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Resting Oxygen Consumption Rates in Divers Using Diver Propulsion Devices

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Biomedical Engineering
Department of Chemical & Biomedical Engineering
College of Engineering
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Injection Rate, Nitrox, Semiclosed

Dedication

This thesis is dedicated to my family who have loved and supported me throughout my studies. I am blessed to have such great role models as my parents.

Acknowledgments

First, I would like to express the deepest of gratitude to Dr. John Clarke. After beginning an internship with the Navy Experimental Diving Unit, Dr. Clarke familiarized me with his experiment and invited me to contribute. I will always be grateful for the hard work he put into the experimental design and for bringing me up to speed on diving physiology, a subject which I knew very little about going into this project. This work would have not been possible without his continual advisement and support.

I would also like to thank the other members of my committee, Drs. Bill Lee and Doug Shytle. Dr. Lee has always taken the time to make sure that I choose courses which compliment my research interests and strengthen my education. Dr. Shytle hired me as his research assistant. Not only did this support my financial requirements, but the experience and knowledge gained has already proven to be paramount to my graduate education.

Those responsible for the Office of Naval Research: Naval Research Enterprise Intern Program (NREIP) should not be overlooked. This is the program which funded my trip to the Navy Experimental Diving Unit in Panama City Beach, FL. If it were not for this program, I would have never had the opportunity to be involved in this project. Ed Linsenmeyer is the coordinator of the NREIP program at the Naval Surface Warfare Center. Because of his hard work and dedication, students like me have the opportunity to experience working for the Department of Defense.

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ABSTRACT

The Marine Corps Systems Command documented mission requirements that cannot be met by current rebreathers. They need to extend dive times without compromising the stealth and compact design of existing devices. This can be accomplished by reducing the fresh gas flow rate. The current flow rate is adequate to support a diver in heavy work. However, the diver will be utilizing a Diver Propulsion Device (DPD) during a large portion of the mission in question. The assumption, then, is that this portion of the mission will not require "hard work". Thus, a new fresh gas flow rate can be established which is sufficient to sustain a Marine diver using a DPD but is conservative enough to extend the duration of the dive.

This experiment was designed for manned testing of the rebreathers in such a way to establish the average oxygen consumption rate for divers using a DPD. Marine divers were fitted with a Divex Shadow Excursion (DSE) rebreather modified with a Draeger C8A PO_2 monitor coupled with a Delta P VR3 dive computer. The DSE is a semiclosed-circuit underwater breathing apparatus that provides a constant flow of mixed gas containing oxygen and nitrogen or helium to the diver. The partial pressure of oxygen (PO_2) and diver depth were monitored and recorded at ten-second intervals. The Navy Experimental Diving Unit has developed and tested a computational algorithm that uses the PO_2 and depth to compute the oxygen consumption rate.

Two techniques were employed to estimate the error in this approach: curve fitting and propagation of error. These methods are detailed and the results are presented. They show that the fresh gas flow rate can be safely reduced while the diver is utilizing the DPD, which consequently, will substantially increase the dive time allowed by the device.

Chapter 1

Introduction

United States Marine Corps Combatant Divers are trained to perform mainly reconnaissance and raid type missions. These divers have proven to be paramount in these types of military applications. Many of the missions require the USMC Combatant Divers to remain undetected by the enemy. They accomplish this by utilizing rebreathers which, depending on the type, either greatly reduce or eliminate bubbles from being emitted into the water and revealing their location. Until recently, they have been able to successfully complete their missions by utilizing the MK 25 Oxygen Rebreather.

However, the Marine Corps System Command has since documented a mission requirement that cannot be met by the current rebreather in use. They intend to replace their inventory with a multi-purpose, O_2 closed-circuit or nitrox semiclosed-circuit rebreather named the Enhanced Underwater Breathing Apparatus (EUBA). Previously, the Navy Experimental Diving Unit was asked to review whether the rigs would meet the mission profile. Three UBA's underwent testing to determine if they could meet the mission profile. It was discovered that, under their current configurations, none of the devices could meet the mission profile. However, if properly reconfigured, all of the UBAs could meet the mission requirements (Clarke 2007). One of these UBAs, the Divex Shadow Excursion (DSE), was selected for use during this thesis.

The mission profile requires that, during a large portion of the dive, the divers will be propelled by a Diver Propulsion Device (DPD). A DPD is a vehicle which can transport two divers underwater and, as a result, allow them to travel longer distances, deliver increased payloads, minimize fatigue, and maximize endurance (McCarter 2005). Therefore, because the divers will be using a DPD, they will actually be performing very light work. This highlights the key assumption that would permit the extension of the total dive time allowed by the DSE (in order to meet the USMC mission requirements). This assumption is that while the divers are being towed by a DPD, their oxygen consumption rate is similar in magnitude to the previously documented resting oxygen consumption rate. This assumption had to be tested and verified. Consequently, this study was designed in such a way as to provide confirmatory measurements of oxygen consumption rates during the towed portion of the mission.

1.1 Motivation for Thesis

The United States Military utilizes rebreathers for underwater reconnaissance and raid missions. There are advantages to the use of rebreathers over conventional open-circuit scuba rigs. They offer better gas efficiency and near-silent operation with few to no bubbles (depending on the type of rebreather). However, the mission capabilities are limited by the dive time offered by the device. Semiclosed rebreathers, like the ones conventionally used by the military, have a constant fresh gas flow rate. This flow rate is generally set at 6.0 L/min. This has been shown to meet the oxygen demands of a hard working diver with a common nitrox gas mixture (60% oxygen, 40% nitrogen). There have been several reports that show that 3.0 L/min is the maximum oxygen consumption rate (Nuckols, Clarke et al. 1998). Unfortunately, a mission requirement is unable to be met due to the limited dive time that this, all-encompassing, fresh gas flow rate offers. The Navy Experimental Diving Unit was tasked to test solutions to this problem.

1.2 Risks

As with all manned experiments, there were health risks which had to be carefully considered. All necessary precautions were taken to minimize potential health risks. Marine Combatant divers were required to use an underwater breathing apparatus (UBA) which was new to the United States Military. Even though the Divex Shadow Excursion had not yet been certified for use by the military, it had been used by the British Royal Marines and the following Navies as a Special Operations UBA: Britain (SAS), Norway, Australia, and Germany. Therefore, the DSE's safety has been well documented.

The DSE was tested in semiclosed mode with constant nitrox gas flow. As with all rebreathers, there is a limit to how deep the diver can safely go. This is due to PO_2 changes which will be discussed in the Dive Physiology section below. However, if the driver lost control of the DPD and went deeper than the limits of the rebreather, this would have jeopardized the safety of both divers. For this reason, all manned testing was conducted above a 20 to 30 foot deep hard bottom (along the profile of a beach in Panama City, FL). This eliminated the possibility that the divers might exceed the maximum depth allowed by the U.S. Navy Diving Manual based on the configurations of the DSE (Navy Diving Manual 2005).

Another risk which is inherent to all semiclosed-circuit UBAs is the possibility for hypoxia. Hypoxia is the shortage of oxygen in the body. Unfortunately, there is usually no warning to the diver that they are becoming hypoxic. This is because carbon dioxide is usually what causes a person to experience the sensation of “oxygen hunger”. However, rebreathers filter the carbon dioxide from the breathing circuit which consequently, eliminates the body’s usual warning of oxygen deprivation. The human body is optimized to breath oxygen at a partial pressure of .21 atmospheres absolute (ATA). If the inspired PO_2 drops to a value much less than this, hypoxia ensues and the body begins to shut down (Strauss and Aksenov 2004). To alleviate this risk, the fresh gas flow rate was set to 6.0 L/min, which has already been shown to support a hard working diver (Nuckols, Clarke et al. 1998). Because the experiment called for the divers to be using a diver propulsion device, they would actually be performing very light work. To further increase the safety of the divers, an O_2 monitor was used to monitor the diver’s oxygen partial pressure. This is not a standard feature on the DSE. This modification will be described in detail in the equipment section. The diver's PO_2 will be displayed on a VR3 dive computer. As needed, the diver can manually add fresh nitrox using the demand valve on the rebreather.

Hyperoxia was another potential risk that had to be considered. Hyperoxia occurs when the body receives too much oxygen. Oxygen, when at high partial pressures, is toxic to the human body. This is often referred to as oxygen toxicity. One unfortunate incident is discussed in a case report by a Christopher Lawrence, a forensic pathologist. An experienced diver used 50% nitrox gas during a dive of 47 meters. This resulted in a partial pressure of oxygen which reached a staggering 2.9 atmospheres absolute (Lawrence 1996). This diver died, most likely, from seizures associated with oxygen toxicity. Acute oxygen toxicity mainly affects the central nervous system. If a diver becomes hyperoxic, they can experience visual and audible disturbances nausea, clumsiness, and finally convulsions (Strauss and Aksenov 2004). Hyperoxia was avoided by using nitrox gas (60% oxygen: 40% nitrogen) and by limiting the diver depth in order to control the partial pressure of oxygen.

Finally, there is a risk of hypercapnea in closed-circuit rebreathers. Hypercapnea is an increased concentration of carbon dioxide in the blood. Rebreathers have carbon dioxide scrubbers that prevent carbon dioxide from accumulating in the rig. To mitigate the risk of hypercapnea, the CO_2 scrubbing material, Sofnolime 812 absorbent, was replaced between each dive on the

UBA. In addition, the experiment required a low work rate and, consequently, a low CO_2 production rate. These precautions resulted in a very low risk of hypercapnea to the diver.

Even though numerous precautions were taken to avoid an accident, diving is inherently risky. Equipment failure is usually unforeseen. However, the divers were at relatively shallow depths. Also, a medical monitor, standby diver, dive supervisor, and principal investigator were on hand at all times in case something was to go wrong. Additionally, divers were trained on the DSE in a test pool at NEDU before open water testing.

1.3 Contributions to the Field

Until now, no one had documented the oxygen consumption rate of a diver using a diver propulsion device. Although these findings may not be directly applicable to the typical recreational diver, they are of great importance to the United States Military. Knowledge of the oxygen consumption rate of a DPD-propelled diver could be useful for future device reconfigurations and mission planning. The validity of the methods used by the Navy Experimental Diving Unit to measure a diver’s oxygen consumption with time, although previously documented, was reaffirmed by this study. The major benefit of this experiment is to the United States Navy and Marine Corps with the extension of combat mission capabilities through increased dive time of the underwater breathing apparatus.

1.4 Thesis Structure

This thesis is intended to fully outline the diving concepts, experimental design, and statistical analyses that were utilized in order to best estimate the oxygen consumption of a diver while using a diver propulsion device. The following chapter will begin with physiological concepts which had to be learned in order to safely design this experiment and fully understand the raw data that was collected. Also to be discussed are the governing equations employed to find the oxygen consumption and the statistical concepts which were later used to draw a conclusion.

The remainder of this thesis will detail the experimental design and the equipment that was used. The test results will be presented and their analysis explained. Next, there will be a discussion of some of the trends which were identified and possible sources of error. The limitations of the results will also be disclosed. Finally, the conclusion will be presented along with the next steps of the study.

Chapter 2

Theoretical Foundations

2.1 Diving Physiology

Scuba diving began in the 1940s and 50s. Since then, we have made dramatic leaps in understanding the challenges of getting the human body deeper underwater, keeping it there longer, and bringing it back more safely. These challenges would be almost non-existent if it were not for the behavior of gases under pressure. Otherwise, breathing underwater would not be much different than breathing at the surface. It is of great necessity that anyone who takes interest in diving understands the fundamental gas laws that govern the physiological stresses experienced by divers.

2.1.1 Gas Laws

One of the most well-known gas laws is also the most basic. Boyle's law is essential to understanding diving physiology. This law states that at constant temperature, the absolute pressure and the volume of gas are inversely proportional (Navy Diving Manual 2005). Boyle's law can be observed as a diver descends. All of the air-filled regions in the body shrink. The opposite is true as the diver ascends. When a diver breathes compressed air at depth, they must exhale on the way up as the gas in their lungs continually expands in volume as the pressure is reduced.

This is not the only way in which Boyle's law can be observed in diving physiology. Another phenomenon which is governed by this is barotrauma. Any air-filled, rigid walled cavities are susceptible to this. Two of the most commonly afflicted regions are the middle ears and the sinuses. Here, the same volume changes occur as the pressure is varied. Almost everyone has experienced this phenomenon of swimming to the bottom of a pool or flying in an airplane. We must equalize (pop our ears) in the same manner as a diver must. When a diver does this, air is forced from their lungs into their Eustachian tubes and sinus cavities to relieve the pressure and establish equilibrium. This prevents barotrauma to the middle ears and sinuses.

Another gas law that is of great importance to diving is Dalton's law of partial pressures. The concept of partial pressures must be understood to fully utilize the findings presented in this thesis. Dalton's law states that the "total pressure exerted by a mixture of gases is equal to the sum of the pressures that would be exerted by each of the gases if it alone were present and occupied the total volume" (Strauss and Aksenov 2004). The pressure exerted by each gas is termed the partial pressure. Dalton's law is particularly useful to diving because it allows one to understand the effect that depth has on the amount of gas delivered to the body. As a diver descends, the total pressure increases and, consequently, so does the partial pressure of each gas. This concept comes into play when determining the safe depth that a diver can go while breathing different gas mixes.

Divers utilize Dalton's law of partial pressures to determine which gas mixture is most suitable for their dive. One of the most important considerations is the partial pressure of oxygen. The United States Navy Diving Gas manual suggests that the safe range of partial pressure of oxygen for semiclosed rebreathers is between 0.2 and 1.2 atmospheres absolute (ATA) (Nuckols, Clarke et al. 1999). Divers must select a gas mixture that, at their target depth and dive duration, will keep the partial pressure of oxygen well within this range. If the diver is breathing mixed gases, they must also consider the partial pressure of the other gases. Inert gases such as helium or nitrogen are usually mixed with oxygen to be used for deep water dives or dives with a long duration. The purpose of these inert gases is to avoid oxygen toxicity by keeping the partial pressure of oxygen within a physiologically safe range. This, however, throws another potential problem into the equation: inert gas narcosis. Nitrogen is a narcotic at higher partial pressures. The most common solution to this is to use helium as the inert gas dilutent to either replace or reduce the amount of nitrogen used in the mix (Elliott 1976). Already mentioned in Chapter 1 of this thesis was the importance of maintaining a physiologically safe partial pressure of oxygen. These are ideal examples of the importance of Dalton's law of partial pressures as it relates to diving.

Another gas law which is fundamental to diving physiology is Henry's law. This law says that the amount of a gas which dissolves into a liquid at a given temperature is a function of its partial pressure. This highlights a physiological truth to diving. The deeper that a diver goes, the higher the partial pressures of the gases and, consequently, the higher the amount that is absorbed into the blood and tissues. This phenomenon is well-known and documented. Henry's law is applicable in directions, ascending and descending. Gases that diffuse into the blood and tissues at increased pressures must fall back out at decreased pressures. This is why decompression is necessary for deep divers. They must allow time for off-gassing or they could develop complications such as decompression sickness.

2.2 Rebreathers

Conventional SCUBA dive gear that the majority of recreational divers use is termed "open-circuit". Some of the gas in the tank is used by the diver and the rest is exhaled directly into the water. For military applications, rebreathers are much more common for many reasons. Primarily, the military uses them because they eliminate most of the noise that open-circuit SCUBA's make (few to no bubbles released into the water) and they are much more gas efficient. For example, a closed-circuit rebreather is said to be 20 times more efficient in oxygen use as its open-circuit counterpart (Strauss and Aksenov 2004).

Rebreathers can have a closed-circuit or a semiclosed-circuit. Closed-circuit rebreathers emit no gas. The simplest types of closed-circuit rebreathers are oxygen rebreathers. These UBAs consist only of pure oxygen tanks. Gas is injected into the device to fill up the breathing bag. The exhaled carbon dioxide from the diver is absorbed by a carbon dioxide scrubber. When the breathing bag collapses, more oxygen is added to refill the device. This type of closed-circuit rebreather, although relatively simple, constrains the diver to very shallow depths to avoid oxygen toxicity. The current rebreather in use by the USMC, the MK 25, is one example of an oxygen closed-circuit rebreather. To illustrate the limitations of this type of rebreather, the MK 25's normal working limit is in 25 fsw for 240 minutes (Navy Diving Manual 2005).

One way to get around the oxygen closed-circuit rebreathers' limitations is by utilizing a constant PO_2 closed-circuit rebreather. These rebreathers have two gas tanks: an oxygen tank and a dilutent gas tank to keep the PO_2 within a physiologically safe range. Gases are injected into a breathing bag in concentrations which vary with depth and the diver's metabolic oxygen consumption rate. The carbon dioxide that is exhaled by the diver is absorbed by a carbon dioxide scrubber while the rest of the gas is circulated and "rebreathed". The oxygen is injected at the rate at which it is consumed, thus, achieving nearly 100 percent efficiency. While this may seem like the ideal dive rig, there are many downsides to constant PO_2 closed-circuit rebreathers. They have a much higher cost due to the technological components that measure oxygen levels and control the release of fresh gas into the breathing loop. This complicates the device significantly, requiring many hours of training. These components also make it much more difficult and expensive to maintain the device. Accordingly, there are also many more opportunities for equipment to fail and compromise the safety of the diver. For these reasons, many believe that the semiclosed rebreather is a much better alternative.

As the name implies, the semiclosed rebreather has features of both a closed and an open-circuit SCUBA rig. The most commonly used semiclosed UBA's inject fresh gas at a constant rate from a mixed-gas tank, the contents of which must be determined before the dive based on the dive profile. During operation, the semiclosed rebreather emits small amounts of excess gas into the water while the breathing bag is constantly being replenished with fresh gas. Similarly to the closed-circuit rebreathers, the carbon dioxide is chemically absorbed using a carbon dioxide scrubber. Please refer to Figure 1 (below) for a schematic of a standard semiclosed rebreather.

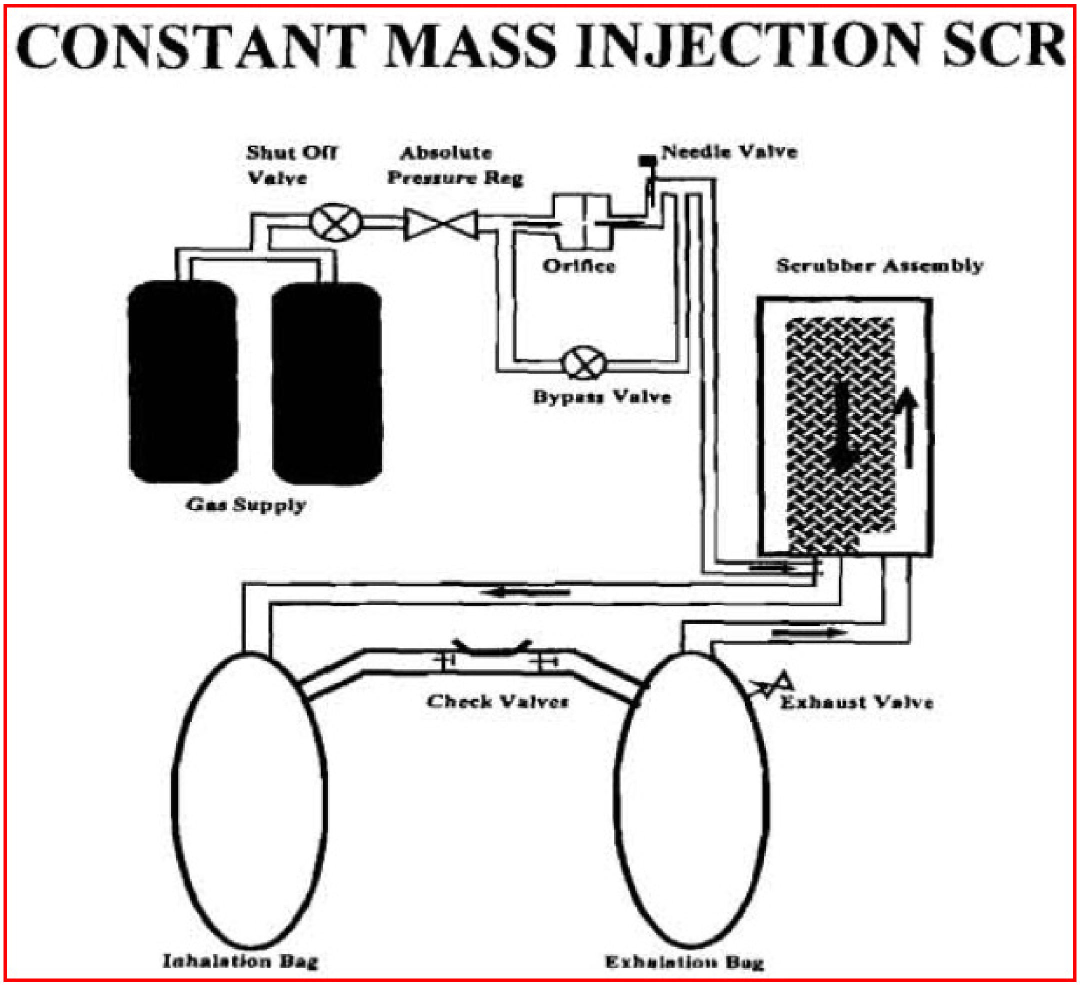


Figure 1. Schematic of a Semiclosed Rebreather. (Nuckols, Clarke et al. 1999)

The simple design of these devices keeps the maintenance cost low and reliability high. These qualities make it a more desirable rebreather for many military applications. Unfortunately, its simplicity does not come without risk. The partial pressure of oxygen in the breathing bag tends to have much more variance than that of a fully closed-circuit rebreather. Hypoxia and hyperoxia are serious concerns with semiclosed rebreathers. Sufficient planning and strict adherence to the planned dive profile can minimize this risk.

2.3 Governing Equations

There is no need to point out the importance of estimating the oxygen consumption rate of divers. The development of an equation to do so has been ongoing since NEDU's E.T. Flynn derived the steady state solution of the mass balance equation for semiclosed-circuit rebreathers in 1974 (Flynn 1974). His equation, however, required the knowledge of far too many variables to be easily utilized during operation.

J.R. Clarke of NEDU derived a steady state solution for oxygen levels in semiclosed UBA's. This led to NEDU's development of a method to measure the oxygen consumption rate of divers. This was possible due to the advent of oxygen sensors and dive computers. The equations that were used to estimate the divers' oxygen consumption rates are described on the next page.

$$FIO_2 = \frac{PO_2}{(1 + \frac{fsw}{33})}$$

Equation 1. Inspired Fraction of Oxygen

$$\dot{V}O_2 = \frac{\dot{V}inj \cdot (FO_2 - FIO_2)}{(1 - FIO_2)}$$

Equation 2. Estimated Oxygen Consumption Rate

Where $\dot{V}O_2$ is the estimated oxygen consumption rate, V_{inj} is the fresh gas injection rate, FO_2 is the fraction of oxygen in the injected gas, FIO_2 is the inspired oxygen fraction, PO_2 is the partial pressure of oxygen, and fsw is ambient pressure in units of feet sea water.

The above oxygen consumption formula is a simplified version of the full time-dependent equation that Clarke originally solved for. Because these steady state formulas require some variables to be fixed (even though they might vary slightly), mathematical corrections were applied as necessary. Also, additional measurements were taken and calibrated in order to ensure the accuracy of the data collected. The result was an equation that could be used to estimate the oxygen consumption of a diver during an operational dive by simply measuring the partial pressure of oxygen being inspired by the diver and the diver's depth.

Chapter 3

Materials and Methods

3.1 General

In order to best simulate a typical mission scenario, all tests were performed in full US Marine Corps Combatant Divers dress. Additionally, only trained USMC Combatant divers were used for this evaluation. This ensured that the experiment would yield results which were optimized for application to the USMC mission protocol. Because human subjects were used for this study, the protocol was reviewed extensively and approved by the NEDU Institutional Review Board (IRB).

3.1.1 Divex Shadow Excursion

The Divex Shadow Excursion was selected for this experiment for many reasons. By design, the DSE is capable of mounting the gas tanks on the front or back of the diver. By utilizing the DSE in its front-mounted configuration, this enabled the Combatant divers to wear a rucksack on their back. Additionally, the Divex Shadow Excursion can operate in both closed and semiclosed-circuit modes. The Navy Experimental Diving Unit has already established a safe method for monitoring the PO_2 of a diver who is using a semiclosed rebreather (Clarke and Southerland 1999). Semiclosed rebreathers also contribute to the overall safety of the diver. When in semiclosed nitrox mode, a constant mass flow orifice supplies nitrox gas to the breathing loop. During descent, the automatic demand valve adds gas in order to maintain adequate lung volume. The diver can also use this demand valve to add fresh gas in the event that the partial pressure of oxygen drops too low.

3.2 Experimental Design

The Divex Shadow Excursion was set to semiclosed-circuit nitrox mode. Please refer to Figure 1 for a general schematic of a semiclosed rebreather. This mode was chosen for this study because it can most accurately characterize the oxygen consumption rate since the mass flow rate is constant (assuming the automatic demand valve is not activated). Oxygen consumption was estimated over 24 manned dives with the DSE. The divers rotated between the pilot and passenger positions on the diver propulsion device. The data collected was used to determine the estimated oxygen consumption rates throughout the experiment.

3.3 Rebreather Modifications

The Divex Shadow Excursion was modified in order to determine the divers' oxygen consumption rates at ten-second intervals during testing. The Draeger C8a oxygen monitor, using a Teledyne R22D oxygen sensor was used to measure the partial pressure of oxygen. This device was coupled with a Delta

P VR3 dive computer which was used as a data logger. These modifications made it possible to record the diver depth and partial pressure of oxygen, updated every ten seconds. Additionally, the recordings were displayed continuously on the VR3 display making it possible for the divers to make corrections to their depth and ensure that their PO_2 was within a physiologically safe range. Figure 2 (below) is a simulation of a dive computer analogous to the one that was used in this experiment.

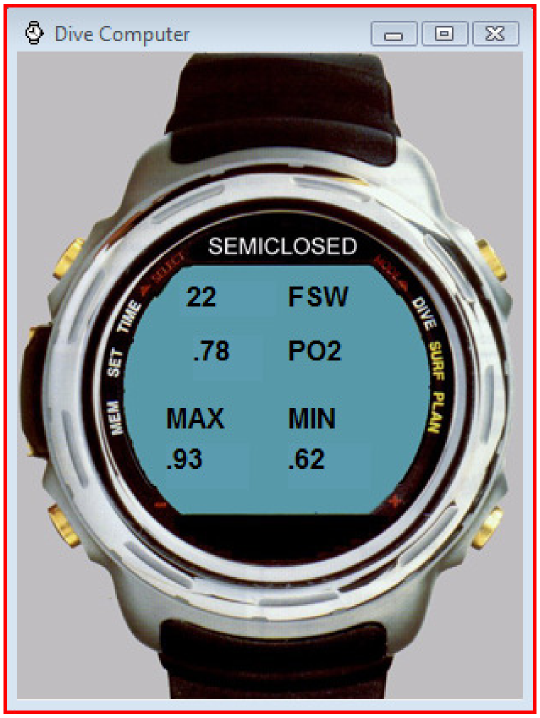


Figure 2. Dive Computer

As previously mentioned, the DSE was operating in semiclosed nitrox mode. The rig was equipped with a 300 bar, two liter oxygen cylinder and an additional 300 bar, 2 liter nitrox cylinder (60% O_2 / 40% NO_2). The nitrox fresh gas flow rate was fixed at 6.0 L/min throughout the experiment. The oxygen cylinder was only used as needed. Typically, it only became necessary toward the end of the run if the diver “wasted” too much of the nitrox before commencement of the experiment.

3.4 Test Procedures

Four U.S. Marine Reconnaissance Divers stayed in Panama City, FL for the duration of the testing. Over a two day period, the divers were trained by the USMC and Divex personnel on the maintenance and use of the Divex Shadow Excursion, dry suits, and the Diver Propulsion Device. The initial training took place in the Navy Experimental Diving Unit (NEDU) test pool. Following the completion of these training sessions, three days of open water training commenced. This initially took place at Shell Island, but was moved to St. Andrew’s Bay due to complications from rough waters.

Testing took place over the course of three days. Two test dives were accomplished each day, one in the A.M. and one in the P.M. Data was obtained from both the driver and passenger for each dive.

The divers were instructed to maintain a target depth of 20 feet sea water (fsw). Their maximum depth was limited to 30 feet by the sea floor. The total dive time was approximately 60 minutes (30 minutes out, 30 minutes back). The Diver Propulsion Device with an attached safety buoy was boarded with one diver as a pilot and the other, a passenger. Each dive consisted of a run parallel to the beach. After the DPD travels for 30 minutes, the divers will reverse positions and travel for 30 minutes in the other direction. A USMC SAFE boat was used to separate the divers from open water. The SAFE boat also monitored the bottom depth to ensure that the divers could not exceed the maximum depth of 30 feet sea water (fsw).

The DSE's carbon dioxide scrubbers were repacked, bottles recharged, divers debriefed, and dive logger data downloaded following the completion of each run. The downloaded data included the depth of the diver and the partial pressure of oxygen updated at ten-second intervals.

3.5 Data Analysis

The raw data, including diver depth and PO_2, was used to calculate the fraction of inspired oxygen (FIO_2) and estimated oxygen consumption rate ($\dot{V}O_2$) for each diver at ten second intervals. This was accomplished by employing Clarke's equations (Equations 1 and 2) in Chapter 2 of this report. Next, the data was organized so that it could be compiled for statistical analysis.

Two methods were used to analyze the data. First, curve fitting was performed to identify a curve that had the best fit to the plotted data for a maximum F value and the lowest number of fit parameters (Systat 2000). Next, it was predicted that there would be some error in the results. It was necessary to perform a propagation of error analysis in order to most accurately characterize the error that resulted from the use of the oxygen consumption formula (Equation 2). These statistical analyses will be discussed further in the following chapter.

Chapter 4

Results

4.1 Curve Fits

Curve fitting was used to identify trends in the data and to achieve 95% confidence and prediction intervals. The software package, TableCurve 2D v5.01 (Systat Software), was used to perform the various curve fits.

The 95% confidence and prediction intervals are represented in each of the graphs in this thesis. The outer, blue lines represent the 95% prediction interval. The prediction limits indicate how accurately the curve is determined in relation to the next experiment's expected values. This means that if the experiment were repeated, 95% of the $\dot{V}O_2$ values would fall in between those two limits. The inner, purple lines represent the 95% confidence interval. The confidence interval is a measure of how accurately the average curve for repeated experiments is determined. More specifically, it means that there is a 95% probability that the range contains the true mean value of oxygen consumption.

TableCurve color codes the data points based on the number of standard errors represented by the residual. Data points that are less than one standard error from the curve are blue. Green points are between 1 and 2 standard errors and yellow is between 2 and 3 standard errors. Red dots indicate a deviation of more than three standard errors. Any red dots were considered for removal if determined to be outliers.

Specific groups of data were compiled for analysis. These groups included all of the drivers, all of the passengers, and a total compilation (both drivers and passengers). The purpose of this was to identify possible trends in the data, establish a mean and 95% prediction intervals, and determine to what extent the gas flow rate of the rebreathers can be reduced.

4.1.1 Initial Curve Fit

Initially, the full data sets were plotted. However, it was quickly discovered that the full data set was not representative of the oxygen consumption rate of a diver using a DPD. The result of a curve fit performed on the total compilation of complete data is presented in Figure 3:

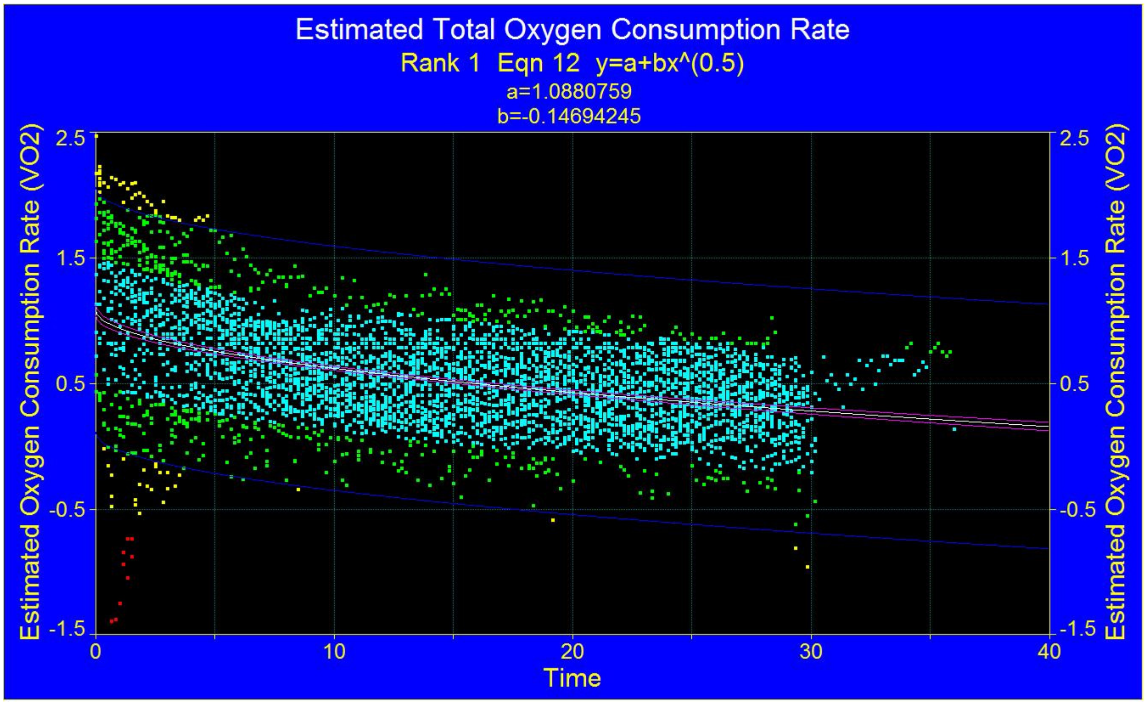


Figure 3. Curve Fit of Total Compilation of Data Files

This initial trial revealed an interesting, but undesirable outcome. It took approximately 10 minutes for the oxygen consumption rate to "level off". Initially, this could be caused by a couple of things. The negative $\dot{V}O_2$ values could be due to the breathing bag of the rebreather filling up with gas. The higher $\dot{V}O_2$ values can be caused by the divers struggling to get into position on the DPD. This would cause an elevated oxygen consumption rate. Additionally, this would explain why the values seem to approach a steady state after 10 minutes from the start of the experiment.

Another observation is that the data points near the end seem to go in the negative direction. Additionally, some data was included beyond the end of the experiment (beyond 30 minutes). These inconsistencies do not likely represent the true oxygen consumption rates of the divers while riding the diver propulsion device.

It was determined that all of the data should be truncated to eliminate these false readings. Only data points collected between 10 minutes and 25 minutes were used to characterize the divers' $\dot{V}O_2$.

4.1.2 Driver Compilation

To identify any possible trends in the data, the files were grouped into driver and passenger compilations. It was decided that only simple equations should be selected for the curve fits. This is because there is no reason to suspect that the estimated oxygen consumption rate should have a complex relationship with time. As indicated in the previous section, if the data collected had reached a steady state, a linear regression model would be appropriate. However, initial trials indicated that this was not the case. Potential explanations for this will be presented in the discussion of this thesis. Nonetheless, in order to ensure that the true trend of the data was modeled, nonlinear equations were considered and chosen if they were statistically better fits. The resulting curve of the truncated driver files (n=1092) is depicted in Figure 4.

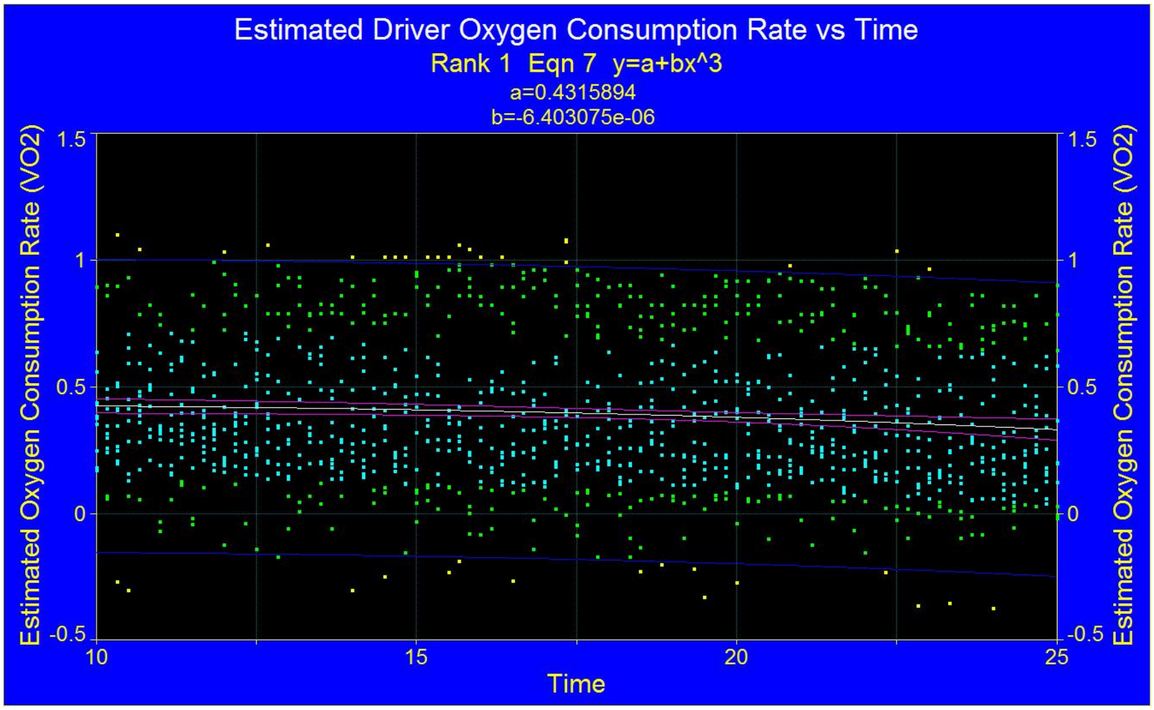


Figure 4. Estimated Driver Oxygen Consumption Rate vs. Time

Figure 4 indicates that the mean $\dot{V}O_2$ of the drivers is close to 0.4 L/min. This is approximately the outcome that was expected. In a previous study by the Navy Experimental Diving Unit, the mean resting oxygen consumption rate was measured as 0.37 L/min (Knafelc 2007). Therefore, these results appear to agree with the hypothesis that the mean oxygen consumption rate of the divers while using a DPD is near the resting oxygen consumption rate. Also important in this figure is that the 95% prediction interval indicates that 95% of the data points of a repeat experiment are likely to be within 1.0 liter per minute or less. That being said, it is important to realize that this graph only includes data from the drivers of the DPD.

The numeric summary of the chosen model from TableCurve can be found in Appendix A of this thesis. This output includes all of the statistics of the curve fit. One of the most important quantities is the P-value. For the chosen driver curve fit in Figure 4, this value is 0.0022. Generally, a 95% confidence level is used as the criterion in determining the significance of the model. Because 0.0022 is less than α=0.05, it can be concluded that the findings presented in Figure 4 are statistically significant.

4.1.3 Passenger Compilation

The next compilation of data included only the passenger files. The resulting graph for 1092 data pairs is depicted in Figure 5:

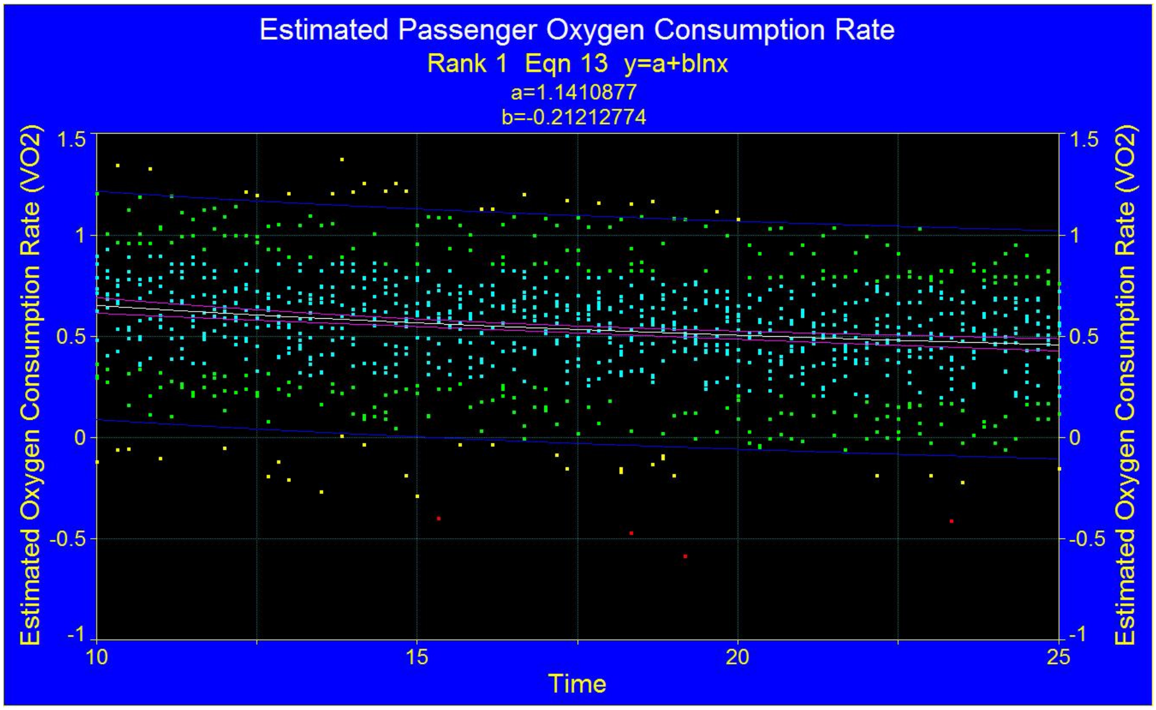


Figure 5. Estimated Passenger Oxygen Consumption Rate vs. Time

This graph also has 95% prediction and confidence limits. Notice that there are four points which fell more than 3 standard errors from the curve. Although it could be argued that these are outliers, they were kept in the analysis because they did not have a significant effect on the curve fit calculations.

Figure 5 indicates that the average passenger oxygen consumption rate appears to be just over 0.5 L/min. This is a significant increase over that of the drivers. Possible explanations for this will be discussed in the next chapter.

The numerical summary for Figure 5 can be found in Appendix B of this thesis. The P-value was for this model was found to be less than or equal to 0.0001. This is indicative of a probability that is much lower than required for statistical significance at the 95% confidence level (α=0.05).

4.1.4 Total Compilation

Finally, the truncated compilation of driver and passenger data sets were imported into TableCurve 2D. The results for 2184 data points are presented in Figure 6.

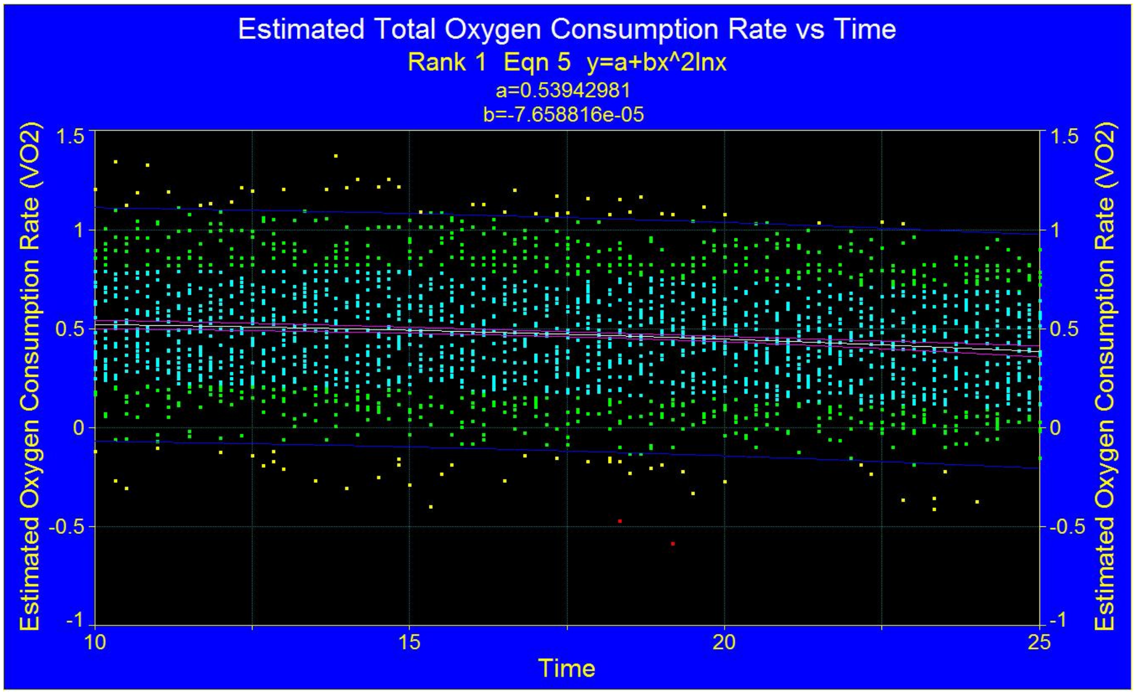


Figure 6. Estimated Total Oxygen Consumption Rate vs. Time

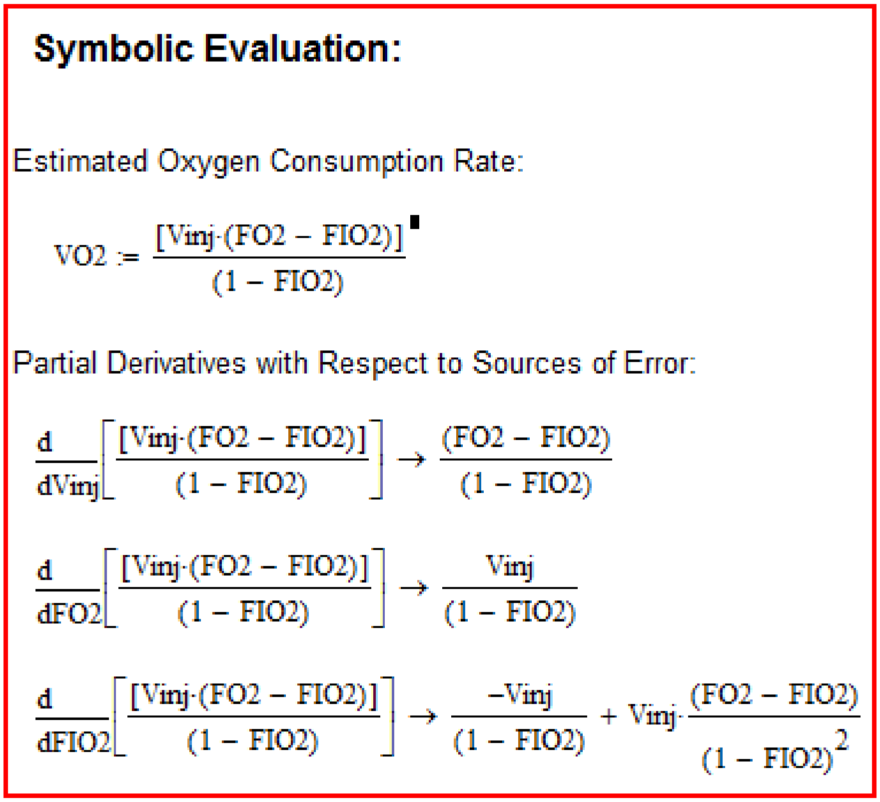
Figure 6 depicts a model that is as expected after seeing the separate compilations. The average oxygen consumption rate appears to be below 0.5 L/min with a 95% prediction interval just above 1.0 liter per minute.

The numerical summary in Appendix C shows that the P-value of the chosen model is less than or equal to 0.0001. This highlights the statistical significance of the findings in Figure 6. This figure is paramount in determining how far the fresh gas flow rate can be reduced for the USMC Combatant Divers during missions where the DPD will be utilized. Further discussion of this will take place in the conclusion of this thesis.

4.2 Propagation of Error

Propagation of error was employed to estimate the uncertainty of the calculated estimated oxygen consumption rate. It was important to use propagation of error and not just find the uncertainty in our $\dot{V}O_2$ calculation because the $\dot{V}O_2$ was not measured. Thus, the uncertainty of each measurement propagated throughout Clarke's oxygen consumption rate formula.

The first step to finding the propagation of error was to compile all of the data and calculate the mean and uncertainty of each measurement. Next, the partial differential of each variable in the $\dot{V}O_2$ formula that had error had to be solved for symbolically. In this case, all three of the variables had error. Figure 8 is a screenshot from MathCAD Professional (Mathsoft, 2001) that shows the symbolic evaluation of the partial differentials.



Symbolic Evaluation:

Estimated Oxygen Consumption Rate:

$$VO2 := \frac{[Vinj \cdot (FO2 - FIO2)]}{(1 - FIO2)}$$

Partial Derivatives with Respect to Sources of Error:

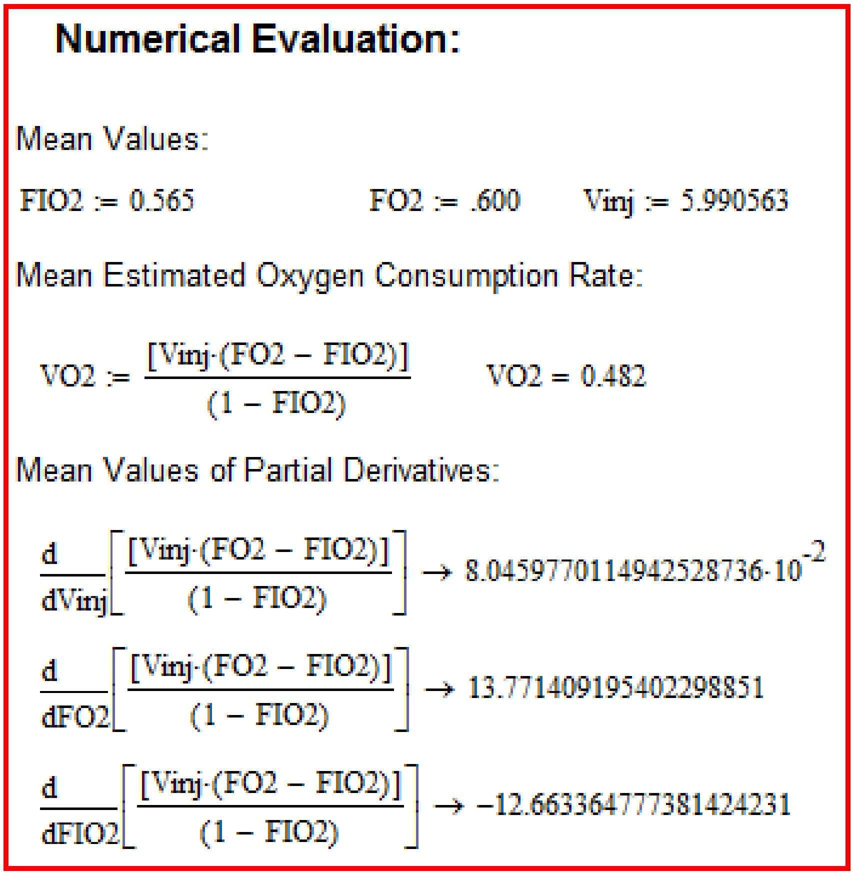
$$\frac{d}{dVinj}\left[\frac{[Vinj \cdot (FO2 - FIO2)]}{(1 - FIO2)}\right] \rightarrow \frac{(FO2 - FIO2)}{(1 - FIO2)}$$

$$\frac{d}{dFO2}\left[\frac{[Vinj \cdot (FO2 - FIO2)]}{(1 - FIO2)}\right] \rightarrow \frac{Vinj}{(1 - FIO2)}$$

$$\frac{d}{dFIO2}\left[\frac{[Vinj \cdot (FO2 - FIO2)]}{(1 - FIO2)}\right] \rightarrow \frac{-Vinj}{(1 - FIO2)} + Vinj \cdot \frac{(FO2 - FIO2)}{(1 - FIO2)^2}$$

Figure 7. Symbolic Evaluation of Partial Derivatives

Next, the mean values for each variable had to be plugged into these symbolic evaluations. This is shown in Figure 8:



Numerical Evaluation:

Mean Values:

FIO2 := 0.565 FO2 := .600 Vinj := 5.990563

Mean Estimated Oxygen Consumption Rate:

$$VO2 := \frac{[Vinj \cdot (FO2 - FIO2)]}{(1 - FIO2)} \qquad VO2 = 0.482$$

Mean Values of Partial Derivatives:

$$\frac{d}{dVinj}\left[\frac{[Vinj \cdot (FO2 - FIO2)]}{(1 - FIO2)}\right] \rightarrow 8.0459770114942528736 \cdot 10^{-2}$$

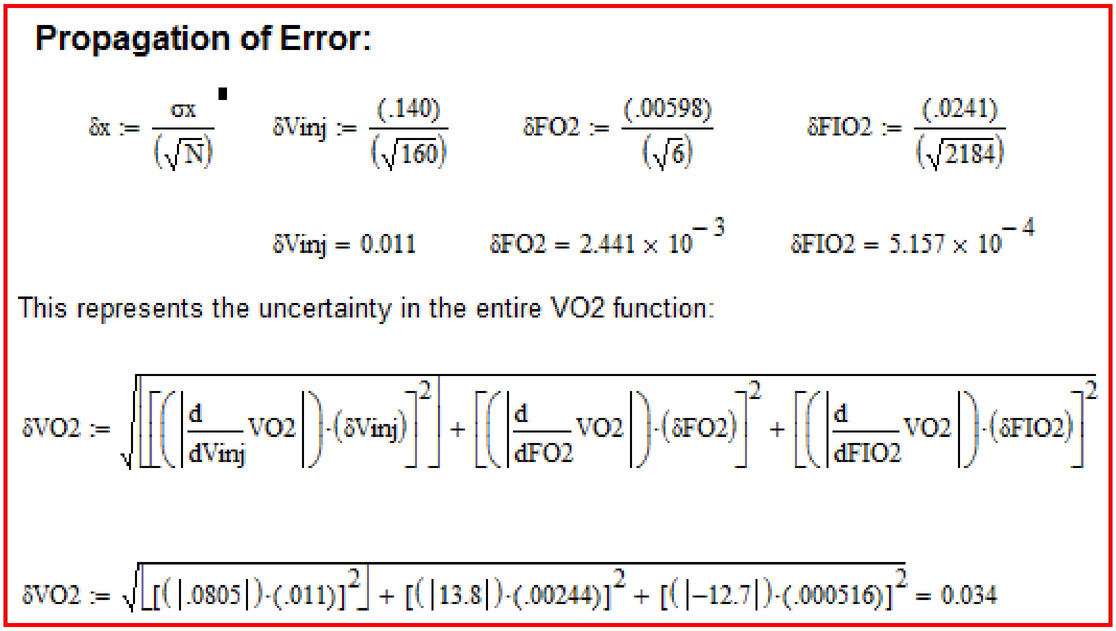
$$\frac{d}{dFO2}\left[\frac{[Vinj \cdot (FO2 - FIO2)]}{(1 - FIO2)}\right] \rightarrow 13.771409195402298851$$

$$\frac{d}{dFIO2}\left[\frac{[Vinj \cdot (FO2 - FIO2)]}{(1 - FIO2)}\right] \rightarrow -12.663364777381424231$$

Figure 8. Numerical Evaluation of Partial Derivatives

Each partial differential represents a sensitivity factor in the propagation of error formula. From these values, it can be concluded that the injection velocity is the least sensitive variable. This means that the error in the measured injection velocities will contribute the least to the overall uncertainty of the $\dot{V}O_2$ calculation. This is because the absolute value of the solved partial differential yields the lowest number.

The general formula for propagation of error is listed below in Figure 9. This formula assumes that there is no covariance between the variables (Taylor 1982).



Propagation of Error:

$$\delta x := \frac{\sigma x}{(\sqrt{N})} \qquad \delta Vinj := \frac{(.140)}{(\sqrt{160})} \qquad \delta FO2 := \frac{(.00598)}{(\sqrt{6})} \qquad \delta FIO2 := \frac{(.0241)}{(\sqrt{2184})}$$

$$\delta Vinj = 0.011 \qquad \delta FO2 = 2.441 \times 10^{-3} \qquad \delta FIO2 = 5.157 \times 10^{-4}$$

This represents the uncertainty in the entire VO2 function:

$$\delta VO2 := \sqrt{\left[\left[\left(\left|\frac{d}{dVinj} VO2\right|\right)\cdot(\delta Vinj)\right]^2\right] + \left[\left(\left|\frac{d}{dFO2} VO2\right|\right)\cdot(\delta FO2)\right]^2 + \left[\left(\left|\frac{d}{dFIO2} VO2\right|\right)\cdot(\delta FIO2)\right]^2}$$

$$\delta VO2 := \sqrt{[(|.0805|)\cdot(.011)]^2 + [(|13.8|)\cdot(.00244)]^2 + [(|-12.7|)\cdot(.000516)]^2} = 0.034$$

Figure 9. Propagation of Error

The first step in Figure 9 indicates how the uncertainty in the mean of N measurements was found (Taylor 1982). Even though the injection velocity has a relatively high uncertainty, the sensitivity factor (partial derivative) is so low that it keeps that variable’s contribution to the total uncertainty minimal. The propagation of error is 0.034 for the estimated oxygen consumption rate. This is a very reasonable level of uncertainty and serves to validate Clarke’s method.

Chapter 5

Discussion

5.1 Curve Trends

5.1.1 Driver vs. Passenger

After studying the curves, it was clear that there were some interesting trends. First, the driver and passenger graphs were compared. In order to ensure that the results from each data set could be compared accurately, an F test was performed to compare the variations for each compilation (driver and passenger). The results of this test can be viewed in Appendix D of this thesis. The F ratio of 1.03 indicates that the variances seen in each compilation are not statistically different. This is very important because it allows for accurate conclusions to be drawn from the comparison of the two data sets.

Please refer to Figure 10 in order view the two graphs together. Also, notice that in this figure, the graphs are scaled identically to facilitate simple visual comparison. One might assume that the driver will likely have a higher oxygen consumption rate because they have to manually control the Diver Propulsion Device (DPD). However, the results indicate that this is not the case. It is clear that the passenger has an average oxygen consumption rate that is more than 0.1 L/min higher than that of the driver. Upon further examination of the raw data, it was found that the mean estimated oxygen consumption rate of the driver data was 0.3908 L/min. The mean $\dot{V}O_2$ of the passenger data was 0.5410 L/min. Therefore, the mean passenger $\dot{V}O_2$ was found to be 38.4% higher than the mean driver $\dot{V}O_2$. One possible explanation for this is that the passenger experiences more drag resistance from the water. If this is the case, the passenger might have to work harder to hold on to the DPD which could increase their $\dot{V}O_2$.

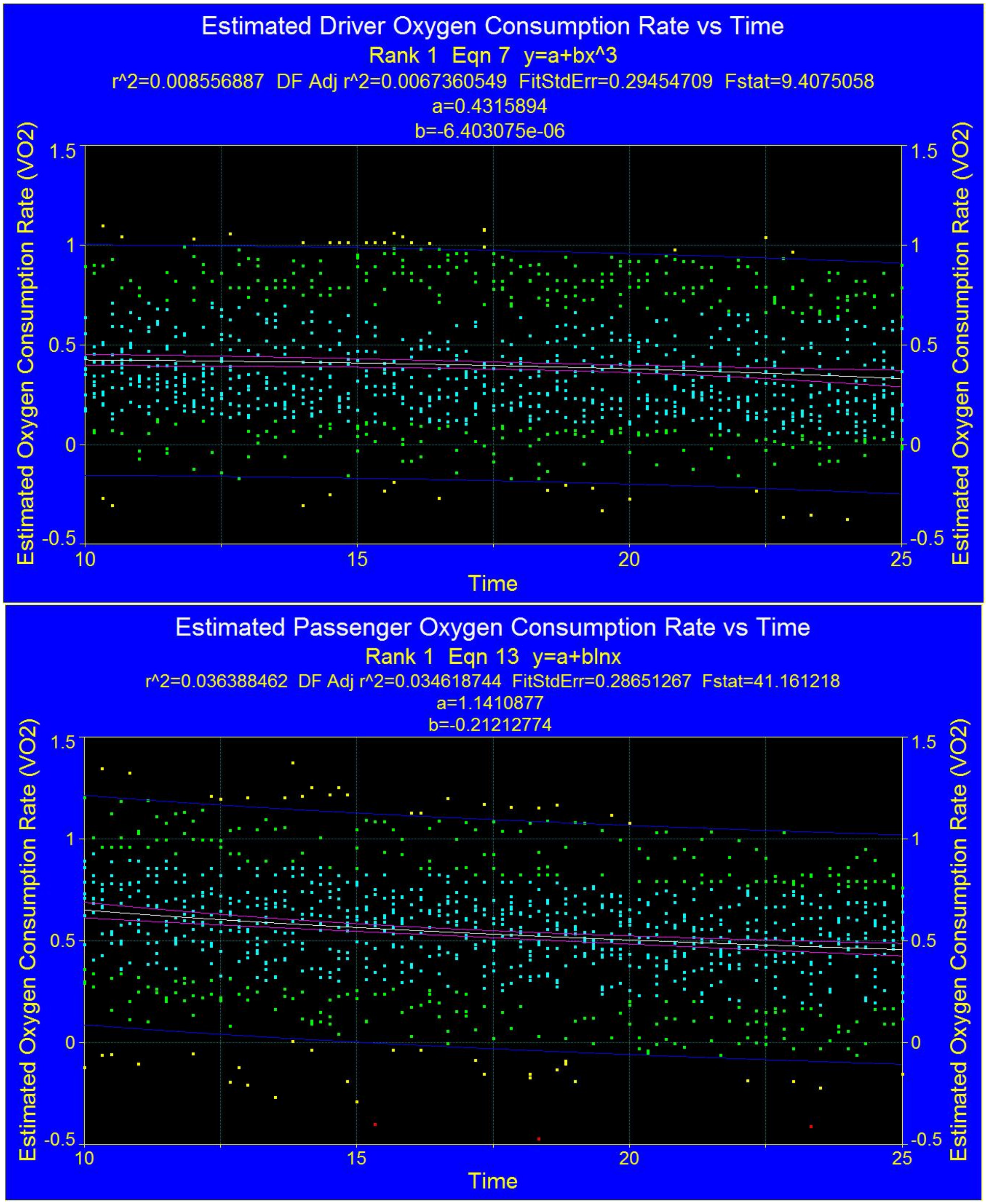


Figure 10. Driver vs. Passenger Comparison

5.1.2 Negative Slope

Another trend that could be identified in all of the curve fits is that they have slightly negative slopes. In Figures 4 and 6, this downward trend seemed to appear more toward the end of the experiment. This could be caused by a number of things. It might be an indication that an insufficient number of data points were truncated in the tail end of the data set, leaving some of the false reads from the divers preparing to surface. Although this is a possibility, it is not a likely one. It was expected that there would be a need for truncating the first 10 minutes of the data so that the rebreather could equilibrate. However, it is unlikely that the divers did anything that would affect the estimated oxygen consumption rate further than 5 minutes prior to the end of the experiment. They were instructed to maintain their positions for the entire duration (30 minutes) of each leg. The decision was made to truncate the last 5 minutes in order to be certain that we were using data which accurately portrayed their $\dot{V}O_2$ while using the DPD. That being said, there is not enough justification to truncate the data set any further. Furthermore, the passenger data set appeared to show a consistent decline in the estimated oxygen consumption rate throughout the entire duration of the experiment. This seems to indicate that it might take a longer period of time for the divers' $\dot{V}O_2$ to reach a steady state.

5.2 Propagation of Error

The propagation of error analysis yielded positive results. The mean $\dot{V}O_2$ was calculated to be 0.482 L/min (Figure 8). The uncertainty of this estimated oxygen consumption rate is only 0.034 L/min. This validates the use of Clarke's equations (Equations 1 and 2) for this application. However, it was concluded that for the $\dot{V}O_2$ formula, the FO_2 and FIO_2 are by far the most sensitive variables. A large uncertainty in either of these two measurements would cause the propagation of error to increase drastically. This can be clearly observed in Figure 8. The partial derivatives of these variables are quite high. For this reason, great care should be taken in the measurement of these two variables.

5.3 Limitations

As mentioned in the introduction, this study was designed specifically for the application to the Marine Corps Combatant Divers. These divers maintain a high level of physical fitness and their metabolic rates have been documented. Thus, the mean oxygen consumption rate of this subject group might vary considerably from that of the average diver.

One aspect that could not be accounted for was the affect that stress might have on the divers' $\dot{V}O_2$. It is probable that during a real-life mission, the divers might experience significantly more stress than they did in this experiment. One study reported that hormones which are released when a person is under stress can cause an increase in the oxygen consumption rate (Weissman, Askanazi et al. 1986).

Additionally, the negative slope indicates that the experimental trials were not long enough for the estimated oxygen consumption to reach a steady state. Fortunately, the most likely result of this is that the $\dot{V}O_2$ is overestimated. It is unlikely that the steady state value will be significantly lower. Furthermore, a slight overestimation will contribute to the overall safety of the new fresh gas flow rate that will be discussed in the conclusion of this thesis.

Chapter 6

Conclusion

6.1 Recommendation

This study revealed that the mean oxygen consumption rate of Marine Combatant Divers using a Diver Propulsion Device is similar to that of the documented resting oxygen consumption rate. However, we have added new information concerning the variance of that data during DPD operations. These preliminary results indicate that the amount of oxygen made available to the diver should not fall below 1.0 L/min. Even though the mean $\dot{V}O_2$ was just 0.482 L/min, there were a significant number of data points that were closer to the 1.0 L/min mark. With all of this taken into consideration, the preliminary recommendation is to reduce the fresh gas flow rate in the DSE (semiclosed nitrox mode with 60% oxygen mix) to 2.0 L/min of a 60% O_2 (40%N_2) mixture for a net O_2 injection rate of 1.2 L/min . This will triple the dive time offered by the Divex Shadow Excursion while the divers are utilizing the diver propulsion device.

In order to understand the significance of this adjustment, one could assume a set of default DSE settings: (2) two liter nitrox tanks (60% oxygen / 40% nitrogen) filled to 300 Bar. Assuming these conditions, the standard gas flow rate of 6.0 L/min would provide a maximum theoretical dive time of 3 hours.

If the flow rate were reduced to 2.0 L/min, the maximum dive time would theoretically increase to 9 hours. It is important to note that these dive times are only theoretical. Realistically, the adjusted fresh gas flow rate might sustain a diver for 7-8 hours on a diver propulsion device. Nonetheless, this would significantly increase the mission capabilities of the United States Marine Corps.

6.2 Next Steps

These preliminary results will now need to be tested and verified with reduced fresh gas flow rates. Additionally, the duration of the testing should be increased in order to most accurately characterize the long term oxygen demands of the divers using a DPD. This would offer more time for the divers' bodies to reach a steady state metabolic rate. As stated in the limitations, it is possible that the true resting $\dot{V}O_2$ is lower than this thesis indicated. If this were determined to be the case, it is possible that the fresh gas flow rate could be reduced further, enabling the United States Marine Corps to achieve even longer dives. Only once substantial testing is completed and the flow rate of 2.0 L/min of 60% O_2 nitrox is proven to be safe should this be attempted in a real mission scenario.

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Appendices

Appendix A: Driver Curve Fit – Numeric Summary

```
Rank 1  Eqn 7  y=a+bx3

r2 Coef Det       DF Adj r2         Fit Std Err       F-value
0.0085568870                        0.0067360549      0.2945470853          9.4075058440

 Parm  Value           Std Error        t-value         95% Confidence Limits       P>|t|
 a     0.431589399                      0.016001414                     26.97195360
       0.400192340                      0.462986458                     0.00000
 b     -6.4031e-06   2.08762e-06   -3.06716577   -1.0499e-05   -2.3069e-06   0.00221

Area Xmin-Xmax        Area Precision
5.8645483747          0.0000000000
Function min      X-Value           Function max      X-Value
0.3315413517                        25.000000000      0.4251862873          10.000018938
1st Deriv min     X-Value           1st Deriv max     X-Value
-0.012005766      25.000000000                        -0.001920930      10.000018938
2nd Deriv min     X-Value           2nd Deriv max     X-Value
-0.000960461      25.000000000                        -0.000384185      10.000018938

Soln Vector       Covar Matrix
Direct            LUDecomp
r2 Coef Det       DF Adj r2         Fit Std Err       Max Abs Err
0.0085568870                        0.0067360549      0.2945470853          0.7270770390
r2 Attainable
0.0273181822
Source    Sum of Squares     DF        Mean Square          F Statistic         P>F
Regr      0.81617626         1         0.81617626           9.40751             0.00221
Error     94.566204          1090      0.086757985
Total     95.38238           1091

Lack Fit  1.789497           89        0.020106708          0.216938            1.00000
Pure Err  92.776707          1001      0.092684023

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Appendix B: Passenger Curve Fit – Numeric Summary

```
Rank 1  Eqn 13  y=a+blnx

r2 Coef Det      DF Adj r2        Fit Std Err      F-value
0.0363884625                      0.0346187443     0.2865126668       41.161217521

 Parm  Value           Std Error       t-value         95% Confidence Limits      P>|t|
 a      1.141087729                     0.093937594                12.14729567
        0.956768759                     1.325406699                0.00000
 b     -0.21212774  0.033063846  -6.41570086  -0.27700373  -0.14725176  0.00000

Area Xmin-Xmax          Area Precision
8.1123322574            1.552475e-12
Function min     X-Value          Function max     X-Value
0.4582748639                      25.000000000     0.6526451475       10.000018938
1st Deriv min    X-Value          1st Deriv max    X-Value
-0.021212734     10.000018938                      -0.008485110       25.000000000
2nd Deriv min    X-Value          2nd Deriv max    X-Value
0.0003394044                      25.000000000     0.0021212694       10.000018938

Soln Vector      Covar Matrix
Direct           LUDecomp
r2 Coef Det      DF Adj r2        Fit Std Err      Max Abs Err
0.0363884625                      0.0346187443     0.2865126668       1.0998009883
r2 Attainable
0.0584570732
Source     Sum of Squares     DF       Mean Square         F Statistic        P>F
Regr       3.3789041          1        3.3789041           41.1612            0.00000
Error      89.477564          1090     0.082089508
Total      92.856468          1091

Lack Fit   2.0492132          89       0.023024868         0.26362            1.00000
Pure Err   87.428351          1001     0.08734101

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Appendix C: Total Curve Fit – Numeric Summary

```
Rank 1  Eqn 5  y=a+bx^2lnx

r^2 Coef Det     DF Adj r^2      Fit Std Err     F-value
0.0175016006                     0.0166006392       0.3005031636        38.868757991

 Parm  Value           Std Error       t-value        95% Confidence Limits       P>|t|
 a      0.539429808                    0.013432012                  40.16001461
        0.513088937                    0.565770680                  0.00000
 b      -7.6588e-05   1.22846e-05  -6.23448137  -0.00010068  -5.2497e-05   0.00000

Area Xmin-Xmax         Area Precision
6.9906876383           2.420723e-09
Function min     X-Value         Function max     X-Value
0.3853499484                     25.000000000       0.5217946517        10.000018938
1st Deriv min    X-Value         1st Deriv max    X-Value
-0.014241093     25.000000000                     -0.004292908      10.000018938
2nd Deriv min    X-Value         2nd Deriv max    X-Value
-0.000722820     25.000000000                     -0.000582466      10.000018938

Soln Vector      Covar Matrix
Direct           LUDecomp
r^2 Coef Det     DF Adj r^2      Fit Std Err      Max Abs Err
0.0175016006                     0.0166006392       0.3005031636        1.0415069878
r^2 Attainable
0.0270350712
Source     Sum of Squares      DF       Mean Square         F Statistic         P>F
Regr       3.5099325           1        3.5099325           38.8688             0.00000
Error      197.03929           2182     0.090302151
Total      200.54923           2183

Lack Fit   1.9119302           89       0.021482361         0.230427            1.00000
Pure Err   195.12736           2093     0.093228554

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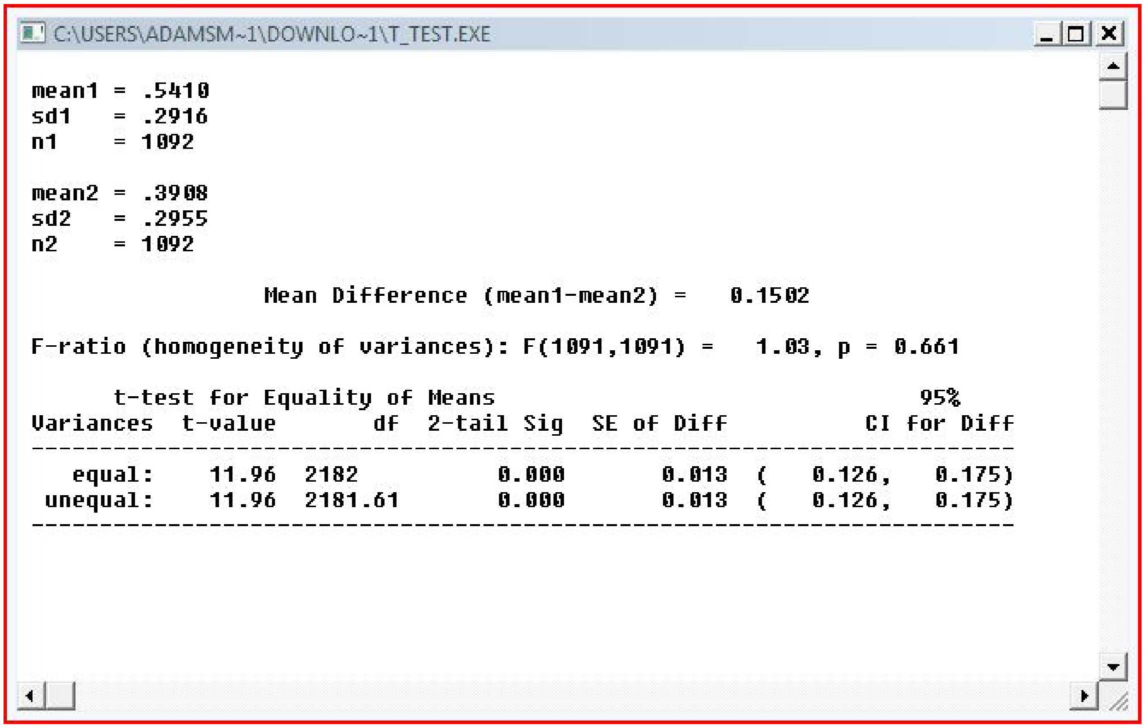
Appendix D: Comparison of Variances



```
mean1 = .5410
sd1   = .2916
n1    = 1092

mean2 = .3908
sd2   = .2955
n2    = 1092

                 Mean Difference (mean1-mean2) =   0.1502

F-ratio (homogeneity of variances): F(1091,1091) =   1.03, p = 0.661

      t-test for Equality of Means                              95%
Variances  t-value       df  2-tail Sig  SE of Diff          CI for Diff
------------------------------------------------------------------------
   equal:    11.96  2182          0.000       0.013  (   0.126,   0.175)
 unequal:    11.96  2181.61       0.000       0.013  (   0.126,   0.175)
------------------------------------------------------------------------
```

This is a screen shot from a freely-available executable posted in the public domain. Only the F-ratio was used for this thesis.