THEORETICAL CONSIDERATIONS IN THE DESIGN OF CLOSED CIRCUIT OXYGEN REBREATHING EQUIPMENT

by

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Project 4/69

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THEORETICAL AND PRACTICAL CONSIDERATIONS REGARDING THE USE OF OXYGEN REBREATHING EQUIPMENT FOR DIVING

1. RATIONALE FOR THE NEED OF HIGH EFFICIENCY OXYGEN REBREATHING EQUIPMENT.

Oxygen rebreathing equipment has several advantages over compressed air "scuba" or oxygen/inert gas mixture sets. Most important is that it is not possible for a diver to be detected by the presence of bubbles. In view of this the equipment must be regarded as an instrument for clandestine operations. In accepting this surmise, one must also accept that the physical and emotional stress of the diver using this equipment could be extreme. It could theoretically be possible for multiple motor units to be utilized at once, a situation which cannot be produced voluntarily in a laboratory. This would produce over a short period, figures for O_2 consumption, CO_2 production and tidal volume far in excess of experimentally produced situations. e.g. a diver under conditions of stress may be able to ventilate at his maximum breathing capacity for a period of several minutes. Bearing in mind these factors I think that a safety margin in the use of equipment should be as high as possible. It should be made impossible for equipment malfunction to threaten the diver.

2. THE THEORETICALLY IDEAL OXYGEN REBREATHING EQUIPMENT.

Unless one can theorise on what is ideal it is not possible to unify thought on what improvements are needed in existing closed cirduit O_2 sets. To this end I suggest the following criteria are mandatory. (Certain other points are more open to opinion and these are discussed later in this report).

(a) The duration of use of the set must be dictated by one factor only - the exhaustion of the O_2 supply. This is a finite point in time. It represents no direct threat to the divers life. The use of pure O_2 limits the depth of dives to approximately 25 feet and a free ascent from this depth would normally be easy to accomplish. The only threat to the diver from this factor, is from exposure to possible capture. In order to avoid this, the second principle is evolved.

(b) An emergency O_2 supply must be carried allowing a minimum of 5 to 10 minutes increase in duration of the dive. This supply must be completely independent of the main supply of O_2 both with regard to the cylinder itself and any reducing valves or constant mass valves associated with it.

(c) The set must operate on the principle of a completely closed circuit. Acceptance of these three principles imposes acceptance of a fourth.

(d) The carbon dioxide absorption system must be such that all expired CO_2 produced, even under the most extreme conditions, must be fully absorbed. It is true to say that O_2 rebreathing equipment is built around its CO_2 absorption system. This is therefore discussed in greater detail later.

Use of the above principles as a working basis for a set would tend to rule out sets in current use by the Royal Australian Navy e.g. the UBA 5561. The LAR III and Fenzy sets, at present under test by the navy, would also be unsatisfactory on the same basis. All these would be ruled out on the inadequate CO_2 absorption that these sets offer. In all sets the CO_2 elimination is not adequate from the first minutes of use at high tidal volumes. (Experiments performed in S.U.M. Laboratory, HMAS PENGUIN).

3. CONSIDERATIONS OF STRESS PHYSIOLOGY.

It is advisable to digress from equipment design and focus attention on the physiology of diving and stress as related to O_2 rebreathing equipment. The diver upon entering the water is immediately a hyperbaric mobile organism and as such is subject to all the limitations of hyperbaric O_2 therapy in a compression chamber. Our knowledge of hyperbaric O_2 is far from complete, but a working knowledge of some of the principles involved must be taught to all divers. The subject of suitability testing to high pressure O_2 breathing is beyond the scope of this article. It is doubtful whether suitability testing is even a valid procedure as the time taken to produce signs of acute O_2 toxicity vary from man to man and from day to day. It is therefore impossible to use any form of suitability test as a rigid criteria for the safety of a diver at any set depth.

The inhalation of 100% O_2 at 1 atmosphere absolute produces certain important changes in respiratory and cardiovascular physiology. These include many alterations in haemodynamics and a shift to a lower pH, a reduction in minute volume and, assuming a constant O_2 consumption, a slight reduction in peak flow rates. The magnitude of these changes is so small compared to the large tidal volumes found with severe exercise that they will result in little practical advantage. At 2 atmospheres absolute there is little change in these figures compared to 1 atmosphere absolute. At 2 atmospheres the density of O_2 will be doubled and thus the work of breathing will be increased. This report is not intended to go into the problems of O_2 toxicity but one or two points need to be mentioned.

There are basically two types of O_2 toxicity. These are traditionally known as the Lorraine-Smith effect and the Paul Bert effect. The former is concerned with pathological changes in the lung from breathing high O_2 partial pressures. The duration of the dives with O_2 breathing equipment is so short that this should not become a problem.

The Paul Bert effect is concerned with neurological symptoms and signs and is highly relevant. Oxygen at high pressures produces changes in metabolism at cellular level and more particularly changes in enzyme activity and neuronal and cellular excitability. The end result being unconsciousness, muscular twitching and finally convulsions. These neurological signs are dependant on the partial pressure of O_2 and the duration of exposure. They are not usually encountered under a partial pressure of 1400mm Hg. Thus dives with oxygen must be limited to less than 33 feet (2 atmospheres absolute $\doteq$ 1500 mm Hg).

The presence of a raised partial pressure of CO_2 in the blood greatly increases the risk of these complications. It is noted that at severe exercise the partial pressure of CO_2 in the blood is lower than at rest. The excess cellular CO_2 produced being more than adequately removed by the increase in cardiac output. The result of failure to absorb all expired CO_2 is to produce an unsatisfactory physiological situation in the blood. In addition to this,blood pH and pCO_2 are strongly interelated. (The Henderson-Hasselbach relationship).

Any rise in CO_2 causes a rise in Hydrogen ion concentrations and an increase in acidity of the blood. Under conditions of extreme exercise the acidity of the blood is high for metabolic reasons. If now the diver is forced to inspire a mixture containing CO_2, the acidity of the blood will be further increased to unacceptable levels.

The design of CO_2 towers is therefore the most important single factor in any closed circuit diving set.

4. OXYGEN SUPPLY.

As was stated, the duration of the ideal set must be dictated by the O_2 supply. In order to establish how much O_2 is required it is necessary to know two factors:

1. How long the diver may be required to stay in the water.
2. What is the maximum O_2 consumption per minute that a man can achieve in the water for this period.

The most economical swimming speed for a diver would appear to be about 0.8 knots. (United States Navy Experimental Diving Unit Report, 8th March, 1957). At a minute volume of 30 to 40 litres the actual O_2 consumption incurred for the work of breathing starts to increase disproportionately with the increase in the minute volume. The minute volume of 40 L/min. would be associated with an overall O_2 consumption of 1650 cc/min. This O_2 consumption is equal to a swimming speed of 0.8 knots to 1.1 knots according to individual variation in the diver. The mean is 0.9 knots. In order to last 2 hours underwater a man swimming at 0.8 knots could utilise 1000cc to 1500 cc/min of O_2. As the set should be designed to have a constant mass valve, this will be the limiting factor on maximum duration. In practice, the constant mass will be around 1500 cc/min., both to limit the duration of the set and to obviate the necessity of constantly filling the rebreathing bag whilst swimming.

These refer to O_2 flows at 1 atmosphere absolute. At 2 atmospheres absolute the actual flow would be half of this but the mass of gas would remain the same. In other words the number of molecules of oxygen passing through the valve would be the same whether the flow was 1500cc at 1 atmosphere absolute or 750cc at 2 atmospheres absolute.

To calculate the maximum amount of O_2 that could be utilised in 2 hours is very difficult. It has been shown that an O_2 consumption of 2 L/min. is possible over a prolonged period. This means that 240 litres will be necessary for 2 hours. Allowing 10% over this gives a figure 265 litres. It is therefore suggested that the main oxygen supply to the set should contain at least this. In addition to these requirements an indefinite volume is required for by-passing during descents, and for loss incurred during ascents. For this reason a figure of 300 litres will be necessary. It is very difficult to fill cylinders if the required filling pressure is in excess of 3000 p.s.i.. It is therefore recommended that the oxygen cylinders in oxygen breathing sets should be capable of holding 300 litres of oxygen at a pressure of 3000 p.s.i.. This will obviously dictate the size of any given cylinder depending on material utilized in its construction.

The amount of oxygen carried now places criteria for the CO_2 absorbent i.e. the absorbent carried must be able to absorb CO_2 for the period of time that a swimmer can stay under the water with 300 litres of O_2. This in turn is controlled by the constant flow valve. Assuming a constant flow of 1.5 litres with an O_2 capacity in the cylinder of 300 litres then the set must be able to accommodate a diver swimming along at 0.8 knots for 200 minutes i.e. 300 divided by 1.5.

The above remarks apply to the actual function of the set only, irrespective of time limits imposed upon it by the navy. However, the first criteria set out for the set in this report must apply i.e. O_2 exhaustion must be the limiting factor on the use of the set. This concept is vital in order to allow for a high safety margin in the equipment even if it is used over and above the usual diving time. The O_2 cylinder needs to be as small as possible compatible with the filling pressure mentioned above. (If the filling pressure were to exceed 3000 p.s.i., difficulty could be encountered both in getting it recharged and in testing the cylinder).

A pressure reducing valve must be incorporated to drop the pressure to around 60 p.s.i. from the 3000 p.s.i. within the cylinder itself. This will allow for a flood rate to the reservoir bag of at least 50 L/min. Assuming a reservoir bag or counterlung volume of 6 litres this flow would fill the bag from empty to full in 9 seconds. In order to increase the flow rate above 50 L/min the operating line pressure would have to be above 60 p.s.i.. Certain difficulties are encountered in obtaining a constant flow with an operating pressure of 60 p.s.i. and it maybe necessary to compromise and increase the operating pressure to above this figure. It has been shown however, with some other sets in current use that high pressure lines are to be deplored as it is possible for O-rings and other connections to break away or leak. The ideal O_2 rebreathing set therefore would have no high pressure lines that were not welded at the joints or screw seals, i.e. there would be no O-rings.

An emergency O_2 cylinder must be incorporated to fulfil two purposes. Firstly in the event of failure of the reducing valve of the main cylinder there is a reserve supply of O_2 to enable the diver not just to surface, and hence reveal himself, but to enable him to swim some distance away underwater. Secondly when the diver exhausts his main O_2 supply he still has enough O_2 to swim some distance from where he is at the time. The cylinder must not be of sufficient volume to allow a diver to use this supply as a routine to prolong the dive. It is important however, that the diver should be able to return from the site of his operation on his emergency tank assuming the main tank has failed. It would be reasonable therefore to make the emergency supply something in the region of 90 litres. This emergency cylinder would not go through a constant flow valve and the diver would be forced to open the valve to fill his bag as necessary, "on demand". The main reason for my objection to the use of another reducing valve and constant flow valve is that the more sophisticated equipment becomes, the greater is the risk of mechanical failure. There is no need for this 90 litres to be under a high pressure, if however, dictations of the size of the set force the loading pressure of this cylinder to be in excess of 1500 p.s.i., a pressure reducing valve would become desirable. The extra duration imposed by the addition of the emergency O_2 cylinder, must be taken into account when the duration of activity of the soda lime canisters are considered.

5. THE COUNTERLUNG OR REBREATHING BAG.

This needs to be placed in a position that minimises the effect of hydrostatic pressure on inspiration or expiration. The only parts of a diving set subject to the effects of hydrostatic pressure are those which are compressible, and the most compressible of these is the rebreathing bag. The ideal position is probably at the level of the carina, but the position of the diver in the water will affect resistance imposed by this factor. The carina seems to be the optimum place for the bag to be positioned as this represents the mid point in the lung where the gas flow will be deviated to the various lobes.

The volume of the bag must be at least equal to the maximum vital capacity of any diver using the set. A figure of at least 6 litres is probably the minimum acceptable. It is worth remembering however that the vital capacity at a depth of 33 feet (corresponding to 2 atmospheres absolute) would be something less than the vital capacity at one atmosphere absolute (at the surface). Exact changes in the vital capacity imposed by the increase in pressure have not yet been measured by this laboratory.

The material of which the bag is constructed is also of importance. If the material is too thick then considerable resistance is imposed on breathing by the work involved in collapsing and re-expanding the bag; if it is too thin there is some risk of the bag being torn or ruptured if the pressure should rise suddenly. It has been found that latex rubber is probably the optimum material with which to construct this bag.

6. CARBON DIOXIDE ABSORPTION CANISTERS

The efficiency of an O_2 set is limited by the efficiency of the CO_2 absorption system.

A closed circuit system makes the highest demands on any diving set, on the CO_2 absorbent. All expired CO_2 must be removed from the inspired gases. In mixture sets the constant blow off removes some of the expired CO_2 from the circuit.

The CO_2 absorbent must be able to remove all CO_2 expired under all conditions. The theoretical maximum CO_2 output of a diver under exercise (assuming the most disadvantageous respiratory quotient of 1) will be approximately 3500cc per minute for short periods. It must also be remembered that the tidal volume under these conditions can also be as high as 3500cc.

As stated at the beginning of this report, the duration of the set must be dictated by the O_2 supply. In other words the CO_2 absorbent system (with an O_2 supply of 300 litres plus a 90 litres reserve) must continue at 100% efficiency for 260 minutes at an O_2 consumption of 1.5 litres per minute or 130 minutes at an O_2 consumption of 3 litres per minute. It would not be difficult to design a canister to perform this function but its size would be prohibitive and impractical. The canister must therefore be the smallest possible size compatible with the above requirements.

If the set carries 390 litres of O_2 it is possible with a respiratory quotient of 1 for this to correspond to a CO_2 production of approximately the same figure. In other words it is possible to calculate for any given amount of O_2 carried exactly how much the maximum amount of CO_2 absorbed would be.

In order for CO_2 to be absorbed it must come into contact with absorbent chemical. As the action is not instantaneous it is necessary for the exhaled gas to remain in contact with the absorbent for as long as possible. This means that the whole of one expired breath must be accommodated inside the absorbent packed canister. i.e. there must be an air space between the granules of say 3500cc. This factor above all others imposes a minimum size on the canister. If the canister air space was able to accommodate say only 2500cc of air when packed, the following sequence of events would occur. Let us assume that the diver expires 3000cc air. The first 130ccs or so would be dead space air. This would not contain any CO_2. The remaining 2850cc would contain CO_2 at a partial pressure of around 45mm Hg. As the canister could only hold 2500 ccs of gas, 350cc (2850 minus 2500) of gas containing CO_2 would come to rest outside the canister and out of contact with absorbent. Some of the CO_2 (an unknown quantity) would be absorbed in passage through the canister. This means that the diver would inhale gas containing CO_2. This would cause a rise in tidal volume which after a few breaths would further impair absorption efficiency of the canister.

In order to provide an air space of 3500cc, it is necessary to use 12.5 lbs of soda lime of mesh size 4-8 (with an average of 6). With a smaller granule a greater weight is required to provide this air space. With a larger granule less weight is necessary.

The concept of air space is vital to an understanding of the size requirements. Reducing the size to an equivalent of 10 lbs of soda lime reduces the air space. Under condition of exercise the CO_2 absorption with this quantity would never be 100% efficient even for a few minutes. In other words there would always be a little CO_2 in the inspired gas.

The criterian for efficiency of soda lime canisters must be complete removal of all expired CO_2. Anything less is liable to result in a rapid CO_2 build up, under conditions of severe exercise.

Having provided enough soda lime to give sufficient air space the duration of the canisters becomes academic as it far exceeds any requirement. In our own experiments they were not exhausted after 4½ hours.

It has been shown by Adriani that the shape of CO_2 canisters is important in relation to getting an even flow of gas through all parts of the tower. This was done with anaesthesia in mind, when conditions are basal and CO_2 production is around 200cc a minute. Care must be taken in extrapolating this to canisters designed for diving.

Under anaesthesia peak flow rates rarely exceed 30 L/min., with diving PFR can be as high 180 litres per minute. Further work needs to be done on this problem. Bearing in mind the flow rates and CO_2 production it is not unreasonable to assume that the shape of canisters is even more critical than Adriani suggests.

He has shown that the overall shape should be cylindrical and that the length to diameter ratio should not exceed 2 to 1. This is of importance with regard to both good distribution of gas, the preventing of channelling and the problem of resistance.

The problem of resistance to breathing in the canister is discussed elsewhere, it can be overcome by using a twin canister rig with the canister in parallel. This would reduce resistance and flow rates through the towers. A system like this has been tested and found to be highly efficient. The size of these canisters is at the moment too large to be practicable in diving equipment.

7. THE REDUCING VALVE AND CONSTANT FLOW VALVES.

The reducing valve must be simple in design and small in size. It must reduce the high pressure in the cylinder to the operating pressure of the set which, as we have said before should ideally be around 60 p.s.i.. The orifice whould allow a constant mass of gas at differing ambient pressures from one to three atmospheres.

The problem of whether to supply constant flow valves or demand valves is a difficult one. It is probably more convenient for the diver to have a demand system, but certainly in the interest of safety a constant flow valve is more desirable. With a demand system it is possible for the diver to breathe his own expired gas until the bag is filled with an ever increasing concentration of nitrogen and a decreasing concentration of O_2. A constant flow of 1.5 litres per minute coming into the bag will mean that it will be difficult for the diver to get to hypoxic levels of O_2 if he has only partially denitrogenated his lungs or the counterlung. The constant flow valve will not replace the need for denitrogenation of the lung. It is merely a safety device in case the denitrogenation is not completely adequate. This point must still be made to all divers and the physiology of this problem explained in detail.

8. VALVES.

Uni-directional valves are essential to prevent rebreathing of exhaled gas. These must be designed so that no decrease in cross sectional area occurs and the minimum disturbance of gas flow is incurred. Owing to the various position in which the set will be used these valves cannot be gravity operated. Spring loaded valves are not satisfactory owing to the high resistance at high flow rates. Flap valves have the advantage that they can be made light in weight and alter the direction of the flow of the gas to a lesser extent than the spring loaded valve. The position of these valves in a fully closed circuit, is probably not important except that they must be capable of being examined for wear and be easy to replace. It is necessary to incorporate two valves into the circuit and not just one. It has been found that teflon provides the ideal material of which to construct the flaps of these valves. One of the problems of rubber is that it tends to stick up on the valve seating and also tends to vibrate when a high flow of gas passes across it. These problems would appear to be irradicated by the use of Teflon.

9. RELIEF VALVES AND PURGE VALVES.

A relief valve is required for the expulsion of gas during ascent. Without it, gas must escape from the mouthpiece or mask - with a resultant loss of a watertight fitting. The volume of gas expelled may be 10 litres or more during ascent from 33 feet, (i.e. total lung volume plus breathing bag volume). Without this source of escape, the expanding gas may well predispose to pulmonary barotrauma.

A mouth to atmosphere purge valve is required to denitrogenate the lungs and the set, and is of value in closing the circuit and using the equipment as a buoyancy vest, in emergency.

10. RESISTANCE TO BREATHING.

This problem must be considered from both physiological and practical points of view. Various figures are quoted as being acceptable to divers, a total set resistance of 10 cm H_2O/L. flow/sec was regarded by the U.S. Navy as acceptable in 1957. (E.D.U. reports). They believe that the canister should not contribute more than one third of the total resistance. (This figure would appear to be empirical and I can see no reason for agreeing with this. It is the total set resistance which matters.) In 1965 the U.S. Navy changed the total resistance figure to 12.5 cms/L flow/second. For an O_2 consumption of 2.5 L/min, the tidal volume (breathing pure O_2) will be approximately 60 L/min or one L/sec. In other words swimming at a rate corresponding to an O_2 consumption of 2.5 litres a minute, an acceptable resistance figure to the U.S. Navy would be 10 to 12.5 cm H_2O at one atmosphere absolute.

I do not believe these figures are subjectively acceptable. If these figures are halved to 5-6 cm H_2O/L flow/sec there is virtually no subjective sensation of resistance to breathing.

Physiologists have shown that although 10-12 cm H_2O/L flow/sec is an acceptable figure from the point of view of the ventilation perfusion ratio, subjectively figures in excess of 6 to 8 cm H_2O produce difficulty with respiration. Work done on bicycle ergometers has shown that while the subject is most happy with the resistance to respiration on expiration, actual physiological performance is better with the resistance on inspiration. (Research work performed at Royal Prince Alfred Hospital Sydney). This can be explained in the terms of the Starling resistor and the Waterfall theory. Actual impairment of ventilation/perfusion ratio is apparently minimal with resistance on expiration. This problem therefore would appear more theoretical than practical and I would have thought the most important fact r to be considered was the subjective sensation of any person using the set.

With a minute volume of 60 L/min and a peak flow rate of three times this (PFR = II V), a resistance of 3 cm H_2O to inspiration and 6 cm H_2O to expiration does not produce any noticeable effort in breathing. I suggest therefore the following figures be adopted as a working maximum for total resistance in O_2 sets at one atmosphere absolute. Resistance to expiration, 6 cm H_2O/L/sec; resistance to inspiration, 3 cm H_2O/L/sec.

Wet carbon dioxide absorbent creates an increasing resistance by a factor which is difficult to calculate. At the end of a 2 hour dive it is probable that the total resistance would have risen unless the volume of absorbent is so large as to create a problem with the size of the set. In our own experiments, resistance to expiration at the commencement of a test was 5 cm H_2O total resistance; after 3 hours it was 6 cm H_2O total resistance. This could only have come from a change in resistance in the canister itself as other factors remained unaltered.

At this stage it is perhaps pertinent to consider the factors involved in creating a breathing resistance. Gases flowing through a tube system with a laminar flow, follow Pouiselles law.

$$F = (P_1 - P_2)\,\frac{\pi r^4}{8L} \times \frac{1}{\pi}$$

F = flow per unit Time
$P_1 - P_2$ = pressure gradient
r = radius of tube
L = length of tube

This relationship is important as no mention of density is made in the equation. The physical characteristic of the gas in the equation which is used is the viscosity. Viscosity is independent of pressure. In other words providing the flow remains laminar there is no reason for an increase in resistance as the ambient pressure rises from one atmosphere to two atmospheres absolute. Bearing in mind the need for flexible tubing in the breathing set (thus imposing the use of corrugated tubing) it becomes quite impossible to create laminar flow throughout the whole of the set. As the flow rate of a given gas increases in a tube of a given diameter, there is a finite point where the flow changes from laminar to turbulent. At this point the resistance to flow is dependent on the gas density and increases sharply. This relationship is expressed in the terms of the Reynolds number, when this exceeds 1000 the flow becomes turbulent. The American Diving Journals use this figure for all their calculations of the Reynolds number. It is however a gross generalisation, in fact the Reynolds number for anything other than a straight smooth wall tube needs to be computed for each individual set of circumstances. In an O_2 diving set under test at the moment, the Reynolds number may be much less than this.

From these figures it is possible to calculate whether the flow in the canisters and the circuit tubing is turbulent. How important this is depends on how the resistance to breathing increases in any given set, as the pressure rises from one to two atmospheres absolute. Obviously if the pressure fails to rise by more than 1 centimeter of water there is no point in computing the Reynolds number for that set. If however the resistance rises dramatically or doubles, it would suggest the resistance to flow in the set is being dictated by the density of the gas. In this case a thorough breakdown of the resistance in the individual parts of the set will become imperative. Turbulent flow is encouraged by distortion of the pathway of the fluid, such as junctions in the circuitory. It is therefore important that all direction changes of the gases flow be achieved by gradual curves rather than right angled joints.

Sudden changes in diameter are almost unavoidable, thus inducing changes in velocity within the set. These changes will effect gas velocity according to Bournellis theorum. This states that the cross sectional areas multiplied by the velocity is a constant for a fixed volume of fluid in a given circuit. It is therefore possible to compute whether the change is sufficient to cause turbulence. The only other factor involved in changing resistance in the circuit is the slight difference in consititution of the gases during inspiration and expiration. During expiration the gas would contain approximately 40mm Hg partial pressure of carbon dioxide which would alter the viscosity relative to inspired mixture which contains only 1 mm Hg carbon dioxide. This change is so slight that it may be ignored.

In summary then the circuitory must be of large diameter tubing of near constant diameter. This must be of such a size so that the tendency for the flow becomes turbulent is minimised. Uni-directional valves must not constrict this diameter, The overall length of the tubing must be kept down to a minimum possible compatible with the ease of use.

11. CONCLUSION

A description on the ideal form of oxygen breathing equipment is given. Many of the requirements are not met by existing equipment. Although operation diving sets will never reach the ideal, they could be designed to be much closer to it than is seen in current equipment.

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