Health and Safety Executive

# The provision of breathing gas to divers in emergency situations

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# The provision of breathing gas to divers in emergency situations

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The report examined the diving industry guidance provided to divers and supervisors in the amount and method of determining how much emergency gas a diver can require. A literature search was carried out into the human gas consumption rate as measured in scientific studies of workers, divers and athletes. Data was also sourced from operators and divers using dive computers with gas integration.

The data from the guidance, scientific studies, operators and live data from divers are compared to provide a recommended gas consumption rate that industry can use to plan the volume of gas to be available to a diver in an emergency. It was found that some industry sectors could increase the recommended gas consumption rate to provide sufficient gas to a diver in an emergency.

How the gas is provided to the diver in an emergency is discussed. Current industry practices across the different sectors use a wide range of methods, some of which could be improved. The sizes of gas containers, the pressure that containers can be charged to, along with how gas can be passed to the diver are covered. A standardised coupling is recommended to allow connection between a diver and an emergency gas supply.

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ABCO
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# KEY MESSAGES

Current industry wide guidance documents give varied gas consumption rates for a diver in an emergency situation. Reviewing scientific papers and real time data recordings indicated that consumption rates could be much higher than rates specified in guidance and gas availability to a diver in an emergency may be below what a diver requires, with potentially life-threatening consequences.

It would be preferable to consolidate guidance across the diving industry and adopt the use of scientifically researched breathing consumption rates.

Divers, when operating from a wet bell or from a basket, may have adequate gas to hand as well as the carried bail-out gas, but no secure methodology of administering gas to a diver requiring an emergency gas supply apart from passing a hose between the diver's neck and the neck dam of the helmet.

The introduction of a secure alternative gas source connection to the divers' helmet would overcome this problem. This could be achieved using readily available gas supply products.

# EXECUTIVE SUMMARY

## Objectives

The UK diving industry is required within each sector ACOP[1,2,3,4,5] to ensure that divers, who are at work, will have a reserve supply of gas that is independent from their main source. Different sectors of the industry provide guidance to companies and divers alike on how to comply with the law. These guidance documents specify a large range of gas consumption rates and different methods on how the diver accesses the reserve of gas.

The Health and Safety Executive (HSE) commissioned this research to examine diver breathing gas consumption rates in emergency situations and to review the current methods of supplying emergency gas to divers. The data collected were then compared to gas consumption rates given in physiology text books and peer reviewed papers on exercise testing of subjects. Further research was undertaken into how divers are supplied with emergency reserve gas and proposed new methods of gas supply have been included.

## Main findings

- Across the diving industry, the breathing rates used for planning divers gas consumption are within that required for normal or light work load levels, they do not address requirements for heavy workload levels.

- A diver could only maintain a maximal breathing rate for a maximum of a couple of minutes before exhaustion would cause them to reduce their breathing rate.

- The reserve of gas available and the method of supply to a diver should give the diver sufficient time to reach a place of safety. It may be impractical for the diver to carry the amount of gas that the research indicated could be the maximal consumption rate in an emergency. Therefore a risk based assessment of the gas supply requirements should be conducted to identify the amount of emergency gas required.

- Current emergency supply methods in the commercial sector, where either a spare demand valve in a basket, or wet bell, or even the pneumo hose, could be more effectively designed to provide a rapid and secure supply of emergency gas to a diver.

- Some Full Face Mask (FFM) designs only have a single supply feed to the mask demand valve. In an emergency situation a diver must remove the FFM and fit a half mask and demand valve to maintain life support. In cold or polluted conditions this can be difficult or dangerous to achieve.

- A single standardised design of supply coupling should be selected or developed, to allow for standardised provision of emergency gas to a diver. The effect of any such modification on the equipment's CE marking should however, be taken into account.

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# 1. INTRODUCTION

## 1.1 BACKGROUND

A working diver requires a source of gas to maintain life in an environment where the human body has not developed the means to remain beyond the time that it can hold its breath, or at a depth where the musculature of the chest is unable to overcome the external water pressure and re-oxygenate the gas in the lungs. The development of pumps and helmets allowed human divers to spend longer times and to go deeper underwater when supplied from the surface. The use of compressed air cylinders has freed divers from having to rely on gas being supplied from the surface of the water. The use of diving cylinders has made the recreational diving industry possible. Further developments have modified the gas mixtures used to allow the diver to work at extreme depths and live at depth for days and weeks at a time.

Current requirements (2014) within the approved code of practice (ACOP)[1,2,3,4,5] for each industry sector require the diver to carry sufficient gas as follows:

- Whatever type of breathing apparatus is in use, each diver must carry an independent reserve supply of breathing gas that can be quickly switched to the breathing circuit in an emergency[1]
- An alternative breathing gas source or secondary life support system should be provided for emergency use[2]
- The alternative system should have sufficient capacity to allow the diver to reach a place of safety
- When a diving basket is used by surface-supplied divers, emergency breathing gas cylinders should be supplied in the basket in a standard layout. This allows divers to access the cylinders rapidly in an emergency[3]
- Appropriate alternative breathing gas source/secondary life support system[4,5].

The requirements in the ACOPS lead to the question, what is “sufficient capacity”?

## 1.2 OBJECTIVES

The objectives of this work were to:

- Research the typical breathing gas consumption rate for a diver during normal work, and in an emergency situation.
- During emergency events, consider how long a diver will be able to maintain the raised breathing rate before exhaustion.
- Carry out a thorough review of all industry surface breathing rates used for planning gas needs, and consider how long an emergency gas supply, will last under different circumstances of use.
- Review the current methods of supplying emergency gas to divers and comment on how effective they are.

- Suggest potential research into suitable alternative supply methods that provide a safe, easy to use and secure technique.

# 2. IMPLICATIONS

## 2.1 PRESENT INDUSTRY POSITION

Guidance documentation on the provision of emergency gas to divers is available within various sectors of the diving industry.

### 2.1.1 Gas Volumes

The amount of gas a diver might require during an emergency to maintain life is covered within some of these industry documents. These data may have originated from diving manuals; calculations of gas consumed during historical dives, or from data obtained using equipment of a lower performance than available today. There may or may not have been adjustments made to take into account anxiety or work-rate induced increased breathing rates.

### 2.1.2 Delivery methods

The methods described in these documents for emergency breathing gas provision can be as simple as having available a standby demand valve, or even the open end of a hose. For a diver wearing a state of the art helmet costing thousands of pounds, having the open end of a hose pushed up within the neck dam of the helmet does work, though perhaps this might not be considered to represent a secure method of ensuring that the diver will continue to receive gas. The hose may become dislodged or pulled from the helmet; also the hose may not supply sufficient gas to the diver in distress. The alternative method is provision of a separate demand valve attached to a standby cylinder. However, the diver is again wearing a helmet, which can require the assistance of a second person to extract the wearer from the helmet quickly. If the diver is on their own it could take them some considerable time to extract their head from the helmet, this may not be achievable quickly enough to ensure survival.

### 2.1.3 Single point of failure

Divers using some Full Face Mask (FFM) models only have a single gas supply to the mask. In the event of a failure of the demand valve fitted to the mask, or loss of supply, the diver will need to remove the mask and fit a half mask and demand valve to maintain their gas. In cold or polluted water conditions, the effect of removing the mask from the face can be difficult to deal with, even for the most experienced diver.

# 3. METHODOLOGY

Initially a literature search was undertaken for scientific papers from 1970 to present, for gas consumption rates of divers. Alongside the search for diving papers, a search was carried out for studies using different types of subjects, from the general population to elite athletes. The search was initially internet based for published papers. A further literature search was then carried out into the measurement methods of human physiological testing. This gave clarification of how the volume of oxygen consumed per minute ($\dot{V}O_2$) and minute expired ventilation ($\dot{V}_E$) are interrelated. The search also looked at calculation methods to substantiate the findings. Alongside this, further physiological texts including diving medical textbooks were sourced and reference checked.

## 3.1 SCIENTIFIC PAPERS

Papers were sourced through the "Rubicon Foundation research repository", which is a specialist library for underwater science papers. These papers cited further papers, which were sourced through general internet search engines and, if full text versions were unavailable, were requested through the HSE Knowledge Centre. References to papers in diving text books held at HSL were also sourced.

## 3.2 INDUSTRY DOCUMENTATION AND GUIDANCE

Other searches were made into current guidance provided by industry. This was followed up with e-mails to specific personnel from industry sectors where guidance was not immediately available. From these searches, a list of organisations that provide guidance was produced as shown below:

- The Association of Diving Contractors (ADC)
- International Maritime Contractors Association (IMCA)
- International Association of Oil and Gas Producers (OGP)
- Royal Navy
- US Navy
- National Oceanic and Atmospheric Agency (NOAA)
- British Sub Aqua Club (BSAC)
- Professional Association of Diving Instructors (PADI)

## 3.3 INFORMATION REQUEST TO DIVING OPERATORS

To collate and enable access to information on gas supply levels used within all aspects of the diving industry; bodies that are involved with the Commercial sector and recreational diving agencies were contacted. Companies involved in commercial diving projects were contacted using email addresses from the company websites. All contacts were asked for the information on the gas supply amount planned for use by a diver in an emergency where the documentation received had not shown an emergency gas supply rate.

## 3.4 DIVE COMPUTER DATA

Data was requested from several diving equipment manufacturers who use high-pressure electronic pressure sensing data in their diving instrumentation. Additionally data was requested from Divers Alert Network (DAN) in Europe and the US, as DAN is sent dive computer data by their members for use in research studies.

Requests were also made to recreational divers for their personal dive logs from air integrated dive computers. Although this data would be uncontrolled and unverifiable for accuracy, it could provide indications on the variability of different divers breathing rates and may be a future tool for use in studies of divers breathing rates.

### 3.4.1 Lab Trial

Comparison tests were carried out using two air integrated computers, one held in the HSL dive laboratory equipment store and the other the author's personal unit. The method employed to validate this data involved the use of the HSL dive lab's Life Support Test Facility (LSTF) test rig. This test rig is used to validate the work of breathing performance of diving regulators. The rig breathes through a diving regulator at a calibrated rate, thereby using a known gas consumption rate. Therefore by fitting a self-contained breathing apparatus (SCUBA) first stage with two high pressure ports (one to allow for attachment to the LSTF measurement system and a second for the dive computer connection) a controlled consumption rate can be checked against the readings recorded into the dive computer logbook. The LSTF uses a flywheel cam that produces a stroke volume on the breathing machine. For these tests the stroke volume was set at 2.5 litres. To alter the Respiratory Minute Volume (RMV) the breathing machine running speed was adjusted. An initial run with one system was carried out at the maximum breathing rate of 100 l $min^{-1}$ RMV for 2 minutes on the LSTF. The breathing rate was then reduced to 87.5 l $min^{-1}$ RMV for 2 minutes; at this point the cylinder was approaching empty and the run was terminated. To enable a longer run the second dive computer was tested at the minimum 25 l $min^{-1}$ RMV which was then increased to 37.5 then up to 50 l $min^{-1}$ RMV.

Contact was made with the manufacturer of the author's dive computer with the air integration, and a request was made for further logbooks that could be used in the research project or for a further study.

The findings of the literature and data searches are summarised in section 4.

# 4. GAS CONSUMPTION RATES

## 4.1 BACKGROUND

The human basal breathing rate is commonly understood to be around 13 to 17 breaths per minute with a total volume per breath of between 500 to 600 ml body temperature and pressure saturated (BTPS). Of that, a young adult male will consume 250 ml of $\dot{V}O_2$. This would give an expected minute expired ventilation $\dot{V}_E$ of approximately 6.5 l/min to 10.2 l/min at rest[6].

As the diver works, the breathing rate increases, which is partly due to the body's responses to the increased level of metabolic $CO_2$ being produced. When a diver finds themself in an emergency situation a number of physical and psychological effects occur and include an increase in breathing rate. These effects can be influenced by various factors, such as training level, competence in dealing with an emergency, or the perceived threat to the diver.

The depth of the dive can have an effect on the diver's breathing rate, with the gas being used increasing in density along with the increase in depth. This also has the added effect that at extreme depth the diver will find it physically more difficult to clear the $CO_2$ produced by the body if he is working extremely hard. To allow for accurate comparison of gas consumption levels all data were corrected where needed by the author and set at 1.013 BTPS (1 bar), which allowed for direct comparability of data received.

## 4.2 SCIENTIFIC PAPERS AND STANDARDS FOR METABOLIC RATES

The relevant data were collated and placed into Tables 1 to 3. As some of these papers were published some time ago the measurement units were not contemporary and required some conversion to allow comparison. Therefore cubic foot minutes were converted into litres per minute, and all the exercise data that used Watts or similar were converted to Metabolic equivalent tasks or Mets. A Met is a method of measuring the energy cost of an exercise. One Met is the amount of 3.5 ml of oxygen consumed per kilo of body weight multiplied by time in minutes whilst at rest in a seated position. The papers were then sorted into diving specific papers, workplace studies and athletic performance studies.

### 4.2.1 Diving and hyperbaric papers

The papers selected had data from studies where divers and workers had been tested at different ambient pressures. Some data were collected at 1 bar or surface pressure and others at varying pressures down to 42.4 bar or an equivalent depth of 414 metres in hyperbaric facilities[7]. Some of the papers reviewed, tested subjects immersed and some in the dry. To enable comparison of data the breathing rates detailed in this series of tables have been converted back to surface pressure.

Review of these data identified that there were variations in gas consumption rates measured during trials by scientific groups. Many of these variations could be attributed to age, stature, as well as gender of the subjects.

Another reason behind variations in the results could be taken from the paper by W Norfleet et al (1987), "A comparison of respiratory function in divers breathing with a mouthpiece or a full face mask"[8]. This paper indicated that there was a small difference in $\dot{V}_E$ depending on whether a mouthpiece or full face mask was used. When the diver was using a mouthpiece, he would use less gas than with the full face mask set up in demand mode. Some of the trials in the papers involved divers using one or the other of these styles of respiratory measurement equipment.

The effect of static lung loading with the diver working a cycle ergometer in either an upright or prone position also had an effect on the volume of gas that the diver consumed. This was due to the difference in the static lung loading, from the hydrostatic pressure imposed on the lung. In one paper, in the prone position, the diver has a smaller loading on the lung, and is able to breathe easier, than when in the upright position. Being upright the diver has to work harder to overcome the increased hydrostatic pressure and will consume more oxygen. However, there are other papers that state that there is an increase in Dyspnea, or a feeling of difficulty in breathing, when divers are in the prone position compared to the upright and this is believed to be due to the effects of pressure on extra-thoracic airways.

The document DD ISO/TS 16976-1:2007 'Respiratory Protective devices-human factors-part 1: Metabolic rates and respiratory flow rates'[9] states that metabolic requirements take account of the body size and efficiency of how the person works. The ISO recommends a maximal consumption rate of 116 lpm should be used when selecting RPE for a male with a body surface area of 2.11m$^2$, or using the Mostellar method calculation a person of 180cm height and a weight of 89kg.

The breathing rates in red in Tables 1 to 3 are represented graphically in Figures 1 and 2.

***Table 1 Respiratory text book and ISO RPE standard breathing rates***

| Paper | Consumption rate l/min | Work rate in Mets | Comments |
|---|---|---|---|
| At rest (Respiratory Physiology)[6] | 5-8 | | |
| ISO/TS 16976-1:2007<br><br>Respiratory protective devices-Human factors- part 1: Metabolic rates and respiratory flow rates [21] | **Male 116** | | 2.11 m$^2$<br><br>body surface area |

***Table 2 Hyperbaric Research paper breathing rates***

| Paper | Consumption rate l/min | Work rate in Mets | Comments |
|---|---|---|---|
| Exercise tolerance at 4 and 6 ATA [22] | **Mean $\dot{V}_E$ 109** | 10.4-12.6 | dry ≈ 30 and 50 m depth |
| Effects of immersion and static lung loading on submerged exercise at depth of ≈ 57.6 m[23] | **Wet 84**<br><br>**Dry 134** | 12.8 Mets | |

| Paper | Consumption rate l/min | Work rate in Mets | Comments |
|---|---|---|---|
| Maximal Physical work capacity of man at 43.4 ATA[19] | Diver 1 **109.63** | 6.3 Mets | Maximal measurement taken at 1.6 ATA in water |

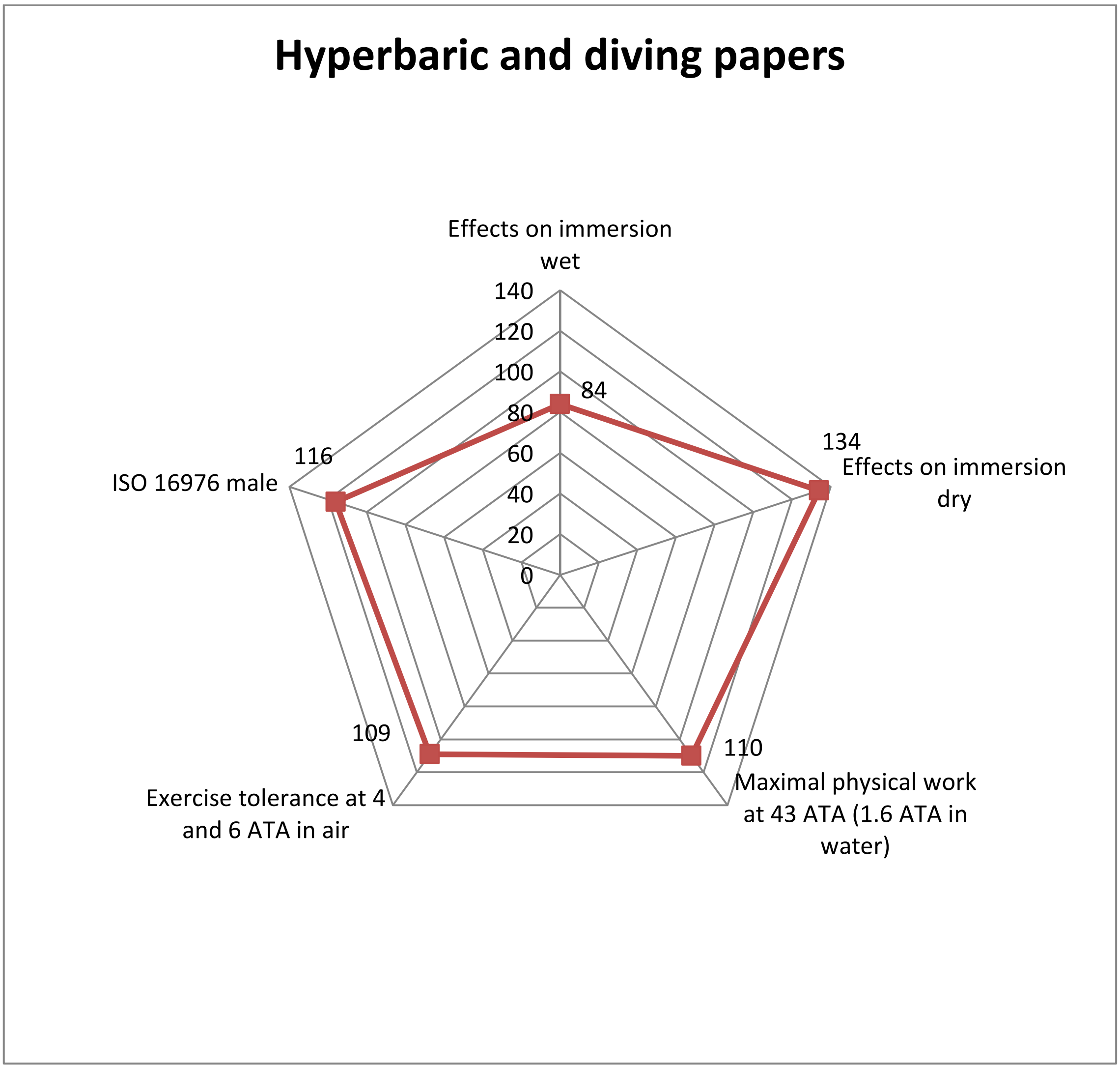


Figure 1. Graph of hyperbaric and diving papers maximal breathing rates including ISO respiratory rate in l/min.

*Table 3 Workplace Research paper breathing rates*

| Paper | Consumption rate l/min | Work rate in Mets | Comments |
|---|---|---|---|
| Comparison of Submaximal cycling and treadmill exercise at similar work rates. Cycling rates[24] | 31.9 SD±4.5<br>43.0 SD± 4.1<br>57 SD± 7.4<br>71.2 SD± 9.6<br>**82.0 SD± 13.9** | 4.1-4.4<br>5.2-5.6<br>6.2-6.8<br>7.3-8.1<br>8.4-9.3 | |
| Normal values and ranges for ventilation and breathing pattern at maximal exercise[25] | **114 SD ± 23**<br>88 SD ± 19 | | Male<br>Female |
| Workplace breathing rates: Defining anticipated values and ranges for respirator certification testing. Result shown in Table A.4 Axe chopping hard[26] | 20<br>35<br>50<br>60<br>80<br>80<br>**162** | 3<br>6<br>8<br>10<br><12<br>>12<br>17 | Light/mild<<br>Light/moderate<<br>Heavy/optimal<<br>Heavy/strenuous<<br>Severe/maximal<<br>Severe/exhausting> |
| Body composition and peak aerobic power in international level Hungarian Athletes[27] | 150.73 to 162.96 | 17 - 21 | |

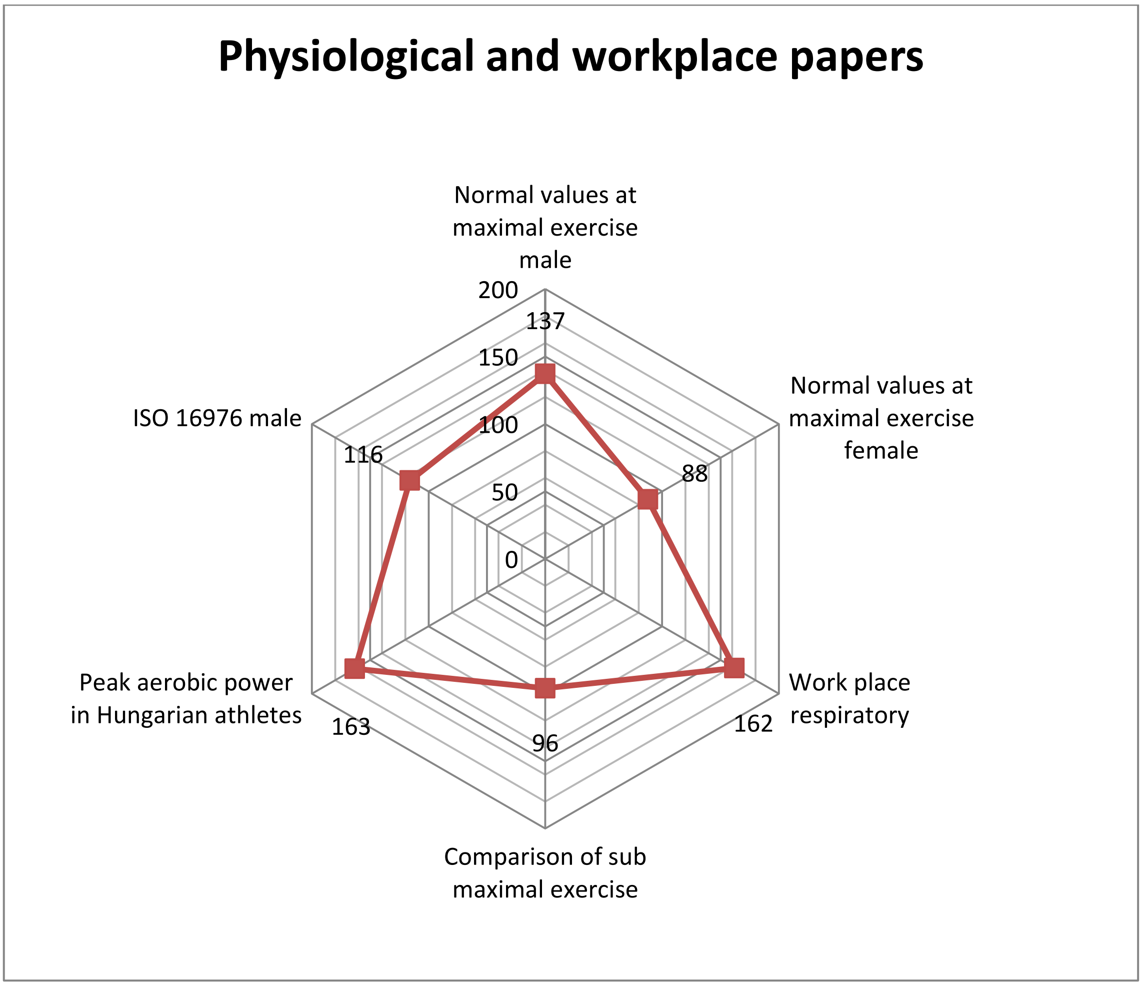


Figure 2. Graph of Physiological and workplace papers maximal breathing rates including ISO respiratory rate in l/min

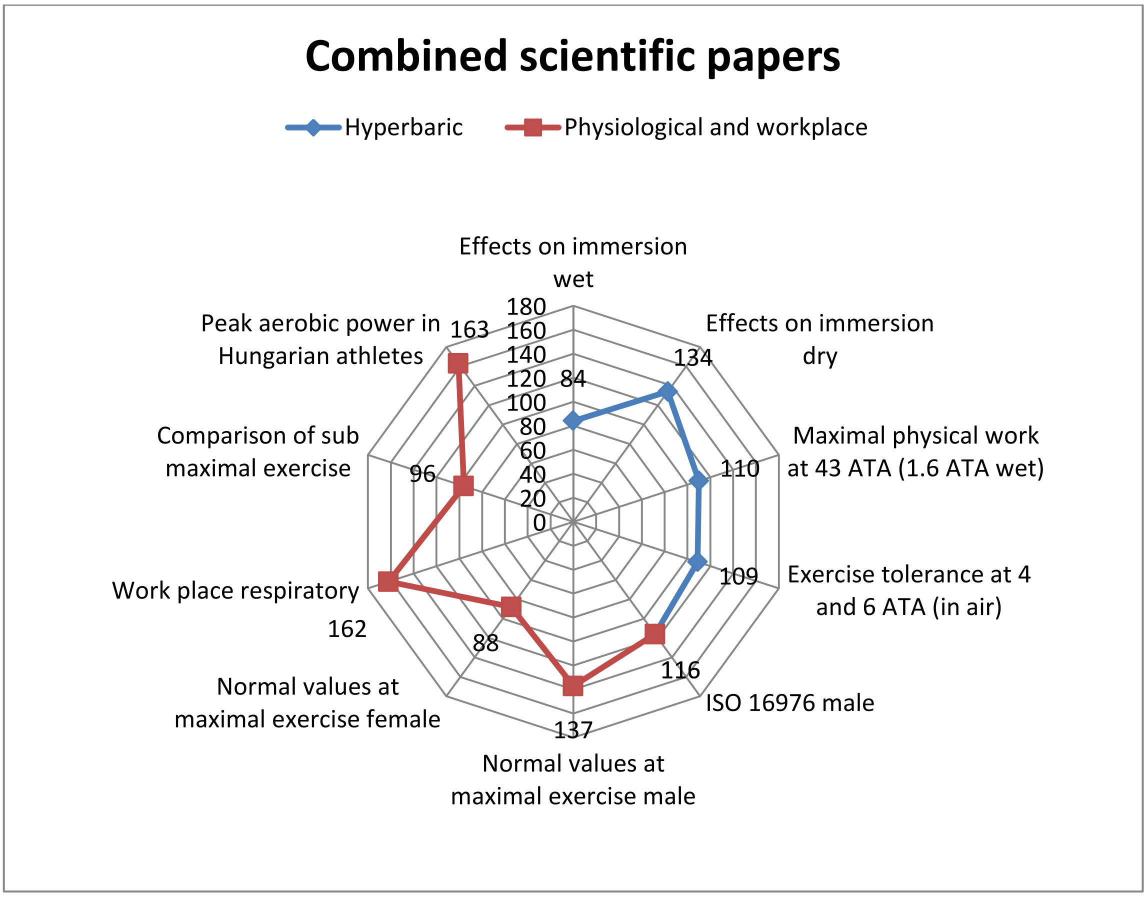


Figure 3. Combined graph of hyperbaric and physiological maximal breathing rates.

Comparing the figures it can be seen that there is a wide spread of results from 84 l/min up to 163 l/min being recorded, and in one paper a maximum breathing capacity of 227 l/min over 15 seconds BTPS was recorded. One reason for the variance is the type of person used as a subject within the study being reported. For example the figure recorded in Hagan and Smith[16] was for a forestry worker using an axe in a fast rhythm. Another reason behind the variation in the measured breathing rates is that the subjects are different builds and ages. In the paper by Blackie et al[13] the subjects were placed into 10 year age groups from 20 to 29, 30 to 39 etc. and results indicated a consistent reduction in $\dot{V}_E$ with increase in age.

One important paper for diving purposes is about Maximal physical-work capacity of man at 43.4 ATA[7]. It has the subjects being tested in cold water (4.44°C). Therefore the divers would be wearing thermal protection and working at depth with a gas that would be dense. The paper gives results that show that there are differences in the $\dot{V}_E$ from shallow water to depth. The mean $\dot{V}_E$ for the 4 divers during maximally tolerated work at 1.6 ATA (depth 6 metres) is 77.62 l/min and at 43.4 ATA (Depth 33.4 metres) is 44.37 l/min. The maximum mean $\dot{V}_E$ measured for this group was 109.63 l/min.

### 4.3 INDUSTRY GUIDANCE AND STANDARDS FOR MANUFACTURERS

International guidance and standards that provide information on breathing rates were sourced. These are detailed at Tables 4 to7. The highest respiratory rates given in these sources are highlighted in red in Tables 4 to 7and are presented graphically in Figure 4.

*Table 4 Breathing Rates from Commercial Diving Industry Guidance*

| Agency | Surface consumption rate | Adjustments/comments |
|---|---|---|
| International Marine Contractors Association[7] | 35 l/min<br><br>**40 l/min in an emergency** | |
| International Association of Oil & Gas Producers [8] | **Bail-out gas consumption rate 45 l/min** | |
| Association of Diving Contractors [9] | Normal Working 40 l/min<br><br>**Emergency Events 50 l/min** | |

*Table 5 Breathing Rates from Military and US Government Agency*

| Agency | Surface consumption rate | Adjustments/comments |
|---|---|---|
| Royal Navy[10] | 9 l/min rest<br><br>18 l/min light work<br><br>30 l/min moderate work<br><br>40 l/min heavy work<br><br>50l/min recommended<br><br>**60 l/min severe work** | |
| US Navy Manual Version 6[11]<br><br>*Information from Dr J R Clarke NEDU via email to author, as the standard US Navy ventilation rate for helmeted divers | 40 l/min (normal demand)<br><br>Heavy work 50 l/min<br><br>Severe work 60 l/min<br><br>***62 l/min in demand mode**<br><br>170 l/min with freeflow situation | Diver's helmet has a leaking neck dam |
| National Oceanic and Atmospheric Administration[12] | 22.5 l/min light work,<br><br>40 l/min moderate work,<br><br>62.5 l/min moderate heavy,<br><br>75 l/min heavy, | |

| Agency | Surface consumption rate | Adjustments/comments |
|---|---|---|
| | **90 l/min extremely heavy** | |

*Table 6 Breathing Rates from Recreational Training Agencies*

| Agency | Surface consumption rate | Adjustments/comments |
|---|---|---|
| Sub Aqua Association email from National Diving Officer | 25 l/min<br>**Stress/emergency 30 l/min** | Trainee +20% |
| British Sub Aqua Club [13] | 25 l/min in training literature, **<50 l/min in the BSAC safe diving book** | |
| Scuba Schools International email from P Toomer SSI | Divers are taught to work out their consumption rates from their gas usage during dives | Scuba Schools International email from P Toomer SSI |
| Professional Association of Diving Instructors[24] | Divers are taught to work out their consumption rates from their gas usage during dives | Professional Association of Diving Instructors[10] |
| IANTD email from T Clements IANTD | Divers are taught to work out their consumption rates from their gas usage during dives | IANTD email from T Clements IANTD |

*Table 7 Breathing Rates for Equipment Standards testing*

| Agency | Surface consumption rate | Adjustments/comments |
|---|---|---|
| BS EN 250[15] | **62.5 l/min** | |
| BS EN 15333[16] | 62.5, 70 to **85 l/min** | |
| Norsok U 101 2012[17]<br>Norsok U -100e2 2009[18] | 62.5 l/min,75 l/min, **90 l/min**<br>62.5 l/min | |
| ISO/TS 16976-1:2007 Respiratory protective devices-Human factors- part 1: Metabolic rates and | **Male 116**<br>Female 101 | 2.11 $m^2$<br>1.84$m^2$<br>body surface area |

| | | |
|---|---|---|
| respiratory flow rates [21] | | |

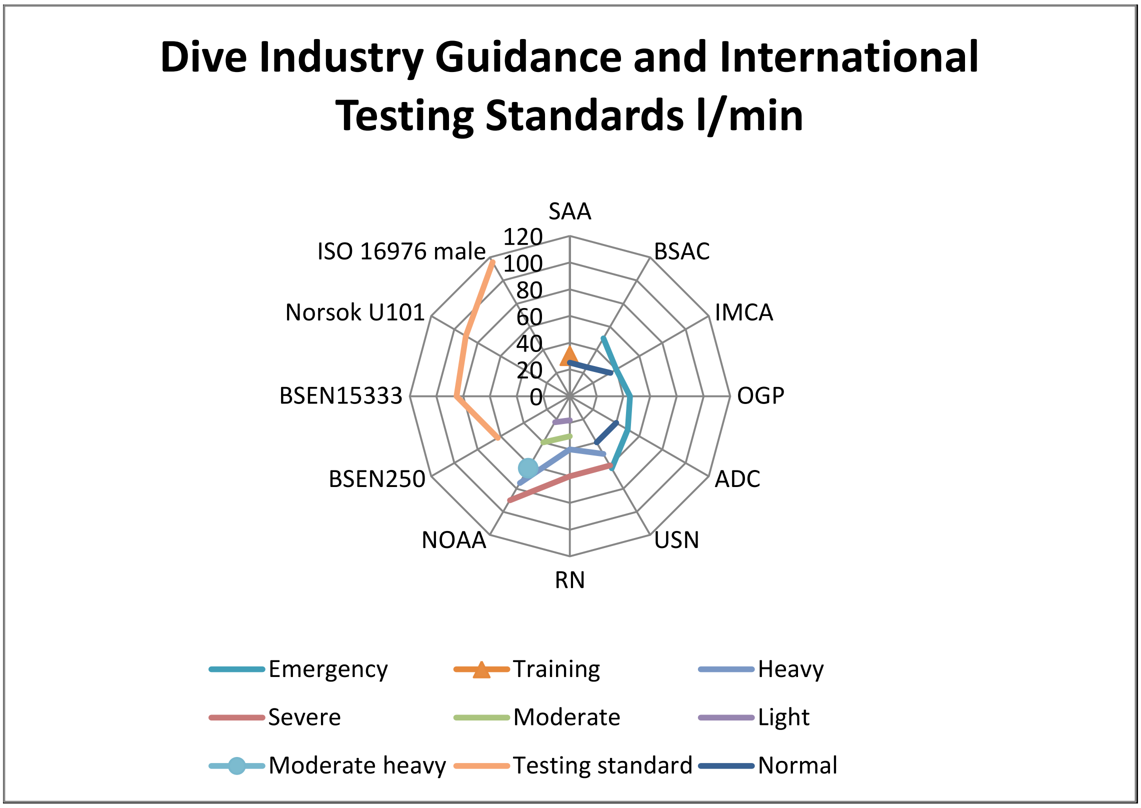


Figure 4. Graph of dive industry and standard recommended surface breathing rates and test rates for diving equipment in l/min.

From these data shown in Figure 4 it can be seen that there is a wide variance within the rates used within industry guidance. Looking at the emergency and the severe rates, the lowest is 40 l/min from the IMCA documentation to the highest being shown on the NOAA axis at 90 l/min. The ISO 16976 measurement is included with these data for comparison with the information from the research paper section. Again this indicates that a breathing rate that is above the industry guidance can be attained by a person doing hard physical work.

### 4.3.1 Dive computer received data

The data received from owners of dive computers with integrated High-Pressure sensors was uncorroborated by comparable data and can be subject to temperature change as well as other factors that could happen during the dive. Therefore these data have been used as indicators for background knowledge to the research, whilst giving an indication into the range of breathing rates that can be measured by these systems.

The logbooks that held gas consumption data showed that there were a number of dives in the logbooks that had surface gas consumption rates from one diver which were between 15 l/min to 195 l/min and another of between 18 l/min to 98 l/min. These upper rates of consumption are above those recommended in the advice from industry bodies for periods of the dive. Unfortunately, no indication on what was occurring at the time of the gas consumption rate increase is known unless the diver annotates information into the logbook. Further testing with the dive computers used and those from other manufacturers would improve the knowledge on how accurate the readings stored in the computers logbooks are.

## 4.4 DISCUSSION ON GAS CONSUMPTION RATES

### 4.4.1 Physiology and psychology

The physiological data available on air consumption rates is vast and so defining essential information to be included in the research has required careful consideration. This was due to the amount of work reported by researchers looking at human performance. Defining the maximal breathing rate the human person can achieve included research of data on elite athletes with the correct data sets[15]. While it is acknowledged that not all divers will be elite athletes, the rate at which a fit diver will breathe in an emergency high stress situation is likely to be better reflected by data which includes such research.

Whether the diver is in an upright or prone position also has an effect on how easy it is for the diver to breathe. The influence is caused by the hydrostatic load on the lungs relative to the position of the demand valve.

How a diver breathes is also of interest, ISO 16976-1[9] states that when the person increases their breathing rate because of an increased workload, the breathing pattern changes from the sinusoidal to a trapezoidal pattern. As non-human testing for certification of diving equipment relies on a sinusoidal pattern, it could mean that the diver may not get the amount of gas he is demanding at the start of his inhale. However, it is acknowledged that these do not state how long the subject remained at their maximum demand before succumbing to fatigue.

### 4.4.2 Comparison between Research papers and diving guidance

The comparison between the information from the scientific papers and industry guidance is shown in the graph at Figure 5. This combines these data from both sides of this part of the study and clearly provides a graphical illustration on the lower breathing rates that has been found within the industry guidance.

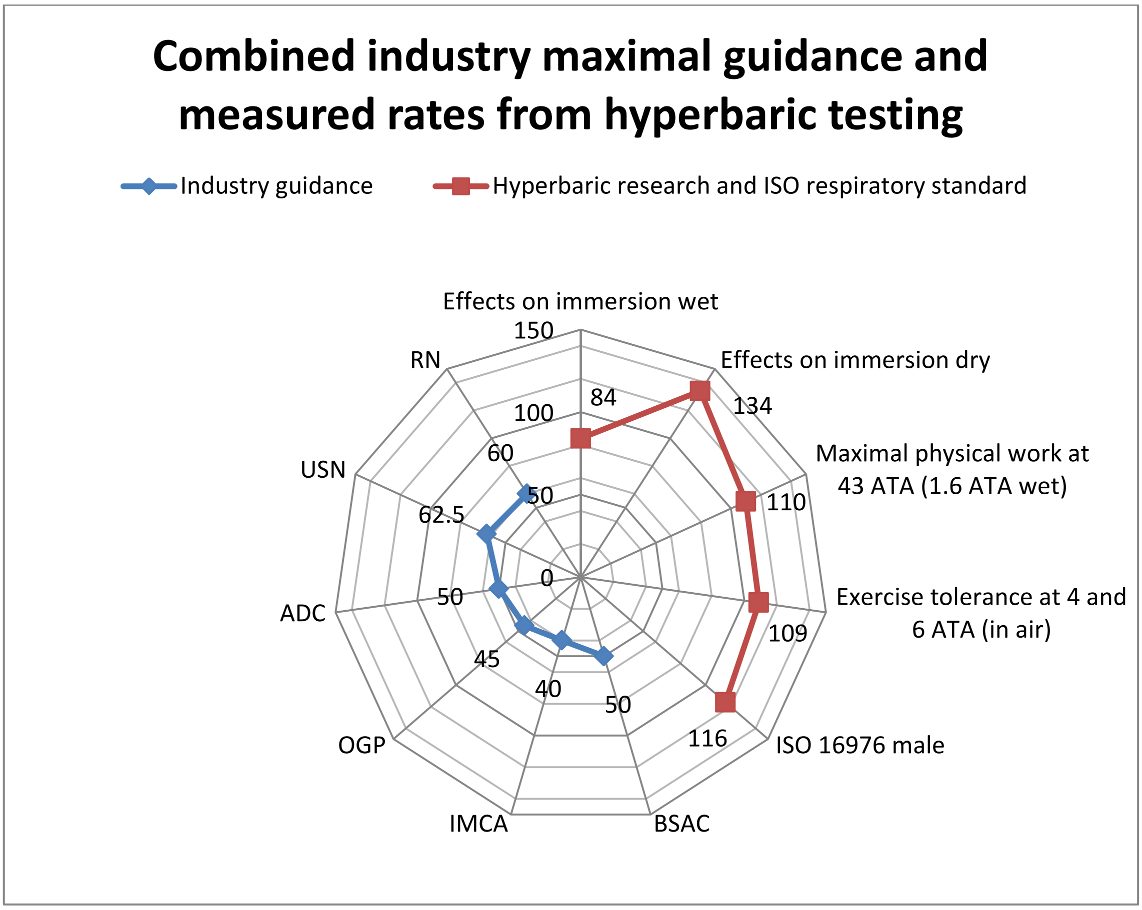


Figure 5. Combined scientific research and industry guidance surface breathing rates in l/min.

The length of time that a person is able to maintain the high breathing rate can be a limiting factor on how much gas would be required. In the Textbook of Work Physiology, Physiological bases of Exercise[29] by Per-Olof Åstrand and Kaare Rodahl, subjects were exercised at a heavy rate until they stopped due to fatigue. The results indicated that the higher the power output being produced, the quicker the subject stopped. When the subject was tested at over 400 watts (16.5 Mets) the subject kept going for 100 seconds, at 343 watts (14.5 Mets) the subject continued for 180 seconds and at 275 watts (12.0 Mets) the subject continued for more than 8 minutes. Although this does not provide representative data for a person in a panic situation, it could be used as a reference for planning gas requirements.

In addition to the gas consumption rate, a key factor in the calculation of bail out gas that a diver will require is the time it would take the diver to return to a place of safety. For example the bell, wet bell, dive basket or surface, or alternatively, for a standby diver to arrive with an additional gas supply. If a diver is returning directly to the surface, the calculation would need to include the time necessary for any decompression obligation.

It is noted that the research paper dealing with Maximal physical-work capacity of man at 43.4 ATA identifies lower maximal and mean $\dot{V}_E$ rates when compared with the rates identified in non-diving related papers. This suggests that the additional factors that are specific to divers have an effect on breathing rates. These would include:

- The increased density of the gas as the diver goes deeper. This can be reduced by the inclusion of helium into the gas mix.

- The requirement to wear thermal protection and the restrictions this causes to breathing.
- The hydrostatic pressure on the thoracic cavity (depth related).
- The inertia experienced on the thoracic cavity due to immersion.
- The harness to hold the bail-out or main gas supply can constrict the thoracic region of the body restricting full inflation of the lungs.

The evidence in this report suggests that an overall increase in consumption rates would be appropriate to take account of the high breathing rates that have been measured. The research has identified maximal breathing rates up to 110 l/min whilst immersed in hyperbaric applications. The same research paper identifies the mean measured $\dot{V}_E$ for the research subjects during maximally tolerated work at 1.6 ATA is 77.62 l/min and at 43.4 ATA is 44.37 l/min. The data suggest that a value of 110 l/min may be appropriate. However, the mean values identified are significantly lower and this coupled with the problems associated with the length of time that a diver could maintain such a high breathing rate indicate that a figure somewhat lower than 110 l/min might be acceptable.

This may allow for a reduced consumption rate that could be a rate in the region of 75 l/min.

The discussion held at a workshop with industry on the subject, indicated that most of the commercial diving teams working offshore would work to the Norwegian requirement of 62.5 l/min, as they would operate in both UK and Norwegian sectors and therefore work to the higher minimum. The workshop reviewed the higher breathing rates in the scientific papers identified in this research and also discussed the particular physical and physiological effects that are factors in the breathing rates that can be achieved and maintained by a diver. The workshop also identified the safety issues, regarding weight and size of the bail-out cylinder(s) that might be introduced if there was a requirement to significantly increase the volume of gas required. Taking account of these influences, the majority of the workshop participants considered that a consumption rate of 50 l/min or greater was appropriate for the calculation of emergency gas requirements.

The emergency gas consumption rate is an important factor in gas planning strategies for bail-out systems. The endurance of the gas that can be carried by the diver, will depend on the depth, and the breathing rate, the diver may reach. The gas strategy would also need to take into account the time it will take for the diver to reach a place of safety, or for the standby diver to arrive with additional gas supplies.

Furthermore the supply method of both the bail-out gas and any additional emergency gas would need to be reconsidered to see if these remain suitable. The size of the bail-out supply carried by the diver should not significantly restrict the diver's ability to move through the opening of a bell or basket. Similarly, any additional emergency gas provided in a basket should have a quick, simple and reliable method of access by the diver. This may encourage or require the development of different strategies in the provision of emergency gas such as different gas storage/carriage and supply methods, which are addressed in the next section of this report.

# 5. METHODS OF PROVISION OF GAS TO DIVERS

Can the equipment in use today meet typical breathing rates and provide the levels of gas recorded in the physical research used in this paper. An additional complication is the breathing pattern of a diver working hard or in a stressful situation. The pattern may differ significantly from the sinusoidal breathing machine waveforms used by test facilities in measuring the performance of the equipment. Further thought may need to be given as to how to represent the heavy workrate of emergency breathing demand effectively. Also if the diver is calling for help or required to speak to his supervisor this further increases the required flow rate and significantly changes the diver's breathing pattern.

## 5.1 CURRENT METHODS

Different sectors of the industry have different methods of supplying a diver in need of emergency gas.

### 5.1.1 Inshore and Offshore commercial

All divers operating under the inland/inshore and offshore ACOPs are required to carry an independent reserve supply of gas and they may use one or more cylinders. These cylinders will have a regulator connected to a cylinder valve with a medium-pressure hose to the side block of the helmet or mask. In the event of a failure of the gas supply, the diver can open a valve on the side block and allow gas into the breathing zone. The endurance of diver-carried gas is limited by depth of dive and size of cylinders being used; cylinder size also affects ease of access to and from the bell. If a diver is operating from a wet bell or from a basket, at least one, if not more than one, 50 litre cylinder or "J" cylinder should also be available in the basket. A regulator should be fitted to the cylinder and from that both a SCUBA demand valve (DV) and an open ended hose should be attached. Within the U.S. commercial diving sector and possibly used within the UK, is the practice, that when the diver-carried gas has been exhausted, the "Pneumo hose", which is part of the diver's umbilical, or the open ended hose, is inserted in-between the neck dam and diver's neck. This may work, but can leave the diver in a precarious position and it is not clear if this method can supply sufficient gas to a diver. If the diver is wearing a band mask or helmet then he could remove this and utilise the SCUBA DV. However, band mask or helmet removal can be very difficult for the wearer to achieve rapidly themself, and they may require assistance from another diver.

In a situation where the standby diver is sent to assist a diver in trouble, the ability to connect a further supply gas feed direct to the diver in trouble would assist by giving the team more time to effect a rescue. The same system could be connected to the "J" cylinder within the basket or wet bell.

### 5.1.2 Use of Pneumo hose

During the workshop, the use of a hose to be passed through the neck dam was discussed and subsequently a paper was identified from "Dive Lab" by Mike Ward on the provision of Surface Supplied Emergency Breathing discussed the limitations of this method. In an example it displays that a constriction to the umbilical will leave a diver with no gas and if no bail-out is carried, the use of the Pneumo may not work either due to the constriction on the umbilical. If the diver has a standby diver close to hand in the water with him and he is able to manoeuvre his pneumo hose into the neck dam of the diver's helmet it still may not provide sufficient gas to the diver in distress. This method is also not rehearsed by dive teams. The provision of emergency gas from a cylinder and an open ended hose through the neck dam is taught at least one commercial dive school, and appears to work.

### 5.1.3 Full Face Mask

Within industries using full face mask (FFM) assemblies the provision of emergency gas to the diver can require the diver to completely remove the mask if the demand valve has failed. There are only a few masks that have the facility to have a second demand valve mounted to the mask body. Modifications not approved by the manufacturer and therefore invalidating the CE compliance have been seen on some FFMs.

### 5.1.4 Recreational

The recreational sector mainly uses half mask and mouthpiece systems, and although there are some FFM users, these are in the minority. The commonest alternative air supply system used includes every diver having a second demand valve attached to a single main first stage regulator, with the diver being part of a buddy team. It must be emphasised here that a recreational instructor at work will need to comply with the requirements of the ACOP. Until its recent revision the regulator standard (BS EN 250)[15] did not include a test to ensure that first stage regulators could provide sufficient gas to support two divers. However, the newly introduced standard BS EN 250: 2014 for SCUBA regulators does require the testing of the second demand valve at the same time as the main demand valve, but only to a depth of 30 metres, and in water temperatures above those seen in winter months in the UK. At the time of writing this report most if not all regulators used with an octopus system are not approved by the manufacturer for having divers breathing off both demand valves simultaneously. Each diver relies on his buddy to be able to supply gas in an emergency. Recreational divers are trained to provide this assistance from the start of their diver training and the technique should be practised regularly.

In the past twenty years with the advent of "Technical diving" in the recreational sector and the complexities that increased depth has brought to planning for gas problems, the consideration of back up plans in case of an emergency and increased inter-dependability of supplying other divers are now common place. Though not quite in the league of that in the offshore industry, the gas planning and back-up systems typically involve spare cylinders and have adopted methods of plugging these into diver supply systems. This method is also used for rebreathers to increase the range of gas availability to the diver and reduce the amount of cylinders the diver carries at one time.

### 5.1.5 Military and Emergency services

The military and more recently Police dive teams have been using a system that allows one diver to supply another using a quick coupling.

## 5.2 POSSIBLE METHODS OF GAS PROVISION

Rather than having to remove the diver's helmet as a "last resort", or feeding an open ended hose up past the neck dam, the use of a coupling onto the helmet or mask would provide a more secure connection and would remove the need to take the helmet or mask off in extremes. An inter-operable supply connection to enable any diver to access spare gas in the basket or wet bell by means of a connection/coupling that can feed gas to the helmet/mask, demand valve would allow anyone to give gas to another diver and would add an increased safety parameter to diving. The next review of the surface supply umbilical gas supply standard could take this forward, leading to the adoption of this capability across industry. This could be quite simply fulfilled by the use of a readily available quick disconnect coupling of a type that is available off the shelf, though it would be preferable to select one model to be used worldwide. These could be incorporated into the side block of a helmet or mask or into a coupling connected to a first stage regulator medium pressure fitting.

Reading a post on a diving forum, the use of these types of couplings by a group of non-professional divers did indicate that there was a poor understanding of the flow rates required to get acceptable amounts of gas to a diver. Also apparent was that the people who had written these comments would be willing to "file" fittings to make it fit another make of coupling.

The selection of a suitable coupling should account for the fitting reducing the flow of gas through the coupling and with increased depth the density of the gas will increase proportionately as well. Any restrictions or severe changes in direction will also have an effect on the flow of gas to the diver and should be considered prior to selection of a suitable coupling. Compatibility with diving gases should also be a consideration in the make-up of the coupling sealing surfaces. Furthermore, by modifying a current CE approved piece of diving equipment by using a fitting that has not been tested and approved for use with the piece of diving equipment would invalidate the CE approval. Therefore the manufacturers of diving equipment will need to be consulted prior to a modification being made.

## 5.3 ALTERNATIVE GAS PROVISION

Alternative approaches to gas provision may require wider consideration of different ways of providing back up gas to a diver. This could for example include having gas carried on Remotely Operated Vehicles (ROV's) that are working with the dive team. There are also bail-out rebreathers already in use with commercial operations in deep offshore operations that can give the diver more time than typical compressed gas supplies. With developmental rebreather units for the commercial industry being produced, these could also assist with enabling the diver to have enough time to reach a safe environment or extra gas supply. The use of these rebreathers at depth does however present added technical considerations to be addressed; the work of breathing needs to be low enough that the $CO_2$ produced by the diver when working hard can be removed safely.

If a diver is trapped or ensnared, the facility of having a method of connecting a gas supply, in addition to the diver worn bail-out supply would be beneficial. The availability of a Remotely Operated Vehicle (ROV) fitted with a gas reservoir on board might allow a diver to plug into the reservoir enabling him to maintain his breathing supply. Encouraging industry as a whole to adopt a single standardised method to allow any diver to be given gas may be a viable route to look at for future use.

For an 'outside the box' idea for an alternative method of emergency breathing gas supply, generation from liquefied gas may be less bulky than current compressed gas methods. The use of liquid air to supply divers was tried during the 1960's; it then disappeared from use, possibly due to incidents. Developments in technology over the last forty years could bring back this method of supplying gas. The main benefit would be that the size of equipment required to hold the gas required would be more compact than compressed gas. National Aeronautics and Space Administration (NASA) has the use of a system, though one drawback would be the cooling that the diver may experience. However, this could be overcome using thermal heating systems alongside the hot water system used by divers.

## 5.4 RESEARCH FINDINGS

Upward revision of gas consumption rates should be considered for adoption across the diving industry, to ensure safe provision of working and emergency supplies.

Alternative approaches for emergency gas supply, which provide for quicker and more secure connection of any diver to an alternative gas source, are possible. These could largely be achieved using off-the-shelf components, and with diving industry support and co-operation could be adopted to allow a standardised coupling across the industry. The implications of such modifications on the CE marking of equipment should however, be considered.

# 6. CONCLUSIONS

## 6.1 BREATHING RATES

It is clear from this research that the human body can achieve very high breathing rates. The research has also identified that in hyperbaric conditions for immersed subjects the breathing rates measured, whilst still significant, appear to be somewhat lower. The possible reasons for this have been discussed. The research has also identified that whilst such high breathing rates are achievable there is evidence that the onset of fatigue will prevent them being maintained for a long period.

The breathing rates used across industry were found to be below those found within the scientific papers researched for this report.

## 6.2 IS CURRENT EQUIPMENT PERFORMANCE SUFFICIENT?

The results of the literature and dive computer data search indicate that the breathing rates a human can attain are beyond the current limits imposed on dive equipment during testing.

The revised BS EN 250 standard incorporates the simulation of two divers breathing from the same first stage. It is not known what effect this will have on regulators coming onto the market. The higher breathing rates that can be attained by a diver in an emergency should be taken into account by equipment manufacturers, the responsible standards-writing committees and industry bodies.

## 6.3 RECOMMENDATIONS

The data at Figure 3 and 5 indicates that the amount of gas that is currently considered to be required in an emergency is lower than that which a diver might actually need in a high stress emergency situation. The author considers that a surface breathing rate of 110 l/min appears to be appropriate from this research. However, it is unlikely that a diver will be able to sustain such a rate for very long. Furthermore, there is likely to be additional safety implications of employing such a rate with regard to the size and weight of the diver carried bail-out cylinders that would be necessary for a diver to reach a place of safety. Taking these factors into account a general breathing rate of between a more pragmatic 50 l/min or 75 l/min might be appropriate. The decision on the actual breathing rate employed when calculating bail out requirements would need to be derived from the risk assessment for the dive being undertaken.

A recommendation to implement a standard coupling for supplying a diver with emergency gas, if adopted, could represent a large step forward in diving safety. For divers operating in a basket or wet bell environment, the coupling would provide a secure means of accessing a gas source, either by themselves, or with the assistance of a standby diver. In recreational diving, divers do not habitually carry a separate bail-out system. The facility for a buddy diver to connect into the casualty diver's supply would negate the need to have the casualty remove their demand valve in an already stressful situation.

The integration of a standard coupling into diving equipment already on the market would require approval of the equipment manufacturer to ensure the CE marking is not prejudiced.

Development of a smaller system that holds more gas should be encouraged.

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# 9. GLOSSARY

| | |
|---|---|
| ACOPs | Approved Code of Practice. |
| ADC | Association of Diving Contractors. |
| ATA | Ambient pressure 1 ATA surface pressure, 2 ATA equates to being underwater at a depth of 10metres, 3ATA equates to a depth of 20 metres etc. |
| Band Mask | Diver's face mask with regulator and neoprene hood attached usually fed by an umbilical to a side block. Provision for emergency supply to attach to side block. |
| Basket | Method of moving a diver and emergency gas supply to a job site from either a vessel or a shore base. |
| BSAC | British Sub Aqua Club |
| BTPS | Body temperature and pressure saturated with water vapour. |
| DAN | Divers Alert Network |
| Diver's helmet | Helmet that encloses diver's head usually fed by an umbilical to a side block. Provision for emergency supply to attach to side block. |
| DV | Demand Valve. |
| Dyspnea | Shortness of breath or a feeling of being unable to breathe. |
| FFM | Full Face Mask |
| IANTD | International Association Nitrox and Technical Divers |
| IMCA | International Maritime Contractors Association |
| ISO | International Standard Organisation |
| LSTF | Life support test facility. |
| Mets | Metabolic Equivalents |
| Mostellar Method | Method of calculating Human Body Surface Area |
| Neck Dam | Neoprene or latex collar that fits to base of diver's helmet to provide water proof seal. |
| NOAA | National Oceanic and Atmospheric Agency. |
| OGP | International Association of Oil and Gas Producers. |
| PADI | Professional Association of Diving Instructors. |
| PIF | Peak Inspiratory Flow, maximum rate of airflow during inhalation. |

| | |
|---|---|
| RMV | Respiratory minute volume. |
| SAA | Sub Aqua Association. |
| SCUBA | Self-Contained Underwater Breathing Apparatus |
| SD | Standard deviation, upper and lower variance measurements to result |
| $\dot{V}E$ | Minute expired ventilation in Litres per minute |
| $VO_2$ | Volume of oxygen consumed |

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# The provision of breathing gas to divers in emergency situations

The report examined the diving industry guidance provided to divers and supervisors in the amount and method of determining how much emergency gas a diver can require. A literature search was carried out into the human gas consumption rate as measured in scientific studies of workers, divers and athletes. Data was also sourced from operators and divers using dive computers with gas integration.

The data from the guidance, scientific studies, operators and live data from divers are compared to provide a recommended gas consumption rate that industry can use to plan the volume of gas to be available to a diver in an emergency. It was found that some industry sectors could increase the recommended gas consumption rate to provide sufficient gas to a diver in an emergency.

How the gas is provided to the diver in an emergency is discussed. Current industry practices across the different sectors use a wide range of methods, some of which could be improved. The sizes of gas containers, the pressure that containers can be charged to, along with how gas can be passed to the diver are covered. A standardised coupling is recommended to allow connection between a diver and an emergency gas supply.

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