, supported by Lamphier's observations and the SCUBA regulator measurements of Reimers.

The implications of the work of Uhl et al (25) with respect to the external work of breathing are difficult to interpret since they did not differentiate between internal and external work. However, a maximum total external work per liter ventilation of .17 Kg-m/l does not appear to be inconsistent with their data. Their recommended limit of a maximum total ventilatory power requirement (internal plus external) of 11 Kg-m/minute is, however, probably conservative. Test data from open circuit SCUBA regulators (15) has indicated that they can easily have external ventilatory power requirements of 8 to 10 Kg-m/minute in situations where they are known to produce relatively little discomfort. Also, Bradley et al reported several total ventilatory power levels well above that without incurring the respiratory distress levels reported by Uhl.

Standards Recommended for Divers Breathing Apparatus

Based on the foregoing discussion and upon the author's own experience, the most reasonable external work of breathing standard at this time appears to be the standard of Bentley et al, .17 Kg-m per liter minute ventilation. It is considered applicable in the depth range 0 to 1000 fsw on all gas mixtures normally used. With respect to the maximum proportion of the total work that may be due to expiratory work, the proportions proposed by Cooper (6) are recommended, see Figure 8. Specific positive and negative pressure breathing limits are not necessary as they are automatically established by the proposed limits on total external work.

The proposed standard is more liberal than those recommended by Silverman, Senneck and Bradley However, Bentley's work, the subjectively derived standards of Lamphier, and Reimers' regulator test data suggest that it should be sufficiently conservative to prevent the approval of breathing apparatus that will run the risk of causing serious respiratory distress. From an engineering point of view the standard is actually relatively severe. If adopted and enforced, it would force from service many (but by no means all) of the open circuit SCUBA regulators in current civilian and military service. It would also have a considerable effect on neckseal helmets and rebreathing SCUBA's and UBA's.

Respiratory Waveform Parameters to Be Used When Applying the Recommended Standard

The choice of respiratory waveform parameters for use when applying the recommended standard is, of necessity, somewhat arbitrary. Cooper (5) reported that the work done on a breathing apparatus by a sine wave pump closely approximates that done by human subjects. Cooper, however, used a breathing apparatus of very low resistance. The sine wave approximation at higher resistance levels has been found to be inaccurate by a number of investigators (2)(3)(27)(38). Bentley (2) found the respiratory flow rate to be a flattened sinusoid with a shape factor, $Q=2.67\pm 0.23$. (Q=ratio of peak flow to minute volume). The shape factor was observed to be relatively independent of the level of added resistance. A true sine wave has a shape factor equal to 3.14 (π).

Zechman, Hall and Hull (27) have reported respiratory frequencies and waveforms when breathing with expiratory and inspiratory resistances applied both separately and together. The effect of added resistance was to lengthen the phase to which resistance was added with expiratory resistance having more effect than inspiratory resistance. When resistance was added in equal amounts to both phases, both increased in time by proportional amounts yielding a lower respiratory frequency and a higher tidal volume. This tendency of respiratory resistance to reduce minute volume has been widely reported (3)(6)(21)(38). However, Uhl et al (24) found no such variations in their tests.

In neckseal type helmets where the resistance to breathing is predominately elastic, tidal volumes can be expected to be reduced and breathing frequencies increased (17)(18). The respiratory waveform based on helmet pressure-time measurements also appears to be nearly a true sinusoid (17)(18).

Based on the above the following respiratory parameters are considered the most appropriate:

Exhalation to inhalation time ratio:	1.1 to 1.0
Q: SCUBA's and UBA's of all types:	2.7
Neckseal Helmets:	3.14

Cooper (6) recommended testing breathing apparatus at minute volumes of 20, 50 and 100 L/min, BTPS and tidal volumes of 1, 2 and 3 liters respectively. However, in diving situations, even at extreme work rates, minute volumes of over 60 lpm are rarely encountered. Consequently, for test purposes minute volumes of 22.5, 40 and 62.5 liters per minute at tidal volumes of 1.5, 2.0 and 2.5 liters are considered more appropriate. These conditions represent respiratory frequencies of 15, 20 and 25 breaths per minute. The three test conditions cover nearly all of the basic respiratory waveform responses to work reported by Bradley et al in semi-closed circuit UBA's (2) and Reimers et al in neckseal helmets and open circuit SCUBA regulators (17) (18). Most open circuit SCUBA regulators will not support a 62.5 L/min minute volume except at very shallow depths (15).

SUMMARY

The proposed test standards and recommended procedures are summarized in Table 3 and Figure 8.

The proposed standards are not considered to be the ultimate yardstick by which the respiratory impedance of underwater breathing apparatus will be judged. The test procedures, and to a lesser extent the standards themselves, have been designed to be easily applied and to give meaningful and reproducible results in an engineering sense. Consequently some physiological significance has, of necessity, been sacrificed. In particular the assertion that the effects of the internal work of breathing can be safely neglected in the depth range 0 to 1000 fsw is open to some criticism. Also beyond 1000 fsw a different, more restrictive, standard may be required.

The proposed standards, however, appear to represent the most reasonable compromise possible at this time between the levels of external respiratory work tolerable by a diver and the ability of modern underwater breathing apparatus to provide large gas flows at low differential pressures.

The incorporation of the standards proposed herein into the development cycles of underwater breathing equipment should significantly improve the chances of speedy service acceptance.

Maximum permissible external work of breathing:	0.17 Kg-m per liter minute ventilation
Proportion of total external work which may be due to exhalation:	100% at zero minute ventilation decreasing linearly to 50% at $\dot{V}_e$=50 L/min, BTPS and above
Reference Pressure	
Open circuit SCUBA regulators	Hydrostatic pressure at the centerline level of the second stage diaphram
Other types of SCUBA, UBA and helmets	Hydrostatic pressure at the level of the 7th cervical vertibra established for test purposes as 10 cm to the rear and 10 cm below the mouth opening centerline.
Apparatus Orientation	To the extent possible, all normal working orientations should be tested.
Waveform Characteristics	
Minute ventilation	22.5, 40 and 62.5 L/min, BTPS Tidal volumes of 1.5, 2.0 and 2.5 liters at respiratory frequencies of respectively 15, 20 and 25 breaths per minute
Ratio of exhalation time to inhalation time	1.1 to 1.0
Shape:	
a. Neckseal type helmet	Sinusoidal
b. All other apparatus	Flattened sinusoid with a ratio of peak flow rate to minute ventilation of 2.7.

Table 3

Proposed Test Standards and Recommended Test Conditions

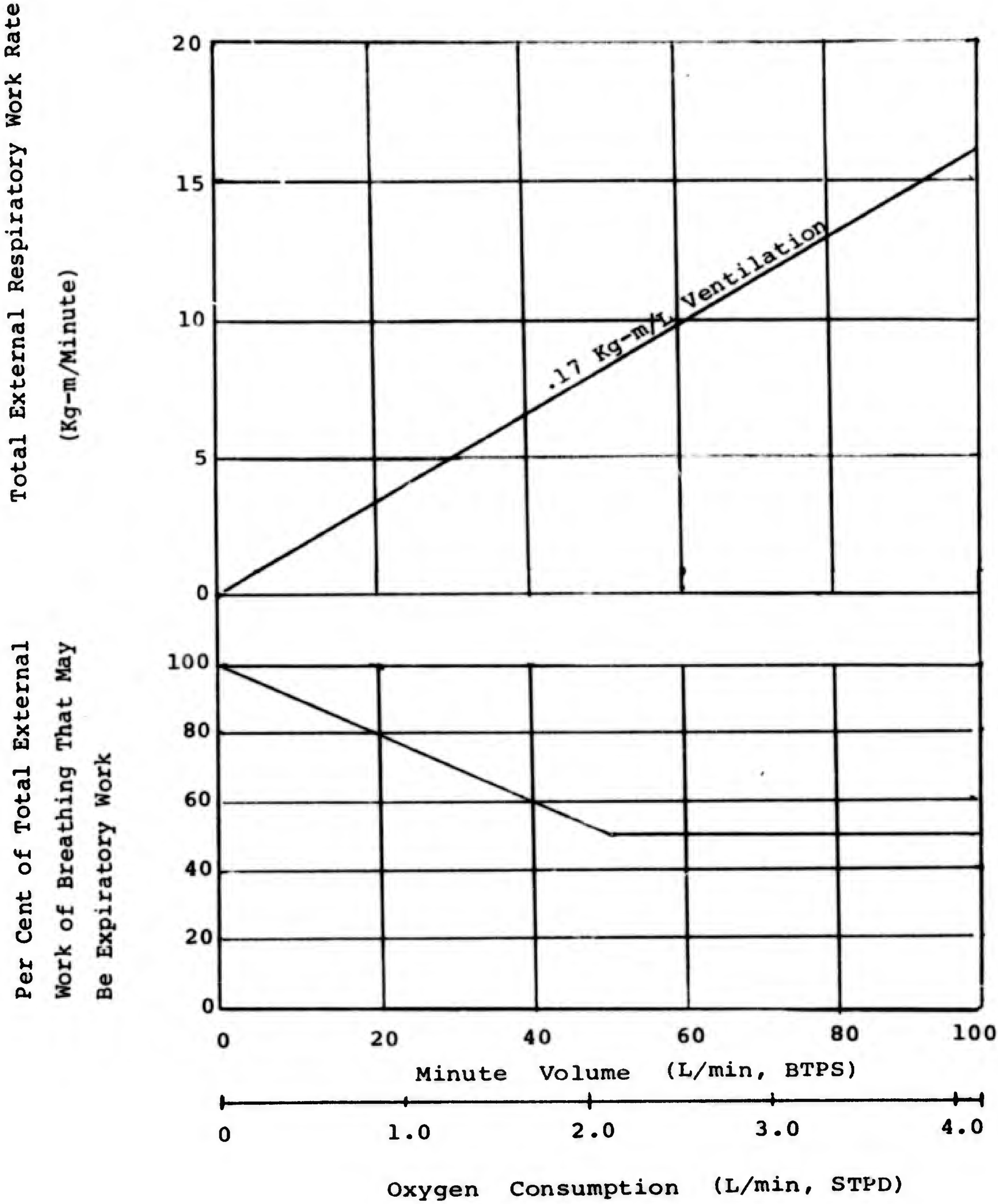


Figure 8

Proposed Limits on External Work of Breathing in the Depth Range 0 to 1000 fsw.

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