# Optimal Breathing Gas Mixture in Professional Diving with Multiple Supply

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Abstract— Professional diving existed since antiquities when divers collected resources from the bottom of the seas and lakes. With technological advancements in the recent century, professional diving activities also increased significantly. Diving has many adverse effects on human physiology which are widely investigated in order to make dives safer. In this study, we focus on optimizing the breathing gas mixture minimizing the dive costs while ensuring the safety of the divers. The methods proposed in this paper are purely theoretical and divers should always have appropriate training and certificates. Also, divers should never perform dives without consulting professionals and medical doctors with expertise in related fields.

*Index Terms*—-professional diving; breathing gas optimization; dive profile optimization

#### I. INTRODUCTION

Though there is no documentation of how diving started, it is known that humankind explored underwater since antiquities. By 4500 BC, diving had already transformed into an industry supplying the community with shells, food and pearls. These people can be considered as the first professional divers. Breath holding diving sponges continued until the nineteenth century. Several diseases caused by diving are observed during this time. Military diving is documented during the Trojan Wars from 1194 to 1184 BC where divers sabotaged enemy ships. In later years, it is known Romans took precautions to prevent these types of underwater sabotage. First underwater breathing devices are made of reeds and bamboos for hunting. Leonardo da Vinci sketched diving sets and fins. Borelli suggested a device to purify the diver's air so it could be reused. It is claimed that Alexander the Great used the first diving bell but there is no concrete evidence. The fully documented use of diving bells dates back to 16<sup>th</sup> century. With the invent of reliable air pumps during the 18<sup>th</sup> century, divers could be supplied with air from the surface which allowed to stay underwater for extended periods of time. In 1837, the Siebe closed dress is introduced. The incorporated air-supply line connected a pump of compressor on the surface to a diving helmet. In 1863 Rouquayrol and Denayrouze invented the first demand regulator for self-contained underwater breathing apparatus (SCUBA) but due to lack of suitable high-pressure air

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compressors and cylinders, it was limited to surface air supply lines. In 1978, Fleuss introduced the first closed circuit oxygen breathing apparatus which removed carbon dioxide from the exhaled gas and did not form bubbles underwater. In 1943, Cousteau and Gangan designed the first proper demand-regulated air supply from compressed air cylinders worn on the back. The scuba equipment with the high-pressure regulator on the cylinder and a single hose to a demand valve was invented in Australia and marketed by Ted Eldred in the early 1950s [1].

With the use of Siebe dress, the first cases of decompression sickness began to be documented. Haldane conducted several experiments on animal and human subjects in compression chambers to investigate the causes of this sickness and how it can be prevented. It is discovered that it is caused by the gases dissolved in tissues when they form bubbles with the sudden reduction of ambient pressure. Haldane defined five tissue types with different capacities and loading speeds [2]. In 1971, Schreiner further improved Haldane's model [3]. In 1984, Bühlmann improved Haldane's theory and defined 16 tissues. Bühlmann's model is still in use in development of dive tables, software and dive computers. In this study we use Bühlmann's model which is publicly available [4].

## II. DECOMPRESSION MODEL

The breathing gas is supplied to divers at ambient pressure. The air primarily consists of 21% Oxygen and 79% Nitrogen. Both gases have undesired effects on human physiology under high pressures. The pressure at sea level is approximately 1 bar. As the diver descents to deeper levels the ambient pressure increases as a result. According to Henry's law "as pressure increases the quantity of gas absorbed by the tissues of the human body increases" which means as the diver descends, the amount of maximum absorbed gas on human body increases. Also, according to Dalton's law, "in mixtures of breathing gases the concentration of the individual components of the gas mix is proportional to their partial pressure". Combining these two laws, we can deduce that, decreasing the percentage of Nitrogen in the breathing gas decreases its partial pressure which in turn results in less absorbed gas in human tissues under pressure. This type of Oxygen enriched gases is referred to as Enriched Air Nitrox (EAN) and is widely used for both recreational and professional diving as it allows longer deep time than air. The fraction of oxygen in the mixture determines the type of the Nitrox (e.g. EAN32 means a breathing gas mixture containing 32% Oxygen and 68% Nitrogen). While using Nitrox, the partial pressure of Oxygen and maximum operational depth should be monitored carefully as high Oxygen partial pressure may also have undesirable effects on human physiology. Generally, for Oxygen a partial pressure of 1.6 bar is accepted to be safe for a short period of time.

As the diver spends time underwater at higher ambient pressure, more Nitrogen is dissolved in different human tissues. The amount of absorbed Nitrogen on a tissue depends on the tissue loading capacity and tissue loading speed. Tissue loading capacity refers to the maximum amount of Nitrogen that can be absorbed by that tissue and tissue loading speed refers to the time it takes to reach a certain level of absorbed gas in a tissue. Both these values increase as the partial pressure of Nitrogen in the breathing gas increases. After a long dive, if the diver ascents too quickly, the excess Nitrogen in the tissues may form bubbles which risks the Decompression Sickness (DCS). In order to reduce the risk of DCS, the diver should ascent gradually and allow the excess Nitrogen in the tissues to be expelled from the body. Several models are proposed to model tissue loading and to determine safe ascent procedures.

In this study, we use Bühlmann's model in order to calculate the dive profile for a given breathing gas mixture. The dive profile refers to the depths and time spent on these depths. As the fraction of Nitrogen changes, the dive profile changes accordingly. As a result, dive time and breathing gas consumption also changes. In this study, the breathing gas supply is assumed to be unlimited.

Bühlmann's Model is based on Haldane's studies. Instead of 5 tissues suggested by Haldane, Bühlmann suggests 16 tissues and provides related coefficients.

## Step 1: Initialize the tissues

The first step is initializing the tissues. Bühlmann's model separates the human body to 16 tissues. While initializing, the partial pressure of water vapor pressure in the lungs should also be considered. At sea level, ambient pressure is assumed to be 1 bar. For each tissue, the initial partial pressure of Nitrogen is calculated.

# Step 2: The Descent

An instant descent can be assumed in order to keep calculations simple but for deep dives descent takes a while and a considerable amount of Nitrogen can be dissolved in the tissues during the descent. A normal descent rate is around 30m/min. For each tissue, the amount of dissolved Nitrogen is calculated.

## Step 3a: The Dive

In case the professional diver performs certain tasks at a constant depth and the task completion time is known, we assume he stays at that depth stationary. During the dive, Nitrogen continues to dissolve in the tissues. The amount of dissolved Nitrogen in each tissue is calculated.

## Step 3b: Checking the Ascent Ceiling

In recreational dives, divers make sure that they would not need to make decompression stops so they can safely surface. For professional divers, a safe ascent ceiling must be calculated. For each tissue a safe ascent ceiling is calculated The deepest (highest) ascent ceiling of the tissues is selected and rounded up to the next multiple of 3m (3m, 6m ...).

Step 5: Calculate the Length of Decompression Stops

The decompression stops lengths for each stop depth ranging in 3m intervals are calculated.

Using this procedure, a safe dive profile can be calculated for a given Nitrox mix. The descent and dive times are unchanged for different Nitrox mixes. The decompression stops and lengths would vary depending on the mixture.

In this model, the diver is assumed to use the same gas for the dive and the decompression. As the partial pressure Oxygen should be kept at a safe level, the fraction of Oxygen cannot be increased above a certain level. As a result, the fraction of Nitrogen is kept high during the decompression. By introducing additional gases for decompression with higher fraction of Oxygen and lower level of Nitrogen, the decompression time can be reduced significantly. For example, it is safe to use pure Oxygen at depths shallower than 6 meters. As pure Oxygen does not contain Nitrogen, Nitrogen dissolved in the body can be expelled more quickly. This in turn results in reduction of decompression time.

## III. MAXIMUM OPERATIONAL DEPTH

In underwater diving activities such as saturation diving, technical diving and nitrox diving, the maximum operating depth (MOD) of a breathing gas is the depth below which the partial pressure of oxygen (pO2) of the gas mix exceeds an acceptable limit. This limit is based on risk of central nervous system oxygen toxicity, and is somewhat arbitrary, and varies depending on the diver training agency or Code of Practice, the level of underwater exertion planned and the planned duration of the dive but is normally in the range of 1.2 to 1.6 bar. [5]

Acute, or central nervous system oxygen toxicity is a time variable response to the partial pressure exposure history of the diver and is both complex and not fully understood.

Central nervous system oxygen toxicity manifests as symptoms such as visual changes (especially tunnel vision), ringing in the ears (tinnitus), nausea, twitching (especially of the face), behavioral changes (irritability, anxiety, confusion), and dizziness. This may be followed by a tonicclonic seizure consisting of two phases: intense muscle contraction occurs for several seconds (tonic phase); followed by rapid spasms of alternate muscle relaxation and contraction producing convulsive jerking (clonic phase). The seizure ends with a period of unconsciousness (the postictal state) [6,7]. The onset of seizure depends upon the partial pressure of oxygen in the breathing gas and exposure duration. However, exposure time before onset is unpredictable, as tests have shown a wide variation, both amongst individuals, and in the same individual from day to day [6,7,8]. In addition, many external factors, such as underwater immersion, exposure to cold, and exercise will decrease the time to onset of central nervous system symptoms [9]. Decrease of tolerance is closely linked to retention of carbon dioxide [5,10,11]. Other factors, such as Proceedings of the World Congress on Engineering 2021 WCE 2021, July 7-9, 2021, London, U.K.

darkness and caffeine, increase tolerance in test animals, but these effects have not been proven in humans [12,13].

The maximum single exposure limits recommended in the NOAA Diving Manual are 45 minutes at 1.6 bar, 120 minutes at 1.5 bar, 150 minutes at 1.4 bar, 180 minutes at 1.3 bar and 210 minutes at 1.2 bar [9].

#### IV. COSTS RELATED TO PROFESSIONAL DIVING

In professional diving, there are several types of costs. The main costs considered in this study are the diver cost and the breathing gas cost. The diver cost is assumed to be hourly. The breathing gas is assumed to be prepared by enriching the air with Oxygen, therefore the only cost is pure oxygen added to the breathing gas in order to obtain the Nitrox mixture. As the dive time increases, both the diver cost and breathing gas cost will increase. The dive time can be divided in two stages, the first stage is the dive itself during which the professional diver performs certain tasks. Once the tasks are fully or partially completed, the diver should start the ascent procedure. During this second stage the diver does not perform any task and can be considered idle. The objective is to decrease the idle time of the diver. In order to achieve that, the fraction of Nitrogen in the breathing gas should be lowered as a lower fraction of Nitrogen means shorter and shallower decompression stops. In turn, in order to decrease the fraction of Nitrogen, the fraction of Oxygen of the breathing gas should be increased which in turn will increase the breathing gas cost. The objective of this study is to find the balance between these two costs in order to minimize total cost.

The calculation of the diver cost is simple.

$$\mathbf{C}_l = \mathbf{t} * \mathbf{c}_l \tag{1}$$

where, t is the total dive time in hours and  $c_1$  is the hourly diver cost.

The breathing gas cost depends on the amount of gas consumed in liters during the dive and the cost of breathing gas per liter. Amount of consumed gas is proportional to the depth as with the increase of the ambient pressure, the pressure of breathing gas is also increased. Let p(t) be the ambient pressure at time t and r be the divers breathing rate in liters per hour. Then the surface equivalent total gas consumed during the entire dive can be calculated as

$$\int p(t) * r \,\mathrm{d}t \tag{2}$$

Considering the Nitrox is prepared by mixing Air and Oxygen, the only cost for breathing gas is Oxygen. Let FO<sub>2</sub> be the desired fraction of oxygen in the final breathing gas. Considering the air already contains 21% oxygen, the amount of pure oxygen added to 1 liter of breathing gas is  $(FO_2-0.21)/0.79$ . By multiplying this value by the cost of Oxygen we obtain the breathing gas cost per liter.

$$c_2*(\text{FO}_2-0.21)/0.79$$
 (3)

where  $c_2$  is the cost of Oxygen per liter at an ambient pressure of 1bar.

Finally, the total breathing gas cost can be calculated by multiplying amount of gas consumed by cost of breathing gas.

$$C_2 = (\int p(t) * r \, dt) * (c_2 * (FO_2 - 0.21)/0.79)$$
(4)

If multiple breathing gases are supplied to the diver for different depths, the corresponding cost should be calculated and summed for related depths.

The total dive cost is the sum of diver cost and breathing gas cost.

$$C = C_1 + C_2 \tag{5}$$

The objective is to minimize the total dive cost.

#### V.NUMERICAL APPLICATIONS

A hypothetical problem is solved to illustrate the proposed model. The hourly diver cost is assumed to be \$30 and the Oxygen cost per liter is assumed to be 2¢. The diver performs the task at a depth of 40m for 120min. The upper limit for fraction of Oxygen is set to 30% as this value keeps the partial pressure of Oxygen at 1.5bar which is considered to be safe for a duration of maximum 120min according to DAN (Donald 1947, Lang 2001). As the decompression times are shorter, we allowed a partial pressure of 1.6bar of Oxygen for decompression stops.

Each numerical example is solved with MATLAB using the Genetic Algorithm Optimization Tool.

We first consider a single gas mixture and obtained the dive profile in Figure 1.

Then, we allowed an additional gas for decompression and obtained the dive profile in Figure 2.

As expected, the total dive cost has decreased.

Next, we allowed another additional gas for decompression and obtained the dive profile in Figure 3.

Again, the total gas cost has decreased. Next, we allowed another additional gas for decompression and obtained the dive profile in Figure 4.

The gas cost only decreased marginally, we continued to allow additional gas for decompression and obtained the dive profile in Figure 5.

The decrease in total cost is very marginal, so we did not add additional gas.

The costs for each number of gas mixture are summarized in the graph in Figure 6.

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Figure 1. Single gas mixture dive profile



Figure 2 Four gas mixtures dive profile



Figure 3 Three gas mixture gas profile

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Figure 4 Two gas mixtures dive profile



Figure 5 Dive costs for various number of gas mixtures



Figure 6 Five gas mixtures dive profile

We observe the diver cost decreases as the number of additional decompression gas increases. This result is expected as the diver needs less time for decompression hence the idle time decreases. On the other hand, the gas cost increases gradually as the number of decompression gas increases. This is due to the fact that additional gases are richer with Oxygen which increases the mixture cost. In total the cost decreases, but the most significant decrease happens with the addition of the second gas. The addition of the third gas further decreases total cost but just marginally. With the addition of forth and fifth gases the decrease in cost is negligible. Also, by examining the fractions of gases with 5 mixtures, we observe that the first gas is almost just air with 22% Oxygen and the last decompression mixture is almost pure Oxygen with a fraction of more than 99.5% Oxygen. This last Oxygen is only utilized at depths shallower than 6 meters as at this depth the partial pressure of pure Oxygen is 1.6 which is the maximum limit considered to be safe.

#### VI. CONCLUSIONS AND FUTURE DIRECTION

In recent years, professional underwater activities have increased significantly with underwater tunnels, pipelines, dam constructions etc. The physiological effects of high ambient pressure are widely studied by researchers and different models are proposed. On the other hand, the industrial optimization studies are very limited. In this study, we aimed to model the costs associated with professional dives and proposed a model to minimize this cost while maintaining the DCS risk at acceptable levels.

In previous studies, we had considered a single gas supply for both the dive and the decompression stops. This approach restricts the fraction of the Oxygen in the breathing gas mixture significantly. Allowing additional gas mixtures for decompression greatly increases the flexibility of the model as Oxygen rich mixtures which cannot be used during deeper dives can be used for decompression stops. Even though this approach increases the gas mixture cost, this additional cost is mitigated by the reduction of decompression stop times and as a result the total dive time. As suspected, by allowing additional decompression gas mixtures, the total dive cost decreases gradually.

The proposed model is illustrated by a hypothetical problem and is proved to be useful in realistic scenarios. In our model, Bühlmann's decompression model is utilized as it is publicly available. Other decompression models can also be easily adapted for different types of professional diving applications.

In this study, we assumed unlimited breathing gas supply containing only Oxygen and Nitrogen. Future studies may include other gases such as Helium. Unlimited gas supply is only available if the gas is supplied from the surface which is not always feasible. In that case, limited breathing gas supply should be considered. Also, in this study, we assumed that the tasks can be finished in one dive, for future studies, consecutive dives will also be investigated.

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