Analytical model and simulations of closed-loop rebreather systems for Earth and Space applications

by

Ioana Josan-Drinceanu

Submitted to the Department of Aeronautics and Astronautics
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Abstract

Humans in extreme environments, regardless of whether in space or deep in the oceans of the Earth, rely on life support systems to be kept alive and perform their exploration missions. Diving is similar to extravehicular activities in its duration and the need for human respiratory sustaining. This thesis presents the development of an analytical rebreather model, which is the system that recirculates and conditions the air the diver is breathing during a dive. The capability of simulating rebreather performance is currently lacking in the diving commercial and military industry. We believe that the advantages of having such a model are multi-fold: it can be used for mission planning, evaluating the impact of adding a new technology or modifying existing parameters or operational regime on an hardware configuration without performing expensive and time consuming hardware tests. An analytical model, like the one developed in this thesis, can also be used in complement with hardware testing to fine tune systems and increase resource endurance through the application of different electronic control strategies.

The developed Matlab/Simulink model of this rebreather is modular and can be generalized to study open, semi-closed or closed circuits, in which the breathing gas used is air, oxygen, nitrox or heliox. The system's operational environment can be the ocean's surface (1 atmosphere), space (less than 1 atmosphere pressure) or deep underwater (more than 1 atmosphere pressure). After introducing the analytical modeling process for the rebreather, this thesis goes on to explore the model's applications for the study of different oxygen control strategies in order to maximize the oxygen lifetime during a dive, as well as the model's applicability as an aid in accident investigations.

We aim to determine what is the maximum endurance of a rebreather system, given a particular, set configuration of components, as well as to study the reverse problem: if we set a mission endurance, what architectures would be able to achieve this level? Additionally, we are interested in studying how the tradespace of diving depth versus the diving systems's endurance looks like and how more complex control methods can help in pushing the existent boundary toward higher endurance limits.

We show that more complex control algorithms can extend the duration of the oxygen tanks in a rebreather by a factor of 6.35, and, when given a set endurance level, control can help lower the tank sizes by a factor of 4.

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Title: Professor of Aeronautics and Astronautics and Engineering Systems

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Abbreviations

ABS	Acrylonitrile, Butadiene, Styrene
ADS	Advanced Diving System
BCD	Buoyancy Control Device
BOL	Beginning of Life
BOV	Bail-Out Valve
BSAC	British Sub-Aqua Club
CCOUBA	Closed-Circuit Oxygen Underwater Breathing Apparatus
CCR	Closed-Circuit Rebreather
CMI	Constant Mass Injection
CO_2	Carbon Dioxide
DAN	Divers Alert Network
DCS	Decompression Sickness
eCCR	Electronically-controlled Closed Circuit Rebreather
EOL	End of Life
FMECA	Failure Modes, Effects and Criticality Analysis
FPE	Final Prediction Error
fsw	feet seawater
LED	Light - Emitting Diode
mCCR	Mechanically-controlled Closed Circuit Rebreather
MSE	Mean Squares Error
msw	meters sea water
NAUI	National Association of Underwater Instructors
NOAA	National Oceanic and Atmospheric Administration
OC	Open Circuit
OPM	Object Process Methodology
PADI	Professional Association of Underwater Dive Instructors
PID	Proportional - Integral - Derivative
RBW	Rebreather World
RMV	Respiratory Minute Volume
RQ	Respiratory Quotient
SAC	Surface Air Consumption
SCR	Semi-Closed Circuit Rebreathers
SITS	Scientist in the Sea Program
SPECWAR	Naval Special Warfare Forces
STPA	System Theoretic Process Analysis
UBA	Underwater Breathing Apparatus

Chapter 1

Introduction

Underwater - the other two thirds of our world - is a fascinating place. There are a lot of activities to do under the water, from photography, seeing fish and other critters up close, exploring new places or seeing historic shipwrecks [1] to rescue/salvage missions, submarine repair missions or diving research/development [2]. Diving equipment allows us to visit the underwater world by making it possible to breathe, see and move comfortably under the surface. Gear helps us transform from land-dwellers to somewhat similar to aquatic beings, even for a short while. A mask helps us see clearly, the scuba regulator and gas tanks provide the air we need, fins allow us to swim efficiently and the wetsuit helps maintain our body temperature and stay warm. The diving equipment varies in function of the environment we want to dive in: tropical scuba equipment is for warm water temperature (24°C/75°F and up), temperate scuba equipment is for diving in moderate temperature (cooler than 24°C/75°F), cold water scuba equipment covers water temperatures cooler than 15°C/60°F and the technical diving equipment, used by very experienced, highly trained divers to visit environments beyond the limits of recreational diving [3].

We can classify diving equipments in two broad categories, depending on how the breathing gas is used: open circuit and rebreather systems. Typically, for recreational purposes and when the diver is not a technical diver, (s)he will use an open circuit scuba equipment. The diver inhales gas from the tanks and exhales it to the surrounding environment (shown in Figure 1-1) [3].

Figure 1-1: Open circuit scuba system: the diver inhales air from the tanks and exhales it to the surrounding environment [3]

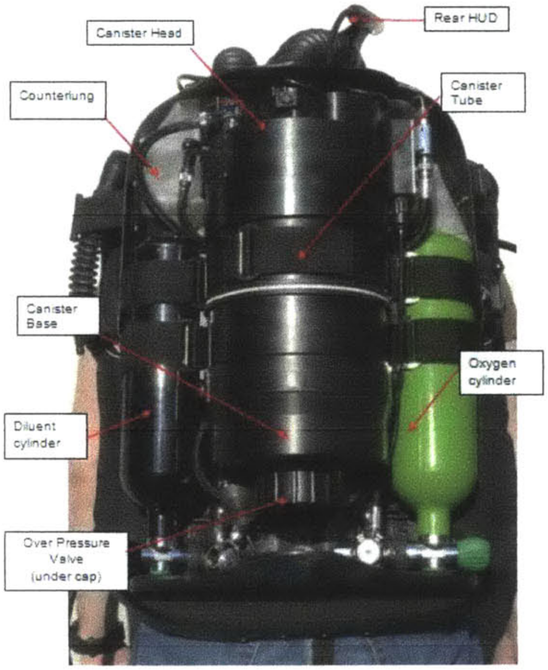


Figure 1-2: A rebreather system and its components [5]

Rebreathers reuse the gas we exhale by recycling the good part and replenishing it from the gas tanks for the next breath. The system also features a carbon dioxide scrubber for removing the carbon dioxide from the diver's exhaled breath. This means that the gas supply is significantly smaller than the one we would carry in open circuit diving, a huge benefit that allows longer dives. Another advantage is the quiet factor: since rebreathers do not vent gas to the environment, no bubbles are formed during diving so we can approach marine animals that would normally shy away from bubble noise. Additionally, because we breathe gas that has been warmed by us and by the recycling process (specifically the absorption of carbon dioxide in the scrubber), rebreather diving keeps us warm, which is a bonus in cool water [4]. There are two rebreather types:

- Closed-Circuit Rebreathers (CCRs) - these systems recycle all the air we exhale, only a few bubbles escape during ascent to release the expanding gas. These systems require two gas supplies: a diluent (air, nitrogen or helium, depending on the depth we are diving at) and oxygen
- Semi-Closed Rebreathers (SCRs).

Figure 1-2 shows a rebreather system components:

- Counterlung, also called a diaphragm, is an expandable bag that expands when we inhale
- Valves, that direct the air circulation from our mouth through the breathing assembly (also called the exhalation mouthpiece) to the carbon dioxide scrubber, to the diaphragm for gas makeup and then back through the inhalation part of the breathing assembly (also called the inhalation mouthpiece)
- Mouthpiece - closes and also connects the Bail-Out Valve (BOV), which is an open-circuit second stage regulator connected to a cylinder with breathing gas for emergencies
- Gas supply - feeds into the gas flow to replenish the oxygen we consume during diving and also increases the diaphragm volume as needed for buoyancy
- Oxygen sensor(s) and control system - located behind the gas cylinder; measure the oxygen partial pressure in the breathing gas, which is then fed to the electronic control system. This system calculates what the necessary oxygen

partial pressure we need for the depth and metabolic rate that we are at and adjusts in accordingly

- Head-up display (HUD) - displays the consumables states in the system (battery state, gas tank pressure, carbon scrubber duration).

After introducing these basic diving concepts, we will present the thesis objective and outline in Section 1.1. Then we will review the motivation and background for the problem we are studying in this thesis, as well as a literature review of previous efforts in this field.

1.1 Thesis objective and outline

The focus of this thesis is on life support systems, specifically air revitalization loops that keep humans alive in harsh environments, such as deep in the oceans or far out in the unwelcoming vacuum of space. Both astronauts and rebreather divers need a specific gas combination at set pressures in order to explore and work in those environments and we use similar systems for these tasks. We have chosen to study, model and simulate a unified system configuration that can be used both for Earth and Space applications. We briefly presented its configuration in Figure 1-2. In the spacesuit, the rebreather is integrated in the life support equipment backpack, shown in Figure 1-3.

On Earth, as well as in space, we would like to extend our exploration time and keep the equipment weight to a minimum, because the effort to carry it would be a burden to the explorer. In order to do this, we need to study other methods to control the oxygen gas addition in the diaphragm. On one hand, there are systems that automatically dose the oxygen, irrespective of the diver's activity. These systems have been shown as being wasteful in their oxygen dosage, and the diver is exposed to oxygen toxicity issues or hypoxia [52]. On the other hand, there are manual oxygen dosing systems, that are heavily prone to failures as shown in Section 1.3.3. Therefore,

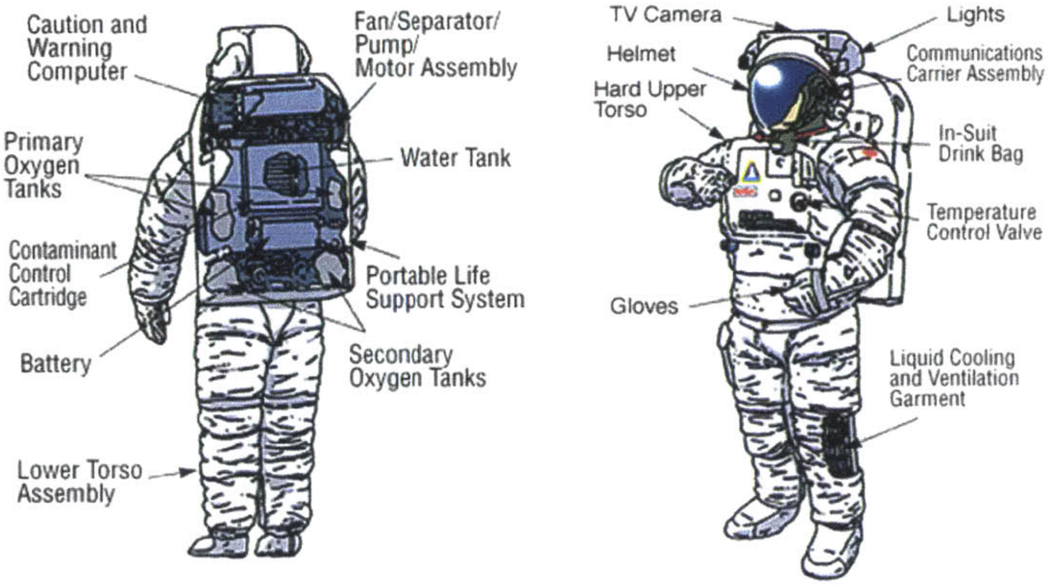


Figure 1-3: A spacesuit - the rebreather system is integrated in the backpack [6]

systems that automatically dose the oxygen and adapt this dosage as a function of diver activity are preferred and these are what we are studying here.

The research questions we are looking into are the following:

1. What configurations of air revitalization systems (gas tank sizes and gas control methods) can achieve a specified mission endurance, where endurance is defined as the lifetime of the mission?
2. What is the maximum endurance that an air revitalization architecture can achieve, given a set gas tank size?
3. How does the tradespace of mission endurance versus the gas control method look like?

We aim to answer the questions above using an analytical model of an air revitalization systems, particularly a rebreather, that we will model and simulate in this thesis.

The hypothesis we are investigating is that more advanced control methods will help increase the oxygen endurance for a fixed gas tank size.

The thesis starts with Chapter 1, containing the motivation, then we introduce the reader to diving, its effects on the human body and then explain why we need life support systems when diving and what are their main tasks. We then present the evolution of rebreather systems over time, what analytical models have been developed and the problems that these systems have experienced during diving, as shown in accident reports.

Chapter 2 illustrates how we constructed the analytical model presented in this thesis. The main challenge was to develop an accurate model of the human breathing process. The human body does it unconsciously, but we explained how we translated this into computer language and the associated assumptions Section 2.1. Then we present the structure of the model and the problem statement in Chapter 2.

We then particularize the generic model we build in Chapter 2 in Chapter 3. We state the assumptions that serve to transform the generic model into a model of the US Navy MK16 rebreather, then, in the following Section, we describe the model components. The Chapter ends by showing several strategies for maximizing oxygen duration documented in the literature and presents the application of some of these on the model developed in this thesis. It also answers the research questions and investigates the tradespace formed by the mission endurance and control complexity.

In Chapter 4 we present advanced applications of the MK16 rebreather model: we vary the diver metabolic rate and the depth at which the system operates and analyze the results. We also show how the model can be used to reconstruct some of the most frequent diving accidents involving rebreathers.

This thesis ends with Chapter 5, where we draw the conclusions and underline the most important points of the analytical model developed in this thesis, as well illustrate the open issues subject to future work. Figure 1-4 summarizes the thesis chapters and their contents.

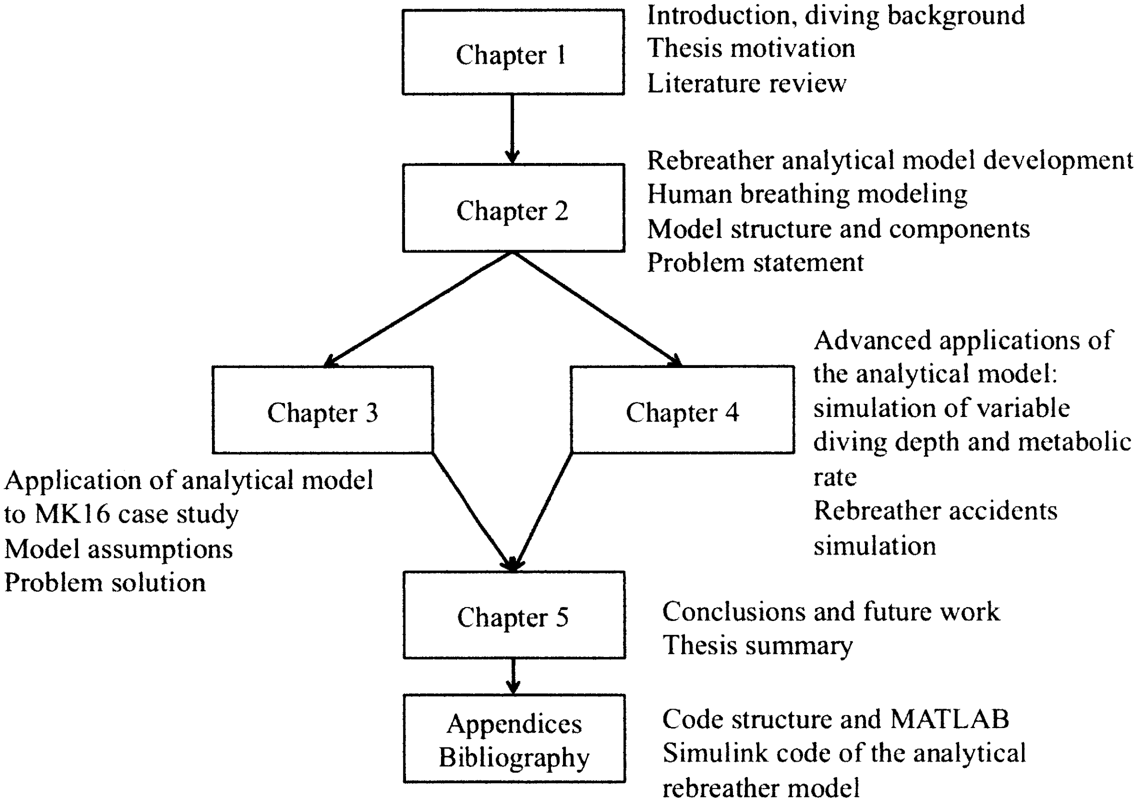


Figure 1-4: Thesis outline

1.2 Motivation and background

Although diving or traveling into space does not need a long motivation list, we need to be aware of the risks and dangers that the human body might face when performing these activities. This keeps us safe and helps us enjoy these activities even more!

The model that will be built in the next chapters is that of a generic ventilation and air revitalization loop for space and Earth applications, but in the next chapters we will use the unified term of a rebreather model to describe it, while keeping in mind its generality and multiple application range.

This Section starts off by introducing basic diving concepts, such as pressure, buoyancy, shows us how to calculate the necessary air for a dive. We then present the effects diving has on the human body and we give the acceptable ranges for oxygen, carbon dioxide and nitrogen during a dive. Having reviewed all this, we will then explain the necessity of life support systems while diving and present a short history of their development.

1.2.1 Diving basic concepts

In order to build an analytical model of a diver's equipment, we need to understand the main forces and challenges that divers encounter underwater, presented in the next subsections.

Pressure

This Section looks at how pressure changes underwater and reviews the fundamentals of pressure and scuba diving.

Pressure increases with depth: the deeper a diver descends, the more pressure the water above him/her exerts on the diver's body. The pressure a diver experiences is a sum of the pressures above him, both of the water and the air. Most pressures in scuba diving are given in a unit called ata, used in place of the atmosphere (atm) to indicate that the pressure shown is the total ambient pressure on the system. For example, an underwater pressure of 3.1 ata would mean that the 1 atm of the air above the water is included in this value. Additionally, every 10 meters (33 feet) of salt water exert 1 ata of pressure [7].

The water pressure will compress the air: the air in a diver's body air spaces and gear will compress as the pressure increases (and expand when pressure decreases). Air compresses according to Boyle's law:

$$pV = constant \tag{1.1}$$

This law states that as the pressure changes, the volume of the gas in the diver's body and soft equipment changes too. As the diver descends, the increase in pressure causes the air in the body's air spaces to compress. The air spaces are for example the ears, mask and lungs feel like vacuum because the compressing air creates a negative pressure. This can cause delicate membranes, like the ear drum, to be sucked into these air spaces causing pain and injuries. On ascent, the reverse happens: the air spaces expand as a consequence of decreased pressure. The air spaces in the lungs and the ears of the diver experience a positive pressure as they become overfull of air. If the diver does not breathe properly under water, this process could burst his/her ears or lungs.

In order to prevent a pressure related injury, divers must equalize the pressure in their body's air spaces to the pressure around them. To equalize the pressure in the diver's air spaces on descent, the diver adds air to his body airspaces to counteract the "vacuum" effect (this can be done by breathing normally, as this adds air to the lungs, adding air to the mask by breathing out of his nose or adding air to the ears and sinuses using pressure equalization techniques). During ascent, the diver needs to release air from his airspaces, because the ambient pressure decrease causes the air to feel as if it has too much volume (this can also be done by breathing normally and allowing the body to eliminate the extra air from the lungs and by ascending slowly and allowing the extra air in the diver's ears, sinuses and mask to bubble out on their own).

Buoyancy

Buoyancy is an object's tendency to float. In scuba diving, the term is used not only to describe the diver's tendency to float, but also the tendency to sink or do neither in the water [9]:

- Positive buoyancy or positively buoyant - the object or person floats upwards in the water or remains floating on the surface
- Negative buoyancy or negatively buoyant - the object or person sinks downwards in the water or remains on the bottom
- Neutral buoyancy or neutrally buoyant - the object or person neither sinks downward nor floats upward, but remains suspended at a single depth in the water.

Buoyancy can be defined as the net pressure acting on an object due to the fact that the object has displaced a certain amount of water: this water has the tendency of filling the space that the object now occupies, thus exerting a force and pressure on that object. This force is pushing the object upward and it is called the buoyant force. A schematic representation of this is shown in Figure 1-5.

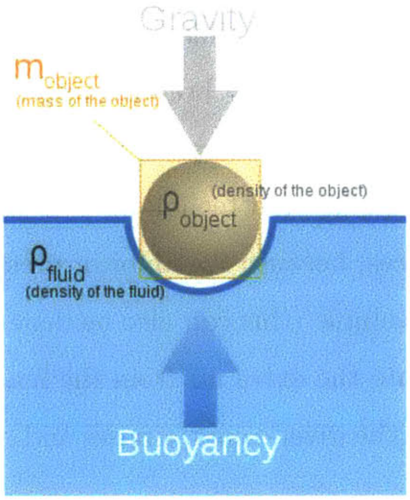


Figure 1-5: A schematic representation of buyoancy and gravity [17]

In order to determine if an object will sink or float, we can apply Archimedes's principle: if the object's weight is greater than its buoyancy, then it will sink; otherwise, it will float, and if the two forces are equal then it will maintain its depth in the water. In diving, we want to sink to a certain depth, maintain it for the duration of the dive and then slowly resurface. This implies that we need to control our buoyancy. Since our bodies displace a fixed amount of water, we need an external device to help control the buoyancy: this is an inflatable jacket called the buoyancy control device (BCD). In general, however, the diver, the gear and the BCD (even with no air inside it) are positively buoyant, so the diver needs to carry weights with him to achieve negative buoyancy and be able to sink to the desired depth.

Calculating the air consumption rate

The air consumption rate is the mass flow rate at which the diver uses his/her air. Air consumption rates are given in the amount of air the diver breathes in one minute at the surface. There are two different methods of measuring air consumption in scuba diving: the Surface Air Consumption (SAC) rate and the Respiratory Minute Volume (RMV) rate [10].
It is useful to know the air consumption rate in scuba diving for three main reasons:

- Dive planning - the diver can use his/her air consumption rate to calculate how much time he can stay underwater at the planned depth and to determine if (s)he has enough gas to make the return trip. The air consumption rate is also useful in determining the required reserve tank pressure for a dive. It is often surprising for divers to see that the calculations indicate that more than the standard 700-1000 psi of reserve pressure may be required to get a buddy team safely to the surface. When decompression stops are made, the air consumption rate is critical in determining how much gas to carry for these stops [10]

- Determining stress or comfort level - the air consumption rate is a great tool to gauge the diver's stress or comfort level: if, during a dive at 45 feet the diver notices that (s)he used 500 psi when the typical air consumption rate for 5 minutes of diving at that depth is 200 psi, then this is an indication that something is wrong

- Identifying equipment problems - a diver who has a major leak may notice that the air consumption rate is unusually high although his/her breathing rate is normal. For example, an increased air consumption rate may be an indication that a diver's regulator may require servicing, as the breathing resistance (and so the air consumption rate) increases when a regulator requires servicing.

In short, an example of different air usage at various depths is illustrated in Figure 1-6.

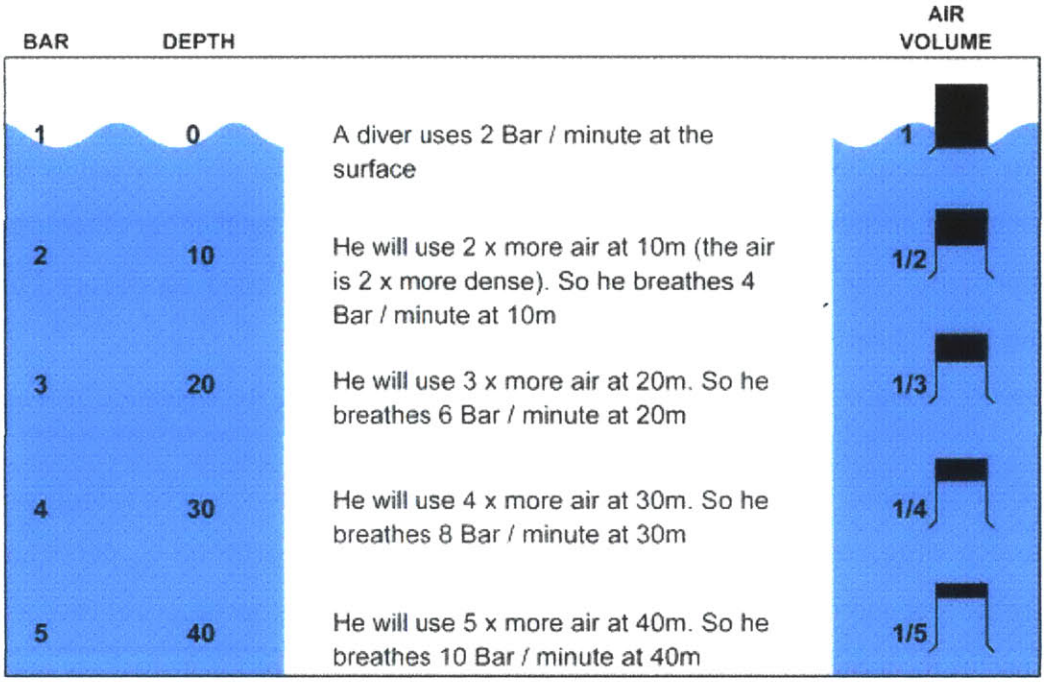


Figure 1-6: Example of an air consumption scenario during a dive [16]

Additionally, the amount of air a diver has can be modified by the tank's surrounding temperature, as described by Gay-Lussac's second law: as the temperature increases the pressure of the air in the diving cylinder increases. This is why a diver who enters the cold water with a warm diving cylinder, for example after a quick refill, will find that the pressure of the cylinder drops by an unexpectedly large amount during the early stages of the dive, when the cylinder cools down.

Calculating the surface air consumption (SAC) rate

The SAC rate is a measure of the amount of breathing gas that a diver consumes in one minute at the surface. This rate is given in units of pressure (bar or psi).

In order to determine this rate, divers will measure their starting pressure (the pressure of the air in the tank after it has been immersed in water and had a chance to cool down) and their end pressure after swimming for 10 minutes at a depth of 10 meters. Although the rate calculated by using this method will be reproducible, it is advisable that divers plan their dives conservatively, by taking into account that the real conditions may be very different from the test conditions. The formula to calculate this rate is the following [8]:

$$\{[(p_{start} - p_{end}) \cdot 10] \div (d \div 10)\} \div t = SAC \tag{1.2}$$

where p_{start} is the pressure in bar in the tank at the beginning of the test period, p_{end} is the pressure in bar in the same tank at the end of the test period, d is the average depth during the dive or the depth of the dive maintained during the test period and the t is the time in minutes is the diving time or the test period time. SAC is measured in bar/minute.

Because SAC rates are given in terms of tank pressure and not volume of air, SAC rates are tank specific:

- 500 psi of air in a standard 80 cubic foot tank correspond to 13 cubic feet of air
- 500 psi of air in a low pressure 130 cubic foot tank correspond to 27 cubic feet of air

therefore, a diver that breathes 8 cubic feet of air per minute will have a SAC rate of 300 psi/minute when diving with a standard aluminum 80 cubic foot tank and a SAC rate of 147 psi/minute when diving with a low pressure 130 cubic foot tank. Because SAC rates are not transferable between different tank sizes, the diver should first calculate its respiratory minute volume (RMV) rate, which is independent of the tank size. The diver then converts the RMV rate to a SAC pressure based on the and working pressure of the tank (s)he plans to use during the dive [8].

Calculating the respiratory minute volume (RMV) rate

The RMV rate is the measurement of the volume of breathing gas that a diver consumes in one minute at the surface. It is expressed in liters per minute or in cubic feet per minute. Unlike a SAC rate, the RMV rate is tank independent: a diver who breaths 8 cubic feet of air per minute will always breathe 8 cubic feet of air per minute, regardless of the tank size used. For this reason, divers remember their air consumption rate in RMV format, and then convert it to bar or psi based on the type of tank to be used. In order to obtain the RMV rate, we simply multiply the SAC rate with the volume of the tank, in liters:

$$RMV = SAC \cdot V_{tank} \tag{1.3}$$

For example, a diver who has a SAC rate of 1.7 bar/minute when diving with a 12 liter tank has an RMV rate of 12 x 1.7 = 20.4 liters/minute.

Having determined the SAC and RMV rates, in order to calculate how much time the air supply will last on a dive we need to calculate the pressure at a particular depth *d*, (in ata). The depth *d* is given in meters.

$$p = (d \div 10) + 1 \tag{1.4}$$

Multiplying the SAC rate with the pressure will give the air consumption rate at that depth:

$$\text{air consumption rate} = SAC \cdot p \tag{1.5}$$

The next step is to determine the available pressure: from a full tank we need to determine at which pressure you want to begin ascent (called the reserve pressure). The difference between the full tank pressure and this reserve pressure will give the available pressure. With this we can now determine how long the air in the tank will last at that depth as:

$$\text{time the air will last} = p_{\text{available gas}} \div \text{air consumption rate at that depth} \tag{1.6}$$

In order to determine the RMV and SAC rates and how long the air supply will last during a dive, we follow these five steps:

1. Determine the SAC rate for the tank we plan to use:
   For example, if a diver has an RMV rate of 0.67 cubic feet/minute, his SAC

rate calculations will be as follows: for an 80 cubic foot tank with a 3000 psi working pressure the tank conversion factor is 0.0267:

$$\text{SAC rate } = 0.67 \div 0.0267 = 25 \text{ psi/minute} \tag{1.7}$$

For an 130 cubic foot tank with a 2400 psi working pressure the tank conversion factor is 0.054:

$$\text{SAC rate } = 0.67 \div 0.054 = 12.4 \text{ psi/minute} \tag{1.8}$$

2. Determine the pressure at which we will diving:
   Using the following formulas we can determine the pressure in atmospheres (ata) experienced at different depths in salt and fresh water:

   - In salt water:

$$\text{pressure } = (\text{depth in feet} \div 33) + 1 \tag{1.9}$$

   - In fresh water:

$$\text{pressure } = (\text{depth in feet} \div 34) + 1 \tag{1.10}$$

   For example, if we descend to 66 feet in salt water we will experience a pressure of 3 ata.

3. Determine the air consumption at the planned depth: In order to do this we apply the following formula:

$$\text{SAC rate} \cdot \text{pressure} = \text{Air consumption rate at depth} \tag{1.11}$$

   For example, a diver with a SAC rate of 25 psi/minute descending at 66 feet will use:

$$\text{Air consumption rate @ 66 feet} = 25 \text{ psi/min} \cdot 3 = 75\text{psi/min} \quad (1.12)$$

4. Determine how much air we have available: first, check the tank pressure to determine our starting pressure, then determine the pressure at which we would like to begin our ascent (reserve pressure) and finally subtract the reserve pressure from the starting pressure

   $$\text{Starting pressure} - \text{ Reserve pressure} = \text{ Available pressure} \quad (1.13)$$

   For example if our starting pressure is 2900 psi and we want to begin our ascent with 700 psi then the available pressure is 2200 psi.

5. Find out how long the air will last: divide our available gas by the air consumption rate at our planned depth

   $$\text{Time air will last} = \text{Available gas} \div \text{Air consumption rate @ depth} \quad (1.14)$$

   If our available pressure is 2200 psi and the air consumption rate is 75 psi/minute at our planned depth then the air will last:

   $$2200 \text{ psi} \div 75 \text{ psi/minute} = 29 \text{ minutes} \quad (1.15)$$

Two other physics laws of relevance to diving are Dalton's law and Henry's law. Dalton's law states that in a mixture of breathing gases, the concentration of individual gas species in the mix is proportional to their partial pressure. Partial pressure is a very useful way we can express limits for avoiding oxygen intoxication or carbon dioxide toxicity, as presented in the next subsection.

1.2.2 Effects of diving on the human body

Like any experiences, diving has its risks. The extreme pressures involved can take a toll on the fragile human body if not handled appropriately. The most important medical conditions involved with diving are decompression sickness and nitrogen narcosis. These are explained in the next sections [11].

Decompression sickness

Decompression sickness, also known as the bends or Caisson disease, is an illness that can affect divers or miners - in general people who are exposed to rapid external pressure changes. It is caused by the build up of nitrogen in the body: as we breathe, we inhale about 79% of nitrogen in the air. As a diver descends, this nitrogen is absorbed in the body tissues. The problem is when the diver ascends and the lowered pressure causes the nitrogen in the blood to come out of the solution. If the diver ascends too quickly, the nitrogen escapes at a fast rate and can cause bubbles, that can transfer to the arterial blood circulation and block the blood flow to areas like the lungs, brain and other essential areas of the body. This is why divers must ascend slowly, to give their bodies time to eliminate this nitrogen through normal breathing. If the diver spent a longer time under the water than the no-decompression limit (this is a time limit that refers to the maximum time a diver can spend underwater and ascend to the surface without decompression stops along the way), then decompression stops are mandatory. Please refer to Section 1.2.2 for diving tables explanations and examples.

The treatment for DCS consists of oxygen administered on site and first aid, followed as soon as possible by recompression treatment in a recompression chamber.

Nitrogen narcosis

Nitrogen narcosis is a state of altered awareness caused by breathing a high partial pressure (or concentration) of nitrogen. The deeper a diver goes, the higher the partial pressure of nitrogen and other gases will be. This will usually limit the depth a diver can go to. Once the nitrogen narcosis sets in, the diver should ascend at a safe rate in order to reduce the partial pressure of nitrogen in the air (s)he is breathing. Thirty meters is the average depth at which divers start to experience nitrogen narcosis.

Narcosis has been called "the rapture of the deep" and many divers compare it to a pleasant state of drunkenness. Some divers use the "Martini rule" to roughly estimate the effects of narcosis during a dive: this rule states that for every increment of 18 meters depth, a diver experiences the narcotic effect of drinking one Martini. At depths of 60 meters divers are likely to experience severe narcosis and even unconsciousness.

Hyperoxia and hypoxia

Hyperoxia is the result of breathing an excessively high partial pressure of oxygen.

Oxygen toxicity is a catastrophic hazard in diving, as the seizures caused can result in near death by drowning [12]. The seizures occur suddenly and with no warning signals. As there is an increased risk of oxygen toxicity on deep dives, long dives or dives in which oxygen-rich gases are used, divers calculate a maximum operating depth for the air mixture that they are using, and the cylinders used are clearly marked with this maximum depth [13]. Diving below 56 meters on air only would expose the diver to oxygen toxicity, as the partial pressure of oxygen exceeds 1.4 bar, so a gas mixture has to be used that contains less than 21% oxygen. Augmenting the nitrogen content of the gas is not a good solution, because it would lead to nitrogen narcosis. This problem is solved by adding helium, which is not narcotic - nitrogen can be completely replaced with helium, and the resulting mix is called heliox, or by replacing a part of nitrogen with helium, and the resulting mix is called trimix.

The opposite of hyperoxia is hypoxia - a condition when there is not enough oxygen in the diver's ventilation circuit to meet metabolic requirements. If oxygen is not added to the ventilation loop, the existing oxygen will be consumed in 2-5 minutes and the remaining gas mixture is not capable to sustain life [14]. The maximum oxygen partial pressure at sea level is 120 kPa and the minimum is 10 kPa.

Hypercapnia

Hypercapnia is a condition caused by abnormally elevated levels of carbon dioxide in the blood. This can be prevented by scrubbing the carbon dioxide from the air in the rebreather system. However, monitoring the partial pressure of CO_2 is important to make sure that the CO_2 scrubbing equipment is functioning normally. The maximum carbon dioxide partial pressure is 2.93 kPa, the equivalent of 22 mm Hg [1].

Diving tables

In order to avoid decompression sickness and other problems associated with residual nitrogen, divers use dive tables. They are called no-decompression dive tables and they tell divers how long they can stay underwater at a certain depth or, conversely, how deep they can go for a certain amount of time. The most commonly used dive tables are from the Professional Association of Underwater Dive Instructors (PADI), National Association of Underwater Instructors (NAUI), National Oceanic and Atmospheric Administration (NOAA) and the US Navy. Table 1.1 shows some of the depths and time limits from this sources. The NOAA and Navy tables are similar, as shown below, and are based on research done over the last several decades by the Navy, primarily with military divers. NAUI and PADI use tables that are slightly more conservative than the Navy's and are specifically oriented towards the sports diver [18].

Note that the table below suggests that there is no time limit when diving at depths less than 20 ft. (6.1 m). While theoretically correct, the practical limit is about six hours.

A typical dive table is shown in Figure 1-7. all of these tables employ the concept of a letter group, which is a relative indicator of the amount of residual nitrogen in the body. The different tables use a different number of letter groups, but all start at A. Letter groups closer to the beginning of the alphabet indicate lower levels of residual nitrogen.Second, each standard table is comprised of three parts [18]:

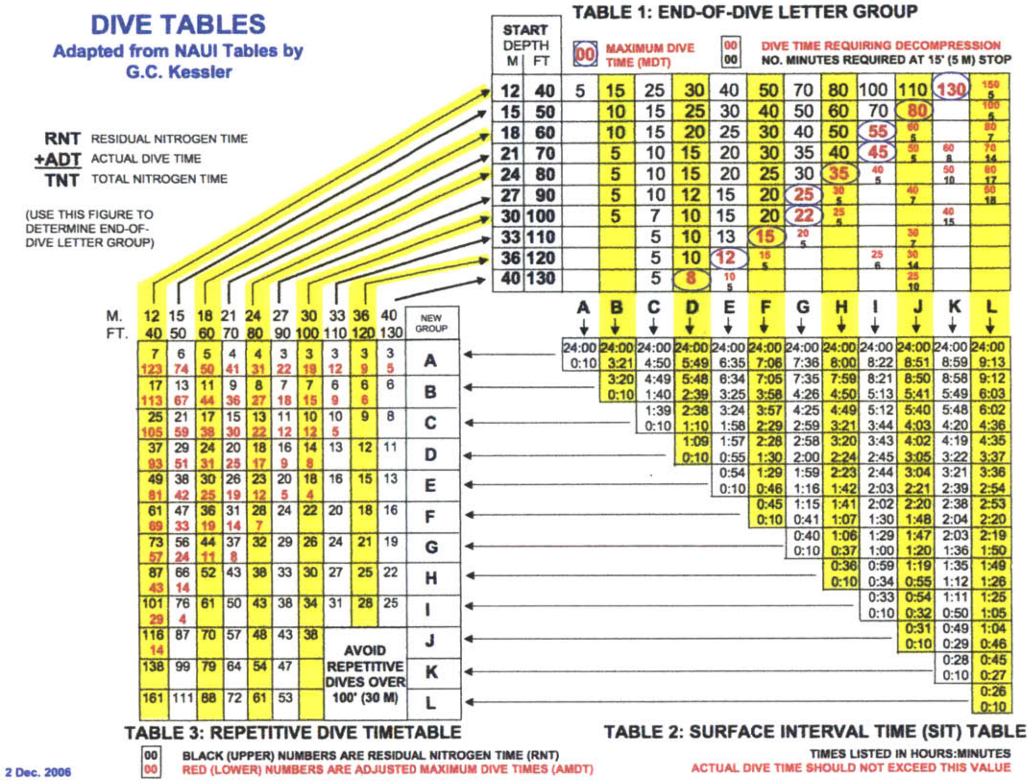
Depth (ft)	Depth (m)	NOAA and US Navy diving table	NAUI table	PADI table
0 - 20	0 - 6.1	No limit	No limit	No limit
21 - 40	6.4 - 12.2	200 min.	130 min.	140 min
41 - 50	12.5 - 15.2	100 min.	80 min.	80 min.
51 - 60	15.5 - 18.3	60 min.	55 min.	55 min.
61 - 70	18.6 - 21.3	50 min.	45 min.	40 min.
71 - 80	21.6 - 24.4	40 min	35 min.	30 min.
81 - 90	24.7 - 27.4	30 min.	25 min.	25 min.
91 - 100	27.7 - 30.5	25 min.	22 min.	20 min.

Table 1.1: No decompression dive table, sources: PADI, NAUI, NOAA and US Navy [18]

- Table 1 - End-of-Dive Letter Group: Shows the time and depth limits for no-decompression dives. Indicates the Letter Group at the end of the dive based upon the dive profile of the current dive, including the level of residual nitrogen from previous dives.
- Table 2 - Surface Interval Timetable: Defines a new Letter Group after the planned surface interval. The new Letter Group will be the same as, or lower than, the Letter Group before the surface interval.
- Table 3 - Repetitive Dive Timetable: Indicates the Adjusted Maximum Dive Time (AMDT) and Residual Nitrogen Time (RNT) for the next dive, based upon the current Letter Group [18].

1.2.3 Life support systems for diving

A rebreather is a breathing device that absorbs the carbon dioxide from the humans exhaled breath and allows the rebreathing (recirculating) of the unused oxygen in the air. Oxygen is added to this loop to replenish the amount metabolized by the user. The rebreather is different from the open-circuit breathing apparatus, in which the exhaled gas is passed to the environment (described in Section 1.2). Rebreather technology is used in a wide variety of areas: in space (when the oxygen supply is limited and the external environment (vacuum) is not able to support life), in firefighting



DIVE TABLES
Adapted from NAUI Tables by
G.C. Kessler

RNT RESIDUAL NITROGEN TIME
+ADT ACTUAL DIVE TIME
TNT TOTAL NITROGEN TIME

(USE THIS FIGURE TO DETERMINE END-OF-DIVE LETTER GROUP)

TABLE 1: END-OF-DIVE LETTER GROUP

00 MAXIMUM DIVE TIME (MDT)

00 / 00 DIVE TIME REQUIRING DECOMPRESSION / NO. MINUTES REQUIRED AT 15' (5 M) STOP

START DEPTH M	FT	A	B	C	D	E	F	G	H	I	J	K	L
12	40	5	15	25	30	40	50	70	80	100	110	130	150 5
15	50		10	15	25	30	40	50	60	70	80		100 5
18	60		10	15	20	25	30	40	50	55	60 5		80 7
21	70		5	10	15	20	30	35	40	45	50 5	60 8	70 14
24	80		5	10	15	20	25	30	35	40 5		50 10	60 17
27	90		5	10	12	15	20	25	30 5		40 7		50 18
30	100		5	7	10	15	20	22	25 5			40 15	
33	110			5	10	13	15	20 5			30 7		
36	120			5	10	12	15 5			25 6	30 14		
40	130			5	8	10 5					25 10		

TABLE 2: SURFACE INTERVAL TIME (SIT) TABLE

NEW GROUP	A	B	C	D	E	F	G	H	I	J	K	L
A	24:00 0:10	24:00 3:21	24:00 4:50	24:00 5:49	24:00 6:35	24:00 7:06	24:00 7:36	24:00 8:00	24:00 8:22	24:00 8:51	24:00 8:59	24:00 9:13
B		3:20 0:10	4:49 1:40	5:48 2:39	6:34 3:25	7:05 3:58	7:35 4:26	7:59 4:50	8:21 5:13	8:50 5:41	8:58 5:49	9:12 6:03
C			1:39 0:10	2:38 1:10	3:24 1:58	3:57 2:29	4:25 2:59	4:49 3:21	5:12 3:44	5:40 4:03	5:48 4:20	6:02 4:36
D				1:09 0:10	1:57 0:55	2:28 1:30	2:58 2:00	3:20 2:24	3:43 2:45	4:02 3:05	4:19 3:22	4:35 3:37
E					0:54 0:10	1:29 0:46	1:59 1:16	2:23 1:42	2:44 2:03	3:04 2:21	3:21 2:39	3:36 2:54
F						0:45 0:10	1:15 0:41	1:41 1:07	2:02 1:30	2:20 1:48	2:38 2:04	2:53 2:20
G							0:40 0:10	1:06 0:37	1:29 1:00	1:47 1:20	2:03 1:36	2:19 1:50
H								0:36 0:10	0:59 0:34	1:19 0:55	1:35 1:12	1:49 1:26
I									0:33 0:10	0:54 0:32	1:11 0:50	1:25 1:05
J										0:31 0:10	0:49 0:29	1:04 0:46
K											0:28 0:10	0:45 0:27
L												0:26 0:10

TIMES LISTED IN HOURS:MINUTES
ACTUAL DIVE TIME SHOULD NOT EXCEED THIS VALUE

TABLE 3: REPETITIVE DIVE TIMETABLE

M. FT.	12 40	15 50	18 60	21 70	24 80	27 90	30 100	33 110	36 120	40 130	NEW GROUP
	7 123	6 74	5 50	4 41	4 31	3 22	3 19	3 12	3 9	3 5	A
	17 113	13 67	11 44	9 36	8 27	7 18	7 15	6 9	6 6	6	B
	25 105	21 59	17 38	15 30	13 22	11 12	10 12	10 5	9	8	C
	37 93	29 51	24 31	20 25	18 17	16 9	14 8	13	12	11	D
	49 81	38 42	30 25	26 19	23 12	20 5	18 4	16	15	13	E
	61 69	47 33	36 19	31 14	28 7	24	22	20	18	16	F
	73 57	56 24	44 11	37 8	32	29	26	24	21	19	G
	87 43	66 14	52	43	38	33	30	27	25	22	H
	101 29	76 4	61	50	43	38	34	31	28	25	I
	116 14	87	70	57	48	43	38	AVOID REPETITIVE DIVES OVER 100' (30 M)			J
	138	99	79	64	54	47					K
	161	111	88	72	61	53					L

00 / 00 BLACK (UPPER) NUMBERS ARE RESIDUAL NITROGEN TIME (RNT)
RED (LOWER) NUMBERS ARE ADJUSTED MAXIMUM DIVE TIMES (AMDT)

2 Dec. 2006

Figure 1-7: Example of a NAUI diving table [18]

(where the environment is toxic) or in hospitals (where it is used by a patient under anesthesia to supply the concentrated gas to the patient without contaminating the air the medical staff breathes).

Different rebreather types are shown in Figures 1-8 and 1-9. The rebreather configuration that the model developed in this thesis is based upon will be discussed in Chapter 3.

In an oxygen rebreather, like the one shown in Figure 1-8, the diver exhales into a bag (called a 'counterlung' (4)). A scrubber (3) removes the carbon dioxide and fresh gas is added to replace the metabolized oxygen (11). This recycled gas in inhaled again by the diver. In the case of a pure oxygen rebreather, the breathing gas contains mainly oxygen, and the partial pressure of oxygen in the circuit is dependent on the

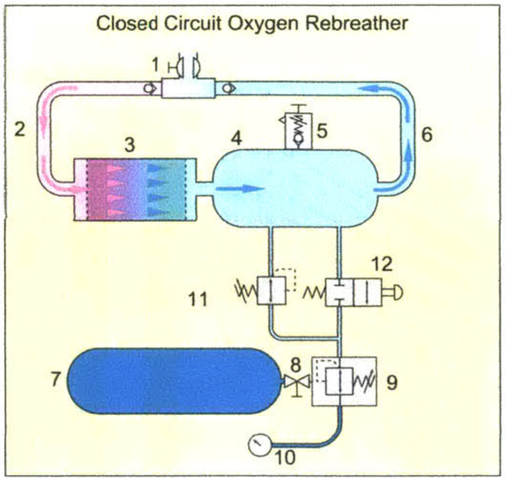


Figure 1-8: Schematic diagram of a closed circuit oxygen rebreather with a loop configuration and axial flow scrubber (1) Dive/surface valve with loop non return valves (2) Exhaust hose (3) Scrubber (axial flow) (4) Counterlung (5) Ovepressure valve (6) Inhalation hose (7) Breathing gas storage cylinder (8) Cylinder valve (9) Regulator first stage (10) Submersible pressure gauge (11) Automatic make-up valve and (12) Manual bypass valve [20]

ambient pressure. This rebreather type maximized the efficiency of gas usage and provides a bubble-free, silent diving capability useful in military applications. Due to the fact that the carbon dioxide absorption in the scrubber (3) is an exothermic reaction, the air is warmed by the heat and so the diver breathes warm, humid gas. The presently recommended oxygen partial pressures for maintaining life range from 0.1 bar (10.1 kPa) to 1.6 bar (162 kPa). A partial pressure above this upper limit may lead to acute oxygen toxicity, manifested by epilepsy-like convulsions, which is fatal underwater. A ppO_2 under this limit will lead to unconsciousness.

Rebreathers are classified into either semi-closed circuit rebreathers (SCR) or manually or electronically controlled closed-circuit rebreathers (mCCR or eCCR). In a SCR, oxygen enriched gas is pumped through a constant flow injector into the circuit, typically at 6-12 bar L/min to substitute the metabolized oxygen. Excess gas in the circuit is vented through an overpressure valve. The maximum depth that a diver can reach using this circuit is limited by the percentage of oxygen in the supply gas. In a CCR, the partial pressure of oxygen is kept at a constant level. In mixed-gas diving, the breathing gas in the CCR contains nitrogen or helium. To maintain a constant

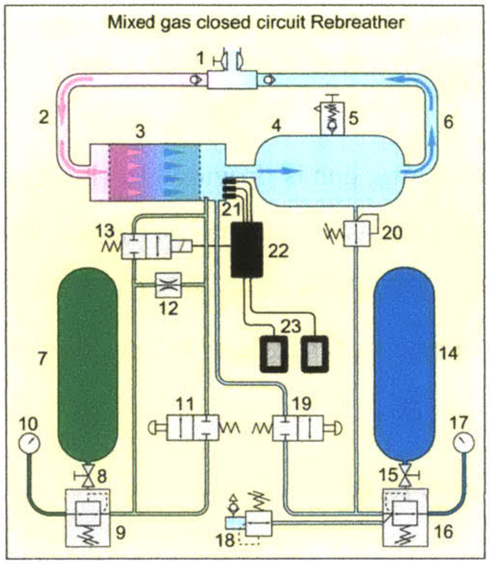


Figure 1-9: Schematic diagram of electronically controlled closed circuit mixed gas rebreather (1) Dive/surface valve and loop non-return valves (i.e. 'mouthpiece') (2) Exhaust hose (3) Scrubber (axial flow) (4) Counterlung (5) Overpressure valve (6) Inhalation valve (7) Diluent cylinder (8) Diluent cylinder valve (9) Absolute pressure diluent regulator (10) Diluent submersible pressure gauge (11) Diluent manual bypass valve (12) Diluent constant mass flow metering orifice (13) Electronically controlled solenoid operated oxygen injection valve (14) Oxygen cylinder (15) Oxygen cylinder valve (16) Oxygen regulator (17) Oxygen submersible pressure gauge (18) Bailout demand valve (19) Manual oxygen bypass valve (20) Automatic oxygen valve (21) Electronic control and monitoring circuits (22) Primary and (23) secondary display units [20]

oxygen partial pressure, a control loop is needed. This loop contains electrochemical oxygen sensors, whose output is proportional to the partial pressure of oxygen; these are the sensor elements. In a mCCR, the diver manually adjusts the oxygen partial pressure by adjusting the oxygen injection valve or adding oxygen manually. In an eCCR, this task is usually performed automatically, by a microcontroller actuating a solenoid valve [43].

Both types of closed rebreather systems have many advantages:

- Gas efficiency: open circuit scuba diving has a gas efficiency of less than 5% on the surface, to below 0.5% at 100 msw depth. In a CCR, because the gas is recycled, this gas efficiency reaches almost 100% and so the design of these rebreathers is smaller and light-weight than OC scuba, but more complex

- Silence: the CCR allows bubble-free operation, only during the ascent phase is gas vented from the circuit

- Warm, humidified breathing gas is provided to the diver, due to the exothermal carbon dioxide absorption reaction in the scrubber. Cold breathing gas in cold water may lead to the regulator freezing; in a CCR this is avoided. The downside to operating a CCR in cold water is that the scrubber efficiency can be impaired.

1.3 Literature review

This Section presents a history of previous rebreather systems and previous efforts to create analytical models to analyze these systems. Here we present some of the characteristics of past rebreather models and that we will incorporate in this development process, shown in Chapter 3. The last part of this Section describes scuba and rebreather accident reports, which the model we are developing will simulate in Chapter 4.

1.3.1 Previous rebreather systems

Although diving was an activity we were interested in for many years (for example pearl divers), the first man to consider a self-contained underwater breathing apparatus was probably Giovanni Alfonso Borelli, a mathematician, in 1680. From that date onwards, numerous people were involved in the development of an Underwater Breathing Apparatus (UBA): Frederic de Drieberg, Klingert, Brize and Fradin, Abbe de la Chapelle just to name a few. Abata Felice Fontana (an Italian monk) and a Dutch physician Ingen Housz, were the first to investigate an UBA with 100% pure oxygen as breathing gas. It was William H. James in 1825 who probably put together the first design for a self contained underwater breathing apparatus. Early compressed oxygen cylinders were made of sheet copper and were formed with hemispherical ends, charged to a pressure of 30 atmospheres (441 lbs per square inch) [27].

The first rebreather that used CO_2 absorption was patented in France in 1808 by

Sieur Touboulic from Brest, a mechanic in Napoleon's Imperial Navy. It worked by circulating the air through a sponge soaked in limewater and progressively adding oxygen from a canister to the diver [15]. The first commercially available rebreather was designed by Henry Fleuss in 1878 and it was a self-contained breathing apparatus consisting of a rubber mask connected to a breathing bag, with an estimated 50-60% of oxygen supplied from a copper tank and CO_2 scrubbed by a rope yarn soaked in a solution of caustic potash, the system having a duration of three hours [19]. However, these rebreathers never actually went into production [27]; although they were purely laboratory modules, they were very relevant to the development of the Closed Circuit Oxygen Underwater Breathing Apparatus (CCOUBA).

The original submarine escape apparatus was designed by R.H. Davies in 1903-1906 and was not frequently used by the British Royal Navy. It consisted of a rubber breathing buoyancy bag, inside which there was a canister containing 1 lb of protosorb for the absorption of exhaled carbon dioxide. At the lower edge of the bag, in a pocket, there was a steel cylinder containing 56 liters of compressed oxygen at 120 atmospheres. The cylinder was providing oxygen to the bag through a control valve; the bag was then connected via a corrugated hose to the mouthpiece. The inhalation was only done through the mouth, the nose was closed using a clip [27]. The oxygen could be supplied either from externally mounted steel cylinders (located in submarines) or from small steel capsules (called oxylets), mounted inside the breathing bag. These capsules had break-off necks and oxygen was released by the diver breaking these, with his hands, in the breathing bag. In World War II, closed circuit breathing apparatus were not only used to escape from damaged or sunken submarines, but also to place demolition charges on the underwater obstructions along the north coast of France. American underwater demolition teams performed the same task on the beaches of the Pacific Islands. Quick [27] reckons that without these devices, the casualties on the beaches would have been much higher than they actually were.

The Mark I amphibian set was developed in 1908 for work in poisonous gas environments or underwater. It consisted of a steel cylinder charged with oxygen, a

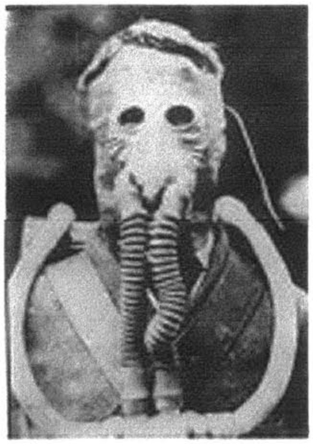


Figure 1-10: Henry Fleuss's rebreather system, the first commercially available rebreather [15]

carbon dioxide absorbent canister, nose clip, goggles, a streamlined breathing bag with excess air escape valve and, for underwater use, a lead balance weight at the back. The Mark II set was modified by adding a relief valve in front of the set and having the ability to be hand operated, as well as the breathing bag being redesigned to fit around the neck. This set had limited use underwater and was mostly employed for sewer work, some of these sets still being in use today [27].

Notable UBA are given in the following, grouped per developing country. Most of the designs are based on the same components as described above [27]:

- in the UK: the Davis submarine escape apparatus(1903-1906), the Proto CCOUBA (1906-1910), the Salvus CCOUBA (1950s), the Mine recovery suit (World War II), the Chariot or Human Torpedo CCOUBA (1941), the Frogman CCOUBA (1941), Clearance diving breathing apparatus (1951), Siebe Gorman Amphibian Mark VI (1970s)
- in Italy: the Pirelli CCOUBA and the sports set Poseidon (1941)
- in Germany: Triton (1800), Draeger submarine escape apparatus (1911-1913)
- in France: the Fenzy oxygers CCOUBA (1957), the Fenzy PO68
- in the United States: the Momsen lung for submarine escape (1927), the Lambertsen amphibious respiratory unit(1940), the Emerson MIN-O-LUNG CCOUBA

(1963).

Patents also make a significant contribution to the development of rebreather systems, for example in oxygen control in breathing apparatus [28], rebreather setpoint controller and display [29], mouthpiece supply valve control system [30], rebreather system with optimal partial pressure determination [31], rebreather having counterlung and a stepper-motor controlled variable flow rate valve [32], rebreather system with depth dependent flow control and optimal oxygen partial pressure detection [33], computer-controlling life support system and method for mixed-gas diving [34], or electronic diving mixture control [35].

The US Navy began supporting scientific diving in 1971, through its partnership with NOAA and the State University System Institute of Oceanography by sponsoring the Scientist in the Sea Program (SITS) [44]. Although the SITS program ended in the mid 1970s, it was revived in the 2000s by Florida State University and was again supported by the US Navy. The many types of US Navy divers can be classified into two broad categories: those who wear fins and those who don't. The ones who don't are the manual laborers of the underwater world, they fix what is broken, salvage debris on the bottom and assist in eliminating obstacles to the navigation. They do not need fins to get around and are carried underwater by an elevator, and then they 'walk' to work. They have assisted in trapped submarines, collecting human remains and debris from crashed aircraft and spacecraft and even collapsed bridges [45].

US Navy divers with fins use water as a means of getting to the job site that may be floating in the water or anchored to the bottom, or across the beach [46]. They use the water as a means of concealing themselves as they get into a hostile area for a potential enemy contact.

Science divers are actively searching for ways to extend their missions with minimum weight addition and expense. Scuba is on one end of the complexity spectrum, while the closed-circuit, computer controlled rebreathers are on the other end. The semi-closed rebreathers are in the middle of this spectrum. Before having computer controlled oxygen partial pressure rebreathers, the Navy used the semi-closed UBA for SEALAB and explosive ordnance disposal.

The Navy developed one of the first computer controlled rebreathers, the EX-19. The design enabled easy breathing at great depth, but the program was canceled after one of the design engineers almost died from a combination of oxygen sensor lock-out and alarm logic failure. Sensor lock-out happens when condensed moisture prevents an oxygen sensor from responding to changes in the UBA oxygen levels. A constantly changing status of the EX-19's three sensors continually reset the alarm circuitry so the alarms did not activate. This led to the affected test diver needing resuscitation [44].

After this incident, the US Navy continued to actively support science diving in terms of the development of cold water regulators, evaluating schedules for deep stops, the development of decompression computers (these run the Navy developed VVAL 18 decompression algorithm). Through NEDU's modeling and simulation efforts, scientists and divers could visualize the carbon dioxide absorption front in scrubber canisters. The stochastic gas method also been used to understand the highly dynamic process involved in freezing and reusing scrubber canisters across mission [44].

Figure 1-11 shows a summary chart in which we plot the diving depth versus the dive endurance time (defined as the lifetime of the diving system, mainly characterized by the duration of the oxygen tank). We have analyzed four main cases: open circuit scuba systems, semi-closed circuit and closed circuit rebreather systems, and Advanced Diving Systems (ADS). The fronts shown in red, orange, green and blue show the limits of a current capability. The goal of this research, as mentioned in Section 1.2, is to push these frontiers towards more endurance (as the purple arrow points to in Figure 1-11). We are investigating here if we can achieve this fact by increasing the oxygen tank control complexity.

1.3.2 Previous analytical models of rebreather systems

The first documented attempt to build a computational tool for the analysis of underwater breathing gas systems was in 1983 by Sexton and Nuckols [47]. It consisted of a "versatile computer simulator" where the virtual UBA was constructed

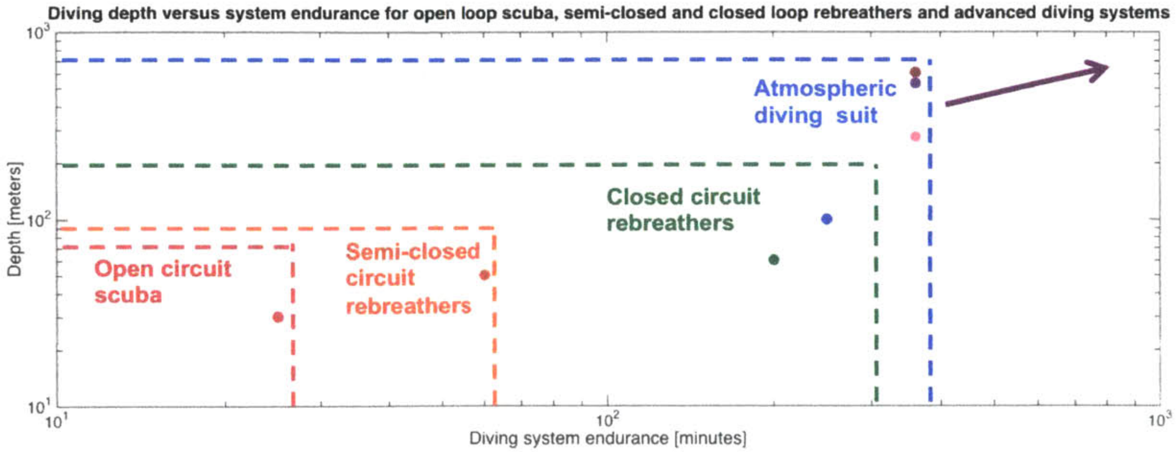


Figure 1-11: Double logarithmic plot of diving depth versus dive system endurance for open circuit scuba, semi-closed and closed circuit rebreathers, and Advanced Diving Systems (ADS)

from modules, which resided in the computer's memory. This modeling technique was to serve as the basis of a proposed breathing system simulator by the US Navy. This model was developed at the Naval Coastal Systems Center, where the design, development and resting of underwater systems was already underway for 20 years at that time. The equipment developed and tested there included everything from Scuba equipment to Mark 11 and Mark 12 diving systems. The Naval Coastal Systems Center collected the experience and the database of components to form the base of development of new systems. The goal of this model was to couple computer simulation methods with the existent diving experience at the base to create a powerful tool for the analysis and design of underwater breathing gas systems. In its final form, the simulation was supposed to reduce the cost and time required for the development of new systems and to considerably reduce the testing time of such systems. The modeled breathing system flow circuit model is shown in Figure 1-12. The model is based on the concept of "nodes" (defined as places in the circuit where the mass flow may accumulate), connected by "components" that affect the flow in some manner. The nodes are identified by circled numbers in Figure 1-12 and the components by boxed numbers. The model was based on the principle of mass conservation. The results were validated against experimental data for the Mark 14

Mod 1 UBA for operation under varying environmental conditions, such as varying diver work conditions and diving depths. The simulation was also used to explore what UBA modifications would best reduce the breathing work and so the diver's energy expenditure during the dive. This Fortran computer model was used in the development of a Navy closed-circuit rebreather, called the EX19, mentioned earlier. This apparatus did not get approved for Navy use and since then the Navy has done very little in-house development of new rebreathers, instead relying on adapting commercial rebreathers (such as the MK16) [57].

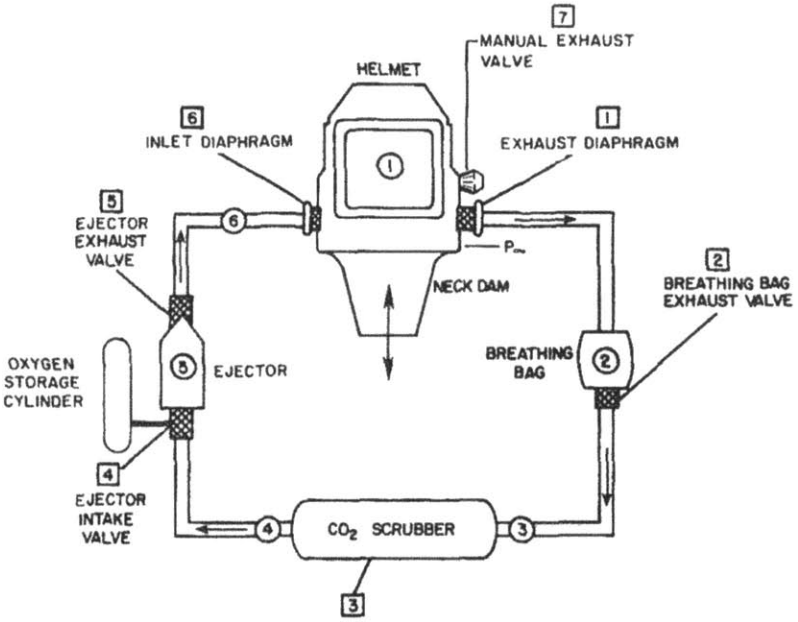
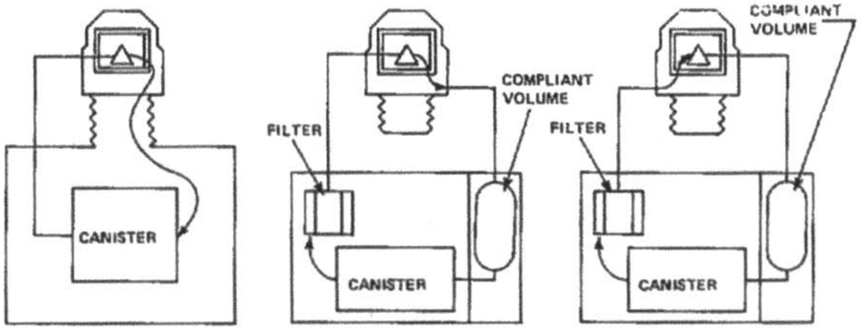


Figure 1-12: System flow circuit modeled in 1983 in Fortran by Sexton and Nuckols [47]

Using the model developed by Sexton, 14 breathing circuit concepts were investigated. Out of these, three models were selected for UBA design (shown in Figure 1-13 [49]). The model not only proved useful in rapid system analyses and computation of peak inhalation/exhalation pressures and external work of breathing (which were the measures of effectiveness for the UBA), but also it was used to derive a series of characteristics that all good UBA candidate designs should have, like for example the backpack should have minimum dry volume, compliant volumes should be used on each side of major resistances in the helmet should have little to no volume to maximize its compliancy [49].



CONCEPT 12: INTEGRATED HELMET/DRY BACKPACK

CONCEPT 13: ORAL/NASAL WITH BREATHING BAG EXHALE INTO HELMET

CONCEPT 14: ORAL/NASAL WITH BREATHING BAG INHALE FROM HELMET

Figure 1-13: Schematic of the 3 UBAs chosen for implementation from the 13 suggested using the Fortran model [49]

In 1987, the same model was used to vary the canister filter resistance, inlet and exit valve areas in the mask and the initial breathing bag volume in order to determine the optimum design for reducing the breathing resistance. As a result of modeling the closed-circuit breathing systems, the article [49] concluded that the area of the inlet and exit valves to the diver's mask are crucial to the diver's comfortable breathing, the resistance of the filter surrounding the carbon dioxide scrubber should be minimized and the initial volume contained in the breathing bag should be set at 25% of the bag's total volume [50].

In the 2000s, the oxygen partial pressures in a semi-closed circuit rebreather were predicted using a similar model to that developed by Nuckols [49]. The aim of these predictions was to develop techniques to prolong the endurance of the oxygen canister and verify that alternatives to the traditional circuit design are feasible. These analyses were applied to semi-closed circuit rebreathers, since closed-circuit rebreathers, such as the MK16, are deemed to be unpopular due to their size and complexity [52].

In 2001, the discrete kinetics of carbon dioxide absorption were modeled in Visual Basic 6.0. It was based on stochastic principles and was used only for didactic purposes. It was based on repetitive applications of small forces acting on up to 250,000 discrete volume elements (cells) within a simulated carbon dioxide absorbent bed in a rebreather scrubber canister [53].

Recent analytical models ([48, 54]) have focused on the development of new mathematical models to describe the gas dynamics in the breathing systems, particularly in semi-closed rebreathers. Their assumptions for this model are the following:

- The breathable air is made up of an inert gas (nitrogen or helium) and oxygen
- The breathing gases behave as a perfect mixture
- The recipient internal pressure instantaneously equals the external pressure
- The respiration is modeled by a partial oxygen subtraction from the collapsible bag
- The carbon dioxide scrubber behaves ideally, capturing all produced carbon dioxide [54].

Klos [48] reports that, up to 2014, only Sweden and the US have tried to build a metabolic simulator and tried to solve the problem of establishing adequate mathematical models of breathing space ventilation in a semi-closed and closed diving apparatus atmosphere. Their focus was on establishing an adequate mathematical model for ventilation of breathing space and human decompression after breathing an artificial hyperbaric atmosphere. Previous models exist for anesthesiology, but work at atmospheric pressure.

1.3.3 Accident reports

Although the principles of operation of closed circuit rebreathers (CCRs) have been well understood for more than a century [27], the practical problems associated with the implementation of the oxygen control unit precluded their widespread use until the 1980s, when reliable oxygen fuel cells were introduced. The consequent miniaturization and cost reduction of these units allowed the CCR to be developed for civilian markets in the late 1990s [26]. Rapid advancements in technical diving triggered a fast adoption of CCRs in recreational diving, especially given the high cost of performing similar divers with Open Circuit (OC) scuba. Shortly after this, civilian uses of rebreathers started to be associated with a number of deaths. Taking into account the fact that the number of CCR units in use is small compared to the OC suba, the number of rebreather deaths seemed out of proportion and seemed to suggest that there might be factors intrinsic to the CCR design that increased the risk of death [36].

Between 1998 and 2010, 181 deaths were recorded in the Deeplife database, associated with rebreather accidents. There was a peak of 24 deaths in 2005, prior to that deaths have averaged 8 per year, after that they averaged 20 per year, as seen in Figure 1-14.

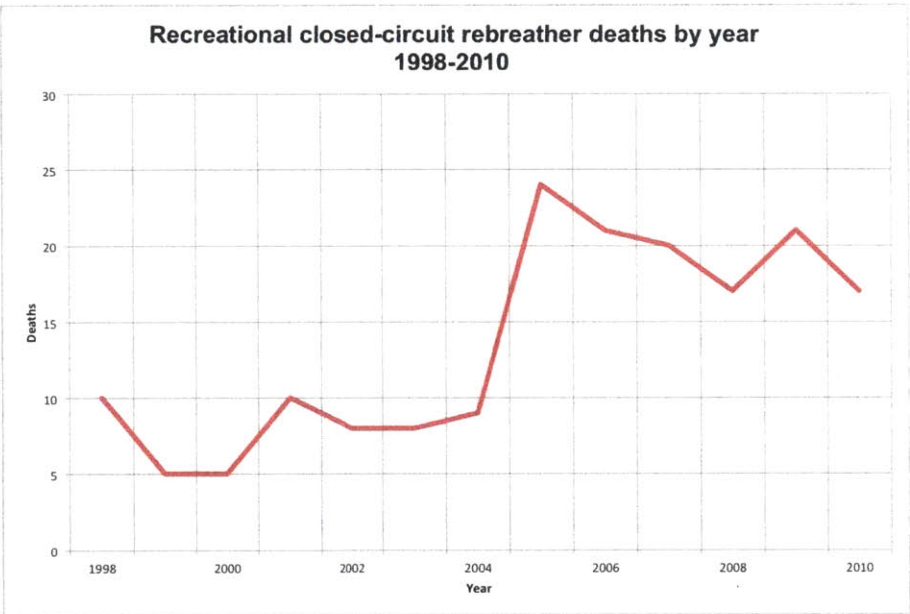


Figure 1-14: Recreational closed-circuit rebreather deaths by year 1998-2010 [26]

Based on survey data, it was estimated that an average of approximately 30 dives per year per CCR diver were performed, with most active divers having between 20-50 dives each year. At an annual rate of 20 dives per year, this equates to an estimated death rate of 4 per 100,000 deaths per year or approximately 10 times that of non-technical recreational OC scuba diving deaths [26]. The Rebreather World (RBW) forum contains registered users of CCR, as well as their equipment type. The mortality data associated with CCR were obtained from the Deeplife database, a British Sub-Aqua Club (BSAC) study covering the period from 1998 to 2009 and the

Divers Alert Network (DAN) Asia - Pacific Australasian diving mortality database [36, 37, 38]. The causes of the 181 fatalities are listed in Table 1.2. Of the total of 181 deaths, 31.5% had insufficient data to form any conclusions, 44% were attributed to equipment-related problems, 24% to diving-related problems and the remainder were a mixture of problems such as acute myocardial infarction, loss of consciousness from diabetes mellitus etc. In the BSAC data (27 deaths), there were scant data in 7 cases, from 14 cases there were 4 in which the equipment failed and 11 cases in which the units were not turned on correctly. Only in 5 cases was the cause of death thought of to be unrelated to the type of breathing apparatus used.

In order to estimate the fatality rate, we need to know the number of active rebreather divers worldwide. However, manufacturers are unwilling to divulge the number of units sold, perhaps for fear of potential litigation if their units were associated with a high proportion of accidents and deaths. Furthermore, for units that have been available for longer than a decade (such as Inspiration^{TM}), the number of units sold no longer represents the number of active units in use. Without a good estimate of the total number of rebreathers in active use, the risk associated with each unit or user is difficult to quantify and, even if manufacturers were to reveal the number of units produced, this would not account for the number of units not in active use nor the number of dives done per year per unit. Assuming 14000 CCRs in current use (from selling reports of different manufacturers) and the fact that CCR divers conduct approximately 20-50 dives per year, we obtain a mortality rate of between 3/100,000 dives and 7/100,000 dives, approximately 10 times those for OC scuba diving. Taking into account the fact that the confidence intervals for these Figures would be very wide, we will assume a rate of 5/100,000 to be correct, then this would make CCR diving approximately 5 times more dangerous than hand gliding and 10 times more so than horse riding, although 8 times less dangerous than base jumping (Table 1.3).

BSAC data from 1998-2010 indicates that CCR divers in the UK were approximately four times more likely to sustain a fatal diving accident than open-circuit divers. These represent 14% of the fatalities but only 4% of the dives. The data from the BSAC is considered to be the most reliable data available by Fock [26]. 38%

Cause of death	**Number**	**%**
Hypoxia	31	17
Hyperoxia	7	4
Hypercapnia	17	9
Acute myocardial infarction	15	8
Arterial gas embolism	12	7
Pulmonary barotrauma	6	3
No training	2	1
Drowning	5	3
Inert gas narcosis	4	2
Entanglement	1	1
Other	24	13
Scant data	57	31
Total	181	100

Table 1.2: Recreational closed-circuit rebreather deaths by stated cause; note the large number of cases in which there is scant information; in many other cases, while a cause of death is given, little evidence is available to corroborate that analysis [26]

Sport	**Death per activity**	**Deaths per 100,000 activities**
Base jumping	2,317 jumps	143.16
CCR diving	18,750 dives	5.33
Sky diving	101,000 jumps	0.99
Hang gliding	116,000 flights	0.86
Horse riding	175,418 rides	0.57
Scuba diving	200,000 dives	0.5

Table 1.3: Comparison of fatality rates of various high-risk sports [26]

of these deaths are associated with diving depths greater than 40 msw, independent of the equipment used. Diving beyond 40 msw represented 11% of the dives in this study, equating to a three-fold increase in the risk of death due to just depth alone. If we assume that CCR are used when diving at those depths, this raises the issue as to what extent the breathing apparatus itself is responsible for these incidents and to what extent are these caused by the deep, dangerous environment. In the BSAC mortality data for OC diving, 13 cases were caused by equipment failure and in 36 cases the divers ran out of gas. Despite the perceived relative simplicity of the OC equipment, almost 9% of deaths were caused by equipment failure. The Deeplife database indicates that this number increases to 30% in the case of CCR.

It is unsure whether the doubling of accidents in 2005 is due to the increase in variety of CCR units available or to a sudden adoption of CCR by the larger diving community. CCR divers were much more commonly seen on commercial dive boats after this time, but there is no increase in corresponding certifications from the major US based training agencies.

Accident analysis must be performed with great care, since the information in databases can often be uncorroborated and be based on scant information. Nonetheless, cases of divers attempting very deep dives with limited experience and divers continuing to dive despite the CCR alarms indicating problems to the equipment seem to recur in reports. While it does appear that much of the increased mortality associated with the CCR use may be due to the high-risk behaviors and the risks of diving at depths, the complexity of the CCR themselves means that they are, by nature, more prone to failure than the OC equipment. In his analysis of mechanical failure risk on the Wakulla Springs project, Stone derived fault trees for various equipment configurations and calculated that the risks of purely mechanical failures for CCR result in a theoretical risk increase of failure of 23 times compared to an OC scuba configuration [39]. Therefore, the assumption that the CCR is less mechanically reliable is considered plausible and this is why most CCR divers carry OC cylinders for 'bailout' in case of CCR failure. When the presence of a redundant scuba is included in the failure risk calculations and compared to an OC diver conducting a decompression dive with two decompression gases, the overall risk of overall mission critical equipment failure becomes similar [39].
The computer simulation of a rebreather system can be used to reconstruct and explain these accidents.

Generally, rebreather fatality investigations attempt to reduce the future occurrences by identifying causative factors, primarily focusing on three areas: medical, equipment and procedural. In order to understand the sequence of events leading to an accident, Vann and Pollock [41] use a simplified Root Cause Analysis shown as a four-event sequence, shown in Figure 1-15. Event (a), called the trigger, is the earliest identifiable root cause that transformed an unremarkable dive into an emergency. Examples of this include insufficient gas, entrapment, equipment trouble (flooded dis-

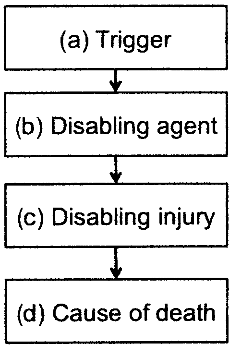


Figure 1-15: Root cause analysis for diving fatalities [41]

plays, oxygen supply failure, valves not on, electronics not turned on, oxygen sensor incorrectly installed, oxygen valve partly blocked, loose connections, gas leak in the breathing loop and bad sensor), rough seas, trauma and buoyancy issues. Some of the causes for divers running out of air include failure to monitor gauge, inexperience, overexertion or a strong current, inadequate training, poor dive planning, panic/anxiety/stress, diving deeper than usual, overweighting, faulty equipment, narcosis, a low starting pressure, the diver being tired or cold, drugs/medication or using a small cylinder [42].

Event (b), called the disabling agent, was a root cause identifiable immediately before the disabling injury. For instance, emergency ascent, insufficient gas (this may seem surprising but recall that the diluent supply in a rebreather is small and can be quickly consumed by multiple upward and downward excursions), entrapment (tangled in lift line or in lift bag, or tied self to coral and drowned).

Event (c) is the disabling injury, that caused death or rendered an incapacitated diver susceptible to drowning. Examples include drowning, hypoxia, oxygen toxicity.

Event (d) is the cause of death as specified by the medical examiner, it might be the same as the disabling injury or might be drowning secondary to the disabling injury. It is not unusual for one or more of the four events to not be identifiable.

In an analysis of the human factors in CCR failures, more than half the failures were attributed to poor training or poor pre-dive checks [40]. The experienced OC diver who takes up CCR diving was identified as being at particular risk of overestimating their ability: with OC scuba systems, there is usually only one correct response to failure. But, because of the complexity of the CCR and the interactions of physics, physiology and equipment, there are many possible responses that allow the diver to continue breathing, not all of which result in a successful outcome. For example, let us consider a diver who entered the water with his CCR turned off. The diver had pre-breathed the unit before entering the water, but for insufficient time for the partial pressure of oxygen to fall to a critical level. Then he descended, which resulted in an increase of the oxygen partial pressure despite the consumption of oxygen from the rebreather loop. At approximately 14 msw, the diver became aware that the electronics were not turned on. His options at this time are as follows:

- bailout to OC scuba
- ascent to 6 msw and flushing the CCR wit O_2 to provide a known breathing mix that was non-hypoxic on the surface
- turning on the electronics (not recommended as the unit would recalibrate the oxygen cells underwater; however this would be possible if the correct sequence is followed).

While the partial pressure of oxygen in the breathing loop at 14 msw was still 0.2 atm and hence still breathable, if the diver ascended the pressure of oxygen in the breathing loop would rapidly descend. This diver was an experienced OC diver, so his first reaction was to return to the surface and correct the problem. As predicted, he became unconscious from hypoxia and drowned near the surface. This event occured in less than 150 seconds from the dive starting time. In this case, the CCR equipment functioned fine, it was rather a problem of failure to complete the pre-dive checks and completing the required pre-dive time. The use of basic check lists and 'good design' have been advocated to reduce the chance of human error as much as possible [40]. Such designs include:

- minimize perceptual confusion
- make the execution of the action and response of the system visible to the user

- use constraints to lock out the possible causes of errors
- avoid multimodal systems.

Ideally, diver training would exercise the acquisition of these basic skills so that they become hardwired, thereby allowing the reduction of the human error while making critical decisions.

In conclusions, in the period from the first introduction of the CCR to the commercial market in 1998 to 2010 there have been 181 reported deaths. While the total number of rebreathers in use is unknown, it is estimated that using the CCR is associated with a four- to ten-fold increased risk of death compared to the recreational OC scuba diving. Two-thirds of the reported deaths are linked to high-risk diving behavior, including starting or continuing dives with the CCR alarms active or with known faults to the equipment. There does not seem to be any particular brand of CCR more susceptible to accidents and, despite popular perception, the mechanically controlled CCR is not associated with a lower mortality than its electronically controlled counterpart. CCRs have an intrinsically increased risk of failure due to their complexity, however good design can help reduce the human error.

1.4 Chapter 1 summary

This chapter introduced the background for the thesis, as well as the most important notions and physics laws that apply to diving. The thesis objective and its outline are shown in Section 1.1: this thesis is concerned with extending the endurance of rebreather systems for Earth and Space application so that the exploration time can be increased. In order to analyze this, we are developing an analytical rebreather model, on which we will study in the next chapters how we can increase the oxygen tank endurance.

The chapter then continues by introducing the background and motivation for the thesis, presents the effects of diving on the human body and illustrates why life support systems are necessary while diving and what are the functions they need to accomplish. Then we present a literature review of rebreather systems and previous analytical models developed for these systems and the chapter ends with a survey of the most frequent diving accidents and their causes.

Chapter 2

Rebreather model development

There are numerous reasons for which analytical models of hardware should be constructed. Software models allow for preliminary calculations and tests to be simulated before the diving mission, can also be used to estimate how many resources we would need for a mission and so aid the mission planning process. These models can also be used to study the impact of different technologies on the mission endurance, for example what advantages could we obtained through the use of breathing hoses with a larger diameter or a different carbon scrubber technology. The most gain is obtained when the analytical model is used in conjunction with the hardware development process: in the beginning of this process, a generic analytical model can be constructed in order to calculate basic parameters such as how much capacity should the carbon dioxide scrubber have given multiple diver metabolic processes or depths or how big the gas tanks need to be and what is their gas composition. As the hardware development progresses, the analytical model can be refined to include the corrugated breathing hoses and calculate the breathing resistance the diver would have to face. This decision can be fed back to the hardware developers, who can adjust the diameter and length of the hoses to pose minimum resistance and so maximum efficiency. Additionally, such a model can help understand if the hoses are the unique factors influencing this breathing resistance and if not, how the other elements (like for example the filters at the input and otput of the carbon dioxide scrubber) influence each other and, in turn, influence the breathing resistance.

Breathing resistance is only one of the areas the model-hardware conjunction can be useful in. Another would be, for example, the carbon dioxide scrubber. If the model's carbon dioxide scrubber would be refined to represent various types of scrubbers available, like Sodasorb or Metox, then simulations can show which of these would be more effective and under which diving circumstances.

Overall, an analytical model can help reduce the hardware development time, improve the quality of the hardware coming out of this process through the possibility of simulating design decisions before they are made and so creating a welcoming environment for design changes and feedback loops, so that in the end the optimal decision is implemented in the final hardware. It also contributes to time and cost savings of the overall design process (when we compare the analytical model aided design process with the traditional build and test approach).

This chapter presents the methodology for the construction of the analytical model of the rebreather. All model components existent in this model are common to all types of rebreathers and their sizes can be configured as we wish, therefore we are developing a generalized rebreather model. Furthermore, we can also add or remove additional modules to create and simulate different diving configurations.

The first piece to be coded and simulated is the human breathing process, shown in Section 2.1. After the model of human breathing was built, we simulated its functionality with a 10 liter breathing bag and checked the results with what would be expected for a human breathing in a fixed volume of gas with no gas additions and no carbon dioxide scrubbing. We then added the oxygen and nitrogen tanks into the code, as well as the electronic circuits to control the addition of these gases. Afterwards, we split the single breathing volume mentioned above into two smaller breathing volumes, called mouthpiece exhalation and mouthpiece inhalation. We did this in preparation for the model's specialization to the MK16 rebreather, which features two separate breathing volumes for inhalation and exhalation.

The gas species of the human breath are based on the values indicated in the Bioastronautics Databook [22], as well as the shape of the breathing signal and its amplitude.

After completion of the analytical model of the rebreather, we are stating the problem studied in this thesis in Section 2.3.

2.1 Human breathing modeling

Respiration is the process in which air is moved in and out of the lungs, during which the tissue enzymes oxidate, using oxygen and producing carbon dioxide. Breathing is one of the physiological respiration processes needed to sustain life, delivering oxygen to the body and removing carbon dioxide. Once oxygen reaches the blood, it is moved throughout the body by the circulatory system. In addition to carbon dioxide, breathing also results in a loss of water from the body. Exhaled air has a relative humidity of 100% because of water diffusing across the moist surface of breathing passages and alveoli.

There are four subprocesses of respiration:

1. Breathing or ventilation, detailed in this Section.
2. External respiration, which is the exchange of gases (oxygen and carbon dioxide) between the inhaled air and the blood
3. Internal respiration, which is the exchange of gases between the blood and tissue fluids
4. Cellular respiration.

In addition to these main processes, the respiratory system also serves to:

1. Regulate the blood's pH (this process occurs in coordination with the kidneys) to a nominal value of 7.35 - 7.45.
2. Defense against microbes (bacteria and viruses)
3. Control of body temperature with the help of evaporative loss during exhalation.

For the purpose of this report, only the first process of ventilation will be detailed and modeled, since we are interested in the interaction between human breathing and the environment (an external process) and not in the internal processes of respiration and cellular respiration.

2.1.1 The anatomy of breathing

Ventilation is the exchange of air between the external environment and the alveoli. Air moves in the respiratory system from high pressure to low pressure, with the help of the diaphragm (a schematic of the respiratory system is shown in Figure 2-1): when the abdomen is relaxed, the volume of the body expands, causing a pressure drop in the thorax, leading to an expansion of the lungs. When the diaphragm relaxes, the air leaves the lungs due to their elasticity. This is relaxed breathing and needs little energy. When the need increases, the abdominal muscles resist expansion, the increased abdominal pressure then tilts the diaphragm and ribcage upwards with an increase in volume and the entry of air. Expiration follows the relaxation of the diaphragm and the abdominal muscles, and can be increased by the downward action of the abdominal muscles and rib cage up to the maximum tidal volume as an upper limit (as shown in Figure 2-2).

Breathing is one of the few bodily functions which can be controlled both consciously and unconsciously. The conscious control is common to many forms of meditation and yoga, as it can be used to accelerate or decelerate the heart rate. Unconsciously, the breathing is controlled by specialized centers in the brain stem, which automatically regulate the rate and depth of breathing according to the body's need over time: when the carbon dioxide increases in the blood, it reacts with the water in the blood producing carbonic acid. This causes the blood's pH to go acidic and the breathing frequency to increase, in order for more oxygen to come in to the body and re-establish the blood's pH level to the nominal 7.35 - 7.45.

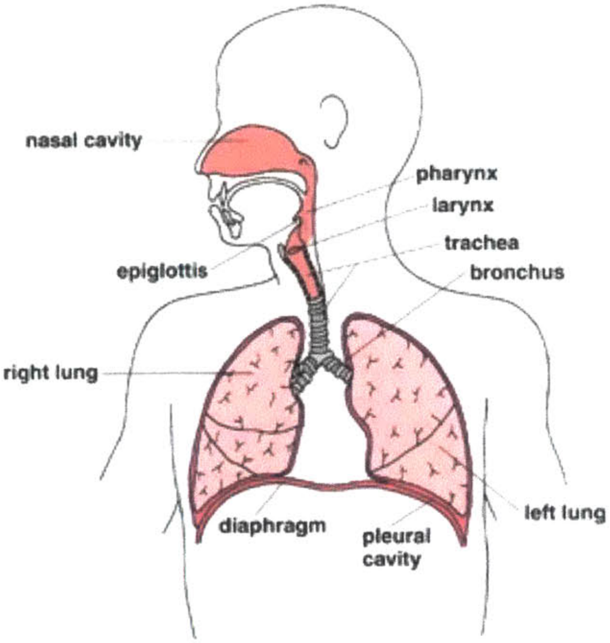


Figure 2-1: Schematic view of the respiratory system [23]

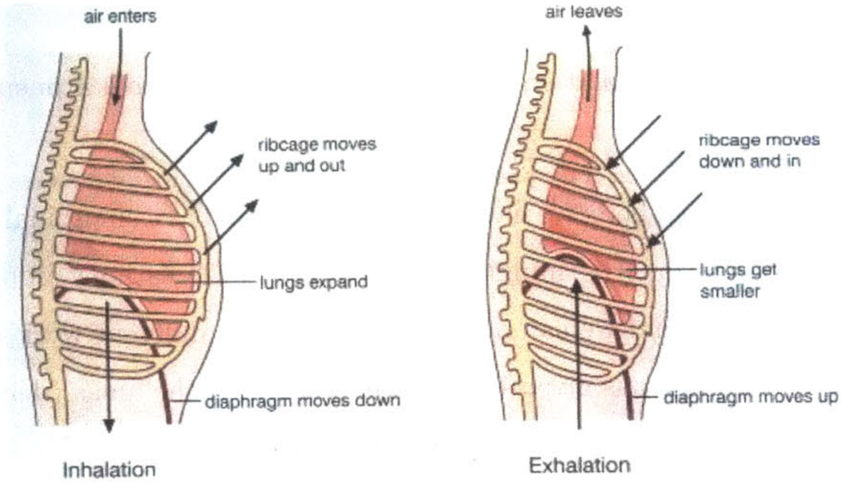


Figure 2-2: Schematic view of the exhalation and inhalation processes [23]

2.1.2 Analytical model of the human breathing

The main aspects of the human model for this research project are driven by the project requirements: to build a model of the human breathing such that we can observe the tend of metabolic gases in the diaphragm. Specifically, the model shall predict the oxygen, carbon dioxide and water concentrations in the air the human is breathing, together with its pressure and temperature.

Firstly, we need to know the shape of the inhalation and exhalation signals. Secondly, we need to know their frequency and amplitude and lastly, the composition of the air that the human inhales and exhales.

The shape of the breathing signal is illustrated in Figure 2-3.

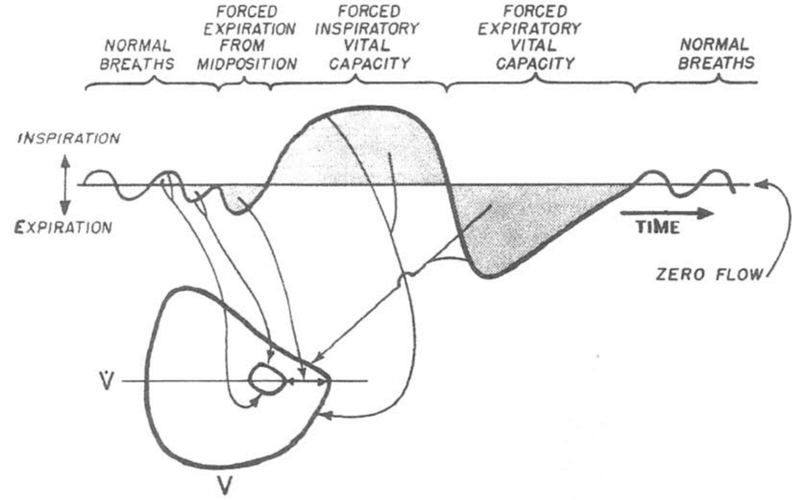


Figure 2-3: The shape of inhalation and exhalation processes from a pneumatogram [22]

In the model developed here, we have been approximated as a sinusoidal waveform, with a frequency of 20 breaths/minute at rest [22]. The breathing amplitude is a parameter in the model and we can adjust it to represent different work intensities. This amplitude of this wave is given by the tidal volume of the lungs (defined as the volume of gas inspired or expired during each respiratory cycle). The Bioastronautics Databook contains Figures (such as Figure 2-5), giving the total lung capacity, vital capacity and residual volume in normal adult males, which can be used to determine the tidal volume (as shown in Figure 2-4) based on the inspiratory and expiratory reserve volumes. Additionally, the normal breathing frequency is indicated as being 5-30 breaths/minute, with the total ventilation as given in Table 2.1.

After combining all the information presented above, we constructed a human breathing model. The signals that trigger the inhalation and exhalation processes are sinusoidal, and shown in Figure 2-7. The composition of the inhaled and exhaled air,

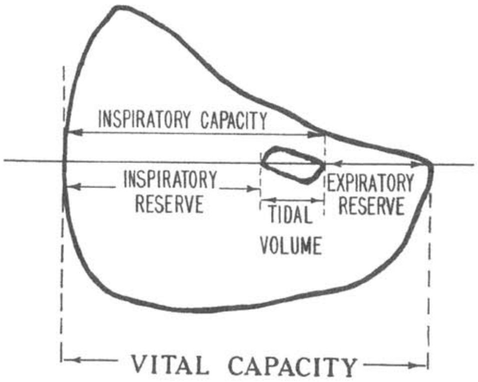


Figure 2-4: A zoom into the breathing shape: the maximum velocity/volume loop; the tidal volume can be determined from the vital capacity of the lungs using the inspiratory and expiratory reserve [22]

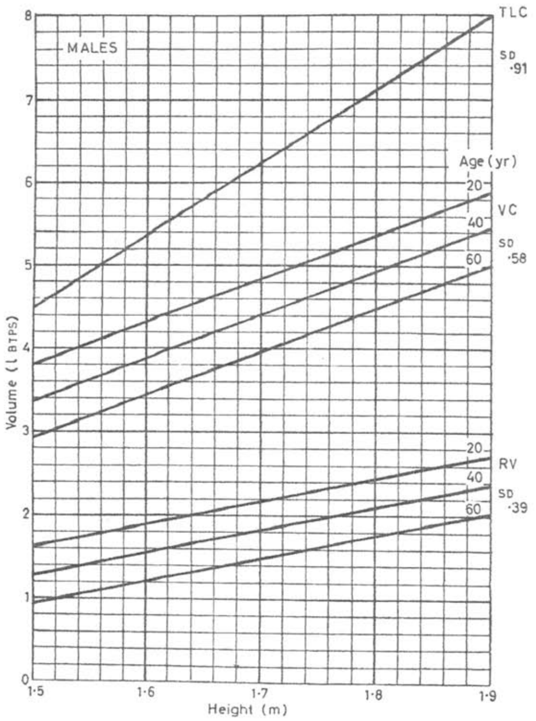


Figure 2-5: Total lung capacity (TLC), vital capacity (VC) and residual volume (RV) in normal adult males [22]. The vital capacity is the most important for diving.

as well as its amplitude, is changing according to a simplified model of the human metabolism, as follows:

1. The carbon dioxide output amount is determined by the oxygen input, multiplied by the respiratory quotient (RQ), considered to be 0.85

Breathing rate (breaths/minute)	Total ventilation (litres/minute)
5	6.75
10	7.5
20	9
30	10.5

Table 2.1: Breathing rate and the corresponding total ventilation [22]

2. The oxygen amount exhaled is $(1 - RQ)$ multiplied by the amount of oxygen inhaled
3. The amount of nitrogen exhaled is 0.94 of the amount of nitrogen inhaled
4. The exhalation breath is considered to be saturated with water vapor (100% relative humidity).

All the numbers above are based on the following Table, detailing the exhaled air composition of a human based on what (s)he inhaled [22].

Activity	Oxygen (mmHg)	Carbon Dioxide (mmHg)	Water (mmHg)	Nitrogen (mmHg)	Total (mmHg)
Inhalation	158	0.3	5.7	596	760
Exhalation	116	32	47	565	760

Table 2.2: Inhalation and exhalation components by partial pressure in a 760mmHg total pressure [22]

The implementation of the human module is shown in Figure 2-6. We start with a sinusoidal signal that gives the frequency and amplitude of the breathing signal. The equation for this signal is:

$$B(t) = (A/2) \cdot sin((2\pi/3) \cdot t) \tag{2.1}$$

where *B(t)* is the breathing signal, A is the amplitude of the inhalation and t is time. Then signal is routed to the breathing signal generator, which takes this trigger signal and splits it into a breathing out and breathing in waveforms. These are then fed to the human model, which, in function of the RQ and the gas composition in the

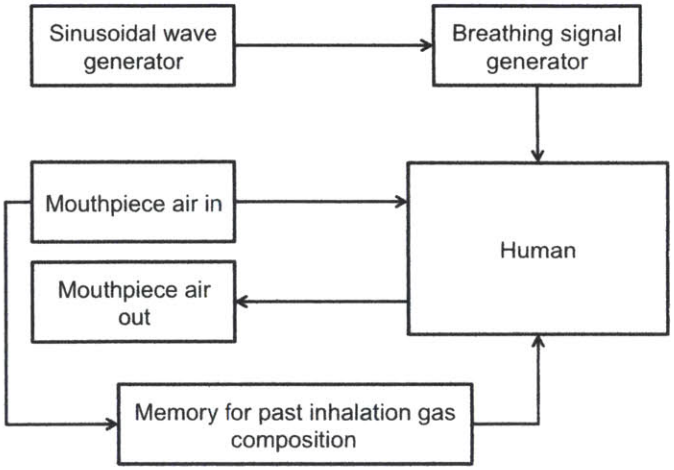


Figure 2-6: The human module implemented in the rebreather analytical model

mouthpiece inhalation, creates the exhaled gas and determines its composition, using Table 2.2. The human model needs memory as well, because the human exhalation composition is based on what was previously inhaled, so we need to remember this and feed it back to the human module to correctly calculate the exhalation gas composition.

The breathing in and out trigger signals are given in Figure 2-7.

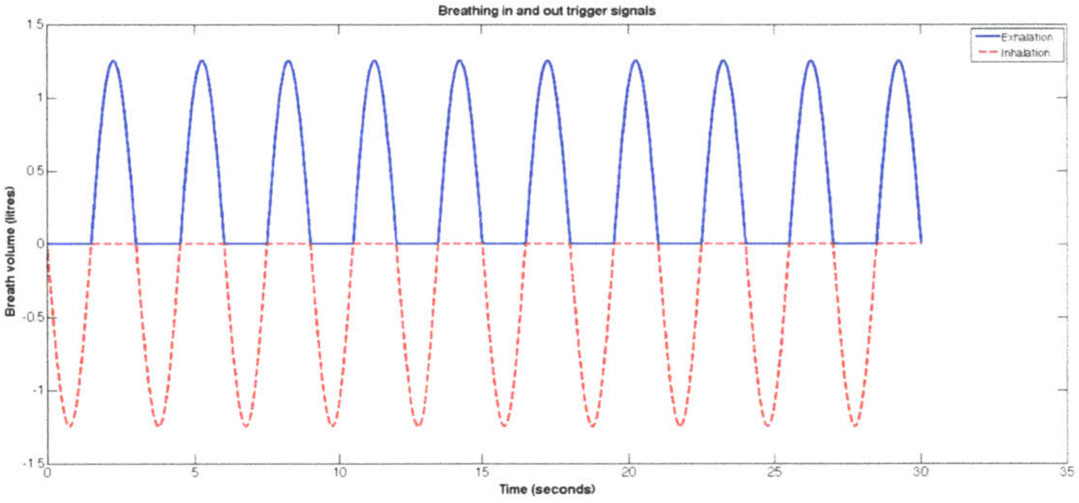


Figure 2-7: The modeled breathing in and out signal

Generally, the model accounts for the fact that the exhalation rate and air composition is a function of the inhaled air in function of different diver metabolic rates.

Specifically, the following are implemented in the model:

- The output air composition and rate is adapted to the inhaled air composition and rate
- The sinusoidal breathing pattern in Figure 2-7 is used to trigger the inhalation and exhalation processes, the rates and compositions are calculated as previously explained
- At each point, the model 'remembers' what was previously inhaled - the model has memory
- The human inhales air from the volume he lives in - the inhalation air composition is modified as the air in the mouthpiece inhalation is modified.

In order to validate that the calculations and the human breathing model, we conducted the following test: we modeled a mouthpiece of 10 liters and assumed the human breathes in it. No gas tanks or carbon dioxide scrubber were implemented at this point. This situation is illustrative for example of the case when a human breathes in a pocket of air under a capsized boat or of a human breathing in a similar air pocket that formed as a result of a mine disaster or avalanche.

The air parameters monitored in the model are:

1. Air pressure [kPa]
2. Air temperature [degrees K]
3. Air mass flow rate [kg/second]
4. Air density [kg/m^3]
5. Air mass [kg]
6. Oxygen mass fraction [-]
7. Carbon dioxide mass fraction [-]

8. Water mass fraction [-]

9. Nitrogen mass fraction [-]

The human is modeled to be a 30-year old male, 1.7 meters height (for this specific human, the Bioastronautics Databook indicates the inhalation and exhalation tidal volumes). The metabolic rate is modeled as heavy exercise. The air in the mouthpiece exhalation is assumed to be 78.24% nitrogen, 20.78% oxygen, 0.0394% carbon dioxide and 0.75% water ([22], Table 11-2). These being given, the following graphs illustrate the evolution of gases in the mouthpiece over one minute.

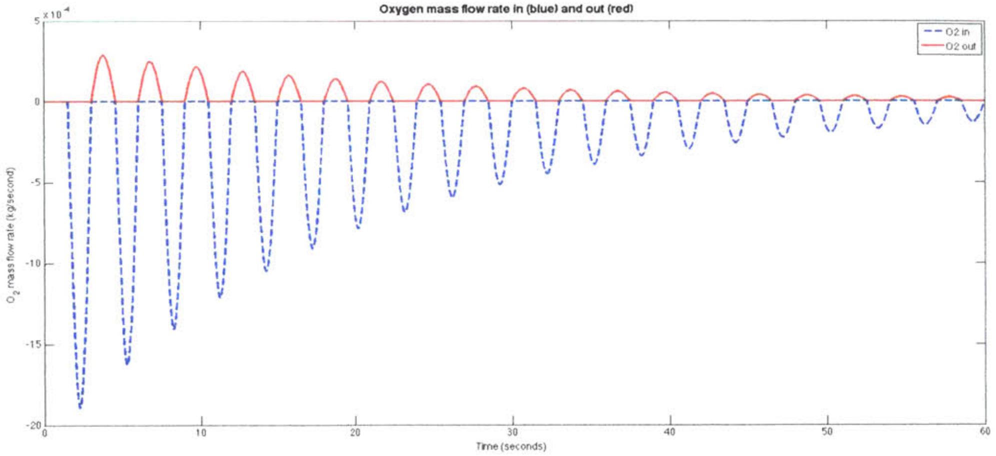


Figure 2-8: The oxygen evolution in the mouthpiece over one minute: inhalation (blue) and exhalation (red)

We observe that both the inhalation and exhalation signals have a decreasing envelope; this is because the human metabolizes oxygen and exhales a small amount of what (s)he inhaled, and without an oxygen tank to make-up for the metabolized oxygen, the total oxygen mass in the mouthpiece will decrease.

The total oxygen mass is recycled in the model; the recycling system is the human metabolism with a yield of 15% ($1 - RQ = 1 - 0.85$).

The amount of carbon dioxide exhaled (red curve) is high in the beginning due to the high oxygen concentration in the mouthpiece. As this concentration decreases

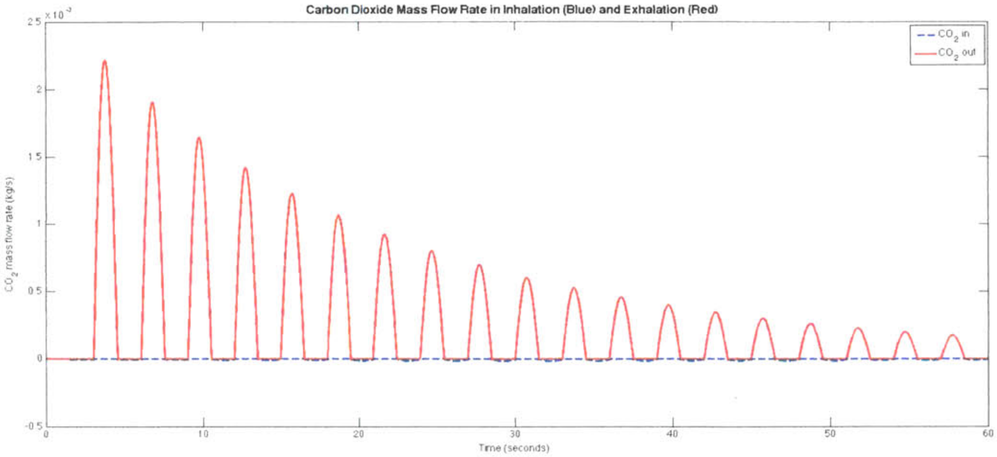


Figure 2-9: The carbon dioxide evolution in the mouthpiece over one minute: inhalation (blue) and exhalation (red)

due to human metabolism, so does the carbon dioxide exhaled mass, as shown in Figure 2-9.

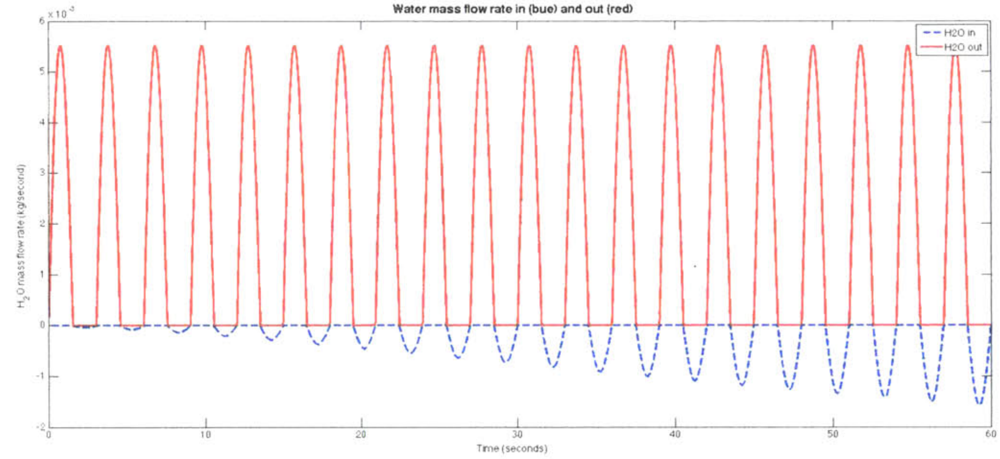


Figure 2-10: The water vapor evolution in the mouthpiece over one minute: inhalation (blue) and exhalation (red)

The water vapor output is constant since the exhaled breath is saturated with water. We can observe that the input water mass increases, this is to be expected since the human is constantly adding water vapor to the mouthpiece, so over he starts inhaling more of it.

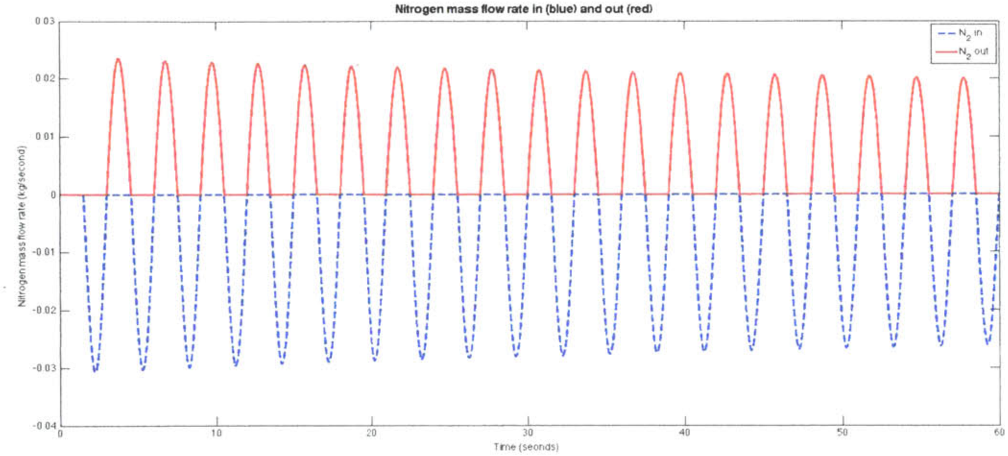
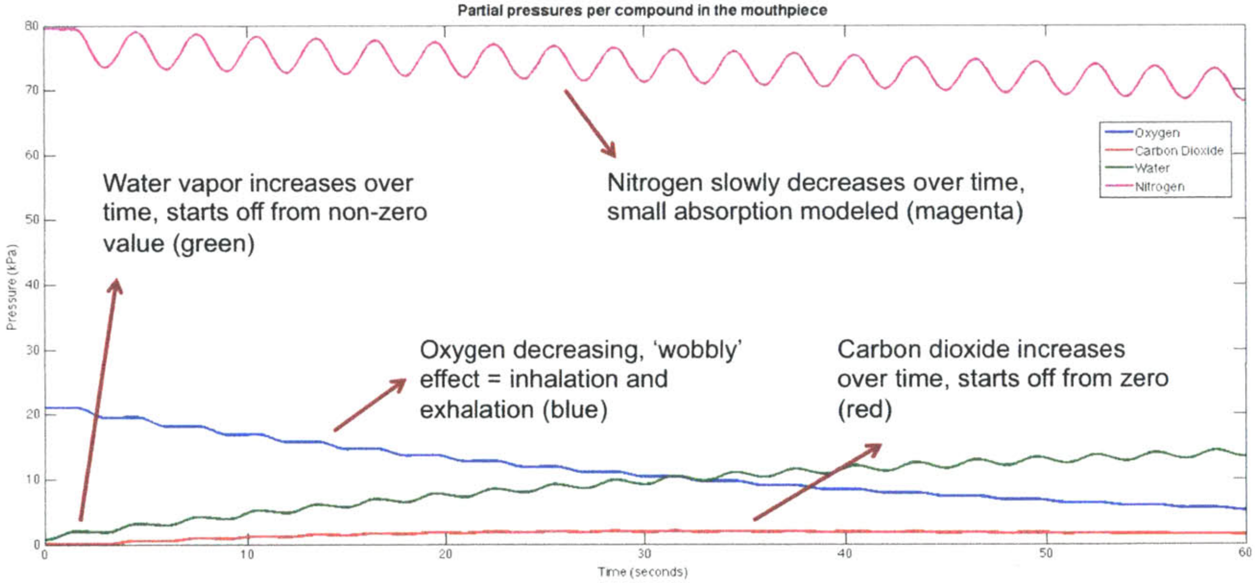


Figure 2-11: The nitrogen evolution in the mouthpiece over one minute: inhalation (blue) and exhalation (red)

The slightly decreasing trend in the amount of exhaled nitrogen is due to a small amount of modeled absorption, as given by Table 2.1. This is implemented in Chapter 4 when different depths and metabolic rates are modeled.



Water vapor increases over time, starts off from non-zero value (green)

Nitrogen slowly decreases over time, small absorption modeled (magenta)

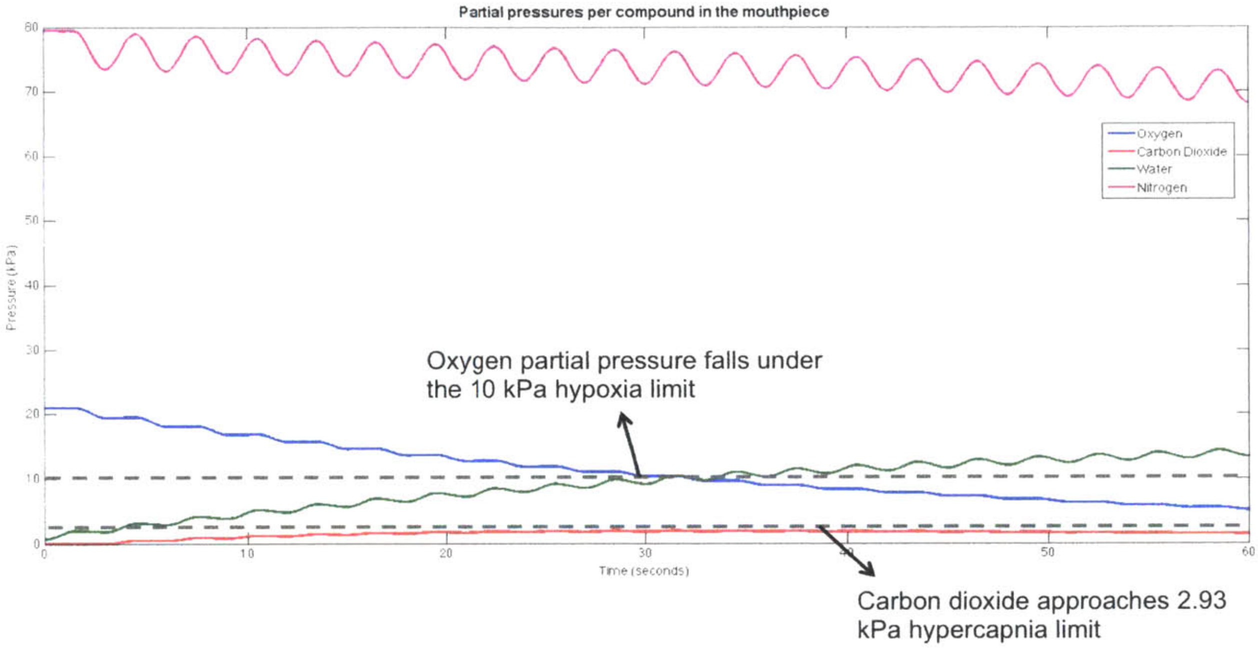
Oxygen decreasing, 'wobbly' effect = inhalation and exhalation (blue)

Carbon dioxide increases over time, starts off from zero (red)

Figure 2-12: The pressure evolution in the mouthpiece per the different gas components for constant volume breathing

If we superimpose the limits presented in Section 1.2.2, we obtain Figure 2-13. From this we can conclude that the biggest threat for humans living off a limited pocket of air is that they will quickly run out of oxygen, before the carbon dioxide concentration rises to a toxic level.

This section presented the model of the human breathing process and an intuitive verification of this process. The next section describes the model structure and components of the rebreather apparatus.


Partial pressures per compound in the mouthpiece

Oxygen partial pressure falls under the 10 kPa hypoxia limit

Carbon dioxide approaches 2.93 kPa hypercapnia limit

Figure 2-13: Pressure trend in the mouthpiece for a 10 liter confined volume: figure shows the hypoxia and hypercapnia limits

2.2 Model structure

The computer model is constructed as a connection of modules, as shown in Figure 2-14, based on the rebreather system composition from the US Navy diver's manual [14] for the MK16 MOD0. The requirements of this analytical model are the following:

1. The model shall monitor O_2, CO_2, H_2O concentrations in the air the human is breathing

2. The model shall monitor air pressure and temperature
3. Modular design (each system shall be represented in code as a block) in order to reconfigure the model as desired
4. A block or module shall be added or removed in less than 1 minute
5. Fast simulation time and data processing - for the purpose of this model, a dive time of 4 hours shall be simulated in less than 15 minutes and the results shall be ready for further processing in under 10 minutes
6. The model shall capture the system dynamics within 20% of accuracy compared to empirical time series data.

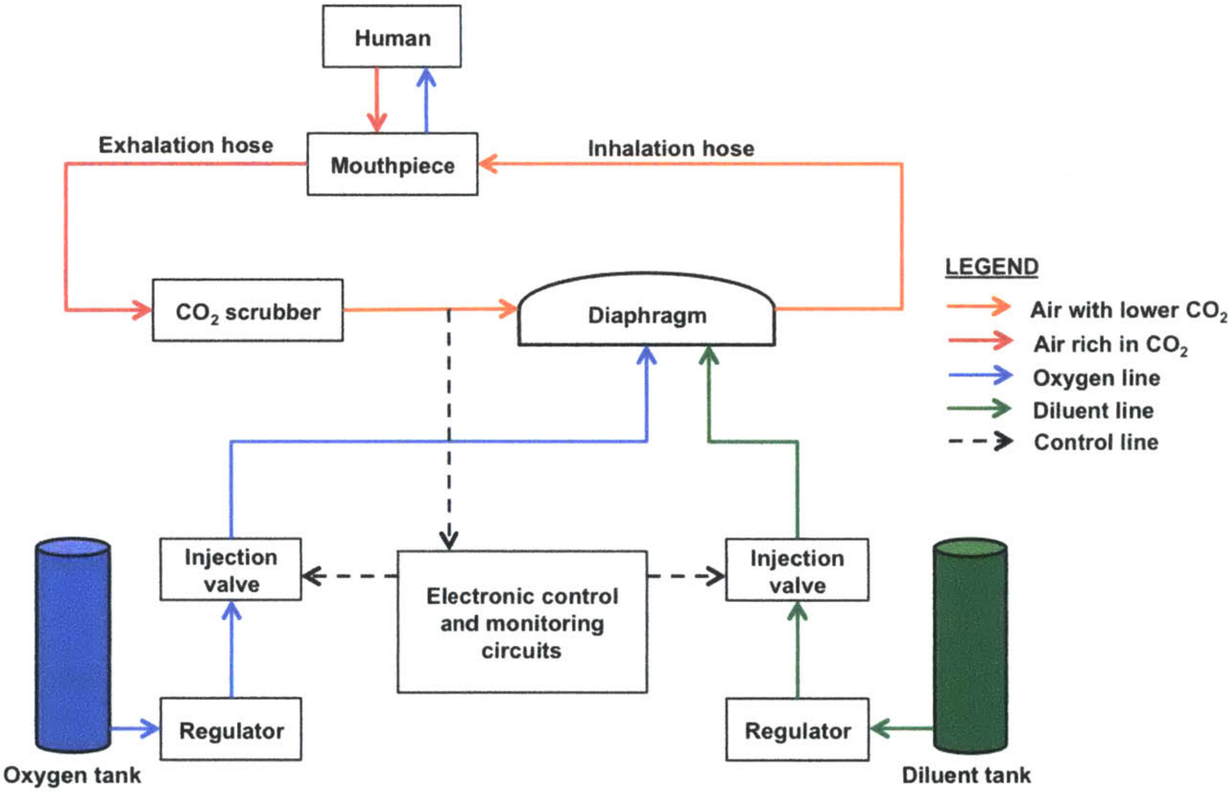


Figure 2-14: The structure of the US Navy MK16 MOD0 rebreather analytical model

The programing language was chosen as Matlab Simulink, due to Simulink's ability to satisfy all the above requirements.

The Simulink representation of the MK16 rebreather is shown in Figure 2-14. The human breathing model is enclosed in the human block, its output and input are air compositions for the exhaled, respectively the inhaled air. The exhaled air (shown with a red arrow) is forwarded to the mouthpiece. The carbon dioxide-laden air is then passed through the carbon dioxide scrubber, which absorbs the carbon dioxide from the air and then transmits it to the diaphragm. This is the point at which the air is reconditioned: the partial pressures of the oxygen and nitrogen are computed and maintained at healthy limits for the diver, according to the depth at which (s)he is operating. From here, the air is inhaled from the diver and, after the metabolic processes have been completed, this air is converted into exhaled air and this process is repeated. The model also contains gas tanks, which store the oxygen and nitrogen gases used to makeup the air for the diver. The electronic control and monitoring circuits contain sensors for measuring the partial pressures of oxygen and nitrogen, control circuits for determining how much gas mass has to be added/subtracted in order for the required partial pressure of gas to be reached or maintained, and valves that are actuated by these circuits for physical addition of the gas from their corresponding tanks. The diluent considered in this analytical model is nitrogen. Nitrox is used for diving up to 40 meters depth, so the analytical model can simulate only these scenarios. For depths greater than 40 meters, the diluent gas used is heliox (helium and oxygen).

The blue and red arrows in Figure 2-14 represents an airway. The red arrows indicate air rich with carbon dioxide, typically coming from the diver's exhalation, and the blue arrows represent conditioned air, ready for the diver to inhale. Each such air way is encoded in Matlab Simulink as a vector, with the following components:

1. Air temperature [K]
2. Air pressure [kPa]
3. Air density [kg/m^3]
4. Air mass [kg]

5. Oxygen mass fraction [-]

6. Carbon dioxide mass fraction [-]

7. Nitrogen mass fraction [-]

8. Water mass fraction [-]

9. Air volume [m^3]

Note that the composition of the air vector contains redundant elements. This is used to check the conservation of mass throughout the simulation through sum of pressures, sum of masses and sum of mass fractions.

2.3 Problem statement

The problems we are exploring are:

1. How to maximize the oxygen tank endurance?

2. What configurations of gas tank sizes and gas control strategies can be used to meet that duration?

In previous literature and in real life, the objective is usually to maximize the endurance of the oxygen tank, so this is the gas that we will consider to maximize in this problem. The diluent consumption rate is relatively small compared to the oxygen consumption rate and mostly used during the descent stage.

The first problem can be formulated as a discrete optimization problem: the objective function $J(x,p)$ is the endurance of the oxygen tank, the parameters p are the diver's body type (height, weight, age and metabolic rate and diving depth). The design variable x is the control type applied to the rebreather and this is a discrete variable. The constraint $g(x,p)$ of this problem are the available oxygen mass in the tank at the beginning of the dive. The mathematical formulation of the problem is given below.

$$\boxed{\begin{aligned} & min\ J(x,p) \\ \text{such that } & g(x,p) \leq m_{initial\ oxygen} \\ \text{where } & x = \text{control type, design variable} \\ & \text{and } p \text{ model parameters} \end{aligned} \qquad (2.2)}$$

where the control type can be : open loop, Constant Mass Injection (CMI), bang-bang, Proportional - Integral - Derivative (PID) and the model parameters are height, weight, age, metabolic rate and diving depth.

The second problem is derived from the first problem: we set a specified mission duration and explore the hardware combinations that can satisfy this.

The solutions of these two problems will be the main topic for chapter 3.

2.4 Chapter 2 summary

This chapter presented the development of the generalized rebreather model: it starts with the human breathing model, then checks its functionality using a 10 liter mouthpiece, with no carbon dioxide scrubber or gas additions. Then we add the scrubber, the gas tanks and the control circuits. The chapter ends with the problem statement, formulated as a multi-disciplinary optimization problem.

Chapter 3

Baseline case study - the MK16 rebreather

The MK16 MOD0 is a constant partial pressure, closed circuit mixed gas underwater breathing apparatus (UBA), used by the Naval Special Warfare (SPECWAR) forces. This UBA combines the advantages of a free-swimming diver with the depth advantages given by mixed gas. The maximum working limits for the MK16 MOD0 UBA are 150 feet seawater (fsw) (45.72 meters) when N_2O_2 (air) is used as a diluent, and 200 fsw (60.96 meters) when 84/16 HeO_2 mix is used [14].

Figure 3-1 shows the assembled UBA [14]. The purpose of this research project is to build an analytical model of the system shown in Figure 3-1, so we will decompose this system according to its subsystems and the functions that they perform.

Figure 3-2 shows an Object Process Methodology (OPM) [21] decomposition of the UBA. OPM is a language similar to SysML, which allows the functions and the systems that perform those functions to be represented in the same environment [58]. The functions are represented by ellipses with a blue contour, and systems by rectangles with a green contour. The black triangle indicates a decomposition, while the lollipop-looking symbol represents a system that enables a particular function.

Figure 3-2 shows only the major subsystems of the UBA, which are the ones that will be incorporated in the model. For completeness, below is a list of all the UBA

Figure 3-1: The MK16 MOD 0 closed circuit UBA [14]

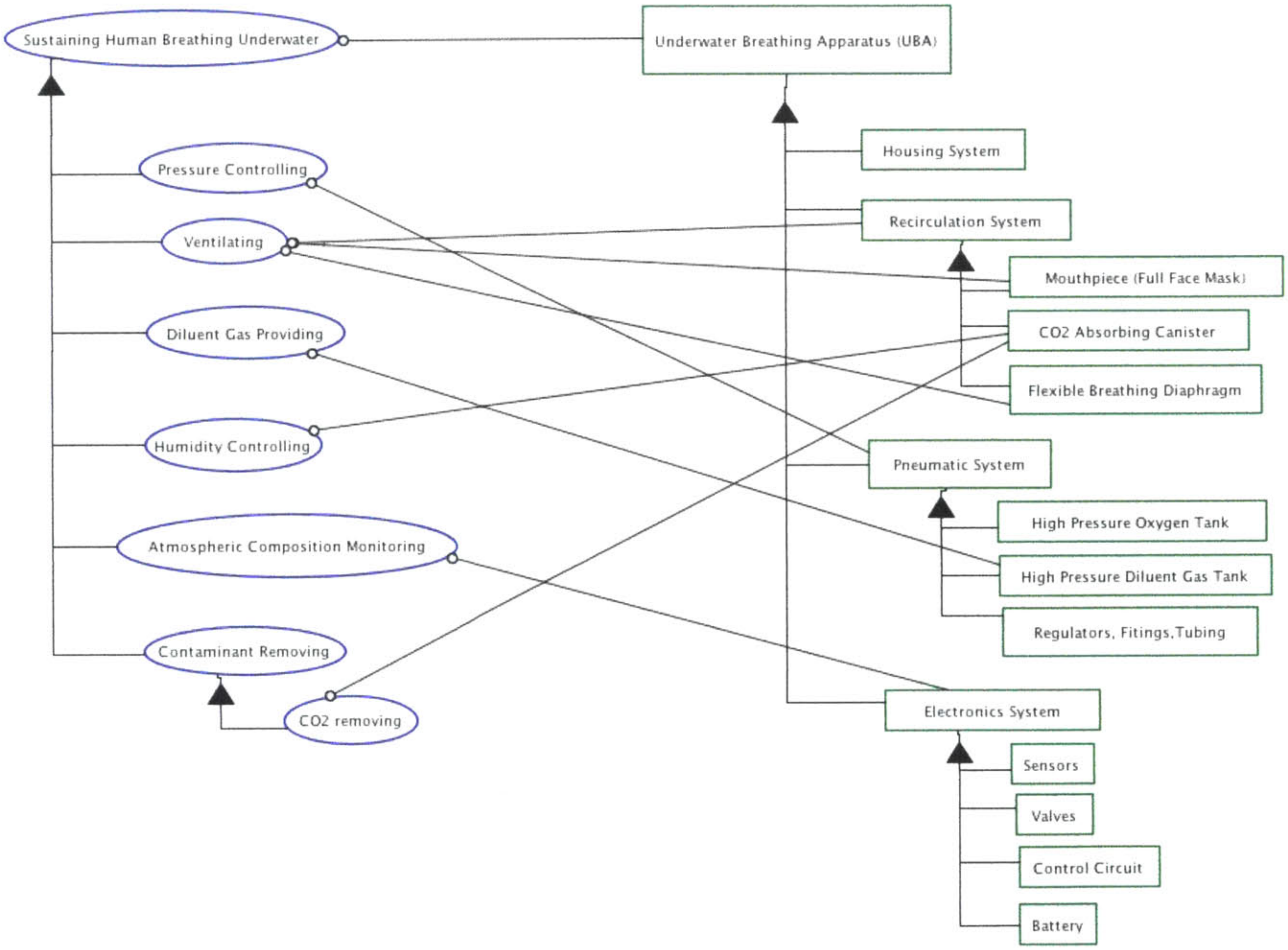


Figure 3-2: Object Process Methodology functional decomposition of the MK16 MOD 0 closed circuit UBA [21]

subsystems and components. The UBA consists of four main systems [14]:

- Housing system - this is a reinforced Acrylonitrile, Butadiene, Styrene (ABS) or fiberglass molded case; this case contains all the main systems, external to it are only the mouthpiece, pressure indicators, hoses, primary and secondary displays
- Recirculation system - contains the mouthpiece, a carbon dioxide absorbent canister and a flexible breathing diaphragm. The CO_2 scrubber removes carbon dioxide and moisture produced by the diver's breath
- Pneumatics system - it contains the high pressure bottles for storing oxygen and diluent gases, indicators to monitor the remaining gas supply and regulators, fittings, tubing, filters and valves that are required to regulate and deliver the oxygen and diluent gases to the recirculation system
- Electronics system - keeps a constant partial pressure of oxygen by processing and conditioning the outputs from the oxygen sensors in the breathing loop, actuating the oxygen addition valve and displaying the oxygen tank state on the primary displays. The partial pressure of oxygen in the loop is monitored by three sensors, and the control circuit uses a voting algorithm to determine what its next action will be based on the sensor readings. The electronics system also has two displays, a primary and a secondary one. The primary display contains two LEDs, which indicate the overall condition of various electronic components and partial pressure of oxygen in the loop. The secondary display provides quantitative information on the condition of the breathing medium, the primary battery voltage and the condition of the secondary batteries.

3.1 Model assumptions

The analytical model is built on the following assumptions:

- The breathable air is made up of an inert gas (nitrogen in this case) and oxygen

- The breathing gases behave as a perfect mixture and their volumes and partial pressures are computed using the ideal gas law
- the recipient internal pressure instantaneously equals the external pressure
- The respiration is modeled by a partial oxygen subtraction from the collapsible bag (counterlung)
- The carbon dioxide scrubber behaves ideally, capturing all produced carbon dioxide [54]
- The temperature of the breathing gas is not influenced by the water temperature the diver is in (this is because the carbon dioxide reaction is exothermal and it warms up the breathing gas)
- The diver metabolic characteristics are as indicated in Chapter 2

The metabolic rate and depth profiles for a typical dive are shown in Figure 3-3 and the simulations of the rebreather using these profiles are shown in Chapter 4.

3.2 Description of model components

This section details the components implemented in the analytical model shown in Figure 2-14, as given in the US Navy Divers Manual [14]. Their particular values are as follows:

- The mouthpiece total volume is 110 mL, this is split evenly between the mouthpiece for exhalation and inhalation [14]
- The diaphragm volume is 10 liters [14]
- The gas tanks have a wet volume of 175 cubic inches, are rated for 3015 psia [14]
- The breathing hoses volumes are included in the diaphragm volume and they are not considered to be corrugated

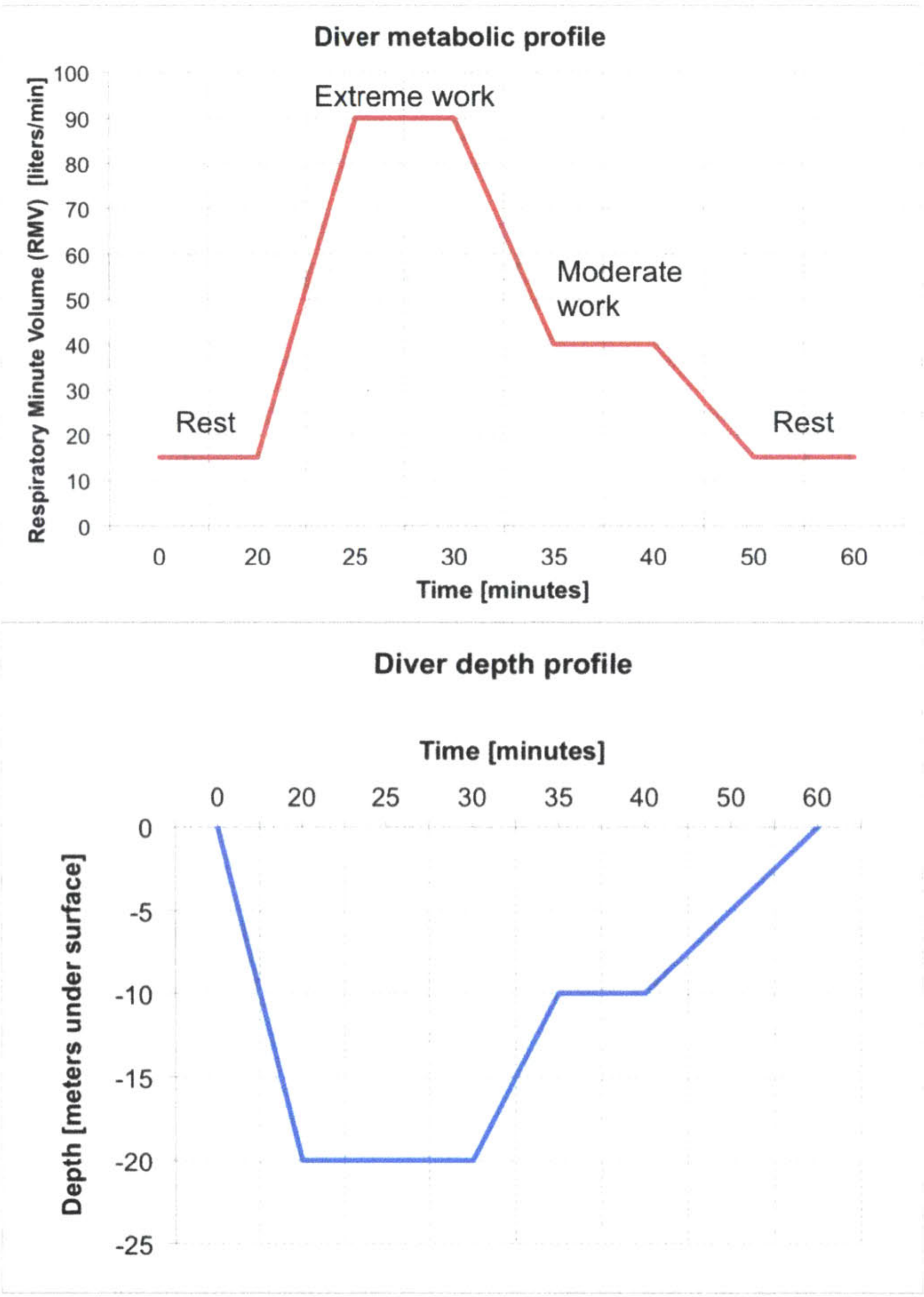


Figure 3-3: The metabolic rate and depth profiles for a typical dive [14]

- The diameter of the breathing hoses is not considered in the model. This can be easily adapted by adding another module to the analytical model to represent the hoses and then subtract their volume from the diaphragm

- The diaphragm is modeled as having variable volume, dependent on the gas it contains. In the real rebreather implementation, the diaphragm is modeled as elastic in order to reduce the breathing resistance.

3.3 Strategies for maximizing oxygen duration

Maximizing the endurance of oxygen is the key to longer dives. Possible solutions to this problem, studied since the 1980s, are best described in a paper by Nuckols, Gavin and Finlayson [52], and are presented in this section. There are four main design approaches for the control of the injection of oxygen in the breathing loop:

1. Constant Mass Injection (CMI) systems - use one or more critical flow orifices to maintain a constant rate of makeup gas into the breathing loop. The rate of gases injected corresponds to the deepest point the diver would get to and at max activity levels. The advantages of this method are that it conserves breathing gas better than open circuits and, if it is used for inert gas injection, it makes deeper dives possible. However, due to the high injection rate and the fact that it is not coupled to the diver's breathing rate, the circuit may experience considerable variations in oxygen partial pressures and in inert gas pressures, leading to risk of hypoxia at great depths and oxygen toxicity at shallow depths.

2. Depth dependent injection systems (DDI) - these systems vary the gas injection rate based on depth, so it counteracts great variation in gases and results in safe breathing mixtures at any depth. On the flipside, due to the fact that the gas consumption increases at depth, this leads to a high injection rate in those conditions.

3. Constant volume injection systems (CVI) - these contain a breathing circuit that alternates between closed and, during fresh gas injection and flushing, semi-closed. The advantage of these systems is that they are coupled to the

diver's respiratory rate: the diver exhales, fills a bellow, which is then vented and refilled with fresh gas.

4. Variable volume exhaust systems (VVE) - couples the injection of fresh gas with the diver's respiration rate (based on the fact that a diver's respiration rate is coupled with his metabolic oxygen requirement). Uses a mechanical coupling device with the counter-lung to control the rate at which gas is exhausted from the loop. The circuit volume is controlled by dumping carbon dioxide as the diver exhales. Oxygen is added only when the gas volume decreases and is not enough to fill the diver's lungs. The advantages of these systems are that the rate of gas dumped is correlated with the diver's respiratory rate, this coupled injection system reduces oxygen level variability as diver activity levels change and that this is the most desirable injection levels for oxygen from the four evaluated systems. On the downside, using this system leads to a high oxygen consumption rate.

From these four systems we chose to implement the first one, Constant Mass Injection (CMI) in our model and compare its performance with three other control types, detailed in the following:

1. Open loop control - this type of control is typical of scuba diving equipments, where the diver inhales air from the tank and expels it in the surrounding environment

2. Constant Mass Injection - detailed above

3. Bang-bang control - also known as an on-off or a hysterezis controller, this is a feedback controller that switches abruptly between two states. For example, most residential temperature control systems contain bang-bang controllers. In optimal control problems, it is sometimes the case that a control is restricted between a lower and an upper bound, like in the case of the rebreather. They are often implemented because of their simplicity and convenience. A simulation of a bang-bang controller applied to a plant is shown in Figure 3-4. If the process

value is greater than the set point + hysterezis then the controller output is set to 1 (ON state). If the process value is less than the set point - hysterezis then the contoller is set to 0 (OFF state). If the process value is between the (set point + hysterezis) and the (set point - hysterezis) then the controller output is maintained at the same level as before.

4. Proportional - Integral - Derivative control - this type of control is a feedback loop controller widely used in industrial systems. A PID controller calculates the error between the process value and a desired setpoint, and then attempts to minimize the error by adjusting the process through a set of manipulated variables. This control algorithm involves three separate control parameters: P, the proportional term which depends on the present error, I, the integral term, depending on the accumulation of past errors, and D is a predictive term of future errors, based on the current rate of change. The weighted sum of these three actions is used to adjust the process via the control element such as a gas valve for the rebreather case. A block diagram of the PID controller in a feedback loop is presented in Figure 3-5 and the form of the algorithm is [56]:

   $$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(\tau)d\tau + K_d \cdot \frac{d}{dt}e(t) \tag{3.1}$$

   In order to determine the values for the three control constants, we can use a trial and error process, or use tables like the one shown in Table 3.1, or other methods such as Ziegler-Nichols or Cohen-Coon.

We studied the implementation of these various control methods and how they impact the endurance of the oxygen tank. We fixed the depth of the dive to surface level and the diver metabolic rate to extreme work (we will vary these in chapter 4), and observed how varying the control type affects the duration of the oxygen tank. The results of this analysis are shown in Figure 3-6. The endurance of the oxygen canister given in this graph is 40 minutes because the diver metabolic rate is extreme work only. In a normal dive, the profile of the diver's activity is a combination of rest, moderate and extreme work, not only extreme work, therefore we expect that

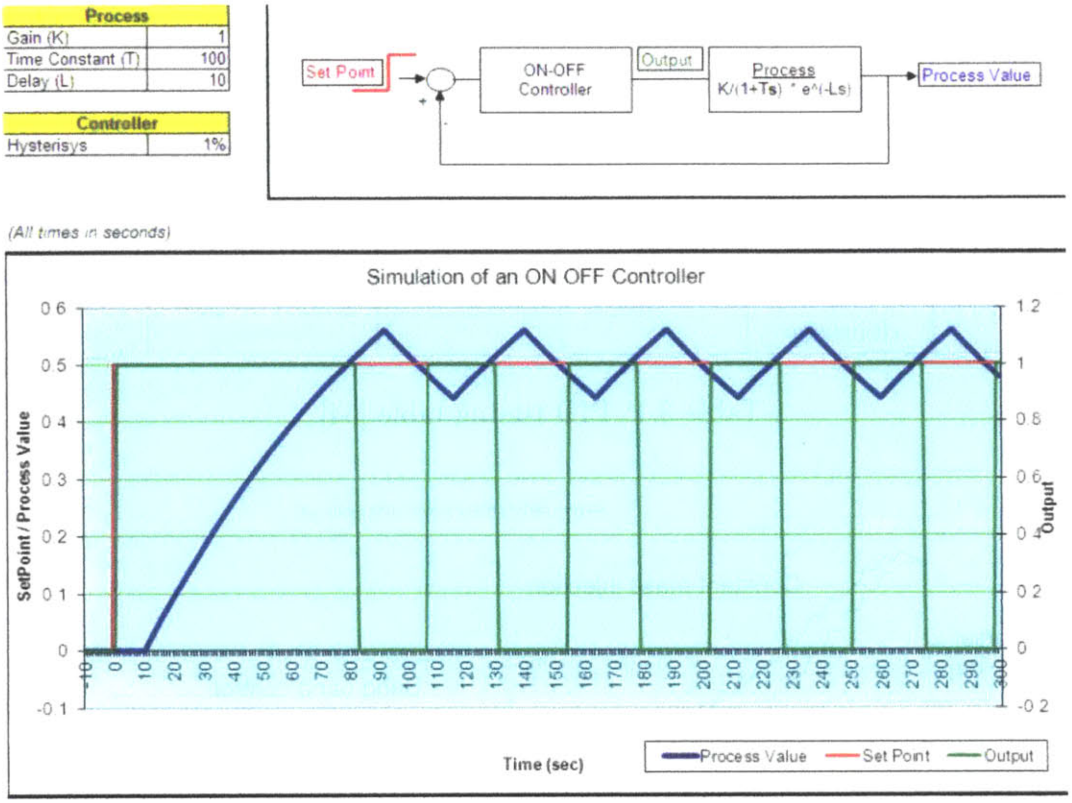


Figure 3-4: Simulation of a typical bang-bang controller applied to a plant: the setpoint is given in red, the dynamics of the plant are shown in blue and the controller behavior is shown in green [55]

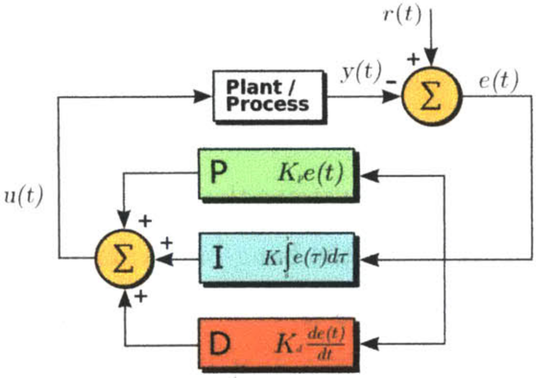


Figure 3-5: A diagram of a PID controller in a feedback loop [56]

in a normal dive, the oxygen canister will last longer than this, this case is a worst case usage scenario. Also, when the depth profile is varied as shown in Figure 3-3, nitrogen is used as a diluent and this fact will additionally extend the duration of the oxygen tank.

Closed loop response	**Rise time**	**Overshoot**	**Settling time**	**Steady-state error**	**Stability**
Increasing K_p	Decrease	Increase	Small increase	Decrease	Degrade
Increasing K_i	Small decrease	Increase	Increase	Large decrease	Degrade
Increasing K_d	Small decrease	Decrease	Decrease	Minor change	Improve

Table 3.1: PID tuning table [64]

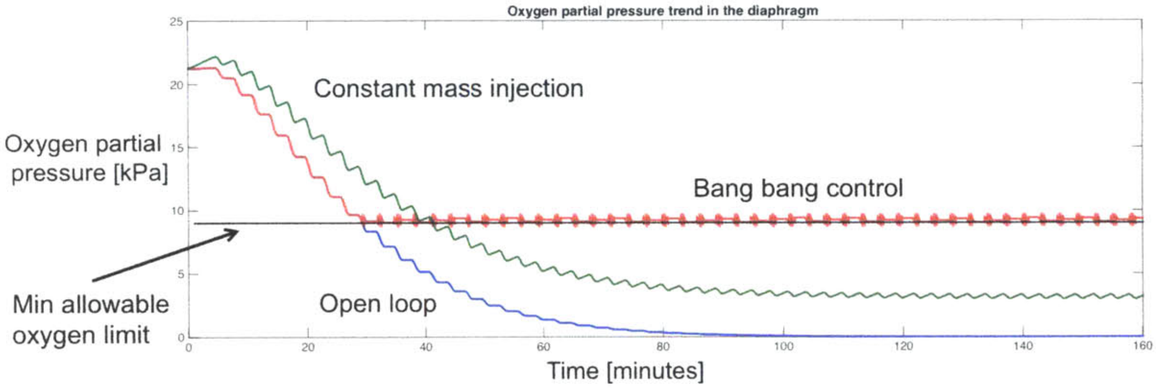


Figure 3-6: Comparison of open loop, bang bang (electronic) and constant mass injection (mechanical) control on a surface level, extreme work dive

We can conclude from Figure 3-6 that fixed mass or volume injection systems will consume the oxygen tank faster than systems that are coupled with the diver's breathing rate, represented in Figure 3-6 by the bang-bang control (the oxygen amount that will be replenished is equal to what was metabolically consumed by the diver). Therefore, we will focus next on systems that adapt the amount of oxygen replenished on the diver's metabolic consumption. We considered the implementation of a PID controller and compared its performance with the bang-bang control.

In order to apply s-domain controllers on a time domain plant, we first had to perform system identification on the plant. In this case, the plant is the model of the human breathing process, and what we want to control is the partial pressure of oxygen in the diaphragm. We do this by modifying the mass of oxygen entering the diaphragm, as shown in Figure 3-7.

The plant is a non-linear process, so in order to apply system identification on it we had to linearize the plant's behavior around a specific operating point, which we chose to be 9kPa. This is the region where the controller will be active. We then subtracted the mean value around this operating point and fed this timeseries data to the system identification toolbox in Matlab. The fitted transfer function for the plant is the following:

$$G_p(s) = \frac{7946s + 3061}{s^2 + 0.964s + 3.733} \tag{3.2}$$

The fit of this transfer function with the test data is 99.49%, the function has one zero and two poles, the Final Prediction Error (FPE) is $5.581 \cdot 10^{-9}$ and the Mean Squares Error (MSE) is $5.559 \cdot 10^{-9}$. Figure 3-8 shows a simulation of the oxygen partial pressure in the diaphragm, as a function of the oxygen mass entering the diaphragm. The green rectangle shows a decreasing oxygen partial pressure, consistent with the diver's breathing (and so inhalation of oxygen from the diaphragm). The controller engages at 9 kPa to maintain the oxygen partial pressure at this level.

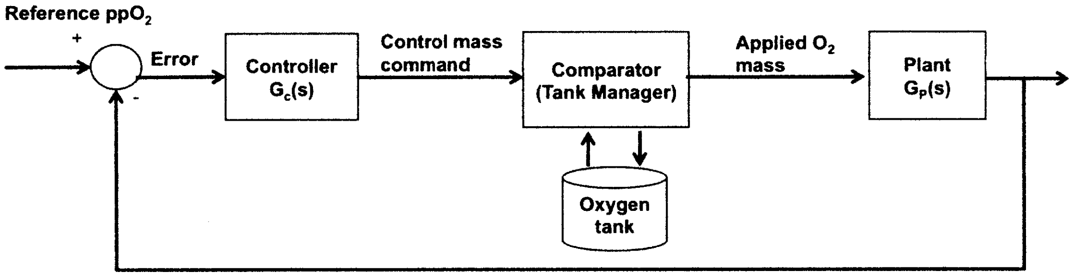


Figure 3-7: The schematic of the partial pressure of oxygen in the diaphragm control problem

The Bode plots of the resulting plant model is shown in Figure 3-9. The PID controller applied to it was designed to maximize the response time and minimize the overshoot. Its equation is given in the following equation:

$$u(t) = 0.00015524 \cdot e(t) + 00002648 \cdot \int_0^t e(\tau)d\tau + 2.2715 \cdot 10^{-5} \cdot \frac{d}{dt}e(t) \tag{3.3}$$

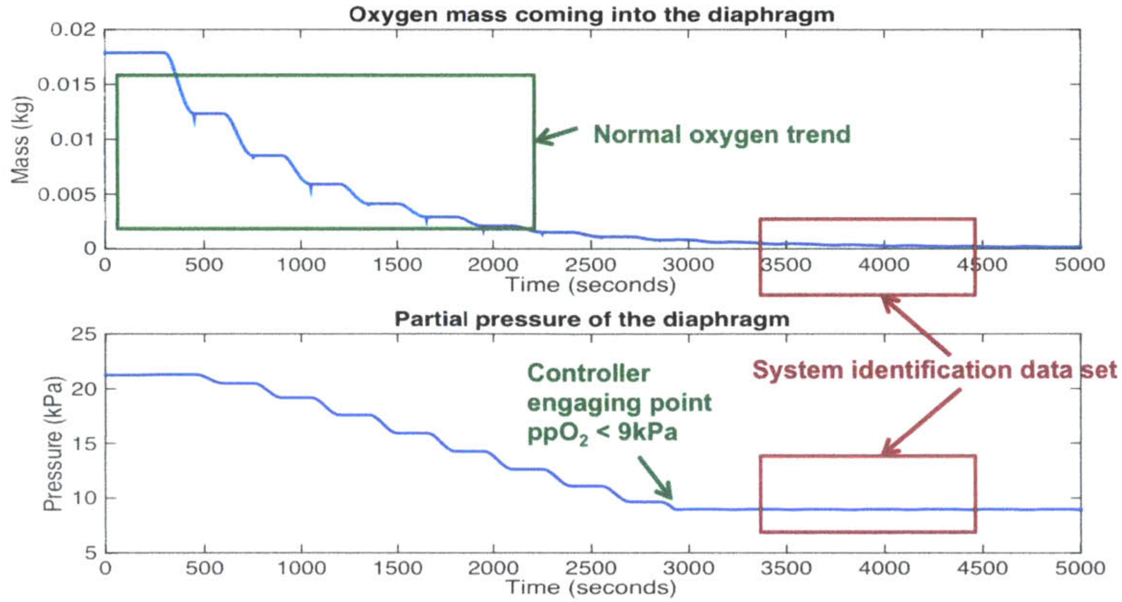


Figure 3-8: The system identification dataset for the plant

As a result of this, the step response of the PID controlled plant shows an undershoot in the beginning, as presented in Figure 3-10. The rise time of the controller is 14.8 seconds, the settling time is 26.9 seconds, we have 0% overshoot, the gain margin is infinity, the phase margin is 109° with a cutoff frequency at 2.44 rad/s. The resulting closed-loop system is stable.

The PID controlled plant has a duration of the oxygen tanks of 18 hours. This high value is explained by the fact that the PID controller assumes a very good model of the plant and leads to an optimal control type, which realistically is not the case. There is a lot of uncertainty in the real human breathing model that has not been captured in this mid-fidelity analysis of the system.

Figure 3-12 presents a classification of control types of the human breathing model in function of the controller complexity. In the past, people used to implement bang-bang or PID controllers because the hardware at that time did not allow more complicated control systems to be implemented. But with the growth of computer systems, any control policy is now implementable [59]. Therefore, control complexity has become a crucial issue in control theory research [60].

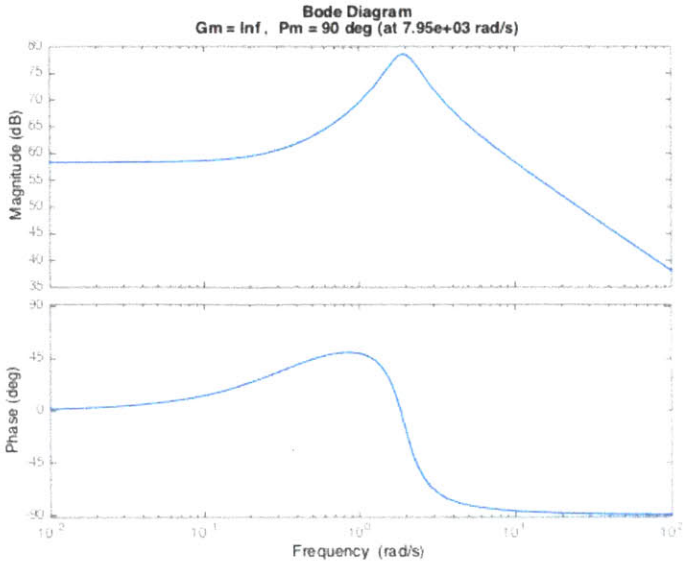


Figure 3-9: The Bode plots for the plant

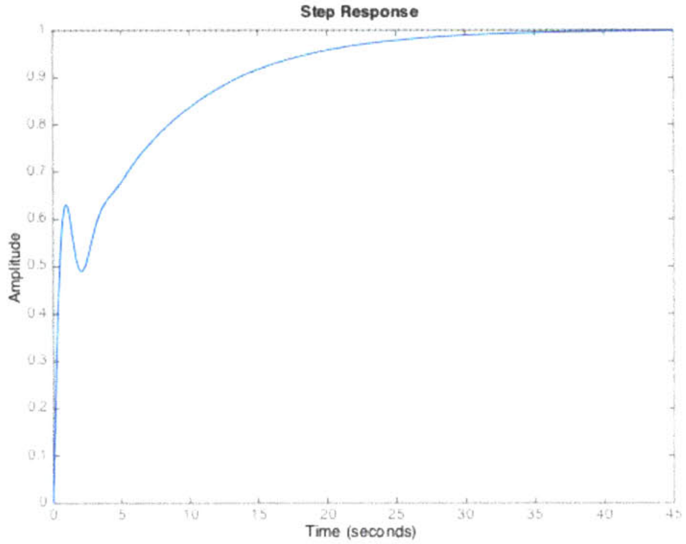


Figure 3-10: The step response for the PID controlled plant

Complexity is defined as the degree to which a process is difficult to analyze, explain or understand. Cardoso [61] defines it as the number and intricacy of activity interfaces, transitions, conditional and parallel branches, as well as the existence of loops. In order to measure this controller complexity, we have two choices:

- Count and sum the number of branch splits [61], also called McCabe's cyclomatic complexity [62], shown in Figure 3-11
- The order of the controller [63]. In this thesis, we use the order of the controller as a measure of controller complexity.

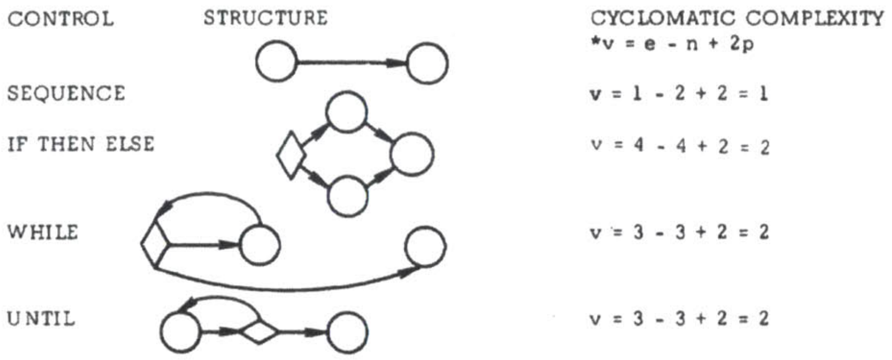


Figure 3-11: Complexity measure for a graph. Control algorithms can be represented as graphs and their complexity is calculated using McCabe's cyclomatic complexity algorithm [62]

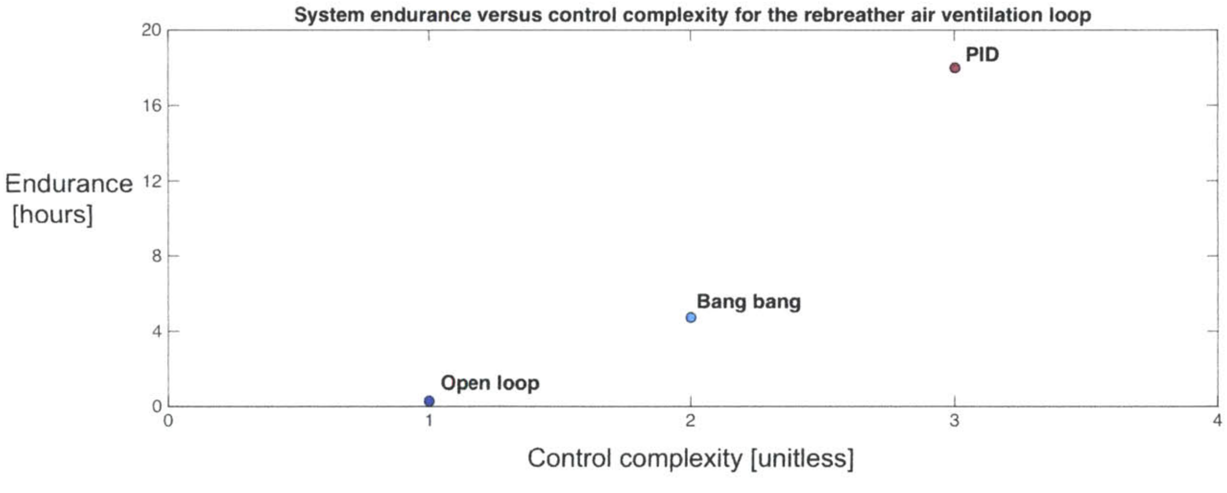


Figure 3-12: Oxygen tank endurance for various control types applied to the human breathing model

If we refer back to the problem described in chapter 2, section 2.3, we have solved the first problem: how to maximize the oxygen tank duration. Figure 3-12 shows the endurance of the oxygen tank in function of different controller types, classified in function of their complexity, as explained above. Out of all the control types implemented, we see the PID controller maximizes the oxygen tank endurance. This result is also shown in Figure 3-14. We can see that better control on the oxygen tank can improve the system's endurance from a typical 170 minutes to 1000 minutes.

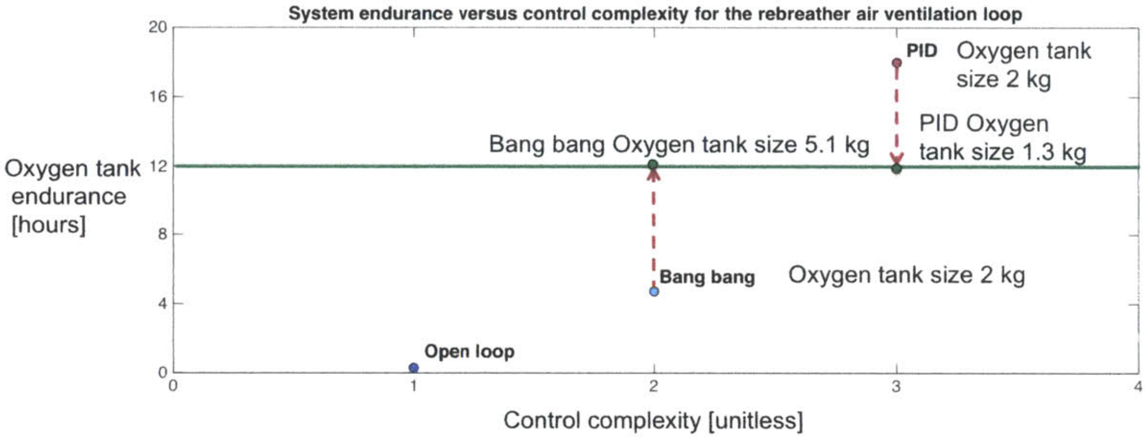


Figure 3-13: Oxygen tank endurance for various control types applied to the human breathing model

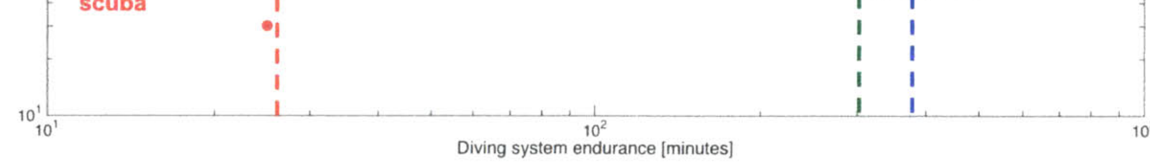


Figure 3-14: Control can extend the endurance of closed-circuit rebreather systems: 1000 minutes instead of the typical 170 minutes

In order to solve the second problem, we will set the endurance of the oxygen tank to 12 hours and, given the two control options we have implemented, derive a combination of control strategies and tank sizes that would enable the rebreather system to attain that set endurance value.

We see that we have two such combinations: we can choose PID control and use an oxygen tank of 1.3 kg or bang bang control and a tank of 5.1 kg. With PID control, we have achieved a 74% reduction in tank size for the same mission endurance. This goes to demonstrate the fact that, using adequate electronic control, the resource endurance can be extended far beyond what mechanical control (constant mass injection systems, see Figure 3-6) can.

3.4 Chapter 3 summary

This chapter shows the application of the generic rebreather model developed in Chapter 3 on a specific rebreather type, namely the US Navy MK16. We start off by performing a functional decomposition of ths rebreather, then we state the model assumptions and go on to describe the model components. We show a typical dive profile that we will implement in Chapter 4. Then we studied different strategies for maximizing the oxygen endurance and answer what control methods lead to the maximum endurance value. Afterwards, we tackled the second problem: we fixed an endurance value and developed two system configurations that will achieve this endurance value. The chapter ends by showing how the tradespace of diving depth versus the diving system endurance looks like, and we illustrate how controls can push the endurance of rebreathers to a higher value.

Chapter 4

Advanced applications of the MK16 rebreather model

We can now use the model constructed in the previous chapters to simulate realistic dive scenarios. This is useful to understand how much gas will be consumed during a dive and will help plan it. We will first simulate a surface-level depth and vary the diver's metabolic profile between rest and extreme work, and then also vary the depth of the dive and observe the simulation results.

4.1 Variable depth and metabolic rate

This section simulates real dive scenarios, in which the diver exerts him/herself and descends to variable depths. The simulated profiles for metabolic rates and depths are shown in Figure 3-3. Subsection 4.1.1 presents the effects of varying the diver's metabolic rate at surface level (constant depth), and subsection 4.1.2 illustrates the results of varying both the metabolic rate of the diver and the depth of the dive.

4.1.1 Variable metabolic rate

The first step to generalize the model built in the previous chapters is to incorporate and simulate a variable metabolic rate of the diver. We do this by varying the amplitude of the respiratory signal and keeping the respiratory frequency constant:

$$B(t) = A/2 \cdot sin(2\pi/3 \cdot t) \tag{4.1}$$

where *B(t)* is the breathing signal, A is the amplitude of the breathing signal, which we are modulating to represent different work regimes. The values for A are taken from US Navy test profiles and the bioastronautics databook [22], and are given in Table 2.1.

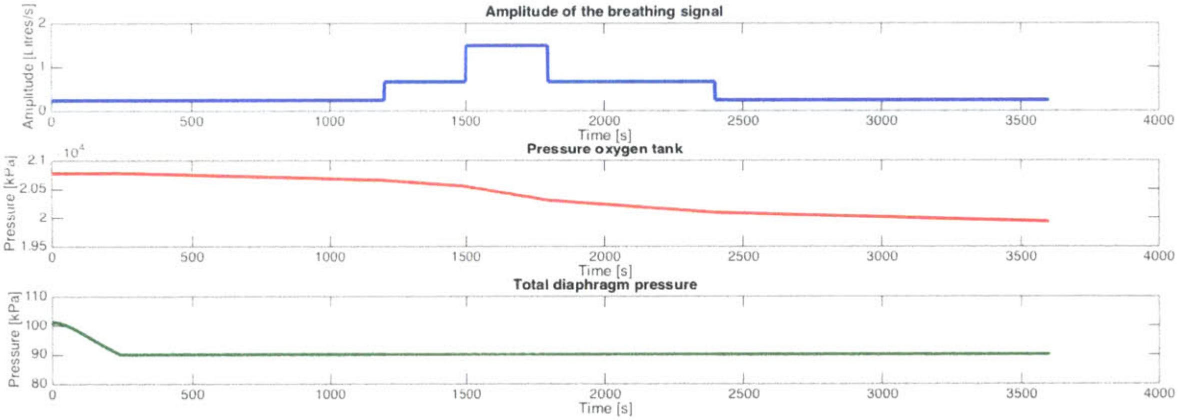


Figure 4-1: Effect of varying the diver metabolic rate on the oxygen tank pressure (we see changes in slope: steepest slope corresponds to extreme work regime, shallowest to rest) and the overall diaphragm pressure (maintained despite metabolic rate variations)

Figure 4-1 shows the effect of varying the diver metabolic rate on the oxygen tank pressure and the way the total diaphragm pressure behaves as a result of this variation: on the top of this Figure we can see how the amplitude of the breathing signal changes to emulate a rest metabolic rate (for time from 0 to 20 minutes), then progress to moderate work and then extreme work (from 25 to 35 minutes) and then reversing this profile until rest (from 50 to 60 minutes). The middle graph shows the pressure of the oxygen tank. We can see that the slope of the pressure changes, indicating a higher depletion rate at extreme work regimes and a smaller one when the diver is resting. The total diaphragm pressure is not affected by this process and this is the result of control on the oxygen and nitrogen partial pressures. The decomposition of the total diaphragm pressure shown in the last graph in Figure 4-1 is presented in Figure 4-2. The oxygen controller kicks in when the oxygen partial pressure drops below 10 kPa and the diver would be in hypoxic danger. The nitrogen controller is active all the time and keeps the nitrogen partial pressure around 80 kPa, which is nominal atmospheric level and is adequate for the depth level at which we are performing this simulation (surface depth). We can observe the transients of nitrogen in the last graph in Figure 4-2, and they quickly die down and the controller maintains the nominal gas partial pressure.

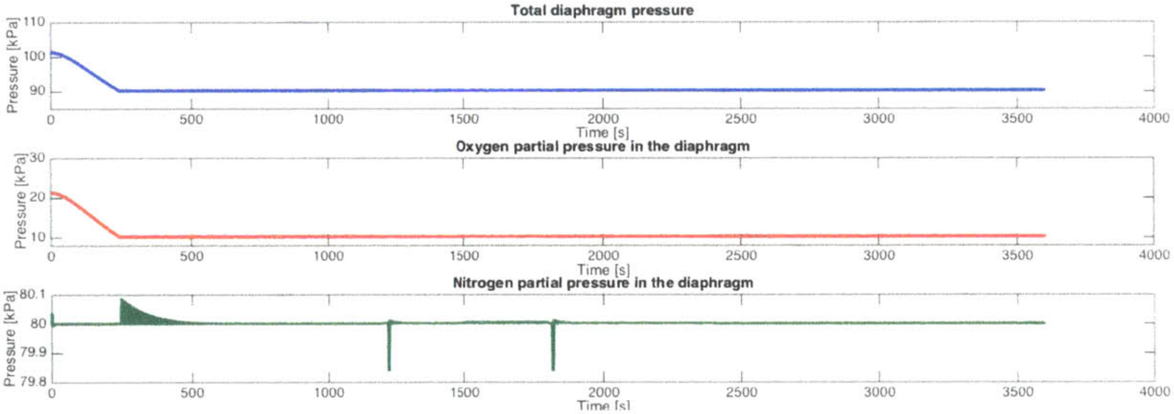


Figure 4-2: Decomposition of total diaphragm pressure from Figure 4-1 in major constituent partial pressures: oxygen and nitrogen

4.1.2 Variable depth

The next simulation we performed was varying the depth profile, while keeping the metabolic rate at a moderate work metabolic level. Both the oxygen and the nitrogen partial pressures in the diaphragm are controlled with a bang-bang control type: the partial pressure for oxyegn is limited at 20% the total diaphragm pressure, and for nitrogen this limit is 70%. The bang-bang controllers are set to maintain these limits, with a tolerance of +/- 10%.

While the oxygen tank is depleting constantly, to replenish the oxygen metabolized by the diver, the nitrogen is used much sparingly and typically during the descent phase of the dive. It is for these reasons that the nitrogen tank is usually smaller than the oxygen tank. If, however, the tanks are the same capacity, then it is expected that the nitrogen tank will last several dives. In most diver rebreather accidents, there are cases in which the divers have endangered their lives by not monitoring the nitrogen tank pressure and performing several descents and ascents.

Figure shows pressure adaptation by the rebreather during a constant metabolic rate dive (set at moderate work), for a variable diving depth (shown in Figure 3-3).

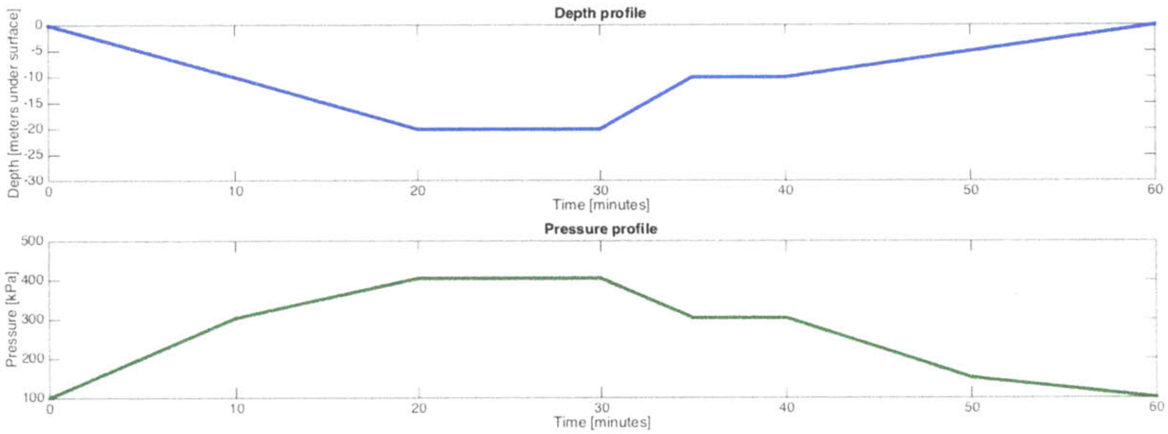


Figure 4-3: The correlation of depth and total external pressure for a typical dive

The depth and external pressure and linked by the equations given in Chapter 1. The correlation between these is shown in Figure 4-3. The controllers are then tasked to maintain the required partial pressures of gases in the diaphragm, according to the external pressure and the control laws described above. The break-down of the diaphragm total pressure in oxygen and nitrogen partial pressures is illustrated in Figure 4-4.

Figure 4-5 shows how the oxygen and nitrogen tanks are used as a function of the depth of the dive. We can see that, as the external pressure increases, the oxygen tank depletion slope increases, showing an increased oxygen flow rate to the diaphragm. The nitrogen tank is used to make up the rest of the required atmosphere composition for that specific depth and it is only used during the descent phase of the dive.

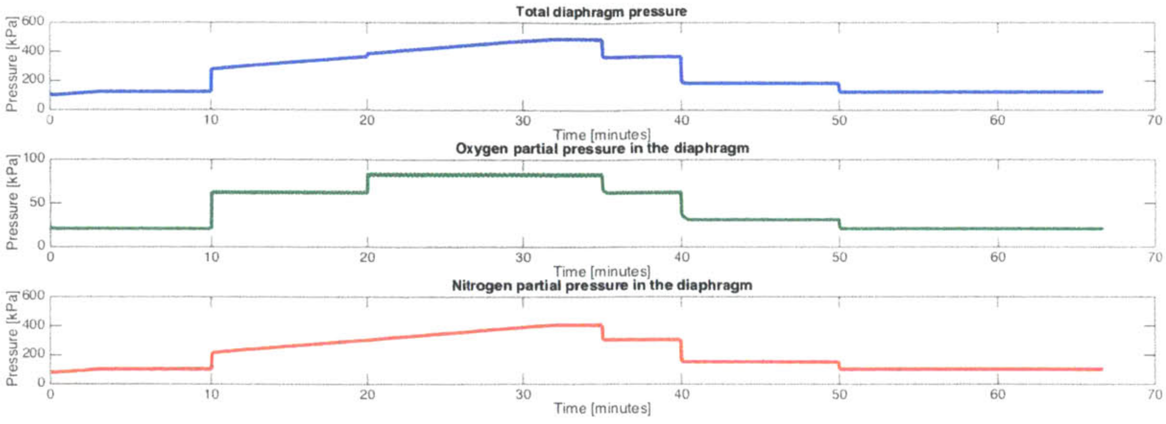


Figure 4-4: The decomposition of diaphragm total pressure in oxygen and nitrogen partial pressures during the dive profile shown in Figure 4-3

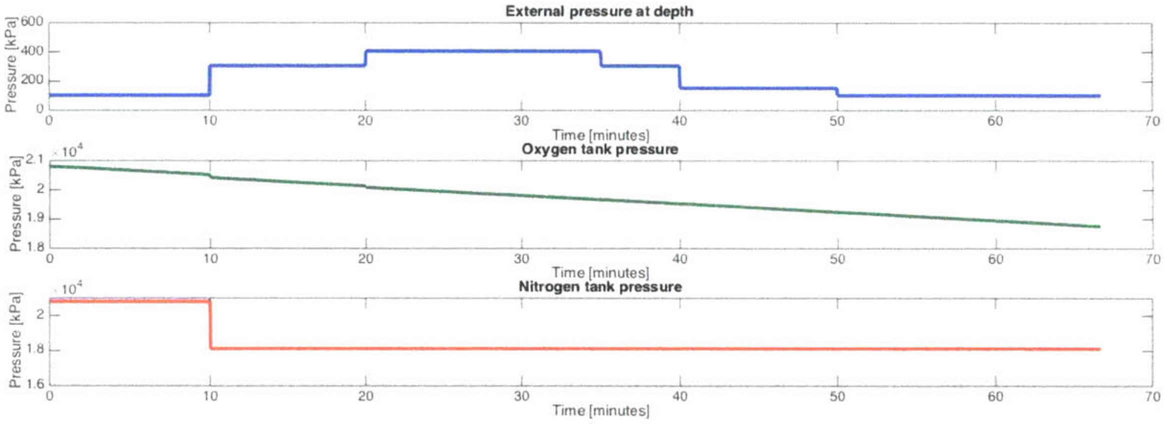


Figure 4-5: The usage of the oxygen and nitrogen tanks as a function of the depth of the dive

4.1.3 Variable depth and metabolic rate

After simulating the model with a variable breathing rate and then, separately, at a varied dive profile, this Section unifies these and presents the model's adaptation to a variable metabolic rate and at a variable depth profile. The amplitude of the breathing signal and the external pressure at that depth are shown in the top part of Figure 4-6, while the bottom part of this Figure illustrates the total diaphragm pressure and its decomposition in the oxygen and nitrogen partial pressures.

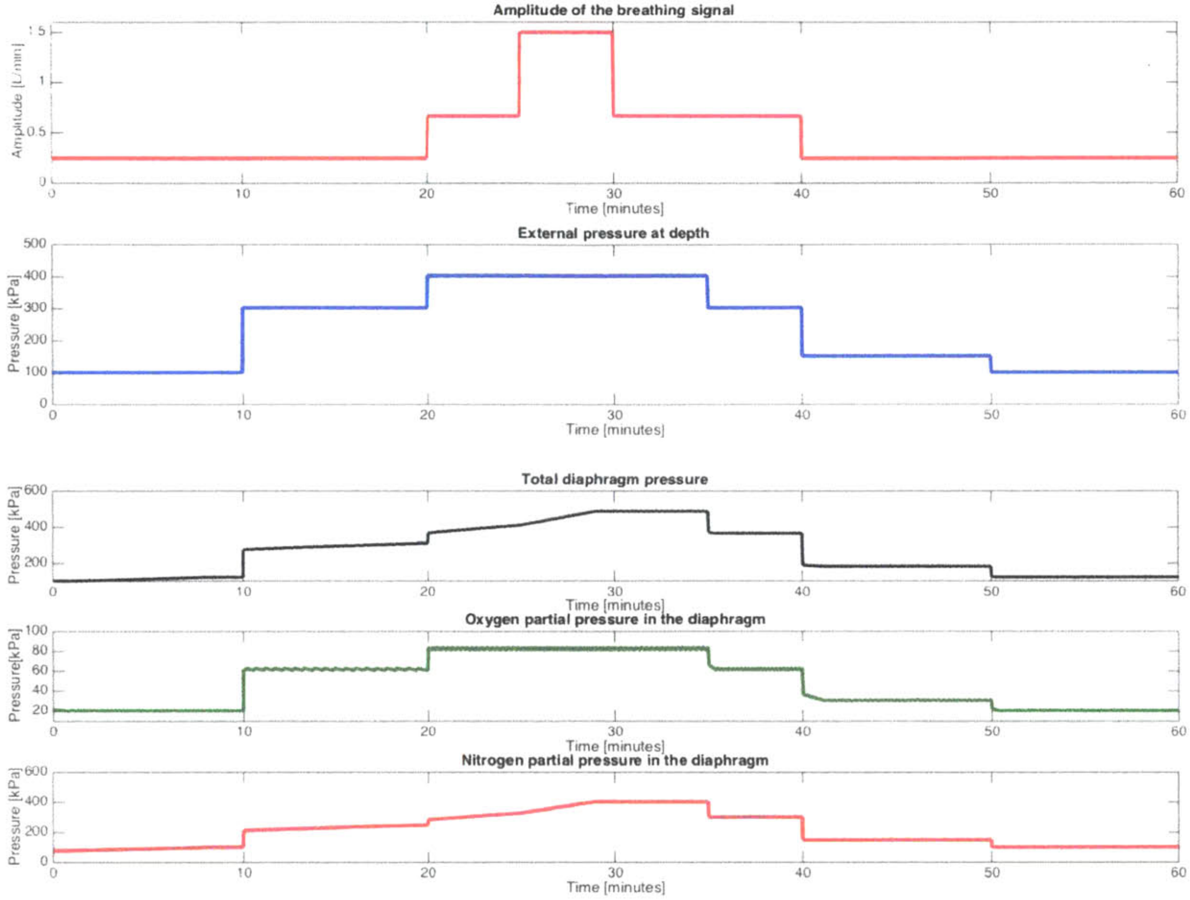


Figure 4-6: Diaphragm pressure adaptation shown in a typical diving profile: variable metabolic rate and variable depth

4.2 Simulation of typical rebreather accidents

Closed-circuit rebreathers (CCRs) are, due to their complexity, more prone to accidents than open-circuit (OC) scuba. In his analysis of mechanical failure risk in the Wakulla Springs project, Stone calculated that the risks of purely mechanical failures for CCR result in a theoretical risk increase of failure of 23 times compared to OC scuba configurations [39]. Therefore, the assumption that the CCRs are less mechanically reliable than OC scubas is considered true and this is why most CCR divers carry OC scuba cylinders for 'bailout' during their dives, in case of CCR failure. When the presence of a redundant scuba is included in the failure risk calculations and compared to an OC scuba diver conducting a decompression dive with two decompression gasses, the overall risk of mission critical equipment failure becomes similar.

This section shows how the developed analytical model presented in chapter 3 can be used to simulate the rebreather's response to common rebreather accidents. We have identified three main failure modes that lead to rebreather accidents:

1. Oxygen supply failure - the reasons for this would be oxygen valves not turned on, control electronics not turned on, oxygen sensors incorrectly installed, oxygen valve partly blocked or damaged sensors
2. Running out of air. There are two separate scenarios here worth considering:
    (a) beginning the dive with a low starting pressure or smaller gas cylinders than required for the dive
    (b) diver overexertion due to rough seas, trauma, buoyancy issues, inexperience, diving deeper than usual
3. Carbon dioxide scrubber faults - this can lead to the scrubber entirely or partly not working, for example when the active ingredient is almost consumed, the scrubber's efficiency drops dramatically or when the scrubber material is not properly packed or sealed.

4.2.1 Oxygen supply failure

Mass from the oxygen tank is introduced into the diaphragm when the oxygen partial pressure drops under 10 kPa, as indicated in chapter 1, subsection 1.2.3. The nominal pressure of the oxygen tank is 3015 psi and it contains 0.8 kg of gas. Figure 4-7 shows the normal functionality of the oxygen tank: it injects mass to the diaphragm to maintain the oxygen partial pressure to the set limit. The top graph of Figure 4-7 shows the decrease of oxygen tank pressure as mass is consumed from it, the middle part of this Figure gives the mass of oxygen that is injected from the tank (it is constant because the injection system is making up for the oxygen that the diver consumes through his metabolism, which is constant since the work regime is extreme work and the depth is constant).

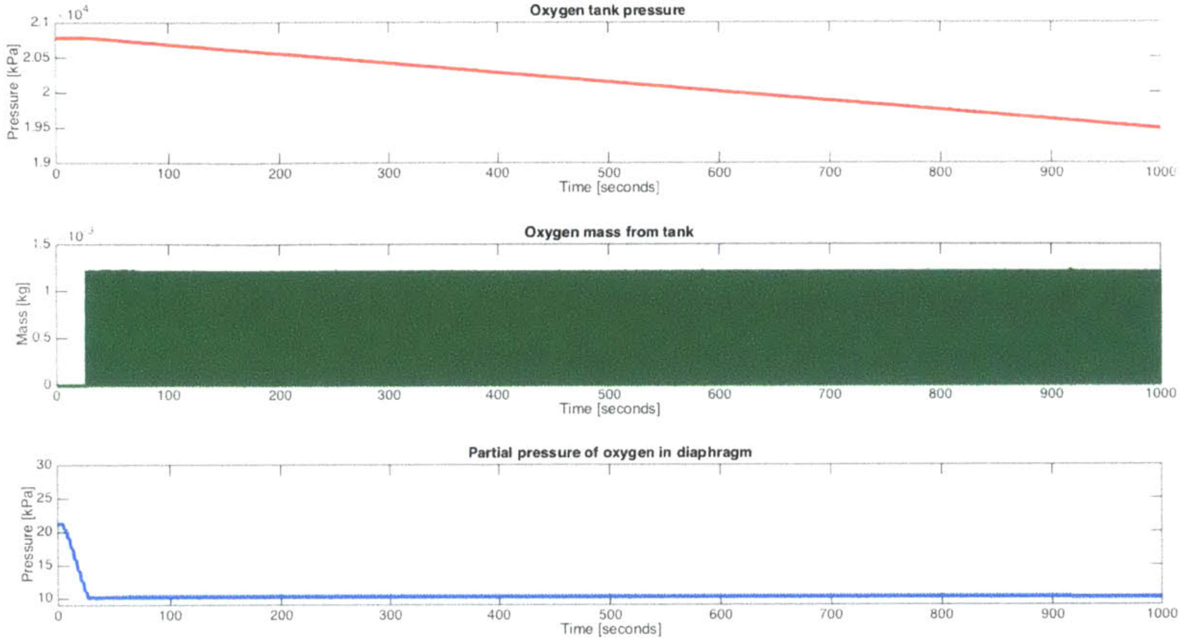


Figure 4-7: Oxygen tank normal functionality: it injects mass to the diaphragm to maintain the oxygen partial pressure to the set limit

Figure 4-8 shows a tank failure 3 minutes into the dive. This is consistent with accident reports, which describe cases of dives where the problems occur due to equipment related failure: failure to monitor oxygen gauge to see that the partial pressure in the diaphragm was decreasing, hoses disconnection, leaky tank, valve failure, bad oxygen sensor, non-tight hose seal or inexperienced diver [36, 37, 38]. The time the diver has to react to correct the problem decreases as the depth dive increases, Figure 4-8 shows a tank failure at surface depth, in which situation the diver has less than 30 seconds to attempt a rescue.

4.2.2 Insufficient amount of air

The main factor that leads to diving accidents when the air was not enough for a dive is that the diver had a low tank pressure at the start of the dive and failed to notice this. The analytical tool we developed in this thesis can simulate this scenario: Figure 4-9 shows the simulation results comparing a dive with a nominal tank start-

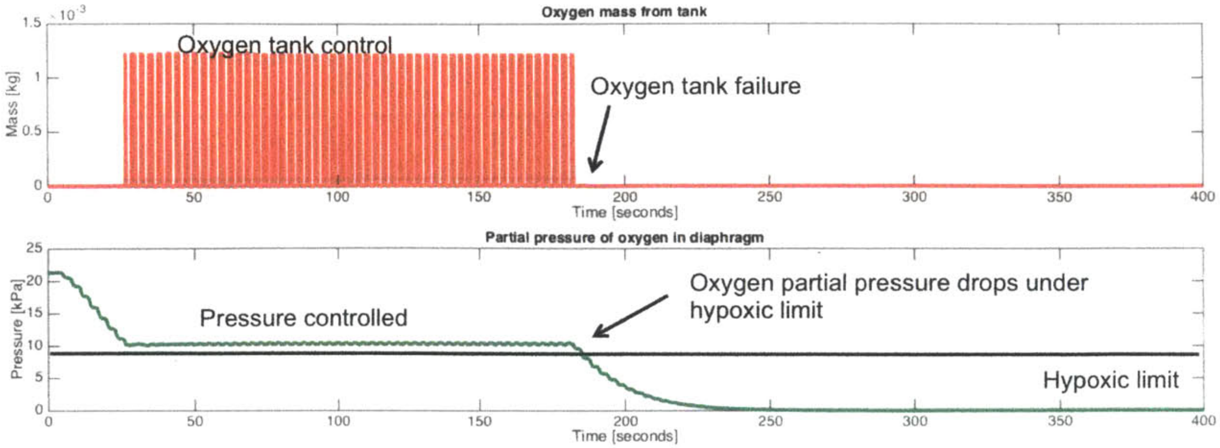


Figure 4-8: Oxygen tank failure

ing pressure and one when the diver started with a tank at one-tenth of the nominal pressure. We can see that the partial pressure in the diaphragm is maintained for roughly ten times longer when the oxygen tank is at the nominal pressure (graph on top) and the tank discharge (on the bottom).

Another cause for accidents of this type are successive descent - ascent trips without oxygen pressure monitoring or the diver working at a higher metabolic rate then originally planned for the mission. The graphs shown in Figure 4-9 are generated when the diver was performing at extreme working conditions throughout the mission and therefore illustrate a worst case scenario in which the air quickly becomes insufficient. If the diver observes the low oxygen partial pressure and reduces his/her work regime, the time it would take to run out of air would be extended to a point where, hopefully, the diver has had enough time to correct this issue.

4.2.3 Carbon dioxide scrubber faults

The carbon dioxide scrubber is a another important failure point in the rebreather configuration. Loose connections to or from the scrubber, a lower operating temperature than expected, the scrubber not being replaced or serviced on time can all lead to failures of the carbon dioxide scrubber. We have modelled two possible failures for the scrubber: Figure 4-10 shows total scrubber failure, in which the air in the

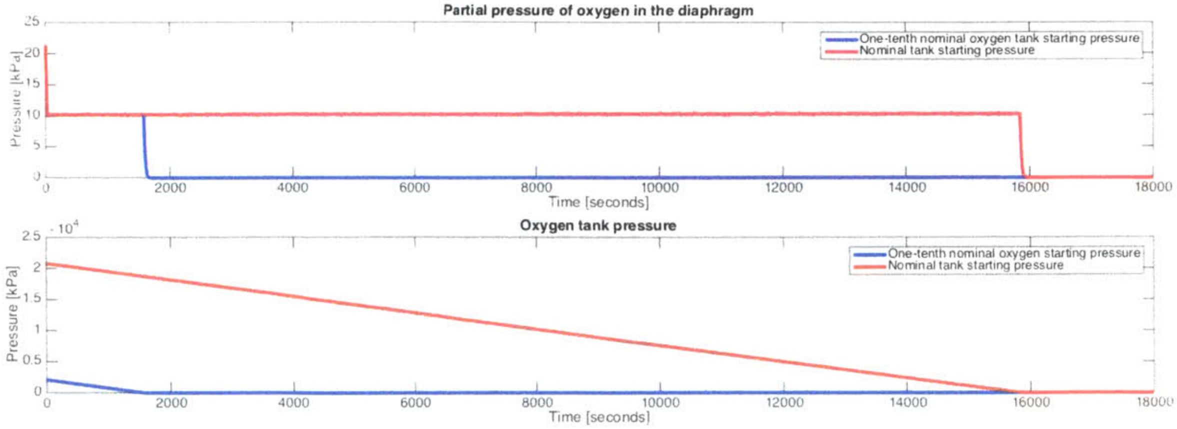


Figure 4-9: Low oxygen tank starting pressure

scrubber has the same carbon dioxide concentration as the air entering the scrubber and no carbon dioxide is removed. We can see that the hypercapnia limit is quickly exceeded, causing the diver to experience symptoms ranging from headaches, confusion, lethargy to disorientation, panic, hyperventilation, convulsions, unconsciousness and eventually death. When the scrubber is not working, the carbon dioxide concentration in the diaphragm increases up to about 90 kPa, when it starts to level off. The reason for this is that the amount of oxygen in the diaphragm is controlled to 10 kPa and so the diver, through metabolic processes, will exhale a constant carbon dioxide amount, equal to (1-RQ) times the inhaled amount of oxygen, which is kept constant. The concentration of carbon dioxide in the diaphragm does not keep on increasing because the human was modeled as inhaling a fixed volume of air from the diaphragm. When the partial pressure of carbon dioxide in the diaphragm increases, the breaths that the human inhales contain increasing amounts of carbon dioxide which dissolve in the blood and are also exhaled as a result of metabolic processes. This leads in the end to a leveling of carbon dioxide in the diaphragm air contents. In a nutshell, the human acts as a carbon dioxide filter up to the point when the carbon dioxide partial pressure in the diaphragm is maintained constant (and much above the hypercapnia limit, so if this situation were to occur during a real dive, the diver would be severely incapacitated after maximum one minute in the dive).

The second scenario we modeled in the simulation was a scrubber working at 30% of its capacity. The results of this are shown in Figure 4-11. After transient effects when the carbon dioxide partial pressure in the diaphragm increases to a level at which very mild hypercapnia effects can be observed, the scrubber manages to create a stable operating level for the partial pressure of carbon dioxide and maintain it at an elevated but not dangerous level of 1 kPa (hypercapnia begins to be observed at 2.63 kPa). The spikes in the middle Figure are transient effects and show the efforts of the carbon dioxide scrubber's attempts to stabilize the output carbon dioxide mass, once a stable operating regime has been attained, the amplitude of these spikes is dramatically decreased.

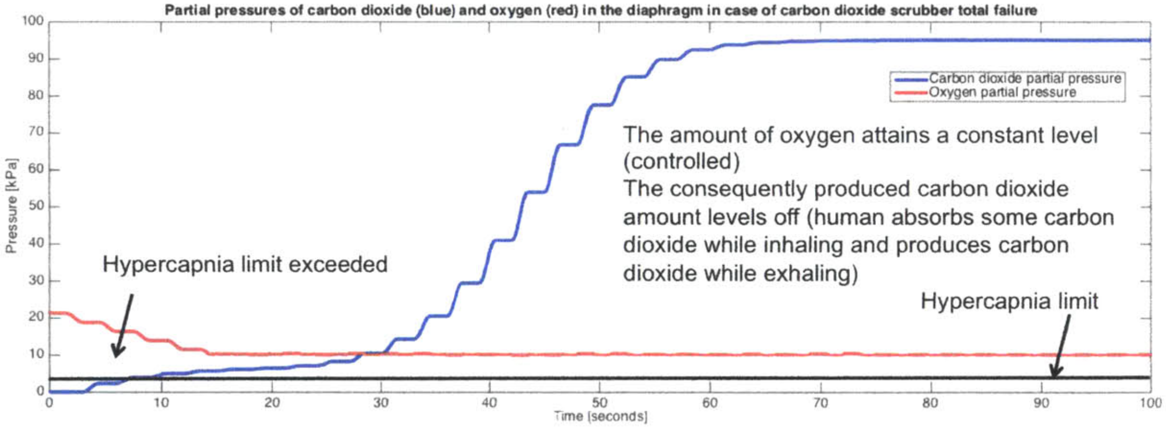


Figure 4-10: Scrubber failure

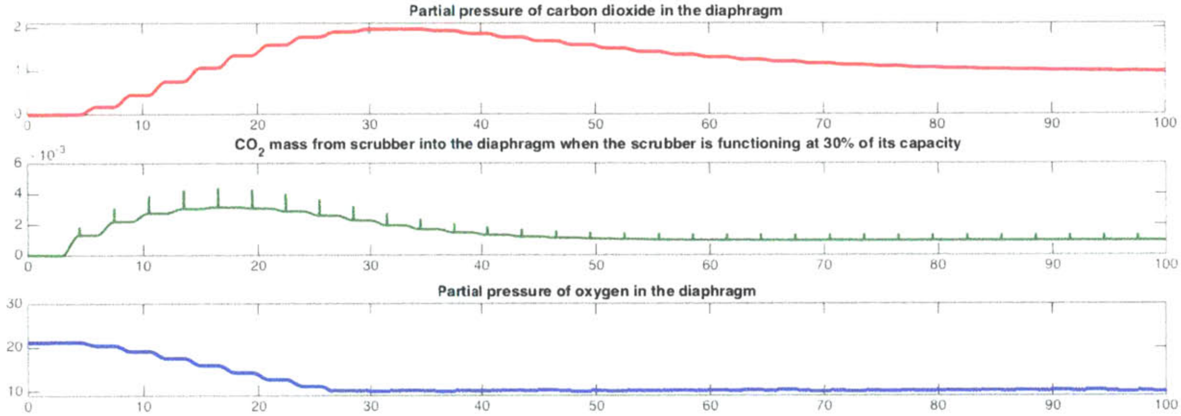


Figure 4-11: Scrubber low yield 30%

4.3 Chapter 4 summary

Chapter 4 presented advanced applications of the MK16 rebreather model. We implemented the depth and metabolic rate profiles shown in Figure 4-3 and we present the results: we first varied the metabolic rate, then we only varied the depth and then we combined both variables in one simulation. With this, we can conclude that the analytical model we have developed is capable of analyzing a typical dive scenario.

The next section illustrates how the model can be applied to simulate diving accidents, from oxygen supply failure, having an insufficient amount of air during the dive, to carbon dioxide scrubber faults.

Chapter 5

Conclusions and future work

5.1 Thesis summary

This thesis developed an analytical rebreather model for Earth and Space applications. Chapter 1 presented the motivation and background for the development of this model and then showed the thesis objective and its outline. We have performed a literature review on rebreather systems, the development of analytical model to simulate these systems and what the most frequent accidents are while using these systems.

Chapter 2 illustrates the process followed to develop the generic analytical model of the rebreather: we started with developing the human breathing module, then integrated the carbon dioxide scrubber, the diaphragm, the gas tanks and the control circuits. At this point, having all the notions introduced, we can pose the problem we are studying in this thesis: how to extend the gas tanks endurance using more complex control methods?

We have separated this problem into two separate sub-problems: firstly, we determined what is the maximum endurance of a system using a set configuration and varying the control algorithm. Then, secondly, we designed a set of architectures to have a set endurance. Lastly, we plotted the endurance versus the operating depth of various diving systems to see how the tradespace looks like.

Chapter 3 presents the applications of the generic rebreather model developed in Chapter 2: we started off by listing the assumptions for the model, described its components and then went on to answer the research questions posed at the end of Chapter 2 and test our hypothesis.

In Chapter 4 we have studied the applicability of the generic rebreather model to a typical dive profile, as well as simulated various diving accidents.

The thesis ends with Chapter 5, in which we draw the conclusions and show what the are next steps for this model development.

5.2 Future work

There are two main avenues that we would like to explore in the future: the first one is related to model validation and the second one to the accident investigations.

We would like to obtain diving data, specifically about the oxygen and nitrogen levels during a typical dive, and compare them with our model and use that data to calibrate it. Additionally, as explained in the introduction, the true value of an analytical model comes not when it stands alone, but when it is used in conjunction with hardware testing. Therefore, we would like to use the model to guide future hardware development, particularly in minimizing the breathing resistance and maximizing the endurance of the gas tanks.

The accident investigation framework shown in Chapter 1 is only one of the numerous available frameworks for accident investigation. An example of such a framework is System Theoretic Process Analysis (STPA) [65], which is a hazard analysis technique designed to take into account potential system failure modes that result from systems interactions and which are not captured by traditional failure analyses, like Failure Modes, Effects and Criticality Analysis (FMECA). We would like to expand the accident analyses capabilities of this model by incorporating notions from STPA into the simulations and so provide a more complete tool for rebreather simulation.

5.3 Conclusions

This thesis presented the development of an analytical rebreather model, which is the system that recirculates and conditions the air the diver is breathing during a dive. The capability of simulating rebreather performance is currently lacking in the diving commercial and military industry. We believe that the advantages of having such a model are multi-fold: it can be used for mission planning, evaluating the impact of adding a new technology or modifying an existing parameters or operational regime on an hardware configuration without performing expensive and time consuming hardware tests. An analytical model, like the one developed in this thesis, can also be used in complement with hardware testing to fine tune systems and increase resource endurance through the application of different electronic control strategies.

The developed Matlab/Simulink model of this rebreather is modular and can be generalized to study open, semi-closed or closed circuits, in which the breathing gas used is air, oxygen, nitrox or heliox. The system's operational environment can be the ocean's surface (1 atmosphere), space (less than 1 atmosphere pressure) or deep underwater (more than 1 atmosphere pressure). After introducing the analytical modeling process for the rebreather, this thesis goes on to explore the model's applications for the study of different oxygen control strategies in order to maximize the oxygen lifetime during a dive, as well as the model's applicability as an aid in accident investigations.

We aim to determine what is the maximum endurance of a rebreather system, given a particular, set configuration of components, as well as to study the reverse problem: if we set a mission endurance, what architectures would be able to achieve this level? Additionally, we are interested in studying how the tradespace of diving depth versus the diving systems's endurance looks like and how more complex control methods can help in pushing the existent boundary toward higher endurance limits.

We show that more complex control algorithms can extend the duration of the oxygen tanks in a rebreather by a factor of 6.35, and, when given a set endurance level, control can help lower the tank sizes by a factor of 4.

In the future, we would like to obtain operational data and compare it to the results in this thesis, as well as couple the analytical model with targeted hardware tests in order to help advance and improve future rebreather systems and so enable humans to explore deeper and for longer periods of time the fascinating underwater world.

Appendix A - Structure of MATLAB code for the rebreather analytical model

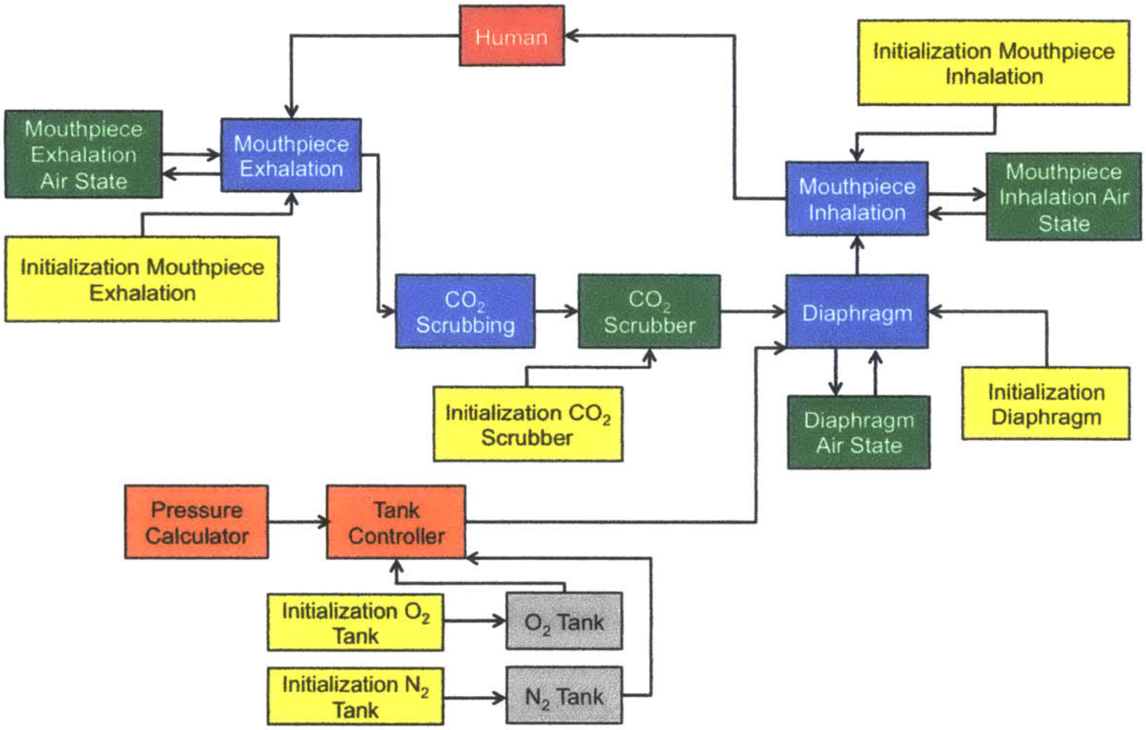


Figure A-1: Schematic of the rebreather analytical model and its constituent modules

Appendix B - MATLAB code for the rebreather analytical model

Human model

Generate breathing in out

```
%************************************************************************
%
% Block name: Generate Breathing In Out
% Description: This is a block that generates the breathing in and out
% signals
% Creator: Ioana Josan-Drinceanu
% Last updated: 31st July 2014
% Citations: Bioastronautics Data Book, Second Edition, NASA SP-3006
%
%************************************************************************


function [Breathing_In_Signal, Breathing_Out_Signal] = ...
    Generate_Breathing (Breathing_Signal)

Breathing_Out_Signal = zeros(1, length(Breathing_Signal));
Breathing_In_Signal = zeros(1, length(Breathing_Signal));

for i = 1:length(Breathing_Signal)
if Breathing_Signal(i) > 0
Breathing_Out_Signal(i) = Breathing_Signal(i);
Breathing_In_Signal(i) = 0;
else
Breathing_In_Signal(i) = Breathing_Signal(i);
Breathing_Out_Signal(i) = 0;
end
end
```

```

end
```

Control air in out

```
%**************************************************************************
%
% Block name: Control Air In Out
% Description: This is a function that reads in the Breathing In and Out
% signals and 'inhales' or 'exhales' air according to these signals
% Creator: Ioana Josan-Drinceanu
% Last updated: 14th August 2014
% Citations: Bioastronautics Data Book, Second Edition, NASA SP-3006
%
%**************************************************************************

function [Air_Out, Air_In, inhale, exhale, mdot_inhaled, ...
    mdot_exhaled, mdot_O2_inhaled, mdot_CO2_inhaled, ...
    mdot_H2O_inhaled, mdot_N2_inhaled, mdot_O2_exhaled, ...
    mdot_CO2_exhaled, mdot_H2O_exhaled, mdot_N2_exhaled, ...
    exhale_O2_mass_fraction, exhale_CO2_mass_fraction, ...
    exhale_N2_mass_fraction, exhale_H2O_mass_fraction, P_exhale, ...
    V_breath_out, P_O2_exhale, P_CO2_exhale, P_H2O_exhale, ...
    P_N2_exhale]     = Control_Air( Breathing_In_Signal, ...
    Breathing_Out_Signal, Air_Mouthpiece, Air_Mouthpiece_Initial, ...
    Breathing_Signal_Delayed)
global mdot_O2_delayed;
global mdot_N2_delayed;
global mdot_H2O_delayed;

coder.extrinsic('get_param');
coder.extrinsic('bdroot');
coder.extrinsic('fprintf');
coder.extrinsic('disp');
coder.extrinsic('str2num');
```

```

t = 0; dt = 0;
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
t = get_param(bdroot,'SimulationTime');
dt = str2num(get_param(bdroot, 'FixedStep'));

%% Global variables



%% Initialize Air Out and Air In

Air_Out = zeros(1,length(Air_Mouthpiece_Initial));
Air_In = zeros(1,length(Air_Mouthpiece_Initial));

if (t==0)
Air_Out = Air_Mouthpiece_Initial;
Air_In = Air_Mouthpiece_Initial;
Air_Mouthpiece = Air_Mouthpiece_Initial;
else
Air_Out = Air_Mouthpiece;
Air_In = Air_Mouthpiece;
end

inhale = 0;
exhale = 0;

%% Constants

M_O2 = 2*16;             % Molecular Mass of O2 [g/mol]
M_CO2 = 12+2*16;         % Molecular Mass of CO2 [g/mol]
M_H2O = 18.02;           % Molar Mass of H2O [g/mol]
M_N2 = 28;               % Molar Mass of N2 [g/mol]
Ru = 8.3144621;          % Universal Gas Constant [J/(mol.K)]
R_O2 = Ru/M_O2*1E3;      % Specific gas constant for O2 [J/(kg.K)]
```

```
R_CO2 = Ru/M_CO2*1E3;    % Specific gas constant for CO2 [J/(kg.K)]
R_H2O = Ru/M_H2O*1E3;    % Specific gas constant for H2O [J/(kg.K)]

%% Determining if the human should inhale or exhale
% If the human should inhale, then calculate the inhalation ...
    parameters and
% make the exhalation parameters zero, and reverse

if (Breathing_In_Signal < 0)
inhale = 1;
exhale = 0;
end

if (Breathing_Out_Signal > 0)
inhale = 0;
exhale = 1;

end

%% Inhalation

% the human will inhale when the Breathing_In_Signal is active
% the gas that the human will inhale is what is in the mouthpiece, ...
    given by
% the Air_Mouthpiece vector

T_air = Air_Mouthpiece(1);                          % air temperature
P_air = Air_Mouthpiece(2);                          % air pressure
mdot_air = Air_Mouthpiece(3);                       % air mass flow rate
m_air = Air_Mouthpiece(5);                          % air mass
O2_Mass_Fraction = Air_Mouthpiece(6);               % mass fraction of ...
    oxygen in the air
CO2_Mass_Fraction = Air_Mouthpiece(7);              % mass fraction of ...
    carbon dioxide in the air
H2O_Mass_Fraction = Air_Mouthpiece(8);              % mass fraction of ...
    water vapor in the air
```

```
N2_Mass_Fraction = Air_Mouthpiece(9);           % mass fraction of ...
    nitrogen in the air
% disp('Executing Air control');
% fprintf('Temp read from mouthpiece = %2.10f\n',T_air);
% fprintf('Pressure read from mouthpiece = %2.10f\n',P_air);
% fprintf('Mdot read from mouthpiece = %2.10f\n',mdot_air);
% fprintf('O2 MF read from mouthpiece = %2.10f\n',O2_Mass_Fraction);
% fprintf('CO2 MF read from mouthpiece = %2.10f\n',CO2_Mass_Fraction);
% fprintf('H2O MF read from mouthpiece = %2.10f\n',H2O_Mass_Fraction);
% fprintf('N2 MF read from mouthpiece = %2.10f\n',N2_Mass_Fraction);


%% Calculate the partial pressures in the inhaled air

m_O2  = m_air * O2_Mass_Fraction;
m_CO2 = m_air * CO2_Mass_Fraction;
m_H2O = m_air * H2O_Mass_Fraction;
m_N2 = m_air * N2_Mass_Fraction;

% number of moles of each gas in the air mixture
n_O2   = m_O2 /M_O2;
n_CO2  = m_CO2/M_CO2;
n_H2O  = m_H2O/M_H2O;
n_N2   = m_N2 /M_N2;


% number of moles of air is the sum of moles of each gas in the gas ...
    mixture
n_air = n_O2 + n_CO2 + n_H2O + n_N2;

% fprintf('No of moles in air = %2.10f\n', n_air);

x_O2  = n_O2/n_air;                        %mole fraction of O2
x_CO2  = n_CO2/n_air;                      %mole fraction of CO2
x_H2O  = n_H2O/n_air;                      %mole fraction of H2O
x_N2  = n_N2/n_air;                        %mole fraction of N2
```

```

ppO2   = x_O2  * P_air;                     %partial pressure of O2 ...
    [kPa]
ppCO2  = x_CO2 * P_air;                     %partial pressure of ...
    CO2 [kPa]
ppH2O  = x_H2O * P_air;                     %partial pressure of ...
    H2O [kPa]
ppN2   = x_N2  * P_air;                     %partial pressure of N2 ...
    [kPa]

% fprintf('Partial pressure O2 = %2.10f\n', ppO2);
% fprintf('Partial pressure CO2 = %2.10f\n', ppCO2);
% fprintf('Partial pressure H2O = %2.10f\n', ppH2O);
% fprintf('Partial pressure N2 = %2.10f\n', ppN2);

VF_O2  = ppO2 /P_air;                       %partial volume of O2
VF_CO2 = ppCO2/P_air;                       %partial volume of CO2
VF_H2O = ppH2O/P_air;                       %partial volume of H2O
VF_N2  = ppN2 /P_air;                       %partial volume of N2

%% Inhalation will occur when the Breathing_In_Signal is active

V_breath_in = Breathing_In_Signal;

% calculate the constituents in this breath
% human_VO2_breath = VF_O2 * V_breath_in * 0.001;
% human_VCO2_breath = VF_CO2 * V_breath_in * 0.001;
% human_VH2O_breath = VF_H2O * V_breath_in * 0.001;
% human_VN2_breath = VF_N2 * V_breath_in * 0.001;

human_VO2_breath = O2_Mass_Fraction * V_breath_in * 0.001;
human_VCO2_breath = CO2_Mass_Fraction * V_breath_in * 0.001;
%human_VCO2_breath = 0;
human_VH2O_breath = H2O_Mass_Fraction * V_breath_in * 0.001;
human_VN2_breath = N2_Mass_Fraction * V_breath_in * 0.001;

```

```

mdot_O2_inhaled  = ppO2 * 1E3 * human_VO2_breath /(Ru * T_air); ...
            % Mass of O2 inhaled per second [kg/s]
mdot_CO2_inhaled = ppCO2 * 1E3 * human_VCO2_breath /(Ru * T_air); ...
          % Mass of CO2 inhaled per second [kg/s]
mdot_H2O_inhaled = ppH2O * 1E3 * human_VH2O_breath /(Ru * T_air); ...
          % Mass of H2O inhaled per second [kg/s]
mdot_N2_inhaled  = ppN2 * 1E3 * human_VN2_breath /(Ru * T_air); ...
            % Mass of O2 inhaled per second [kg/s]

% mdot_O2_inhaled  = ppO2 * human_VO2_breath /(Ru * T_air);          ...
   % Mass of O2 inhaled per second [kg/s]
% mdot_CO2_inhaled = ppCO2  * human_VCO2_breath /(Ru * T_air); ...
          % Mass of CO2 inhaled per second [kg/s]
% mdot_H2O_inhaled = ppH2O * human_VH2O_breath /(Ru * T_air);        ...
   % Mass of H2O inhaled per second [kg/s]
% mdot_N2_inhaled  = ppN2 * human_VN2_breath /(Ru * T_air);          ...
   % Mass of O2 inhaled per second [kg/s]

mdot_CO2_inhaled = 0;
% mdot_N2_inhaled = 0;
mdot_H2O_inhaled = 0;
% mdot_O2_inhaled = 0;

% mdot_O2_inhaled  = P_air * 1E3 * human_VO2_breath /(Ru * T_air); ...
            % Mass of O2 inhaled per second [kg/s]
% mdot_CO2_inhaled = P_air * 1E3 * human_VCO2_breath /(Ru * T_air); ...
          % Mass of CO2 inhaled per second [kg/s]
% mdot_H2O_inhaled = P_air * 1E3 * human_VH2O_breath /(Ru * T_air); ...
          % Mass of H2O inhaled per second [kg/s]
% mdot_N2_inhaled  = P_air * 1E3 * human_VN2_breath /(Ru * T_air); ...
            % Mass of O2 inhaled per second [kg/s]
%


```

```
mdot_inhaled = mdot_O2_inhaled + mdot_CO2_inhaled + mdot_H2O_inhaled ...
    + mdot_N2_inhaled;

% disp('================Inhalation mdot================================')
% fprintf('mdot_O2_inhaled = %2.10f\n', mdot_O2_inhaled);
% fprintf('mdot_CO2_inhaled = %2.10f\n', mdot_CO2_inhaled);
% fprintf('mdot_H2O_inhaled = %2.10f\n', mdot_H2O_inhaled);
% fprintf('mdot_N2_inhaled = %2.10f\n', mdot_N2_inhaled);


%% Exhalation

V_breath_out = Breathing_Out_Signal;

% % Calculate the 'delayed' inhalation rate, so we can accurately ...
    calculate
% % what the exhalation should be based on how much was inhaled
%
% V_breath_in_delayed = Breathing_Signal_Delayed;
%
% human_VO2_breath_delayed = VF_O2 * V_breath_in_delayed * 0.001;
% mdot_O2_inhaled_delayed  = ppO2 * 1E3 * human_VO2_breath_delayed ...
    /(Ru * T_air);          % Mass of O2 inhaled per second [kg/s]
%
% human_VN2_breath_delayed = VF_N2 * V_breath_in_delayed * 0.001;
% mdot_N2_inhaled_delayed  = ppN2 * 1E3 * human_VN2_breath_delayed ...
    /(Ru * T_air);          % Mass of N2 inhaled per second [kg/s]
%
% human_VH2O_breath_delayed = VF_H2O * V_breath_in_delayed * 0.001;
% mdot_H2O_inhaled_delayed  = ppH2O * 1E3 * ...
    human_VH2O_breath_delayed /(Ru * T_air);          % Mass of N2 ...
    inhaled per second [kg/s]


% fprintf('Volume breath out = %2.10f\n', V_breath_out * 0.001);

```

```
% RQ = 0.76; ...
                                                                        ...
    % Respiratory Quotient, defined as the ratio of number of moles ...
    of CO2 released to number of moles of O2 absorbed by the lungs ...
    (Section 6.2.3.1.4 [4])
% mdot_O2_exhaled  = (-1) * (1-RQ) * mdot_O2_inhaled_delayed; ...
                            % Mass of O2 exhaled per second [kg/s]
% mdot_CO2_exhaled = (-1) * mdot_O2_inhaled_delayed * RQ * M_CO2 / ...
    M_O2;          % Mass of CO2 exhaled per second [kg/s]

%mdot_O2_delayed = -0.01;
%RQ = 0.76; ...
                                                                        ...
    % Respiratory Quotient, defined as the ratio of number of moles ...
    of CO2 released to number of moles of O2 absorbed by the lungs ...
    (Section 6.2.3.1.4 [4])
RQ = 0.85;

mdot_O2_exhaled  = (-1) * (1-RQ) * mdot_O2_delayed; ...
                                    % Mass of O2 exhaled per second [kg/s]
mdot_CO2_exhaled = (-1) * mdot_O2_delayed * RQ * M_CO2 / M_O2; ...
                            % Mass of CO2 exhaled per second [kg/s]
%mdot_CO2_exhaled = 0.000001 /dt;

% compute the mdot_N2_exhaled
% this is based on how much the human has inhaled and on the fact ...
    that the
% bioastronautics data book gives a partial pressure of 565mm Hg of ...
    N2 for
% a partial pressure of 596mm Hg inhaled, so this is a fraction of ...
    0.94798

%NF = 0.94798; % Nitrogen fraction - the ration of exhaled nitrogen ...
    to inhaled nitrogen partial pressures
% NF = 0.076;
NF = 1;
```

```
%mdot_N2_delayed = -0.03;
%NF = 1;
%RQ_N2 = 18.22;
mdot_N2_exhaled = (-1) * mdot_N2_delayed * NF ;
%mdot_N2_exhaled = -0.5;
%mdot_N2_exhaled = (-1) * mdot_O2_delayed * NF;



% compute the mdot_H2O exhaled
% the water fraction is 47/4.7 = 8.245614
%RQ_H2O = 1.12;
%mdot_H2O_delayed = -0.01;

%WF = 8.24561;
%mdot_H2O_exhaled = (-1) * mdot_H2O_delayed * WF;

%mdot_H2O_exhaled = (-1) * mdot_H2O_delayed * RQ_H2O * M_H2O / M_O2;
%mdot_H2O_exhaled = (-1) * mdot_O2_delayed * WF;


% % compute mdot_H2O_exhaled (amount of water vapor exhaled)
% % Exhaled breath is saturated with water vapor.  Therefore the ...
   density of
% % water in the air is only dependent on the temperature.

abs_humidity = 44.2000;                      %[g/m3]    From [2]
abs_humidity = 0;
rho_H2O = abs_humidity/1000;                 %[kg/m3]
m_H2O_exhaled = rho_H2O * V_breath_out * 0.00001;

mdot_H2O_exhaled = m_H2O_exhaled / dt;         % Mass of H2O vapor ...
   exhaled per second [kg/s]
mdot_H2O_exhaled = 0;

% Temperature
```

```
T_exhale = 310.15;                              %[K] - Human exhalate ...
    is at body temperature (37C) - from [1] p. 524


% Compute mass fractions
mdot_exhaled = mdot_O2_exhaled + mdot_CO2_exhaled + mdot_H2O_exhaled ...
    + mdot_N2_exhaled;
% fprintf('Mdot exhaled = %2.10f\n',mdot_exhaled);

exhale_O2_mass_fraction  = mdot_O2_exhaled /mdot_exhaled;
exhale_CO2_mass_fraction = mdot_CO2_exhaled/mdot_exhaled;
exhale_H2O_mass_fraction = mdot_H2O_exhaled/mdot_exhaled;
exhale_N2_mass_fraction  = mdot_N2_exhaled /mdot_exhaled;

% disp('*********Exhalation mass ...
    fractions********************************')
% fprintf('exhale_O2_mass_fraction = %2.10f\n', ...
    exhale_O2_mass_fraction);
% fprintf('exhale_CO2_mass_fraction = %2.10f\n', ...
    exhale_CO2_mass_fraction);
% fprintf('exhale_H2O_mass_fraction = %2.10f\n', ...
    exhale_H2O_mass_fraction);
% fprintf('exhale_N2_mass_fraction = %2.10f\n', ...
    exhale_N2_mass_fraction);


% disp('*********Exhalation masses*********************************')
% fprintf('exhale_O2_mass = %2.10f\n', mdot_O2_exhaled);
% fprintf('exhale CO2_mass = %2.10f\n', mdot_CO2_exhaled);
% fprintf('exhale_H2O_mass = %2.10f\n', mdot_H2O_exhaled);
% fprintf('exhale_N2_mass = %2.10f\n', mdot_N2_exhaled);


% Compute partial pressures
P_O2_exhale  = mdot_O2_exhaled  * dt * Ru  * T_exhale / ...
    (V_breath_out * 0.001);
```

```
P_CO2_exhale = mdot_CO2_exhaled * dt * Ru * T_exhale / (V_breath_out ...
    * 0.001);
P_H2O_exhale = mdot_H2O_exhaled * dt * Ru * T_exhale / (V_breath_out ...
    * 0.001);
P_N2_exhale  = mdot_N2_exhaled  * dt * Ru  * T_exhale / ...
    (V_breath_out * 0.001);

if (isnan(mdot_exhaled) || mdot_exhaled < 0.00000000000001)
exhale_CO2_mass_fraction = 0;
exhale_O2_mass_fraction = 0;
exhale_H2O_mass_fraction = 0;
exhale_N2_mass_fraction = 0;
P_CO2_exhale = 0;
P_O2_exhale = 0;
P_H2O_exhale = 0;
P_N2_exhale = 0;
mdot_exhaled = 0;
end


% Compute total pressure
P_exhale = P_O2_exhale + P_CO2_exhale + P_H2O_exhale + P_N2_exhale;
% disp ('*** Exhale pressure ****')
% fprintf('Exhale pressure = %2.10f\n',P_exhale);
%



%% Assign calculated values to Air_Out and Air_In

if (exhale == 1)
Air_Out(1) = T_exhale;
Air_Out(2) = P_exhale / 1000;
Air_Out(3) = mdot_exhaled;
Air_Out(6) = exhale_O2_mass_fraction;
Air_Out(7) = exhale_CO2_mass_fraction;
```

```
Air_Out(8) = exhale_H2O_mass_fraction;
Air_Out(9) = exhale_N2_mass_fraction;
Air_In = zeros(1,9);
end

if (inhale == 1)
Air_In = Air_Mouthpiece;
Air_In(3) = mdot_inhaled;
Air_Out = zeros(1,9);
end

end
```

Mouthpiece exhalation

Mouthpiece exhalation

```
%**************************************************************************
%
% Block name: Mouthpiece
% Description: This is a model of the diver's mouthpiece. The only ...
    output
% of this code is a vector containing the current status of the air ...
    in the
% mouthpiece.
% Creator: Ioana Josan-Drinceanu
% Last updated: 14th August 2014
% Citations: Bioastronautics Data Book, Second Edition, NASA SP-3006
%
%**************************************************************************


function [Air_Parameters_Out, Air_Out_Mouthpiece, Mouthpiece_p_new, ...
    Mouthpiece_O2_MF_new, Mouthpiece_CO2_MF_new, ...
    Mouthpiece_H2O_MF_new, Mouthpiece_N2_MF_new, mass_out, ...
```

```
    Mouthpiece_mass_initial, Mouthpiece_air_mass_after_out, ...
    Mouthpiece_mass_new, Mouthpiece_p_after_out,vdot_human_out, ...
    Mouthpiece_rho]          = Mouthpiece_Exhalation(Air_Out_Human, ...
    Air_Parameters_In, Air_In_Human, Breathing_In_Signal)


%% Simulation parameters
coder.extrinsic('num2str');
coder.extrinsic('str2num');
coder.extrinsic('fprintf');
coder.extrinsic('disp');
coder.extrinsic('Cp_calculator');

t = 0; dt = 0;
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
t = get_param(bdroot,'SimulationTime');
dt = str2num(get_param(bdroot, 'FixedStep'));

%% Constants
M_O2 = 2*16;                 % Molecular Mass of O2 [g/mol]
M_CO2 = 12+2*16;             % Molecular Mass of CO2 [g/mol]
M_H2O = 18.02;               % Molar Mass of H2O [g/mol]
M_N2 = 28;                   % Molar Mass of N2 [g/mol]
Ru = 8.3144621;              % Universal Gas Constant [J/(mol.K)]
R_O2 = (Ru/M_O2)*1E3;        % Specific gas constant for O2 [J/(kg.K)]
R_CO2 = (Ru/M_CO2)*1E3;      % Specific gas constant for CO2 [J/(kg.K)]
R_H2O = (Ru/M_H2O)*1E3;      % Specific gas constant for H2O [J/(kg.K)]
R_N2 = (Ru/M_N2)*1E3;        % Specific gas constant for N2 [J/(kg.K)]
sigma = 5.67e-8;             % Stephan boltzmann constant [W/(m2.K4)]

P_CO2_limit = 2.93;          % CO2 partial pressure limit (22 mmHg, ...
    from divers manual), [kPa]

%% Inputs

```

```
%% Input 1 - what already exists in the mouthpiece
% Air_Mouthpiece is the air that exists in the mouthpiece and that ...
    will be
% mixed with the human's inhalation and exhalation

%Air_Mouthpiece = Air_Parameters_In;

% decompose this

Mouthpiece_T = Air_Parameters_In(1);
Mouthpiece_p = Air_Parameters_In(2);
Mouthpiece_rho = Air_Parameters_In(4);
Mouthpiece_mass_initial = Air_Parameters_In(5);
Mouthpiece_O2_MF = Air_Parameters_In(6);
Mouthpiece_CO2_MF  = Air_Parameters_In(7);
Mouthpiece_H2O_MF = Air_Parameters_In(8);
Mouthpiece_N2_MF = Air_Parameters_In(9);
Mouthpiece_V = Mouthpiece_mass_initial / (Mouthpiece_rho);

% disp('Executing Mouthpiece');
% disp('------------------------------Mouthpiece Exhalation ...
    parameters-----------------')
% fprintf('Temp read from mouthpiece = %2.10f\n',Mouthpiece_T);
% fprintf('Pressure read from mouthpiece before mixing [kPa] = ...
    %2.10f\n',Mouthpiece_p);
% fprintf('Mass read from mouthpiece [kg] = ...
    %2.10f\n',Mouthpiece_mass_initial);
% fprintf('O2 MF read from mouthpiece = %2.10f\n',Mouthpiece_O2_MF);
% fprintf('CO2 MF read from mouthpiece = %2.10f\n',Mouthpiece_CO2_MF);
% fprintf('H2O MF read from mouthpiece = %2.10f\n',Mouthpiece_H2O_MF);
% fprintf('N2 MF read from mouthpiece = %2.10f\n',Mouthpiece_N2_MF);
% fprintf('Mouthpiece volume [m^3] = %2.10f\n',Mouthpiece_V);

%% Partial pressures calculation before mixing

m_O2_initial = Mouthpiece_mass_initial * Mouthpiece_O2_MF;
```

```
m_CO2_initial = Mouthpiece_mass_initial * Mouthpiece_CO2_MF;
m_H2O_initial = Mouthpiece_mass_initial * Mouthpiece_H2O_MF;
m_N2_initial = Mouthpiece_mass_initial * Mouthpiece_N2_MF;

P_O2_initial  = m_O2_initial  * Ru  * Mouthpiece_T / Mouthpiece_V / ...
    1000;
P_CO2_initial = m_CO2_initial * Ru * Mouthpiece_T / Mouthpiece_V / 1000;
P_H2O_initial = m_H2O_initial * Ru * Mouthpiece_T / Mouthpiece_V / 1000;
P_N2_initial = m_N2_initial * Ru * Mouthpiece_T / Mouthpiece_V / 1000;

m_total_initial = m_O2_initial + m_CO2_initial + m_H2O_initial + ...
    m_N2_initial;
p_total_initial = m_total_initial * Ru * Mouthpiece_T / Mouthpiece_V ...
    / 1000;
%p_total2 = (P_O2 + P_CO2 + P_H2O + P_N2);

% disp('-------Total pressure Exhalation recalculated--------------')
% fprintf('total pressure = %2.10f\n',p_total);
% fprintf('total mass = %2.10f\n',m_total);
% fprintf('total pressure2 = %2.10f\n',p_total2);
%
%
% disp ('---------------Partial pressures Exhalation before ...
    mixing------------------');
% fprintf('ppO2 old = %2.10f\n',P_O2);
% fprintf('ppCO2 old = %2.10f\n',P_CO2);
% fprintf('ppH2O old = %2.10f\n',P_H2O);
% fprintf('ppN2 old = %2.10f\n',P_N2);
%
% fprintf('Mouthpiece temp old = %2.10f\n',Mouthpiece_T);
% fprintf('Mouthpiece volume = %2.10f\n',Mouthpiece_V);
% fprintf('m_O2 = %2.10f\n',m_O2);
% fprintf('m_CO2 = %2.10f\n',m_CO2);
% fprintf('m_H2O = %2.10f\n',m_H2O);
% fprintf('m_N2 = %2.10f\n',m_N2);

```

```
%% Input 2 - human exhalation

In2_T = Air_Out_Human(1);
In2_mass = Air_Out_Human(3) * dt;
In2_O2_MF = Air_Out_Human(6);
In2_CO2_MF = Air_Out_Human(7);
In2_H2O_MF = Air_Out_Human(8);
In2_N2_MF = Air_Out_Human(9);

% disp('------------------------------Human ...
    exhalation-----------------')
% fprintf('Temp out human = %2.10f\n',In2_T);
% fprintf('Mass out human [kg] = %2.10f\n',In2_mass);
% fprintf('O2 MF out from human = %2.10f\n',In2_O2_MF);
% fprintf('CO2 MF out from human = %2.10f\n',In2_CO2_MF);
% fprintf('H2O MF out from human = %2.10f\n',In2_H2O_MF);
% fprintf('N2 MF out from human = %2.10f\n',In2_N2_MF);

%% Input 3 - human inhalation
%Input3 = zeros(1,9);

Input3 = Air_Parameters_In;

In3_T = Input3(1);
In3_mass = (-1) * Air_Out_Human(3) * dt;
In3_O2_MF = Input3(6);
In3_CO2_MF = Input3(7);
In3_H2O_MF = Input3(8);
In3_N2_MF = Input3(9);



%% Combining inputs with the air in the mouthpiece

m_O2_new = Mouthpiece_mass_initial * Mouthpiece_O2_MF + In2_mass * ...
    In2_O2_MF + In3_mass * In3_O2_MF;
```

```
m_CO2_new = Mouthpiece_mass_initial * Mouthpiece_CO2_MF + In2_mass * ...
    In2_CO2_MF + In3_mass * In3_CO2_MF;
m_H2O_new  = Mouthpiece_mass_initial * Mouthpiece_H2O_MF + In2_mass ...
    * In2_H2O_MF + In3_mass * In3_H2O_MF;
m_N2_new = Mouthpiece_mass_initial * Mouthpiece_N2_MF + In2_mass * ...
    In2_N2_MF + In3_mass * In3_N2_MF;

% disp('-----------------------------Mixing mass-----------------')
% fprintf('O2 mass [kg] = %2.10f\n',m_O2_new);
% fprintf('CO2 mass [kg] = %2.10f\n',m_CO2_new);
% fprintf('H2O mass [kg] = %2.10f\n',m_H2O_new);
% fprintf('N2 mass [kg] = %2.10f\n',m_N2_new);

Mouthpiece_mass_new = m_O2_new + m_CO2_new + m_H2O_new + m_N2_new;

% fprintf('Mouthpiece total new mass [kg] = ...
    %2.10f\n',Mouthpiece_mass_new)

Mouthpiece_O2_MF_new = m_O2_new / Mouthpiece_mass_new;
Mouthpiece_CO2_MF_new = m_CO2_new / Mouthpiece_mass_new;
Mouthpiece_H2O_MF_new = m_H2O_new / Mouthpiece_mass_new;
Mouthpiece_N2_MF_new = m_N2_new / Mouthpiece_mass_new;


%% Temperature Mixing
% Derived from Andrew's "TEMPERATURE COMBINATIONS" code from 2013.06.09
%
% NOTE: At this time, this calculation does not take into acount ...
    outlet air
% from the mouthpiece. It simply combines the existing air  with the two
% inlets (in1_air and in2_air). The validity of this assumption is ...
    up for
% discussion.
%
% 1.    Determine the number of moles present N [mol] for each body ...
    of air
```

```

% Mouthpiece
Mouthpiece_O2_N  = (Mouthpiece_mass_initial * Mouthpiece_O2_MF) * ...
    1E3 / M_O2;      % moles of O2 in the mouthpiece
Mouthpiece_CO2_N = (Mouthpiece_mass_initial * Mouthpiece_CO2_MF) * ...
    1E3 / M_CO2;     % moles of CO2 in the AR
Mouthpiece_H2O_N = (Mouthpiece_mass_initial * Mouthpiece_H2O_MF) * ...
    1E3 / M_H2O;     % moles of H2O in the AR
Mouthpiece_air_N = Mouthpiece_O2_N + Mouthpiece_CO2_N + ...
    Mouthpiece_H2O_N;

% In2
In2_O2_N = (In2_mass * In2_O2_MF) * 1E3 / M_O2;    % moles of O2 in in1
In2_CO2_N = (In2_mass * In2_CO2_MF) * 1E3 / M_CO2; % moles of CO2 in in1
In2_H2O_N = (In2_mass * In2_H2O_MF) * 1E3 / M_H2O; % moles of H2O in in1
In2_air_N = In2_O2_N + In2_CO2_N + In2_H2O_N;

% In3
% In3_mass_Cp = (-1) * In3_mass;
In3_mass_Cp = In3_mass;
In3_O2_N = (In3_mass_Cp * In3_O2_MF) * 1E3 / M_O2;    % moles of O2 ...
    in in2
In3_CO2_N = (In3_mass_Cp * In3_CO2_MF) * 1E3 / M_CO2; % moles of CO2 ...
    in in2
In3_H2O_N = (In3_mass_Cp * In3_H2O_MF) * 1E3 / M_H2O; % moles of H2O ...
    in in2
In3_air_N = In3_O2_N + In3_CO2_N + In3_H2O_N;

% % in3
% in3_O2_N  = (in3_air_mass*in3_air_O2_MF) *1E3/M_O2;  % moles of O2 ...
    in in3
% in3_CO2_N = (in3_air_mass*in3_air_CO2_MF)*1E3/M_CO2; % moles of ...
    CO2 in in3
% in3_H2O_N = (in3_air_mass*in3_air_H2O_MF)*1E3/M_H2O; % moles of ...
    H2O in in3
% in3_air_N = in3_O2_N + in3_CO2_N + in3_H2O_N;
```

```
%
% % in 4
% in4_O2_N  = (in4_air_mass*in4_air_O2_MF) *1E3/M_O2;  % moles of O2 ...
    in in4
% in4_CO2_N = (in4_air_mass*in4_air_CO2_MF)*1E3/M_CO2; % moles of ...
    CO2 in in4
% in4_H2O_N = (in4_air_mass*in4_air_H2O_MF)*1E3/M_H2O; % moles of ...
    H2O in in4
% in4_air_N = in4_O2_N + in4_CO2_N + in4_H2O_N;


% 2.    Determine the specific heat c_p [J/mol-K] of each body of air

% Assume: value at T ~ 298K is approximately valid across the range of
% temperatures seen in our model. This assumption will need to be
% validated.


Mouthpiece_c_p = 0;
Mouthpiece_c_p = Cp_calculator(Mouthpiece_mass_initial, ...
    Mouthpiece_O2_MF, Mouthpiece_CO2_MF, Mouthpiece_H2O_MF);
%Mouthpiece_c_p = Cp_values; %[J/kg-K]

% In1
In2_c_p = 0;
In2_c_p = Cp_calculator(In2_mass, In2_O2_MF, In2_CO2_MF, In2_H2O_MF);
% In2_c_p = Cp_values; %[J/kg-K]

% In3
In3_c_p = 0;
In3_c_p = Cp_calculator(In3_mass_Cp, In3_O2_MF, In3_CO2_MF, In3_H2O_MF);
% In3_c_p = Cp_values; %[J/kg-K]

% % in3
% Cp_values = ...
    Cp_calculator(in3_air_mass,in3_air_O2_MF,in3_air_CO2_MF,in3_air_H2O_MF);
```

```
% in3_c_p = Cp_values(1); %[J/kg-K]

% % in4
% Cp_values = ...
    Cp_calculator(in4_air_mass,in4_air_O2_MF,in4_air_CO2_MF,in4_air_H2O_MF);
% in4_c_p = Cp_values(1); %[J/kg-K]


% 3.    Calculate the new temperature [K]

Mouthpiece_T_new = ((Mouthpiece_c_p * Mouthpiece_air_N * ...
    Mouthpiece_T) +...
(In2_c_p * In2_air_N * In2_T) + ...
(In3_c_p * In3_air_N * In3_T))  / ...
(Mouthpiece_air_N * Mouthpiece_c_p + In2_air_N * In2_c_p + In3_air_N ...
    * In3_c_p);

% Mouthpiece_T_new = Mouthpiece_T;

%% New partial pressures

P_O2_new  = m_O2_new  * Ru  * Mouthpiece_T_new / Mouthpiece_V / 1000;
P_CO2_new = m_CO2_new * Ru * Mouthpiece_T_new / Mouthpiece_V / 1000;
P_H2O_new = m_H2O_new * Ru * Mouthpiece_T_new / Mouthpiece_V / 1000;
P_N2_new = m_N2_new * Ru * Mouthpiece_T_new / Mouthpiece_V / 1000;

Mouthpiece_p_new = P_O2_new + P_CO2_new + P_H2O_new + P_N2_new;

%% Initialize outputs

Air_Parameters_Out = Air_Parameters_In;

Air_Parameters_Out(1) = Mouthpiece_T_new;
Air_Parameters_Out(2) = Mouthpiece_p_new;
Air_Parameters_Out(3) = 0;
Air_Parameters_Out(4) = Mouthpiece_mass_new / Mouthpiece_V;
```

```
Air_Parameters_Out(5) = Mouthpiece_mass_new;
Air_Parameters_Out(6) = Mouthpiece_O2_MF_new;
Air_Parameters_Out(7) = Mouthpiece_CO2_MF_new;
Air_Parameters_Out(8) = Mouthpiece_H2O_MF_new;
Air_Parameters_Out(9) = Mouthpiece_N2_MF_new;

% fprintf('Pressure read from mouthpiece exhalation after mixing = ...
    %2.10f\n',Mouthpiece_p_new);
mdot_human_out = Air_Out_Human(3);
Air_Out_Mouthpiece = Air_Parameters_Out;
Air_Out_Mouthpiece(3) = mdot_human_out;

mass_out = 0;
Mouthpiece_air_mass_after_out = 0;
Mouthpiece_p_after_out = 0;
vdot_human_out = 0;

end
```

Mouthpiece exhalation air state

```
function Air_Out = Mouthpiece_Exhalation_Air_State(Air_In)

Air_Out = Air_In;

end
```

Initialization mouthpiece exhalation

```
function  Air_Parameters_Initial = Initialize_Mouthpiece_Exhalation()

%************************************************************************
%
% Block name: Initialize mouthpiece
% Description: This is a function initializes the mouthpiece
```

```
% Creator: Ioana Josan-Drinceanu
% Last updated: 4th August 2014
% Citations: Air composition as described in bioastronautics databook,
% table 11-2 page 510
% Notes: Not sure about moutpiece volume, need to update once ...
    correct value
% is found, 0.2 litres assumed for now to check code
%
%*************************************************************************


%% Simulation Parameters
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
coder.extrinsic('fprintf');
t = 0;
t =  get_param(bdroot, 'SimulationTime');

if (t == 0)
% Mouthpiece technical details

V_air = 2 * 0.001;                      % 10 litres converted to m^3

% assume there is already air in the mouthpiece at room temperature and
% pressure
T_air = 293.15;                     % 20 deg C in Kelvin
R = 8.3144621;                      % universal gas constant
p_air = 101.325;                    % kPa, equivalent of 1atm


% mass of air already existent in the mouthpiece volume
m_air = p_air * 1E3 * V_air / (R * T_air);

% density of air already existent in the mouthpiece volume
rho_air = m_air / V_air;

```

```
%% Create initial output

Air_Parameters_Initial = zeros(1,9);

Air_Parameters_Initial(1) = T_air;                       % air ...
    temperature in the mouthpiece [K]
Air_Parameters_Initial(2) = p_air;                       % air pressure ...
    in the mouthpiece [kPa]
Air_Parameters_Initial(3) = 0;                           % mass flow ...
    rate from the mouthpiece
Air_Parameters_Initial(4) = rho_air;                     % density of ...
    the air in the mouthpiece [kg/m^3]
Air_Parameters_Initial(5) = m_air;                       % mass of air ...
    in mouthpiece [kg]
%     Air_Parameters_Initial(6) = 158 / 760;                   % oxygen ...
    mass fraction in the mouthpiece
Air_Parameters_Initial(6) = 163.7 / 760;                   % oxygen mass ...
    fraction in the mouthpiece
Air_Parameters_Initial(7) = 0.3 / 760;                   % carbon ...
    dioxide mass fraction in the mouthpiece
%     Air_Parameters_Initial(8) = 5.7 / 760;                   % water ...
    vapor mass fraction in the mouthpiece
Air_Parameters_Initial(8) = 0 / 760;                   % water vapor ...
    mass fraction in the mouthpiece
Air_Parameters_Initial(9) = 596 / 760;                   % nitrogen mass ...
    fraction in the mouthpiece

else
%% Give zeros, means output has already been initialized
Air_Parameters_Initial = zeros(1,9);
end


end
```

Carbon dioxide scrubbing

Carbon dioxide scrubber

```
function [Air_Out, CO2_Scrubber_Specs_Out, ...
    mass_CO2_adsorbed_current_timestep, P_after, mass_CO2_after, ...
    mdot_air, eta]= CO2_Scrubbing(Air_In, Air_In_Human, ...
    CO2_Scrubber_Specs_In)

%***************************************************************************
%
% Block name: CO2_Scrubbing
% Description: This is a function that emulates the CCC in the EMU ...
    as a
% start for the diver rebreather system
% Creator: Ioana Josan-Drinceanu, based on the HabNet CCC code
% developed by Margaret Shaw
% Last updated: 20th August 2014
% Citations: EMU databook
% Notes: -
%
%***************************************************************************


%% Simulation parameters
coder.extrinsic('Cp_calculator');
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
coder.extrinsic('fprintf');
coder.extrinsic('str2num');

t = 0; dt = 0;
t =  get_param(bdroot, 'SimulationTime');
dt =  str2num(get_param(bdroot, 'FixedStep'));

```

```
%% constants
M_O2 = 2*16;            % Molecular Mass of O2 [g/mol]
M_CO2 = 12+2*16;        % Molecular Mass of CO2 [g/mol]
M_H2O = 18.02;          % Molar Mass of H2O [g/mol]
M_N2 = 28;              % Molar Mass of N2 [g/mol]
Ru = 8.3144621;         % Universal Gas Constant [J/(mol.K)]
R_O2 = Ru/M_O2*1E3;     % Specific gas constant for O2 [J/(kg.K)]
R_CO2 = Ru/M_CO2*1E3;   % Specific gas constant for CO2 [J/(kg.K)]
R_H2O = Ru/M_CO2*1E3;   % Specific gas constant for H2O [J/(kg.K)]
R_N2 = Ru/M_N2*1E3;     % Specific gas constant for N2 [J/(kg.K)]

%% Inputs
%

% % TEST ONLY
%
% Air_Out = Air_In;
% CO2_Scrubber_Specs_Out = CO2_Scrubber_Specs_In;
% mass_CO2_adsorbed_current_timestep = 0;
% P_after = 0;
% mass_CO2_after = 0;
% mdot_air = 0;
% % Inputs from Habitat Vector In
T_air = Air_In(1);
P_air = Air_In(2);
mdot_air = Air_In(3);
O2_MF = Air_In(6);
CO2_MF = Air_In(7);
H2O_MF = Air_In(8);
N2_MF = Air_In(9);


% Inputs from Tech Choice
CO2_capacity = CO2_Scrubber_Specs_In(1);
mass_CO2_adsorbed_pre = CO2_Scrubber_Specs_In(2);
pressure_drop_EOL_req = CO2_Scrubber_Specs_In(3);
```

```

Air_in_Human_mdot = Air_In_Human(3);
if  (Air_In(3) == 0)
mdot_air = (-1) * Air_in_Human_mdot;
end

%% check that air is flowing
if mdot_air == 0
%fprintf('No air flow into CCC! After %2.1f minutes!\n', t/60)
Air_Out = Air_In;
CO2_Scrubber_Specs_Out = CO2_Scrubber_Specs_In;
mass_CO2_adsorbed_current_timestep = 0;
P_after = 0;
mass_CO2_after = 0;
eta = 0;
else
eta = 1.0;
%     eta_initial = 1.0;
%     eta = eta_initial;
%     if (t < 500)
%         eta = eta_initial;
%     else
%         if( t >= 500 && t < 1000)
%             eta = 0.7;
%         else
%             if (t >= 1000)
%                 eta = 0.4;
%             end
%         end
%     end
% mdot of air constituents
mdot_CO2 = mdot_air * CO2_MF;
mdot_O2   = mdot_air * O2_MF;
mdot_H2O = mdot_air * H2O_MF;
mdot_N2 = mdot_air * N2_MF;

```

```
% masses of air constituents
mass_CO2 = mdot_CO2 * dt;
mass_O2  = mdot_O2 * dt;
mass_H2O = mdot_H2O * dt;
mass_N2 = mdot_N2 * dt;

%% Compute effective volume (volume of air that crosses the hardware ...
    over this timestep)
% Assumption: The air is mostly N2 and O2

%number of moles of each gas in the air mixture
n_O2   = mass_O2 / M_O2;
n_CO2  = mass_CO2 / M_CO2;
n_H2O  = mass_H2O / M_H2O;
n_N2 = mass_N2 / M_N2;
n_air = n_O2 + n_CO2 + n_H2O + n_N2;

x_O2  = n_O2 / n_air; % mole fraction of O2
x_N2 = n_N2 / n_air; % mole fraction of N2
ppO2   = x_O2  * P_air; % partial pressure of O2 [kPa]
ppN2 = x_N2 * P_air; % partial pressure of N2 [kPa]


V_eff = (mass_O2 + mass_N2) * Ru *T_air/(ppO2 + ppN2);

%% Exothermic reaction
% Heat is produced by an exothermic reaction

%Enthalpy of formation for reactants and products in kJ/mol

Hf_Ag2O = -30.6;     %kJ/mol
Hf_CO2 = -393.5;     %kJ/mol
Hf_Ag2CO3 = -501.7; %kJ/mol

%Atomic weights
%AW_Ag2O   =
```

```
AW_CO2     = 44.0095; %g/mol
%AW_Ag2CO3 =

%CO2 is the limiting reactant for the reaction
mols_CO2_adsorbed = mass_CO2 * eta / AW_CO2;

Hf_products = Hf_Ag2CO3;
Hf_reactants = Hf_Ag2O + Hf_CO2;

Hf_reaction = Hf_products - Hf_reactants;

%% update the state of the air

% New mdot

mass_CO2_after = mass_CO2 * (1-eta);
mass_O2_after  = mass_O2;
mass_H2O_after = mass_H2O;
mass_N2_after = mass_N2;

mass_air_after = mass_CO2_after + mass_O2_after + mass_H2O_after + ...
    mass_N2_after;
MF_CO2_after = mass_CO2_after / mass_air_after;
MF_O2_after  = mass_O2_after  / mass_air_after;
MF_H2O_after = mass_H2O_after / mass_air_after;
MF_N2_after = mass_N2_after / mass_air_after;

mdot_air_after = mass_air_after / dt;

% New temperature

%energy released, kJ
energy_released = -1*mols_CO2_adsorbed*Hf_reaction;

%      Cp_values = zeros(1,2);
```

```
%      Cp_values = ...
    Cp_calculator(mass_air_after,MF_O2_after,MF_CO2_after,MF_H2O_after);
%      Cp_units = Cp_values(2); %[J/kg-K]

% This temperature calculation needs to be fixed.  T_after nominal ...
    from Databook (Andrew): 103F (312.594)
%      T_after = T_air + (1000 * energy_released ) / (Cp_units * ...
    mass_air_after);
T_after = 312.44;

% New pressure

% Ideal gas law to get partial pressures
P_CO2 = mass_CO2_after * Ru * T_after / V_eff;
P_O2  = mass_O2_after  * Ru  * T_after / V_eff;
P_H2O = mass_H2O_after * Ru * T_after / V_eff;
P_N2 = mass_N2_after * Ru * T_after / V_eff;

P_after = P_O2 + P_CO2 + P_H2O + P_N2;

% pressure drop due to loss of CO2 molecules?
%     pressure_drop = (P_air-P_after);
mass_CO2_adsorbed = mass_CO2_adsorbed_pre + mols_CO2_adsorbed * M_CO2;
mass_CO2_adsorbed_current_timestep = mols_CO2_adsorbed * M_CO2; % ...
    computed for plotting

%% Checks

% check that it was accomplished successfully
if mass_CO2_adsorbed >= CO2_capacity
fprintf('CCC CO2 Capacity exceeded! After %2.1f minutes!\n', t/60)
end

% check that pressure drop isn't higher than EMU data book requirement
if (P_air - P_after) > pressure_drop_EOL_req
```

```
%fprintf('CCC Pressure Drop higher than specification! After %2.1f ...
    minutes!\n', t/60)
P_after = P_air - pressure_drop_EOL_req;
end

%% Outputs

%   update habitat vector
Air_Out = Air_In;
Air_Out(1) = T_after;
Air_Out(2) = P_after;
Air_Out(3) = mdot_air_after;
Air_Out(6) = MF_O2_after;
Air_Out(7) = MF_CO2_after;
Air_Out(8) = MF_H2O_after;
Air_Out(9) = MF_N2_after;

% update technology choice struct
CO2_Scrubber_Specs_Out = CO2_Scrubber_Specs_In;
CO2_Scrubber_Specs_Out(2) = mass_CO2_adsorbed;

%% BYPASS SCRUBBER FOR TEST ONLY
%             Air_Out = Air_In;
%               CO2_Scrubber_Specs_Out = CO2_Scrubber_Specs_In;
%         %  mass_CO2_adsorbed_current_timestep = 0;

%however, if the CCC capacity was exceeded, the CCC doesn't affect the
%air
if mass_CO2_adsorbed_pre + mols_CO2_adsorbed * M_CO2 > CO2_capacity
Air_Out = Air_In;
CO2_Scrubber_Specs_Out = CO2_Scrubber_Specs_In;
end
end

end
```

Initialization carbon dioxide scrubber

```
function  CO2_Scrubber_Specs_Out = Initialize_CO2_Scrubber()

%************************************************************************
%
% Block name: Initialize CO2_Scrubber
% Description: This is a function initializes the CO2 scrubber
% Creator: Ioana Josan-Drinceanu
% Last updated: 18th August 2014
% Citations: -
% Notes: Code contains assumed values, need to replace them with valid
% values
%
%************************************************************************


%% Simulation Parameters
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
coder.extrinsic('fprintf');
t = 0;
t =  get_param(bdroot, 'SimulationTime');

%% Outputs
if (t == 0)
% initial values for tech choice
CO2_Scrubber_Specs_Out = zeros(1,3);

CO2_Scrubber_Specs_Out(1) =  300;      %CO2_capacity, was 0.67
CO2_Scrubber_Specs_Out(2) =  0;         % mass_CO2_adsorbed
CO2_Scrubber_Specs_Out(3) =  224/1000; %kPa

else
CO2_Scrubber_Specs_Out = zeros(1,3);
```

```
end


end
```

Carbon dioxide scrubber

```
function CO2_Scrubber_Specs_Out = CO2_Scrubber(CO2_Scrubber_Specs_In)

%% References
%   Hamilton Sundstrand EMU Data Book

%% Constants
CO2_capacity = 300; %kg, CO2_capacity from Butler et al. 1997
mass = 31.95; % mass
volume = 10 * 13.46 * 3.431; %volume

%% Inputs
mass_CO2_adsorbed = CO2_Scrubber_Specs_In(2);

%% Pressure drop
pressure_drop_BOL_req = 167/1000; %kPa
pressure_drop_EOL_req = 224/1000; %kPa

%% Outputs
CO2_Scrubber_Specs_Out = [CO2_capacity;
mass_CO2_adsorbed
pressure_drop_EOL_req];

end
```

Diaphragm

Diaphragm

```
%*************************************************************************
%
% Block name: Diaphragm
% Description: This is a model of the diver's Diaphragm. The only output
% of this code is a vector containing the current status of the air ...
    in the
% Diaphragm.
% Creator: Ioana Josan-Drinceanu
% Last updated: 14th August 2014
% Citations: Bioastronautics Data Book, Second Edition, NASA SP-3006
%
%*************************************************************************


function [Air_Out_Diaphragm, Air_Parameters_Out, Diaphragm_p_new, ...
    Diaphragm_O2_MF_new, Diaphragm_CO2_MF_new, Diaphragm_H2O_MF_new, ...
    Diaphragm_N2_MF_new, Diaphragm_mass_new, m_O2_new, m_CO2_new, ...
    m_H2O_new, m_N2_new, mdot_in, P_N2_new, mass_N2_to_vent] ...
                = Diaphragm(Air_In_CO2_Scrubber, Air_Parameters_In, ...
    Breathing_In_Signal, Air_In_Human, Air_In_O2_addition, ...
    Air_In_N2_addition, pressure_out_total, pressure_out_N2)


%% Simulation parameters
coder.extrinsic('num2str');
coder.extrinsic('str2num');
coder.extrinsic('fprintf');
coder.extrinsic('disp');

t = 0; dt = 0;
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
t = get_param(bdroot,'SimulationTime');
dt = str2num(get_param(bdroot, 'FixedStep'));

%% Constants
```

```
M_O2 = 2*16;                 % Molecular Mass of O2 [g/mol]
M_CO2 = 12+2*16;             % Molecular Mass of CO2 [g/mol]
M_H2O = 18.02;               % Molar Mass of H2O [g/mol]
M_N2 = 28;                   % Molar Mass of N2 [g/mol]
Ru = 8.3144621;              % Universal Gas Constant [J/(mol.K)]
R_O2 = (Ru/M_O2)*1E3;        % Specific gas constant for O2 [J/(kg.K)]
R_CO2 = (Ru/M_CO2)*1E3;      % Specific gas constant for CO2 [J/(kg.K)]
R_H2O = (Ru/M_H2O)*1E3;      % Specific gas constant for H2O [J/(kg.K)]
R_N2 = (Ru/M_N2)*1E3;        % Specific gas constant for N2 [J/(kg.K)]
sigma = 5.67e-8;             % Stephan boltzmann constant [W/(m2.K4)]

P_CO2_limit = 2.93;          % CO2 partial pressure limit (22 mmHg, ...
    from divers manual), [kPa]

%% Input 1 - what already exists in the Diaphragm
% Air_Diaphragm is the air that exists in the Diaphragm and that ...
    will be
% mixed with the human's inhalation and exhalation

%Air_Diaphragm = Air_Parameters_In;

% decompose this

Diaphragm_T = Air_Parameters_In(1);
Diaphragm_p = Air_Parameters_In(2);
Diaphragm_rho = Air_Parameters_In(4);
Diaphragm_mass_initial = Air_Parameters_In(5);
Diaphragm_O2_MF = Air_Parameters_In(6);
Diaphragm_CO2_MF  = Air_Parameters_In(7);
Diaphragm_H2O_MF = Air_Parameters_In(8);
Diaphragm_N2_MF = Air_Parameters_In(9);
Diaphragm_V = Diaphragm_mass_initial / (Diaphragm_rho);

%% Partial pressures calculation before mixing

m_O2 = Diaphragm_mass_initial * Diaphragm_O2_MF;
```

```
m_CO2 = Diaphragm_mass_initial * Diaphragm_CO2_MF;
m_H2O = Diaphragm_mass_initial * Diaphragm_H2O_MF;
m_N2 = Diaphragm_mass_initial * Diaphragm_N2_MF;

P_O2  = m_O2  * Ru  * Diaphragm_T / Diaphragm_V /1000;
P_CO2 = m_CO2 * Ru * Diaphragm_T / Diaphragm_V /1000;
P_H2O = m_H2O * Ru * Diaphragm_T / Diaphragm_V /1000;
P_N2 = m_N2 * Ru * Diaphragm_T / Diaphragm_V /1000;

m_total = m_O2 + m_CO2 + m_H2O + m_N2;
p_total = m_total * Ru * Diaphragm_T / Diaphragm_V /1000;
p_total2 = (P_O2 + P_CO2 + P_H2O + P_N2);

%% Partial pressures calculation before mixing
m_O2 = Diaphragm_mass_initial * Diaphragm_O2_MF;
m_CO2 = Diaphragm_mass_initial * Diaphragm_CO2_MF;
m_H2O = Diaphragm_mass_initial * Diaphragm_H2O_MF;
m_N2 = Diaphragm_mass_initial * Diaphragm_N2_MF;

P_O2  = m_O2  * Ru  * Diaphragm_T / Diaphragm_V /1000;
P_CO2 = m_CO2 * Ru * Diaphragm_T / Diaphragm_V /1000;
P_H2O = m_H2O * Ru * Diaphragm_T / Diaphragm_V /1000;
P_N2 = m_N2 * Ru * Diaphragm_T / Diaphragm_V /1000;

m_total = m_O2 + m_CO2 + m_H2O + m_N2;
p_total = m_total * Ru * Diaphragm_T / Diaphragm_V /1000;
p_total2 = (P_O2 + P_CO2 + P_H2O + P_N2);

% disp('-------Total pressure recalculated--------------')
% fprintf('total pressure = %2.10f\n',p_total);
% fprintf('total mass = %2.10f\n',m_total);
% fprintf('total pressure2 = %2.10f\n',p_total2);
%
%
% disp ('---------------Partial pressures before ...
    mixing------------------');
```

```
% fprintf('ppO2 old = %2.10f\n',P_O2);
% fprintf('ppCO2 old = %2.10f\n',P_CO2);
% fprintf('ppH2O old = %2.10f\n',P_H2O);
% fprintf('ppN2 old = %2.10f\n',P_N2);
%
% fprintf('Diaphragm temp old = %2.10f\n',Diaphragm_T);
% fprintf('Diaphragm volume = %2.10f\n',Diaphragm_V);
% fprintf('m_O2 = %2.10f\n',m_O2);
% fprintf('m_CO2 = %2.10f\n',m_CO2);
% fprintf('m_H2O = %2.10f\n',m_H2O);
% fprintf('m_N2 = %2.10f\n',m_N2);

%% Input 2 - air from CO2 scrubber

In2_T = Air_In_CO2_Scrubber(1);

if (Breathing_In_Signal < 0)
mdot_in = Air_In_CO2_Scrubber(3);
else
mdot_in = 0;
end

In2_mass =  mdot_in * dt;
In2_O2_MF = Air_In_CO2_Scrubber(6);
In2_CO2_MF = Air_In_CO2_Scrubber(7);
In2_H2O_MF = Air_In_CO2_Scrubber(8);
In2_N2_MF = Air_In_CO2_Scrubber(9);

% disp('------------------------------Human ...
    exhalation-----------------')
% fprintf('Temp out human = %2.10f\n',In2_T);
% fprintf('Mass out human [kg] = %2.10f\n',In2_mass);
% fprintf('O2 MF out from human = %2.10f\n',In2_O2_MF);
% fprintf('CO2 MF out from human = %2.10f\n',In2_CO2_MF);
% fprintf('H2O MF out from human = %2.10f\n',In2_H2O_MF);
% fprintf('N2 MF out from human = %2.10f\n',In2_N2_MF);
```

```

%% Input 3 - air pulled into the mouthpiece inhalation

Input3 = Air_Parameters_In;
In3_T = Air_Parameters_In(1);
In3_mass = Air_In_Human(3) * dt;                % this will be ...
    negative, corresponding to inhalation (volume subtraction)
In3_O2_MF = Air_Parameters_In(6);
In3_CO2_MF = Air_Parameters_In(7);
In3_H2O_MF = Air_Parameters_In(8);
In3_N2_MF = Air_Parameters_In(9);

% disp('------------------------------Human ...
    inhalation-----------------')
% fprintf('Temp in human = %2.10f\n',In3_T);
% fprintf('Mass in human [kg] = %2.10f\n',In3_mass);
% fprintf('O2 MF in from human = %2.10f\n',In3_O2_MF);
% fprintf('CO2 MF in from human = %2.10f\n',In3_CO2_MF);
% fprintf('H2O MF in from human = %2.10f\n',In3_H2O_MF);
% fprintf('N2 MF in from human = %2.10f\n',In3_N2_MF);


%% Input 4 - from oxygen tank

Input4 = Air_In_O2_addition;
%Air_In_O2_addition = zeros(1,9);
In4_T = Air_In_O2_addition(1);
In4_mass = Air_In_O2_addition(3);
%In4_mass = 0;
In4_O2_MF = 1;
In4_CO2_MF = 0;
In4_H2O_MF = 0;
% In4_N2_MF = Air_In_O2_addition(9);
In4_N2_MF = 0;

%% Input 5 - from nitrogen tank
```

```
Input5 = Air_In_N2_addition;
% Air_In_N2_addition = zeros(1,9);
In5_T = Air_In_N2_addition(1);
In5_mass = Air_In_N2_addition(3);
In5_O2_MF = 0;
In5_CO2_MF = 0;
In5_H2O_MF = 0;
In5_N2_MF = 1;


%% Combining inputs with the air in the Diaphragm

m_O2_new = Diaphragm_mass_initial * Diaphragm_O2_MF + In2_mass * ...
    In2_O2_MF + In3_mass * In3_O2_MF + In4_mass * In4_O2_MF + ...
    In5_mass * In5_O2_MF;
m_CO2_new = Diaphragm_mass_initial * Diaphragm_CO2_MF + In2_mass * ...
    In2_CO2_MF + In3_mass * In3_CO2_MF + In4_mass * In4_CO2_MF + ...
    In5_mass * In5_CO2_MF;
m_H2O_new  = Diaphragm_mass_initial * Diaphragm_H2O_MF + In2_mass * ...
    In2_H2O_MF + In3_mass * In3_H2O_MF + In4_mass * In4_H2O_MF + ...
    In5_mass * In5_H2O_MF;
m_N2_new = Diaphragm_mass_initial * Diaphragm_N2_MF + In2_mass * ...
    In2_N2_MF + In3_mass * In3_N2_MF +  In4_mass * In4_N2_MF + ...
    In5_mass * In5_N2_MF;

% disp('------------------------------Mixing mass-----------------')
% fprintf('O2 mass [kg] = %2.10f\n',m_O2_new);
% fprintf('CO2 mass [kg] = %2.10f\n',m_CO2_new);
% fprintf('H2O mass [kg] = %2.10f\n',m_H2O_new);
% fprintf('N2 mass [kg] = %2.10f\n',m_N2_new);

Diaphragm_mass_new = m_O2_new + m_CO2_new + m_H2O_new + m_N2_new;

% fprintf('Diaphragm total new mass [kg] = %2.10f\n',Diaphragm_mass_new)

Diaphragm_O2_MF_new = m_O2_new / Diaphragm_mass_new;
```

```
Diaphragm_CO2_MF_new = m_CO2_new / Diaphragm_mass_new;
Diaphragm_H2O_MF_new = m_H2O_new / Diaphragm_mass_new;
Diaphragm_N2_MF_new = m_N2_new / Diaphragm_mass_new;

% disp('------------------------------New mass ...
    fractions----------------')
% fprintf('O2 MF new = %2.10f\n',Diaphragm_O2_MF_new);
% fprintf('CO2 MF new = %2.10f\n',Diaphragm_CO2_MF_new);
% fprintf('H2O MF new = %2.10f\n',Diaphragm_H2O_MF_new);

% Temperature mixing - using HabNet code - add later if necessary?

%% Temperature Mixing
% Derived from Andrew's "TEMPERATURE COMBINATIONS" code from 2013.06.09
%
% NOTE: At this time, this calculation does not take into acount ...
    outlet air
% from the mouthpiece. It simply combines the existing air  with the two
% inlets (in1_air and in2_air). The validity of this assumption is ...
    up for
% discussion.
%
% 1.    Determine the number of moles present N [mol] for each body ...
    of air

% Diaphragm
Diaphragm_O2_N  = (Diaphragm_mass_initial * Diaphragm_O2_MF) * 1E3 / ...
    M_O2;     % moles of O2 in the mouthpiece
Diaphragm_CO2_N = (Diaphragm_mass_initial * Diaphragm_CO2_MF) * 1E3 ...
    / M_CO2;    % moles of CO2 in the AR
Diaphragm_H2O_N = (Diaphragm_mass_initial * Diaphragm_H2O_MF) * 1E3 ...
    / M_H2O;    % moles of H2O in the AR
Diaphragm_air_N = Diaphragm_O2_N + Diaphragm_CO2_N + Diaphragm_H2O_N;

% In2
In2_O2_N = (In2_mass * In2_O2_MF) * 1E3 / M_O2;    % moles of O2 in in1
```

```
In2_CO2_N = (In2_mass * In2_CO2_MF) * 1E3 / M_CO2; % moles of CO2 in in1
In2_H2O_N = (In2_mass * In2_H2O_MF) * 1E3 / M_H2O; % moles of H2O in in1
In4_air_N = In2_O2_N + In2_CO2_N + In2_H2O_N;

% In3
% In3_mass_Cp = (-1) * In3_mass;
In3_mass_Cp = In3_mass;
In3_O2_N = (In3_mass_Cp * In3_O2_MF) * 1E3 / M_O2;     % moles of O2 ...
    in in3
In3_CO2_N = (In3_mass_Cp * In3_CO2_MF) * 1E3 / M_CO2; % moles of CO2 ...
    in in3
In3_H2O_N = (In3_mass_Cp * In3_H2O_MF) * 1E3 / M_H2O; % moles of H2O ...
    in in3
In3_air_N = In3_O2_N + In3_CO2_N + In3_H2O_N;

% In4
In4_O2_N = (In4_mass * In4_O2_MF) * 1E3 / M_O2;     % moles of O2 in in4
In4_CO2_N = (In4_mass * In4_CO2_MF) * 1E3 / M_CO2; % moles of CO2 in in4
In4_H2O_N = (In4_mass * In4_H2O_MF) * 1E3 / M_H2O; % moles of H2O in in4
In4_air_N = In4_O2_N + In4_CO2_N + In4_H2O_N;

% In5
In5_O2_N = (In5_mass * In5_O2_MF) * 1E3 / M_O2;     % moles of O2 in in4
In5_CO2_N = (In5_mass * In5_CO2_MF) * 1E3 / M_CO2; % moles of CO2 in in4
In5_H2O_N = (In5_mass * In5_H2O_MF) * 1E3 / M_H2O; % moles of H2O in in4
In5_air_N = In5_O2_N + In5_CO2_N + In5_H2O_N;


% 2.    Determine the specific heat c_p [J/mol-K] of each body of air

% Assume: value at T ~ 298K is approximately valid across the range of
% temperatures seen in our model. This assumption will need to be
% validated.


Diaphragm_c_p = 0;
```

```
Diaphragm_c_p = Cp_calculator(Diaphragm_mass_initial, ...
    Diaphragm_O2_MF, Diaphragm_CO2_MF, Diaphragm_H2O_MF);
%Mouthpiece_c_p = Cp_values; %[J/kg-K]

% In1
In2_c_p = 0;
In2_c_p = Cp_calculator(In2_mass, In2_O2_MF, In2_CO2_MF, In2_H2O_MF);
% In2_c_p = Cp_values; %[J/kg-K]

% In3
In3_c_p = 0;
In3_c_p = Cp_calculator(In3_mass, In3_O2_MF, In3_CO2_MF, In3_H2O_MF);
% In3_c_p = Cp_values; %[J/kg-K]



% In4
In4_c_p = 0;
In4_c_p = Cp_calculator(In4_mass, In4_O2_MF, In4_CO2_MF, In4_H2O_MF);

% In5
In5_c_p = 0;
In5_c_p = Cp_calculator(In5_mass, In5_O2_MF, In5_CO2_MF, In5_H2O_MF);

% 3.    Calculate the new temperature [K]

Diaphragm_T_new = ((Diaphragm_c_p * Diaphragm_air_N * Diaphragm_T) +...
(In2_c_p * In4_air_N * In2_T) + ...
(In3_c_p * In3_air_N * In3_T) + ...
(In4_c_p * In4_air_N * In4_T) + ...
(In5_c_p * In5_air_N * In5_T))  / ...
(Diaphragm_air_N * Diaphragm_c_p + In4_air_N * In2_c_p + In3_air_N * ...
    In3_c_p + In4_air_N * In4_c_p + In5_air_N * In5_c_p);



```

```
% Diaphragm_T_new = Diaphragm_T;

% New partial pressures after mixing to determine the new pressure

% m_O2_new  = Diaphragm_mass_new * Diaphragm_O2_MF_new;
% m_CO2_new = Diaphragm_mass_new * Diaphragm_CO2_MF_new;
% m_H2O_new = Diaphragm_mass_new * Diaphragm_H2O_MF_new;
% m_N2_new = Diaphragm_mass_new * Diaphragm_N2_MF_new;

P_O2_new  = m_O2_new  * Ru  * Diaphragm_T_new / Diaphragm_V /1000;
P_CO2_new = m_CO2_new * Ru * Diaphragm_T_new / Diaphragm_V /1000;
P_H2O_new = m_H2O_new * Ru * Diaphragm_T_new / Diaphragm_V /1000;
P_N2_new = m_N2_new * Ru * Diaphragm_T_new / Diaphragm_V /1000;

%% Checking ppN2 to see if we need to vent something...
max_pp_N2 = pressure_out_total;

if (P_N2_new >= max_pp_N2)

delta_ppN2 = P_N2_new - max_pp_N2;
mass_N2_to_vent = ((delta_ppN2 * Diaphragm_V) / (Ru * ...
    Diaphragm_T_new)) * 1000;
new_N2_mass = m_N2_new - mass_N2_to_vent;
Diaphragm_mass_new = m_O2_new + m_CO2_new + m_H2O_new + new_N2_mass;
Diaphragm_N2_MF_new = new_N2_mass / Diaphragm_mass_new;
else
mass_N2_to_vent = 0;

end

%% New pressure calculations

Diaphragm_p_new = P_O2_new + P_CO2_new + P_H2O_new + P_N2_new;

% disp('------------------------------New partial pressures after ...
    mixing----------------')
```

```
% fprintf('ppO2 new = %2.10f\n',P_O2_new);
% fprintf('ppCO2 new = %2.10f\n',P_CO2_new);
% fprintf('ppH2O new = %2.10f\n',P_H2O_new);
% fprintf('ppN2 new = %2.10f\n',P_N2_new);
% fprintf('Diaphragm temp new = %2.10f\n',Diaphragm_T_new);
% fprintf('Diaphragm volume = %2.10f\n',Diaphragm_V);



%% Initialize outputs

Air_Parameters_Out = Air_Parameters_In;

Air_Parameters_Out(1) = Diaphragm_T_new;
Air_Parameters_Out(2) = Diaphragm_p_new;
Air_Parameters_Out(3) = 0;
Air_Parameters_Out(4) = Diaphragm_mass_new / Diaphragm_V;
Air_Parameters_Out(5) = Diaphragm_mass_new;
Air_Parameters_Out(6) = Diaphragm_O2_MF_new;
Air_Parameters_Out(7) = Diaphragm_CO2_MF_new;
Air_Parameters_Out(8) = Diaphragm_H2O_MF_new;
Air_Parameters_Out(9) = Diaphragm_N2_MF_new;

% fprintf('Pressure read from Diaphragm after mixing = ...
    %2.10f\n',Diaphragm_p_new);

%% Air Out

Air_Out_Diaphragm = Air_Parameters_In;
Air_Out_Diaphragm(3) = Air_In_Human(3); %this is negative, but it is ...
    taken care of in mouthpiece inhalation
end
```

Diaphragm air state

```
function Air_Out = Diaphragm_Air_State(Air_In)

Air_Out = Air_In;

end
```

Initialization diaphragm

```
function  Air_Parameters_Initial = Initialize_Diaphragm()

%***********************************************************************
%
% Block name: Initialize diaphragm
% Description: This is a function initializes the diaphragm
% Creator: Ioana Josan-Drinceanu
% Last updated: 18th August 2014
% Citations: Air composition as described in bioastronautics databook,
% table 11-2 page 510
% Notes: Not sure about the diaphragm volume, need to update once ...
    correct value
% is found, 10 litres assumed for now to check code
%
%***********************************************************************


%% Simulation Parameters
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
coder.extrinsic('fprintf');
t = 0;
t =  get_param(bdroot, 'SimulationTime');

if (t == 0)
% Mouthpiece technical details

```

```
V_air = 7 * 0.001;                    % 10 litres converted to m^3

% assume there is already air in the mouthpiece at room temperature and
% pressure
T_air = 293.15;                   % 20 deg C in Kelvin
R = 8.3144621;                    % universal gas constant
p_air = 101.325;                  % kPa, equivalent of 1atm


% mass of air already existent in the mouthpiece volume
m_air = p_air * 1E3 * V_air / (R * T_air);

% density of air already existent in the mouthpiece volume
rho_air = m_air / V_air;

%% Create initial output

Air_Parameters_Initial = zeros(1,9);

Air_Parameters_Initial(1) = T_air;                   % air ...
    temperature in the mouthpiece [K]
Air_Parameters_Initial(2) = p_air;                   % air pressure ...
    in the mouthpiece [kPa]
Air_Parameters_Initial(3) = 0;                       % mass flow ...
    rate from the mouthpiece
Air_Parameters_Initial(4) = rho_air;                 % density of ...
    the air in the mouthpiece [kg/m^3]
Air_Parameters_Initial(5) = m_air;                   % mass of air ...
    in mouthpiece [kg]
Air_Parameters_Initial(6) = 159.6 / 760;               % oxygen mass ...
    fraction in the mouthpiece
Air_Parameters_Initial(7) = 0 / 760;                 % carbon ...
    dioxide mass fraction in the mouthpiece
Air_Parameters_Initial(8) = 0 / 760;                 % water vapor ...
    mass fraction in the mouthpiece
```

```
Air_Parameters_Initial(9) = 600.4 / 760;                     % nitrogen ...
    mass fraction in the mouthpeice

else
%% Give zeros, means output has already been initialized
Air_Parameters_Initial = zeros(1,9);
end


end
```

Mouthpiece inhalation

Mouthpiece inhalation

```
%************************************************************************
%
% Block name: Mouthpiece
% Description: This is a model of the diver's mouthpiece. The only ...
    output
% of this code is a vector containing the current status of the air ...
    in the
% mouthpiece.
% Creator: Ioana Josan-Drinceanu
% Last updated: 14th August 2014
% Citations: Bioastronautics Data Book, Second Edition, NASA SP-3006
%
%************************************************************************


function [ Air_Parameters_Out,  Mouthpiece_p_new, ...
    Mouthpiece_O2_MF_new, Mouthpiece_CO2_MF_new, ...
    Mouthpiece_H2O_MF_new, Mouthpiece_N2_MF_new, m_O2_new]          ...
    = Mouthpiece_Inhalation(Air_In_Human, Air_Parameters_In, ...
    Air_In_Diaphragm)
```

```


%% Simulation parameters
coder.extrinsic('num2str');
coder.extrinsic('str2num');
coder.extrinsic('fprintf');
coder.extrinsic('disp');

t = 0; dt = 0;
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
t = get_param(bdroot,'SimulationTime');
dt = str2num(get_param(bdroot, 'FixedStep'));

%% Constants
M_O2 = 2*16;                 % Molecular Mass of O2 [g/mol]
M_CO2 = 12+2*16;             % Molecular Mass of CO2 [g/mol]
M_H2O = 18.02;               % Molar Mass of H2O [g/mol]
M_N2 = 28;                   % Molar Mass of N2 [g/mol]
Ru = 8.3144621;              % Universal Gas Constant [J/(mol.K)]
R_O2 = (Ru/M_O2)*1E3;        % Specific gas constant for O2 [J/(kg.K)]
R_CO2 = (Ru/M_CO2)*1E3;      % Specific gas constant for CO2 [J/(kg.K)]
R_H2O = (Ru/M_H2O)*1E3;      % Specific gas constant for H2O [J/(kg.K)]
sigma = 5.67e-8;             % Stephan boltzmann constant [W/(m2.K4)]

P_CO2_limit = 2.93;          % CO2 partial pressure limit (22 mmHg, ...
    from divers manual), [kPa]

%% Inputs


%% Input 1 - what already exists in the mouthpiece
% Air_Mouthpiece is the air that exists in the mouthpiece and that ...
    will be
% mixed with the human's inhalation and exhalation

```

```
Air_Mouthpiece = Air_Parameters_In;

% decompose this

Mouthpiece_T = Air_Mouthpiece(1);
Mouthpiece_p = Air_Mouthpiece(2);
Mouthpiece_rho = Air_Mouthpiece(4);
Mouthpiece_mass_initial = Air_Mouthpiece(5);
Mouthpiece_O2_MF = Air_Mouthpiece(6);
Mouthpiece_CO2_MF  = Air_Mouthpiece(7);
Mouthpiece_H2O_MF = Air_Mouthpiece(8);
Mouthpiece_N2_MF = Air_Mouthpiece(9);
Mouthpiece_V = Mouthpiece_mass_initial / (Mouthpiece_rho);

% disp('Executing Mouthpiece');
% disp('------------------------------Mouthpiece ...
    parameters-----------------')
% fprintf('Temp read from mouthpiece = %2.10f\n',Mouthpiece_T);
% fprintf('Pressure read from mouthpiece before mixing [kPa] = ...
    %2.10f\n',Mouthpiece_p);
% fprintf('Mass read from mouthpiece [kg] = ...
    %2.10f\n',Mouthpiece_mass_initial);
% fprintf('O2 MF read from mouthpiece = %2.10f\n',Mouthpiece_O2_MF);
% fprintf('CO2 MF read from mouthpiece = %2.10f\n',Mouthpiece_CO2_MF);
% fprintf('H2O MF read from mouthpiece = %2.10f\n',Mouthpiece_H2O_MF);
% fprintf('N2 MF read from mouthpiece = %2.10f\n',Mouthpiece_N2_MF);
% fprintf('Mouthpiece volume [m^3] = %2.10f\n',Mouthpiece_V);

%% Partial pressures calculation before mixing

m_O2 = Mouthpiece_mass_initial * Mouthpiece_O2_MF;
m_CO2 = Mouthpiece_mass_initial * Mouthpiece_CO2_MF;
m_H2O = Mouthpiece_mass_initial * Mouthpiece_H2O_MF;
m_N2 = Mouthpiece_mass_initial * Mouthpiece_N2_MF;

P_O2  = m_O2  * Ru  * Mouthpiece_T / Mouthpiece_V /1000;
```

```
P_CO2 = m_CO2 * Ru * Mouthpiece_T / Mouthpiece_V /1000;
P_H2O = m_H2O * Ru * Mouthpiece_T / Mouthpiece_V /1000;
P_N2 = m_N2 * Ru * Mouthpiece_T / Mouthpiece_V /1000;

m_total = m_O2 + m_CO2 + m_H2O + m_N2;
p_total = m_total * Ru * Mouthpiece_T / Mouthpiece_V /1000;
p_total2 = (P_O2 + P_CO2 + P_H2O + P_N2);

% disp('-------Total pressure recalculated--------------')
% fprintf('total pressure = %2.10f\n',p_total);
% fprintf('total mass = %2.10f\n',m_total);
% fprintf('total pressure2 = %2.10f\n',p_total2);
%
%
% disp ('---------------Partial pressures before ...
   mixing------------------');
% fprintf('ppO2 old = %2.10f\n',P_O2);
% fprintf('ppCO2 old = %2.10f\n',P_CO2);
% fprintf('ppH2O old = %2.10f\n',P_H2O);
% fprintf('ppN2 old = %2.10f\n',P_N2);
%
% fprintf('Mouthpiece temp old = %2.10f\n',Mouthpiece_T);
% fprintf('Mouthpiece volume = %2.10f\n',Mouthpiece_V);
% fprintf('m_O2 = %2.10f\n',m_O2);
% fprintf('m_CO2 = %2.10f\n',m_CO2);
% fprintf('m_H2O = %2.10f\n',m_H2O);
% fprintf('m_N2 = %2.10f\n',m_N2);

%% Input 2 - air coming from the diaphragm

In2_T = Air_In_Diaphragm(1);
In2_mass = (-1) * Air_In_Diaphragm(3) * dt;
In2_O2_MF = Air_In_Diaphragm(6);
In2_CO2_MF = Air_In_Diaphragm(7);
In2_H2O_MF = Air_In_Diaphragm(8);
In2_N2_MF = Air_In_Diaphragm(9);
```

```

% disp('------------------------------Human ...
    exhalation-----------------')
% fprintf('Temp out human = %2.10f\n',In2_T);
% fprintf('Mass out human [kg] = %2.10f\n',In2_mass);
% fprintf('O2 MF out from human = %2.10f\n',In2_O2_MF);
% fprintf('CO2 MF out from human = %2.10f\n',In2_CO2_MF);
% fprintf('H2O MF out from human = %2.10f\n',In2_H2O_MF);
% fprintf('N2 MF out from human = %2.10f\n',In2_N2_MF);

%% Input 3 - human inhalation

In3_T = Air_In_Human(1);
In3_mass = Air_In_Human(3) * dt;                    % this will be ...
    negative, corresponding to inhalation (volume subtraction)
In3_O2_MF = Air_In_Human(6);
In3_CO2_MF = Air_In_Human(7);
In3_H2O_MF = Air_In_Human(8);
In3_N2_MF = Air_In_Human(9);

% disp('------------------------------Human ...
    inhalation-----------------')
% fprintf('Temp in human = %2.10f\n',In3_T);
% fprintf('Mass in human [kg] = %2.10f\n',In3_mass);
% fprintf('O2 MF in from human = %2.10f\n',In3_O2_MF);
% fprintf('CO2 MF in from human = %2.10f\n',In3_CO2_MF);
% fprintf('H2O MF in from human = %2.10f\n',In3_H2O_MF);
% fprintf('N2 MF in from human = %2.10f\n',In3_N2_MF);


%% Combining inputs with the air in the mouthpiece

m_O2_new = Mouthpiece_mass_initial * Mouthpiece_O2_MF + In2_mass * ...
    In2_O2_MF + In3_mass * In3_O2_MF;
m_CO2_new = Mouthpiece_mass_initial * Mouthpiece_CO2_MF + In2_mass * ...
    In2_CO2_MF + In3_mass * In3_CO2_MF;
```

```
m_H2O_new  = Mouthpiece_mass_initial * Mouthpiece_H2O_MF + In2_mass ...
    * In2_H2O_MF + In3_mass * In3_H2O_MF;
m_N2_new = Mouthpiece_mass_initial * Mouthpiece_N2_MF + In2_mass * ...
    In2_N2_MF + In3_mass * In3_N2_MF;

% disp('------------------------------Mixing mass-----------------')
% fprintf('O2 mass [kg] = %2.10f\n',m_O2_new);
% fprintf('CO2 mass [kg] = %2.10f\n',m_CO2_new);
% fprintf('H2O mass [kg] = %2.10f\n',m_H2O_new);
% fprintf('N2 mass [kg] = %2.10f\n',m_N2_new);

Mouthpiece_mass_new = m_O2_new + m_CO2_new + m_H2O_new + m_N2_new;

% fprintf('Mouthpiece total new mass [kg] = ...
    %2.10f\n',Mouthpiece_mass_new)

Mouthpiece_O2_MF_new = m_O2_new / Mouthpiece_mass_new;
Mouthpiece_CO2_MF_new = m_CO2_new / Mouthpiece_mass_new;
Mouthpiece_H2O_MF_new = m_H2O_new / Mouthpiece_mass_new;
Mouthpiece_N2_MF_new = m_N2_new / Mouthpiece_mass_new;

% disp('------------------------------New mass ...
    fractions----------------')
% fprintf('O2 MF new = %2.10f\n',Mouthpiece_O2_MF_new);
% fprintf('CO2 MF new = %2.10f\n',Mouthpiece_CO2_MF_new);
% fprintf('H2O MF new = %2.10f\n',Mouthpiece_H2O_MF_new);

% Temperature mixing - using HabNet code - add later if necessary?

Mouthpiece_T_new = Mouthpiece_T;

% New partial pressures after mixing to determine the new pressure

% m_O2_new  = Mouthpiece_mass_new * Mouthpiece_O2_MF_new;
% m_CO2_new = Mouthpiece_mass_new * Mouthpiece_CO2_MF_new;
% m_H2O_new = Mouthpiece_mass_new * Mouthpiece_H2O_MF_new;
```

```
% m_N2_new = Mouthpiece_mass_new * Mouthpiece_N2_MF_new;

P_O2_new  = m_O2_new  * Ru  * Mouthpiece_T_new / Mouthpiece_V /1000;
P_CO2_new = m_CO2_new * Ru * Mouthpiece_T_new / Mouthpiece_V /1000;
P_H2O_new = m_H2O_new * Ru * Mouthpiece_T_new / Mouthpiece_V /1000;
P_N2_new = m_N2_new * Ru * Mouthpiece_T_new / Mouthpiece_V /1000;

Mouthpiece_p_new = P_O2_new + P_CO2_new + P_H2O_new + P_N2_new;

if (P_CO2_new/1000) > P_CO2_limit
fprintf('Astronaut has CO2 poisoning due to high CO2 partial pressure!')
end

% disp('------------------------------New partial pressures after ...
    mixing----------------')
% fprintf('ppO2 new = %2.10f\n',P_O2_new);
% fprintf('ppCO2 new = %2.10f\n',P_CO2_new);
% fprintf('ppH2O new = %2.10f\n',P_H2O_new);
% fprintf('ppN2 new = %2.10f\n',P_N2_new);
% fprintf('Mouthpiece temp new = %2.10f\n',Mouthpiece_T_new);
% fprintf('Mouthpiece volume = %2.10f\n',Mouthpiece_V);

%% Initialize outputs

Air_Parameters_Out = Air_Parameters_In;

Air_Parameters_Out(1) = Mouthpiece_T_new;
Air_Parameters_Out(2) = Mouthpiece_p_new;
Air_Parameters_Out(3) = 0;
Air_Parameters_Out(4) = Mouthpiece_mass_new / Mouthpiece_V;
Air_Parameters_Out(5) = Mouthpiece_mass_new;
Air_Parameters_Out(6) = Mouthpiece_O2_MF_new;
Air_Parameters_Out(7) = Mouthpiece_CO2_MF_new;
Air_Parameters_Out(8) = Mouthpiece_H2O_MF_new;
Air_Parameters_Out(9) = Mouthpiece_N2_MF_new;

```

```
% fprintf('Pressure read from mouthpiece after mixing = ...
    %2.10f\n',Mouthpiece_p_new);

end
```

Initialization mouthpiece inhalation

```
function  Air_Parameters_Initial = Initialize_Mouthpiece_Inhalation()

%************************************************************************
%
% Block name: Initialize mouthpiece
% Description: This is a function initializes the mouthpiece
% Creator: Ioana Josan-Drinceanu
% Last updated: 4th August 2014
% Citations: Air composition as described in bioastronautics databook,
% table 11-2 page 510
% Notes: Not sure about moutpiece volume, need to update once ...
    correct value
% is found, 10 litres assumed for now to check code
%
%************************************************************************


%% Simulation Parameters
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
coder.extrinsic('fprintf');
t = 0;
t =  get_param(bdroot, 'SimulationTime');

if (t == 0)
% Mouthpiece technical details
```

```

V_air = 2 * 0.001;                    % 10 litres converted to m^3

% assume there is already air in the mouthpiece at room temperature and
% pressure
T_air = 293.15;                   % 20 deg C in Kelvin
R = 8.3144621;                    % universal gas constant
p_air = 101.325;                  % kPa, equivalent of 1atm



% mass of air already existent in the mouthpiece volume
m_air = p_air * 1E3 * V_air / (R * T_air);

% density of air already existent in the mouthpiece volume
rho_air = m_air / V_air;

%% Create initial output

Air_Parameters_Initial = zeros(1,9);

Air_Parameters_Initial(1) = T_air;                      % air ...
    temperature in the mouthpiece [K]
Air_Parameters_Initial(2) = p_air;                      % air pressure ...
    in the mouthpiece [kPa]
Air_Parameters_Initial(3) = 0;                          % mass flow ...
    rate from the mouthpiece
Air_Parameters_Initial(4) = rho_air;                    % density of ...
    the air in the mouthpiece [kg/m^3]
Air_Parameters_Initial(5) = m_air;                      % mass of air ...
    in mouthpiece [kg]
Air_Parameters_Initial(6) = 159.6 / 760;                % oxygen mass ...
    fraction in the mouthpiece
Air_Parameters_Initial(7) = 0 / 760;                    % carbon ...
    dioxide mass fraction in the mouthpiece
Air_Parameters_Initial(8) = 0 / 760;                    % water vapor ...
    mass fraction in the mouthpiece
```

```
Air_Parameters_Initial(9) = 600.4 / 760;              % nitrogen mass ...
    fraction in the mouthpiece

else
%% Give zeros, means output has already been initialized
Air_Parameters_Initial = zeros(1,9);
end


end
```

Mouthpiece inhalation air state

```
function Air_Out = Mouthpiece_Inhalation_Air_State(Air_In)

Air_Out = Air_In;

end
```

Pressure calculator

```
function [pressure_out_total, pressure_out_O2, pressure_out_N2] = fcn()

% pressure_out_total = 150;
%
% pressure_out_O2 = pressure_out_total * 0.2;
% pressure_out_N2  = pressure_out_total * 0.7;


coder.extrinsic('num2str');
coder.extrinsic('str2num');
coder.extrinsic('fprintf');
coder.extrinsic('disp');

```

```
t = 0; dt = 0;
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
t = get_param(bdroot,'SimulationTime');
dt = str2num(get_param(bdroot, 'FixedStep'));

pressure_out_total = 101.325;
pressure_out_O2 = pressure_out_total * 0.2;
pressure_out_N2  = pressure_out_total * 0.7;
%%

if (t <10*60) %then you are at surface level
pressure_out_total = 101.325;
pressure_out_O2 = pressure_out_total * 0.2;
pressure_out_N2  = pressure_out_total * 0.7;
else
if (t >=10*60 && t<20*60)
pressure_out_total = 3* 101.325;
pressure_out_O2 = pressure_out_total * 0.2;
pressure_out_N2  = pressure_out_total * 0.7;
else
if (t >=20*60 && t<=30*60)
pressure_out_total = 4 *101.325;
pressure_out_O2 = pressure_out_total * 0.2;
pressure_out_N2  = pressure_out_total * 0.7;
else if (t >=30*60 && t<35*60)
pressure_out_total = 4 *101.325;
pressure_out_O2 = pressure_out_total * 0.2;
pressure_out_N2  = pressure_out_total * 0.7;
else if (t >=35*60 && t<40*60)
pressure_out_total = 3 *101.325;
pressure_out_O2 = pressure_out_total * 0.2;
pressure_out_N2  = pressure_out_total * 0.7;
else if (t >=40*60 && t<50*60)
pressure_out_total = 1.5 *101.325;
pressure_out_O2 = pressure_out_total * 0.2;
```

```
pressure_out_N2  = pressure_out_total * 0.7;

end
end
end
end
end
end
end
```

Tank controller

```
function [mass_O2_to_add, mass_N2_to_add, O2_Tank_Specs_Out, ...
    N2_Tank_Specs_Out, available_O2_mass_in_tank] = ...
    Tank_Controller(pressure_out_total, pressure_out_O2, ...
    pressure_out_N2, Diaphragm_Air_State, O2_Tank_Specs_In, ...
    N2_Tank_Specs_In)

coder.extrinsic('get_param');
coder.extrinsic('bdroot');
coder.extrinsic('fprintf');
coder.extrinsic('str2num');
coder.extrinsic('num2str');
coder.extrinsic('disp');
t = 0; dt = 0;
t =  get_param(bdroot, 'SimulationTime');
dt = str2num(get_param(bdroot, 'FixedStep'));


%% Constants
Ru = 8.3144621;                    % universal gas constant

%% read in state of diaphragm

p_diaphragm = Diaphragm_Air_State(2);
```

```
O2_MF = Diaphragm_Air_State(6);
CO2_MF = Diaphragm_Air_State(7);
H2O_MF = Diaphragm_Air_State(8);
N2_MF = Diaphragm_Air_State(9);

% calculate partial pressures
ppO2 = O2_MF * p_diaphragm;
ppCO2 = CO2_MF * p_diaphragm;
ppH2O = H2O_MF * p_diaphragm;
ppN2 = N2_MF * p_diaphragm;

% set limit pressures in kPa for oxygen and carbon dioxide

% max_ppO2 = 120;
% min_ppO2_lower = 10;
% min_ppO2_higher = 11;

max_ppO2 = pressure_out_total;
min_ppO2_lower = pressure_out_O2;
min_ppO2_higher = (pressure_out_O2 + 0.1 * pressure_out_O2); % keeps ...
    it within 10% variation with the min level being the nominal one

max_ppCO2 = 2.93; % correspondent of 22mg Hg found in the divers manual

% min_ppN2 = 60; % arbitrary
% max_ppN2 = 90; % arbitrary

max_ppN2 = pressure_out_total;
min_ppN2_lower = pressure_out_N2;
min_ppN2_higher = (pressure_out_N2 + 0.1 * pressure_out_N2); % keeps ...
    it within 10% variation with the min level being the nominal one


%% read in the O2 tank parameters
T_O2_Tank = O2_Tank_Specs_In(1);
V_O2_Tank = O2_Tank_Specs_In(4);
```

```
p_O2_Tank = O2_Tank_Specs_In(5);
%mass_O2_Tank = O2_Tank_Specs_In(6);
available_O2_mass_in_tank = O2_Tank_Specs_In(6);

%% read in the N2 tank parameters
T_N2_Tank = N2_Tank_Specs_In(1);
V_N2_Tank = N2_Tank_Specs_In(4);
p_N2_Tank = N2_Tank_Specs_In(5);
%mass_N2_Tank = N2_Tank_Specs_In(6);
available_N2_mass_in_tank = N2_Tank_Specs_In(6);

%% calculate partial pressure difference for oxygen

if (ppO2 < min_ppO2_lower)
% add oxygen
delta_ppO2 = min_ppO2_higher - ppO2;
if (p_O2_Tank >= delta_ppO2)
mass_O2_to_add = ((delta_ppO2 * V_O2_Tank) / (Ru * T_O2_Tank));
available_O2_mass_in_tank = available_O2_mass_in_tank - mass_O2_to_add;
new_p_O2_tank = p_O2_Tank - delta_ppO2;
else % tank is empty
mass_O2_to_add = 0;
available_O2_mass_in_tank = 0;
new_p_O2_tank = 0;
end
else % if pressure is not lower than lower bound
if (ppO2 > min_ppO2_higher)
mass_O2_to_add = 0;
new_p_O2_tank = p_O2_Tank;
available_O2_mass_in_tank = 0;
else
% means it is between lower and higher band
mass_O2_to_add = 0;
new_p_O2_tank = p_O2_Tank;
available_O2_mass_in_tank = 0;
%           delta_ppO2_2 = min_ppO2_higher - ppO2;
```

```
%         if (p_O2_Tank >= delta_ppO2_2)
%             mass_O2_to_add = ((delta_ppO2_2 * V_O2_Tank) / (Ru * ...
   T_O2_Tank));
%             available_O2_mass_in_tank = available_O2_mass_in_tank ...
   - mass_O2_to_add;
%             new_p_O2_tank = p_O2_Tank - delta_ppO2_2;
%         else % tank is empty
%             mass_O2_to_add = 0;
%             available_O2_mass_in_tank = 0;
%             new_p_O2_tank = 0;
%         end

end
end
%% %% calculate partial pressure difference for nitrogen

% if (ppN2 < min_ppN2)
%     % add nitrogen
%     delta_ppN2 = min_ppN2 - ppN2;
%
%     if (p_N2_Tank >= delta_ppN2)
%         if (ppN2 < max_ppN2)
%             mass_N2_to_add = ((delta_ppN2 * V_N2_Tank) / (Ru * ...
   T_N2_Tank));
%             new_p_N2_tank = p_N2_Tank - delta_ppN2;
%         else
%             mass_N2_to_add = 0;
%             new_p_N2_tank = p_N2_Tank;
%         end
%     else
%         mass_N2_to_add = 0;
%         new_p_N2_tank = p_N2_Tank;
%     end
% else
%     mass_N2_to_add = 0;
%     new_p_N2_tank = p_N2_Tank;
```

```
% end

if (ppN2 < min_ppN2_lower)
% add oxygen
delta_ppN2 = min_ppN2_higher - ppN2;
if (p_N2_Tank >= delta_ppN2)
mass_N2_to_add = ((delta_ppN2 * V_N2_Tank) / (Ru * T_N2_Tank));
available_N2_mass_in_tank = available_N2_mass_in_tank - mass_N2_to_add;
new_p_N2_tank = p_N2_Tank - delta_ppN2;
else % tank is empty
mass_N2_to_add = 0;
available_N2_mass_in_tank = 0;
new_p_N2_tank = 0;
end
else % if pressure is not lower than lower bound
if (ppN2 > min_ppN2_higher)
mass_N2_to_add = 0;
new_p_N2_tank = p_N2_Tank;
available_N2_mass_in_tank = 0;
else
% means it is between lower and higher band
mass_N2_to_add = 0;
new_p_N2_tank = p_N2_Tank;
available_N2_mass_in_tank = 0;
%         delta_ppO2_2 = min_ppO2_higher - ppO2;
%         if (p_O2_Tank >= delta_ppO2_2)
%             mass_O2_to_add = ((delta_ppO2_2 * V_O2_Tank) / (Ru * ...
    T_O2_Tank));
%             available_O2_mass_in_tank = available_O2_mass_in_tank ...
    - mass_O2_to_add;
%             new_p_O2_tank = p_O2_Tank - delta_ppO2_2;
%         else % tank is empty
%             mass_O2_to_add = 0;
%             available_O2_mass_in_tank = 0;
%             new_p_O2_tank = 0;
%         end
```

```

end
end


%% check tanks to see if mass available

%% update tank status

%% command mass out of tanks

O2_Tank_Specs_Out = O2_Tank_Specs_In;
O2_Tank_Specs_Out(5) = new_p_O2_tank;
O2_Tank_Specs_Out(6) = available_O2_mass_in_tank;

N2_Tank_Specs_Out = N2_Tank_Specs_In;
N2_Tank_Specs_Out(5) = new_p_N2_tank;
N2_Tank_Specs_Out(6) = available_N2_mass_in_tank;

end
```

Initialize nitrogen tank

```
function  Tank_Parameters_Initial = Initialize_Tank()

%************************************************************************
%
% Block name: Initialize tank N2
% Description: This is a function initializes the tank
% Creator: Ioana Josan-Drinceanu
% Last updated: 29th August 2014
% Citations: -
% Notes:-
%
%************************************************************************
```

```


%% Simulation Parameters
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
coder.extrinsic('fprintf');
t = 0;
t =  get_param(bdroot, 'SimulationTime');

Ru = 8.3144621;          % Universal Gas Constant [J/(mol.K)]

Tank_Parameters_Initial = zeros(1,6);

if (t == 0)

Tank_Parameters_Initial(1) = 283.15;            % 10 degC
Tank_Parameters_Initial(2) = 20787.6932;        % 3015 psi
Tank_Parameters_Initial(4) = 0.286774;        % 175 cubic inches to m^3
%    Tank_Parameters_Initial(4) = 0.00286774;        % 175 cubic ...
    inches to m^3
Tank_Parameters_Initial(3) =  Tank_Parameters_Initial(2) * ...
    Tank_Parameters_Initial(4) / (Ru *  Tank_Parameters_Initial(1));
Tank_Parameters_Initial(5) =  Tank_Parameters_Initial(2);
Tank_Parameters_Initial(6) = Tank_Parameters_Initial(3);

else
%% Give zeros, means output has already been initialized
Tank_Parameters_Initial = zeros(1,6);
end


end
```

Initialize oxygen tank

```
function  Tank_Parameters_Initial = Initialize_Tank()

%*************************************************************************
%
% Block name: Initialize tank O2
% Description: This is a function initializes the tank
% Creator: Ioana Josan-Drinceanu
% Last updated: 29th August 2014
% Citations: -
% Notes:-
%
%*************************************************************************


%% Simulation Parameters
coder.extrinsic('get_param');
coder.extrinsic('bdroot');
coder.extrinsic('fprintf');
t = 0;
t =  get_param(bdroot, 'SimulationTime');

Ru = 8.3144621;          % Universal Gas Constant [J/(mol.K)]

Tank_Parameters_Initial = zeros(1,6);

if (t == 0)

Tank_Parameters_Initial(1) = 283.15;            % 10 degC
Tank_Parameters_Initial(2) = 20787.6932;        % 3015 psi
Tank_Parameters_Initial(4) = 2.86774;         % 175 cubic inches to ...
    liters
Tank_Parameters_Initial(3) =  32/1000 * Tank_Parameters_Initial(2) * ...
    Tank_Parameters_Initial(4) / (Ru *  Tank_Parameters_Initial(1)); ...
    % kg of oxygen in the tank
Tank_Parameters_Initial(5) =  Tank_Parameters_Initial(2);
Tank_Parameters_Initial(6) = Tank_Parameters_Initial(3);
```

```

else
%% Give zeros, means output has already been initialized
Tank_Parameters_Initial = zeros(1,6);
end


end
```

Oxygen tank

```
function Air_Out_O2_Tank    = O2_Tank(mass_to_add, O2_Tank_Specs)

Air_Out_O2_Tank = zeros(1,9);

% air coming from the tank is at the tank temperature, at the mass ...
    dictated
% by the controller, at 1 MF of oxygen and 0 all the other mass ...
    fractions

Air_Out_O2_Tank(1) = O2_Tank_Specs(1);
Air_Out_O2_Tank(3) = mass_to_add;
Air_Out_O2_Tank(6) = 1;
Air_Out_O2_Tank(7) = 0;
Air_Out_O2_Tank(8) = 0;
Air_Out_O2_Tank(9) = 0;

end
```

Nitrogen tank

```
function Air_Out_N2_Tank    = N2_Tank(mass_to_add, N2_Tank_Specs)

Air_Out_N2_Tank = zeros(1,9);

```

```
% air coming from the tank is at the tank temperature, at the mass ...
    dictated
% by the controller, at 1 MF of nitrogen and 0 all the other mass ...
    fractions

Air_Out_N2_Tank(1) = N2_Tank_Specs(1);
Air_Out_N2_Tank(3) = mass_to_add;
Air_Out_N2_Tank(6) = 0;
Air_Out_N2_Tank(7) = 0;
Air_Out_N2_Tank(8) = 0;
Air_Out_N2_Tank(9) = 1;

end
```

Appendix C - MATLAB Simulink model snapshots for the rebreather analytical model

Human model

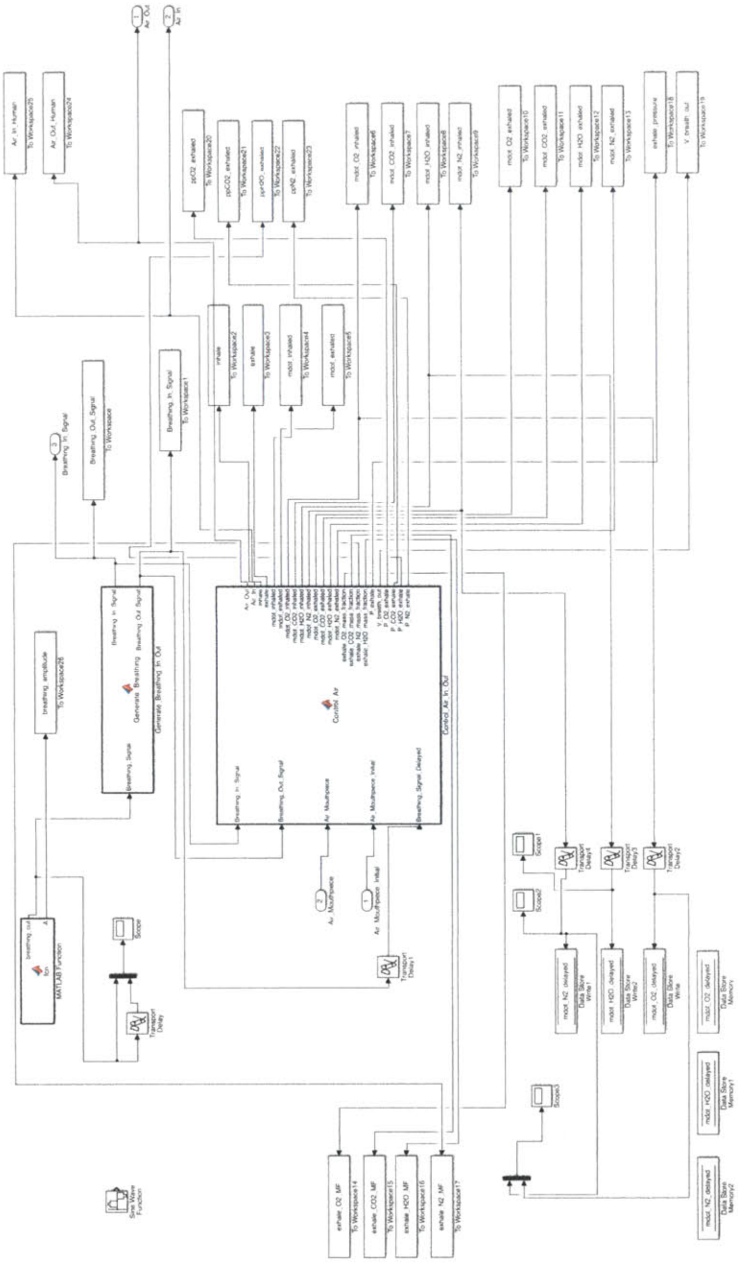


Figure C-1: Snapshot of the implementation for the human breathing process in MATLAB Simulink

Mouthpiece exhalation

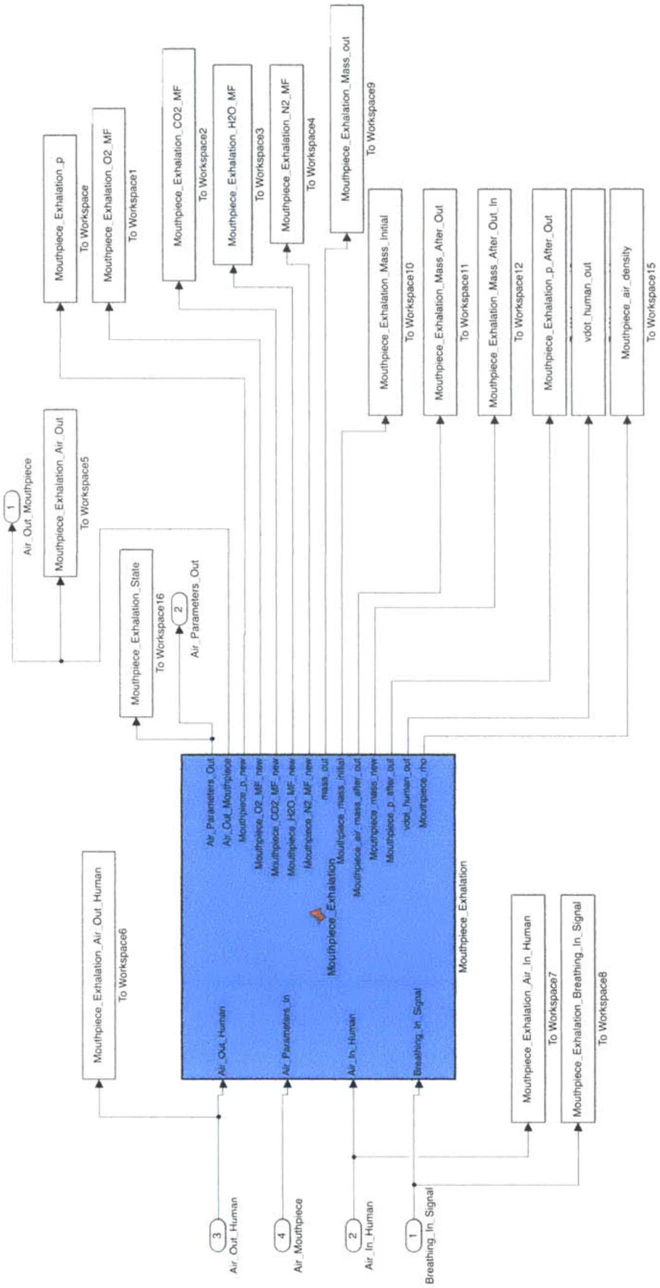


Figure C-2: Snapshot of the implementation for the exhalation mouthpiece in MATLAB Simulink

Carbon dioxide scrubber

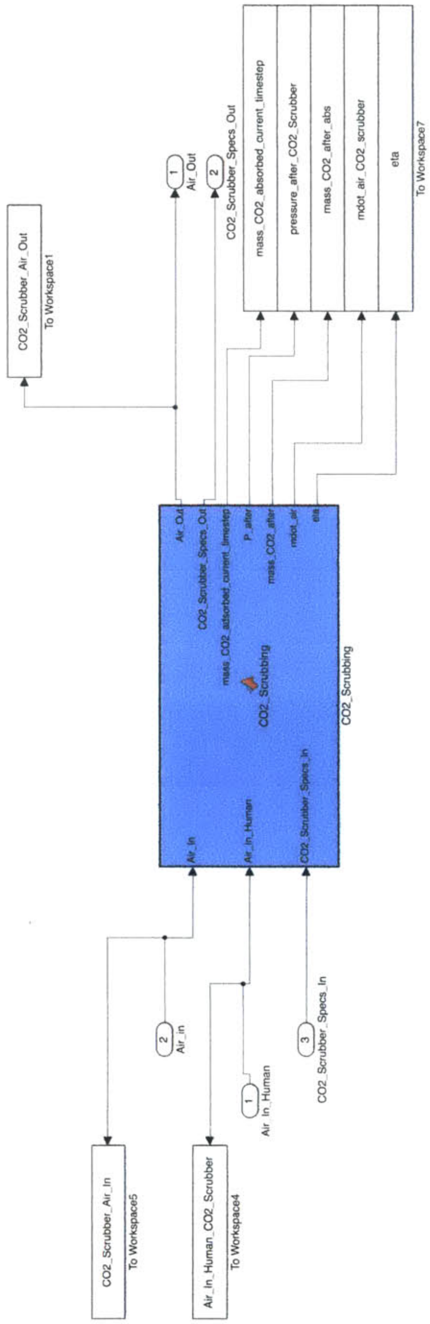


Figure C-3: Snapshot of the implementation for the carbon dioxide scrubber in MATLAB Simulink

Diaphragm

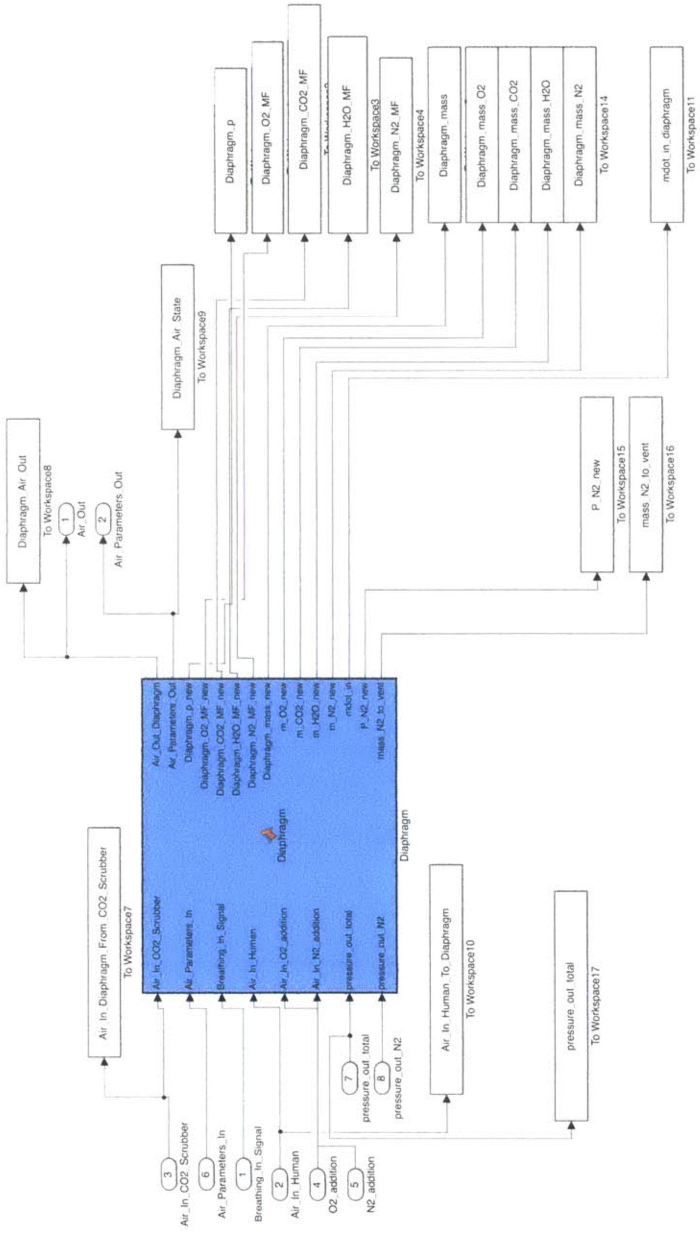


Figure C-4: Snapshot of the implementation for the diaphragm in MATLAB Simulink

Mouthpiece inhalation

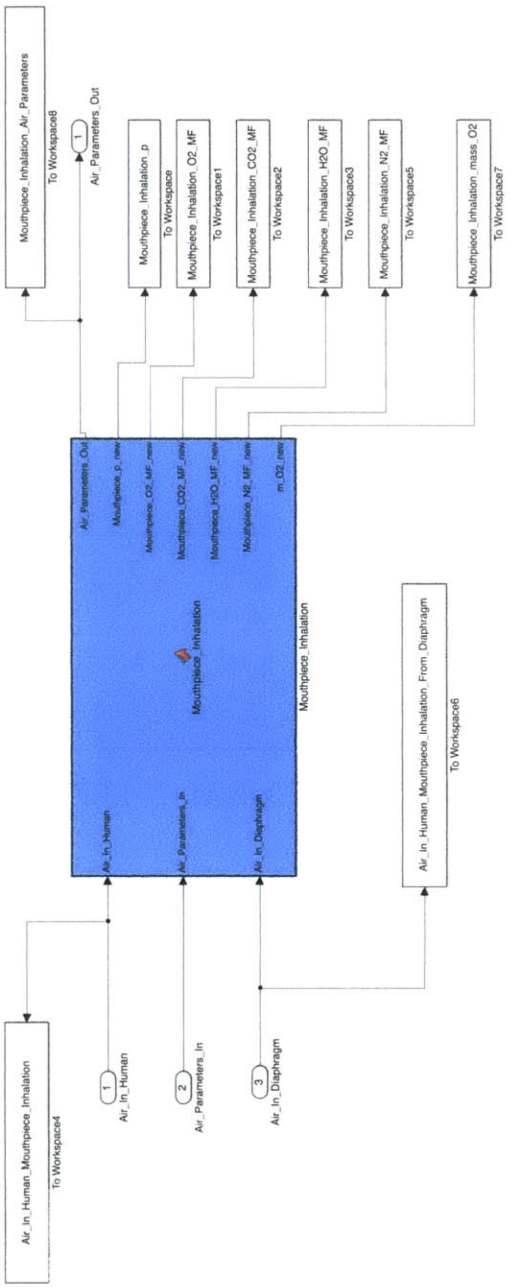


Figure C-5: Snapshot of the implementation for the inhalation mouthpiece in MATLAB Simulink

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