Surviving the Loop

A look a the factors that influence diving accidents in Rebreathers

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Thesis Summary

This dissertation looks at possible reasons for the number of accidents involving experienced divers using semi-closed and fully closed circuit rebreathers

1995 saw the full-scale launch of the first mass produced semi closed circuit rebreather into the mainstream diving industry. This was followed soon after by the launch of the first mass-market closed circuit rebreather. The effect of this technology on the market place was significant. It now allowed a diver to venture deeper, for far longer than could have been imagined just the year before.

The technology was welcomed with open arms as experienced divers saw these systems as a new technology that would allow them to explore depths previously un imagined however, this was not to be without a price. By then of the first year of the launch three extremely experienced divers had perished and by the close of the second year the death toll had dramatically increased and was rising constantly.

As a result of the public outcry as a result of these deaths Cornwall's Trading Standards conducted extensive investigations and it became apparent that it was unlikely to be a technical or design fault with the systems. So why were so many experienced divers dying, in some cases, on what appeared to be iniquitous dives?

This thesis begins to explore the issues by first looking at the human factors, then the subtle practical differences between SCUBA diving and rebreather diving and tries to establish a possible explanation for the high number of incidents.

Key Words: Diver, Scuba, Closed Circuit Rebreather

Rebreather, Semi closed Circuit Rebreather,

Accidents, Human error

Dedication

This work is dedicated to all the rebreather divers who have lost their lives in the search of adventure.

I only hope that their search has not been in vain.

Acknowledgements

As someone in my family once said everybody has at least one book in them. This is mine. If it wasn't for the encouragement of my wife in 1983 when I began my quest for knowledge with the Open University I would not be here now. It is very difficult to say thanks that many times but I do it again.

I would also like to thank a diver called Rob Palmer who was an author, explorer and a very good friend who went missing following a dive in the Red Sea in 1997. It was Rob who in 1994 rekindled my quest for adventure in diving after a long period in the doldrums. There is no question that his favourite saying might be appropriate for this work
"the pioneers are always the ones with the arrows in their backs"

I do miss him!

Two rebreather divers and friends Jon Parlour and Richard Stevenson who performed a "reality check" on Chapter 4 to ensure that I was not going too far off track.

I would also like to thank Amanda Hopkins who with her skills and editing ability plus her brilliant use of WORD sorted out the layout of the dissertation and having read it forced me to translate it from "diver" to English so anyone could read it. Without her, I doubt I would have completed it.

Lastly to my supervisor who has put up with me and with the on again, off again thesis and has stood by me even when, due to work commitments, I have had long periods of inactivity.

Table of Contents

1. **Introduction**
    - 1.1 Aim
    - 1.2 Methodology
    - 1.3 Background to the Study
    - 1.4 Why Rebreathers?
    - 1.5 The Problem
    - 1.6 An Overview of the Development of Rebreathers Since 1995

2. **An Overview of the Possible Causes of Rebreather Incidents**
    - 2.1 Introduction
    - 2.2 Equipment
    - 2.3 Diver's Inexperience
    - 2.4 Diver Error
    - 2.5 Training
    - 2.6 Legal Requirements
    - 2.7 Conclusion
3. **The Evolution of Recreational Diving**
    - 3.1 Introduction
    - 3.2 Background History
    - 3.3 The Growth of the Recreational Diving Industry
    - 3.4 Early Accidents
    - 3.5 Later Accident Statistics
    - 3.6 Consumer Change
    - 3.7 The Role of Training
    - 3.8 The Development of Diver Education
    - 3.9 Diver Instructor Training and the Introduction of the New Diver Training Scheme
    - 3.10 The Development of Emergency Support Facilities
    - 3.11 Conclusion
4. **Research/Results**
    - 4.1 Introduction
    - 4.2 Specific Methodology
    - 4.3 The Differences Between SCUBA and Rebreather Techniques
    - 4.4 On the Surface- Failure to turn the set on
    - 4.5 Changes in Buoyancy
    - 4.6 The Descent- Changes in Buoyancy
    - 4.7 On the Bottom-Buoyancy Changes during a shallow dive
    - 4.8 On the Bottom-Accidental Loss of Mouthpiece
    - 4.9 On the bottom-Exhaling through Nose
    - 4.10 System Flood due to component failure
    - 4.11 On the Bottom –Oxygen poisoning
    - 4.12 Ascent-Changes in Buoyancy
    - 4.13 Ascent-Falling oxygen levels
    - 4.14 Ascent-Diver Rescue

Table of Contents (con't)

4.15 On the Surface Loss of Mouthpiece
4.16 Conclusion

5. Conclusions and Recommendations
5.1 Summary
5.2 The Technology
5.3 Training
5.4 Instructor/Diver Requalification
5.5 Information Distribution
5.6 Diver Perception of Risk
5.7 Oxygen Toxicity
5.8 Conclusion

Appendix 1 A Summary of the Published Information on Closed Circuit and Semi-closed Circuit Rebreather Fatalities 1998-2002

Appendix 2 The Evolution of Recreational Diving: A Time Line

Appendix 3 Time line of Key Recreational Diver Issues

Appendix 4 Task Analysis of a Descent Looking at Open Circuit (Scuba), Semi-Closed Circuit (SCR) and Closed Circuit Rebreathers CCR

Bibliography

Glossary of Terms

List of Figures/Tables

Figure 1.1 An Illustration of a Fully Closed Electronic Circuit Rebreather (CCR) **Page 20**

Figure 1.2 An Illustration of a Semi Closed Circuit Rebreather (SCR) **Page 21**

Figure 2.1 A summary of the Principal Causes of Fatal Accidents in Divers **Page 33**

Figure3.4 Annual Distribution of SCUBA Diving Deaths in Michigan 1959-1965 from statistics complied by the Vital Statistic Bureau Michigan, Department of Health **Page 48**

Figure 3.5 (a) BSAC Fatalities 1975-2000 **Page 51**

Figure 3.5 (b) Yearly US recreational diving fatalities 1970-1992 **Page 51**

Figure 4.3 Dive Profile Illustrating Component parts of a Dive **Page 64**

Figure 4.4 Line Diagram "Failure to Turn Set On" **Page 66**

Figure 4.5 Requirement to Slow Descent Diver Inhales **Page 68**

Figure 4.6 Minor Changes in Depth/pressure on a Shallow Dive **Page 70**

Figure 4.7 Loss of Mouthpiece on the Bottom **Page 71**

Figure 4.8 Exhaling Through Nose **Page 73**

Figure 4.9 System Flood Due to Component Failure **Page 74**

Figure 4.10 Oxygen Poisoning **Page 76**

Figure 4.11 Change in Buoyancy on Ascent **Page 77**

Figure 4.12 Fall in Oxygen Level on Ascent **Page 79**

Figure 4.13 Loss of Mouthpiece on the Surface **Page 81**

Surviving the Loop

A look a the factors that influence diving accidents in Rebreathers

Chapter 1 Introduction

"Those who fail to learn the lessons of history are doomed to repeat them." *PADI Course Director's Manual*, 1995 Edition

"That men do not learn very much from the lessons of history is the most important of all the lessons that history has to teach."
Aldous Huxley, 1959

1.1 Aim

1.1.1 This dissertation is an investigation into the training and operational issues surrounding Mixed Gas Closed Circuit Rebreathers currently in use in the recreational and commercial diving industry. Rebreathers have been used by the military in clandestine diving operations since the turn of the 20^{th} Century. By the mid 1990's rebreathers began to appear in the scientific and recreational diving community and by 1996 were becoming widespread. However, with this increase in use came a dramatic rise in the number of fatalities by divers using this technology, far more than had been reported by their military counterparts during the same period. (MOD Letter, 19/12/00). As a result of the selection criteria laid down by the training agencies all the divers involved in all these accidents were extremely experienced Open Circuit (scuba) divers yet, despite this high level of experience, fatal accidents continued to occur. Why? In this thesis I intend to try and explore some of the possible causes for these fatalities, by looking at the possibility of equipment or systems failure and some of the human factors that could influence their incorrect operation and try and draw some conclusions.

Chapter 1 Introduction

1.2 Methodology

1.2.1 For this research I intend to use two key methods of investigation:

- To gain a better insight into rebreather diving, I embarked on a course of training using rebreathers in February 2000. After having spent over 32 years in the water comprising of thousands of hours on open circuit SCUBA I initially found the whole experience extremely frustrating. There were subtle differences in how I, as a diver, dive the unit and it seamed to make the system extremely difficult to dive well initially. Following the course, I spent the last year and a half gaining experience on the system and have recently qualified as a rebreather instructor. I now have to date in excess of fifty dives on rebreathers and over 25 hours underwater experience. It is this diving experience that I have gained in the past 18 months together with other rebreather diver's experience, which will form the primary basis for my research, which I will present in Chapter 4.

- In Chapter 2 I intend to look at a variety of sources including texts, magazines and the Internet to investigate why errors occur and try to explore some of the training and legal issues that surround rebreather diver training. Using this information I intend to try and begin to explain how these aspects of rebreather diving and instruction could influence rebreather accidents. My research however, will be limited to some extent due to the breadth of the subject, the fact that a number of the accidents are the subject of legal proceedings. A significant amount of material is not published in the public domain as it remains classified by the owner and that in other cases no research has taken place the area of interest yet.

1.2.2 I also intend to look in Chapter 3 at the history of the scientific and recreational diving community since its inception. It is my intention to see if there are any similarities between the cause of past accidents and those occurring today and whether there are or were, any lessons that could be learned.

1.2.3. Using this qualitative evaluation, I intend to formulate theories as to why so many experienced SCUBA and technical dives have died whilst embarking on rebreather dives.

1.2.4 The ultimate aim of conducting such an analysis is to try to use the lessons learned from history and to prepare a series of recommendations to try and influence the future design and development of rebreather training programmes or systems. My intention is to show how the number of fatalities can be reduced through diver education, guided experience or possible equipment design change. As Russ Orlowsky of Draeger USA states in Technical Diving International Course Guide (TDI, 2000) the keys issues in rebreather diving are; *"Education, attention, responsibility and practice"*.

1.2.5 In Richard Stevenson's article in the diving publication "990" (Volume 1 Issue 1, 990 Publications Ltd) he raises concerns that; *"the training regime needs looking at* *closely*". He goes on to detail the areas of the training program that need reviewing. He finishes by saying, "*The euphoria will subside and the market will understand that rebreathers require more training, more discipline and less hype*." It is submitted that this dissertation and its conclusions in Chapter 5 will go some way in addressing these concerns.

1.3 Background to the study

1.3.1 Up to 1878 there had been a variety of designs for different types of diving equipment. It was at that time that Henry Flues of Seibe Gorman, one of the then manufactures of standard divers' equipment, received the first patent on a pure oxygen-recirculating device – a rebreather. A year later the device was used on the first operational dive. In 1911 Draeger, a supplier of diving equipment and submarine escape apparatus based in Germany introduced the first practical Oxygen Rebreather, which was followed later in 1912 by the first Nitrox Rebreather. This technology now allowed divers to be self-contained without being connected to the surface in any way and allowed them to work deeper and longer without the fear of oxygen poisoning.

1.3.2 Military forces used these developments in technology worldwide. In 1936 Italian navy divers used a modified version of Flues' apparatus to ride underwater Chariots with the intention of harassing enemy shipping. This was ultimately successful during the Second World War when Charioteers damaged two Royal Navy battle ships in Alexandria Harbour. By the mid 1940's other navy's had recognised the value of rebreathers and were beginning to use rebreathers in some form or another for clandestine operations, mine clearance and breach/harbour reconnaissance. (U.S. Navy Manual, Volume 1, Best Publishing Company, 1993)

1.3.3 In 1942, after years of breath hold diving, two Austrian Marine biologists Hans Hass and his wife Lotte led the first diving expedition to the Aegean Sea and subsequently to the Mediterranean using Draeger oxygen rebreathers[1]. Hans and Lotte Hass were keen to make available to the public their research through photography. Until 1942, Hass had recorded all his images whilst breath hold diving, which limited his depth and endurance for filming. Hans was keen to extend his dives and started to use shallow water oxygen rebreather technology. Hans later went on to write 26 books and produce more than 100 films, which were seen in cinemas as trailers throughout the world. As a result of their work diving began to be put within the public domain.

1.3.3 The difficulties associated with rebreather technology still limited divers, specifically with depth. These limits were as a result of the crude nature of the system and the fact that oxygen was being used as a breathing gas.

1.3.4 In an effort to overcome the problems of breathing oxygen at depth, Jacques Cousteau[2] approached L'Air Liquide[3] in Paris in 1943 in an effort to find an open circuit solution using air (Madesen, 1986). Using technology adapted from his

[1] A rebreather is an apparatus that recirculates some or all of a diver's breath and lets him reuse the unused oxygen again. In the recirculation process the by-product of Metabolism, carbon dioxide, is removed and the oxygen is topped up.
[2] Cousteau was a French Naval Officer who is credited with the development and exploitation of the aqualung commonly referred to by its acronym SCUBA or Self Contained Underwater Breathing Apparatus
[3] Due to the petrol shortages in occupied France during the war L'Air Liquide, a gas supplier, developed a gas regulator to convert petrol cars to natural gas.

automatic shutoff valve for natural gas tanks in cars developed as a result of the war, Cousteau persuaded L'Air Liquide to fund a prototype of his "lung". This lung was to be a union of the Air Liquide regulator, Cousteau's corrugated hoses, a mouthpiece and a pair of oxygen cylinders filled with compressed air. After some initial difficulties the system worked and they applied for a joint patent for their breathing apparatus, the *Aqualung* later called scuba. By the close of 1943 Cousteau, Tailiez and Dumas[4] had amassed considerable experience on the system and had performed dives to a depth of 64 metres (Madsen, 1986). By the mid 1950's over a million *Aqualungs* had been sold in the United States and a new sport that of recreational diving had evolved.

1.3.5 Cousteau's initial trials using the *Aqualung* involved several incidents that almost resulted in fatal accidents for Cousteau and his trial divers (Madsen, 1986). These incidents were a result of problems such as Nitrogen Narcosis, Decompression Sickness and problems with Gas Toxicity. These problems associated with diving using air were well known within the military and to some extent the commercial diving industry from their surface supplied experience, yet there significance had been overlooked or was unknown by Cousteau and his diving companions. It is submitted that a parallel oversight and/or lack of knowledge is occurring again in relation to the current problems associated with semi closed and fully closed circuit rebreathers.

[4] Talliez and Dumas were two of the diver's who dived with Cousteau during the early years of the aqualung's development. Dumas reached the maximum depth of it use during 1943 of 72 metres.

Chapter 1 Introduction

1.4 Why rebreathers?

1.4.1 Since 1943 and the development of open circuit diving, divers durations have always been limited by the amount of air they could carry. In addition to this, open circuit divers were limited by the depth they could safely breath air at andthe additional problems of extended durations at depth due to the increased risk of decompression sickness.

1.4.2 In an effort to address these limitations, work was initiated by the United States Navy into the use of alternative breathing mixtures[5] (Mass, 2000). The U.S. Navy ultimately in the salvage of the submarine Squalus at about 85 metres, used the results of these mixed gas trials successfully.[6] Mass describes the U.S. Navy's first operational experiences in the use and benefits of alternative breathing mixtures for diving in his publication The Terrible Hours, (Harper Collins, 2000). The British Navy undertook further tests using nitrox or oxygen enriched air (BR2806 Volume 1). The theory underlying these tests was that the human body metabolises[7] oxygen but not nitrogen and nitrogen was known to cause decompression sickness and affect a diver's performance at depth. If a balance could be struck between oxygen toxicity and nitrogen loading, a perfect gas could be developed. Since the mid nineteen hundreds it had been established that as a diver goes deeper the nitrogen in a breathing

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[5] For example, Oxygen replaces the nitrogen, which reduces a diver's decompression obligation generally used at shallow depths. For deeper diving the nitrogen is replaced with helium to reduce the narcotic effect of air and allow the diver to work deeper effectively. (commonly used in the North Sea for all diving operations below 50 metres

[6] In May 1939 the U.S. submarine Squalus sank off the New England coast in a depth of over 200 feet (65 metres) Following a series of initial unproductive air dives in order to accomplish the rescue the divers started to use a mixture of helium oxygen to breath which allowed them to work effectively at depth without the effect of nitrogen narcosis or 'raptures of the deep'

[7] Metabolism is the breaking down of substances to provide energy, raw materials for anabolism and waste.

mixture becomes more and more narcotic due to its density and it reaches a point were initially the diver cannot function and can eventually lead to death. By reducing or eliminating nitrogen in the breathing mixture the theory was a diver could reduce or eliminate the problems associated with narcosis at depth.

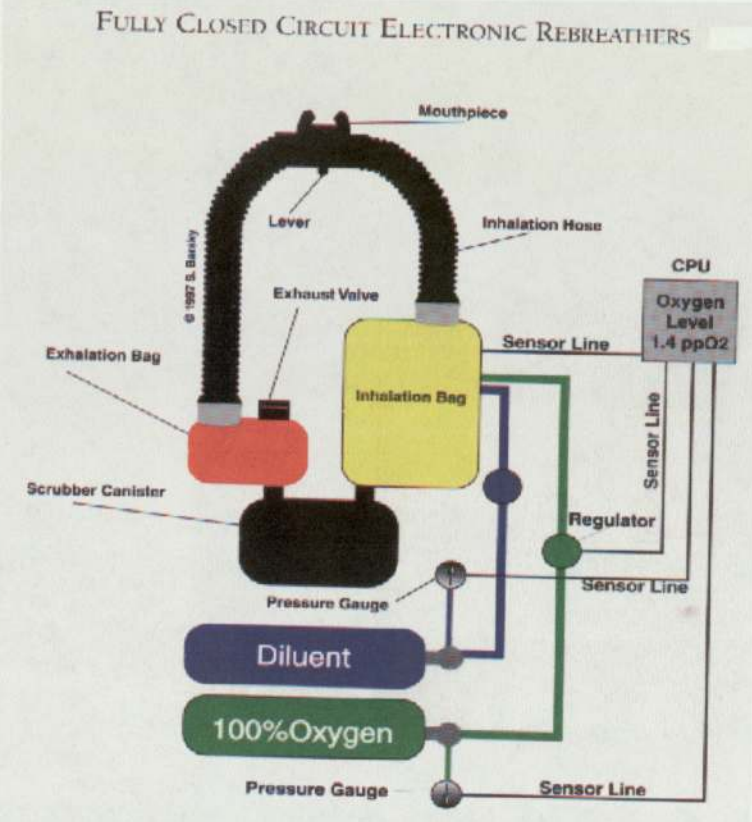
1.4.3 However, the problem remains that the balance changes continuously with depth as the pressure changes. As the diver descends the Partial Pressure of the gas increases (U.S Navy, 1993). However, the same thus the amount of nitrogen in a diver's breathing mix also increases with depth thereby increasing the risk of nitrogen narcosis and decompression sickness. One of the major benefits of closed circuit rebreathers is that they optimise gas usage by delivering gas at a constant partial pressure to the diver and thus reduces the risk of decompression sickness and nitrogen narcosis whilst providing the optimum oxygen mix at all times during a dive.

1.4.4 Despite the advances made in reducing the decompression requirements and narcotic risk of air, divers still had to carry a substantial amount of gas in order to conduct a dive. Added to this was the fact that the majority of gas, with the exception of approximately 4-5% of oxygen used by the diver, was wasted in exhaled breath.

1.4.5 The major advantage of rebreather systems is the economy of gas usage. The current SCUBA system uses approximately 25 litres of air a minute on the surface. Of that only 20% is oxygen. During a breath a diver would only use about a quarter or about 1 litre of oxygen per minute. The balance is exhaled or about 24 litres. If we now translate this to a dive at a depth of 30 metres the pressure becomes four times that on the surface. The diver will now need 100 litres of gas per minute to sustain him depth in order to compensate for the pressure. The diver however still only requires the same 1 litre of oxygen to sustain life. The diver exhales the balance of the gas, about 99 litres including 19 litres of oxygen is vented to atmosphere during his normal breathing cycle. In using open circuit SCUBA in order to stay longer or go deeper a diver must physically carry more gas. Deep divers using a variety of breathing gas mixes to be used during portions of the dive have been known to carry in excess of 14,000 litres of gas in cylinders weighing in excess of 60 kilos for a 20 minute dive to 75 metres!

1.4.6 With closed circuit rebreather (sometimes referred to as **CCR)** technology all the diver's exhaled gas is captured within the breathing loop allowing the diver to use all of the oxygen within his system. A chemical compound (soda lime) removes the toxic carbon dioxide and an electronic system monitors the amount of oxygen in the loop and tops it up from the diving cylinder if required through out the dive.

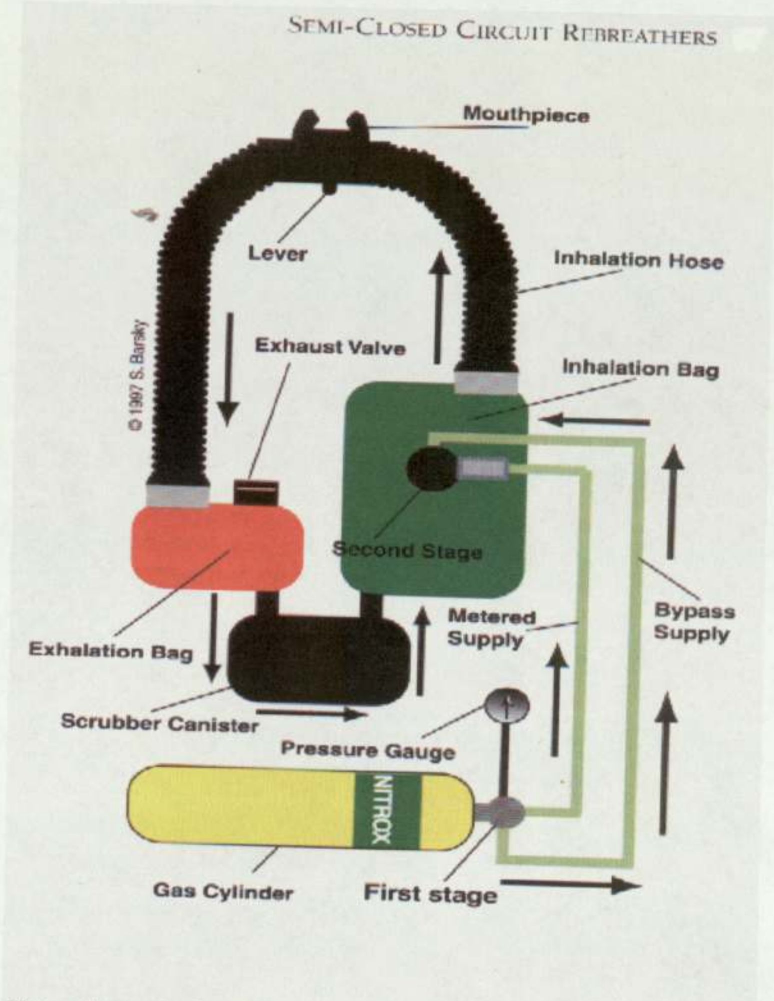
Chapter 1 Introduction



Fully closed circuit electronic rebreathers are more complex than semi-closed circuit systems. This schematic shows the layout of a "typical" closed circuit rebreather

Fig 1.1 From The Simple Guide to Rebreather Diving, (1998) Best Publishing Company. Page 141

1.4.5 In Semi Closed Circuit systems (sometimes referred as **SCR**), more simpler by nature as they have no electronic control system, units continuously feeds the diver between 4 and 10 litres per minute with a pre-set breathing mixture dependent on the maximum depth of his dive. The majority of the gas is kept within the breathing loop thus radically reducing the gas wastage that SCUBA has.



This schematic drawing shows the flow through a semi-closed circuit rebreather that uses pre-mixed nitrox.

Fig 1.2 From The Simple Guide to Rebreather Diving, (1998) Best Publishing Company, USA. Page 87

1.4.6 The benefits of rebreather units in comparison with open circuit (scuba) units are obvious. Divers do not have to carry vast quantities of gas for deep dives and the rebreather system always provides the diver with the optimum oxygen partial pressure mix at whatever depth. An open circuit diver is required to calculate the partial pressure of the mixture and this optimum is always estimated. The result is that the rebreather diver experiences a radical reduction in Inert Gas Loading, thereby reducing the risk of decompression illness as well as the diver's decompression time. The reduction in weight and the economical use of gas means that divers are now capable of diving deeper for longer periods of time and, in theory, more safely.

1.4.7 However, there are also significant disadvantages of using rebreather units. They rely on scrubber or canister technology[8] and electronic devices[9] to ensure the correct gas mix. They are far more complex than open circuit units and as a result require a high standard of training and a great degree of skill, far in excess of the requirements for open circuit SCUBA. BSAC's (British Sub-Aqua Club) National Diving Officer, Bob Boler, stated "with a rebreather, you are a novice again…if we have learned anything from our recent history ….take it slowly. Stay shallow and build up your experience progressively." (*Diver Magazine*, January 1999). This only confirms Richard Stevenson's and Russ Orlowsky's of Draeger USA comments as quoted in 1.2.6 and 1.2.7.

1.5 The Problem

1.5.1 The result of the complex nature of rebreather units is that divers require a greater degree of understanding of the physics and physiology associated with diving these systems. The training for these units must go far beyond the initial elements of open circuit SCUBA. Unfortunately, most divers believe that because 'diving is diving', anyone can use them. During my diving with these systems and my subsequent

[8] Scrubber or canisters are the device within the breathing loop that contains absorbents used for removing the carbon dioxide from the breathing loop

[9] The electronic control devices monitor the oxygen level within the breathing loop and control the oxygen solenoid valves that add oxygen to the system when required

research I have begun to realise how the subtle differences between the two systems could contribute towards accident and ultimately fatalities. We will look at this issue later both in Chapter 2 and 4.

1.5.2 In 1998 the British Navy introduced a new rebreather into service called CDBA (Clearance Diver's Breathing Apparatus). Since its introduction, training has now taken place across the entire Clearance Diving Branch.[10] Despite regular dives to a depth of 60 metres, this training and their subsequent diving operations has been virtually free of accidents.(letter between MOD and author) It is submitted that this is due to the military's high degree of standardisation and its extensive diving experience both in the use of rebreathers and its training. It is apparent that this level of skill and expertise has led to an excellent safety record when compared with the military's recreational counterpart. It is unfortunate that due to the requirements of national security, this experience and knowledge has not been released to the recreational diving community.

1.6 An overview of the development rebreathers since 1995

1.6.1 It can be argued that SCUBA diving has provided access to one of the last unexplored frontiers, the sea. About 75% of the world is covered by water but man has only explored a small portion of it.

[10] Clearance Divers are elite naval divers employed in mine clearance by the Royal Navy.

Chapter 1 Introduction

With the advent of the global technology network, diving has had an increasingly high profile and is now beginning to be seen as a "normal" recreational activity. The result of this high level of public interest, has been an explosion in the numbers of participants.

1.6.2 The Professional Association of Diving Instructors (PADI) is the largest sport diver-training organisation in the world with over a 60% market share in recreational diver instruction (PADI Instructors Seminar, Bristol 1999). As part of its services to instructors they provide research material for members on marketing, education, dive safety and other diving related medical topics of instructional interest. In its Instructor Training Manual, the *PADI Course Director's Manual* (PADI, 1995), the organisation presents a number of marketing surveys looking at the recreational diving population. The research (PADI, 1995), has shown that there are two key motivational factors for people to become involved in the sport. They are:

i) to be with nature

ii) for adventure

It is the second reason, adventure, which has resulted in divers trying to push the frontiers in an effort to further explore the planet and test themselves. This "need" has led to the requirement for divers to stay down longer, go deeper and push the envelope. The key area for future recreational and scientific diver exploration is the "twilight zone". This is the area between about 60 and 150 metres deep which has been previously unexplored by man. No longer is deep diving for the realms of North Sea Commercial divers operating from sophisticated diving support vessels.

1.6.3 In an effort to accommodate this drive many manufacturers have tried to develop new and bold technologies. In 1995 Draeger[11] launched the *Draeger Atlantis*, the first mass produced semi-closed circuit rebreather for the recreational market. The unit was renamed the *Draeger Dolphin* in 1997. Based on Draeger's military experience, this system allowed a diver to stay at depth for considerably longer periods of time without the encumbrance of several heavy diving cylinders. According to Draeger's Sale's team by 2001, Draeger has sold in the region of 16,000 *Dolphin Rebreathers* since its launch in 1995.

1.6.4 The *Dolphin* has an excellent safety record. According to Draeger only three deaths have been associated with the unit and none of these fatalities are directly attributable to the unit. The *Dolphin* is now currently used by many sport and media divers worldwide. Despite its benefits and because of its semi-closed circuit design, divers are still only able to operate to 40 metres, which is the present range of most recreational diving.

1.6.5 In order to try and meet the demand to go deeper, A.P. Valves[12] introduced the first European mass market closed circuit recreational rebreather, the *Inspiration*, in 1998. This system was designed to allow recreational divers to safely operate to depths of 100 metres. A few years before the *Inspiration's* launch the CIS Lunar Development Corporation had unveiled its own closed circuit rebreather, the *Cis-Lunar MK-4P in*

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[11] Draeger a German based diving equipment manufacturer probably one of the oldest making rebreathers. Currently market the Draeger Ray and Dolphin rebreather for recreational divers

[12] AP Valves are equipment manufacturer based in Helston Cornwall

1994.. These two systems have allowed divers to easily extend their range well beyond the previous 40 metre limit.

1.6.6 Until this time, because of the cost involved and the lack of knowledge within the industry, there had only been a limited number of rebreathers in the hands of recreational and scientific divers. Considerable work had been done both by the NOAA (National Oceanographic and Atmospheric Administration) and by enthusiastic marine biologists such as Richard Pyle[13] to further develop the application of these units within the scientific community. In an effort to try and identify new species of marine life in the twilight zone, Pyle had initially developed a compact deep SCUBA system using a number of gasses[14] to allow him to operate to a depth of 130 metres. In 1994 he purchased a *Cis-Lunar* rebreather and this has allowed him to work deeper, safer and for longer periods. By 1996, the new system had allowed him to identify 30 new species. *(A learners Guide to Rebreathers, Proceedings of Rebreather Forum 2.0*, DSAT, 1996)

1.6.7 The mass production and release of these units into the diving market place was a bold step into the unknown for the industry. Previously the main user of this type of technology had been the military in clandestine or EOD (Explosive Ordinance Disposal) operations. Whilst rebreather technology had existed since the late 1800's[15] it had not been introduced to the general public.

[13] Richard Pyle is an Ichthyologist who specialises in collecting marine specimens from the Twilight Zone
[14] Air, Nitrox 36, Nitrox 80, and Heliox (oxygen helium) mix dependent on depth.
[15] Semi Closed Circuit Oxygen Rebreathers limited in duration due to size

As a result there were no technicians, engineers or other fields of experts who the manufactures could turn to for assistance when launching this type of complex equipment to the recreational and scientific market. It is contended that this is one of the major causes of the fatalities resulting from the use of rebreathers.

1.6.8 Within the first year of launch of both the *Inspiration* and *Cis-Lunar* units in the United Kingdom, six divers suffered fatal accidents using closed circuit technology. By the year 2000 this tally had risen to 13 including one of the world's foremost rebreather divers, Dr. Max Hann. The diving industry, the public and government officials refused to believe that diver error could be the cause of these accidents and raised these concerns with Trading Standards Officers who initiated an investigation.

1.6.9 Both the *Inspiration* and *Cis-Lunar* systems had undergone thorough testing prior to their launch and had received national government certification in the form of CE marking. Following the fatalities, consumer outcry resulted in further government investigations into the reliability of the systems. The details of these investigations are currently closed to the public. However, Simon Copas of Truro Trading Standards claims that "the *Inspiration* would have been taken off the market had his department found it to be dangerous during the investigation into Haydon's[16] death." (*Dive Magazine, Volume 45, 2002, page 12)*

[16] Paul Haydon was the first recreational diver to die on a rebreather in the UK in May 1998.

1.6.10 In a similar vein, Martin Parker of A.P. Valves states that "at this time, there is no evidence that suggests the equipment [the *Inspiration*] to be of a faulty design or manufacture" (*990's, Autumn 1998*). These two expert opinions indicate that the training regime may not be sufficient for the type of diving these diver's embarked on. This supposition will be explored in detail throughout this dissertation. In the Proceedings from the Rebreather Forum 2.0 held in California in September 1996 (DSAT 1996) the Forum made it clear that at that time "*consumer rebreather training was in its infancy and was not yet standardised*" unlike the military.

1.6.11 In the ACSNI Study (HSE 1990) they comment that *"....it is in the potential for human error that the major source of accidents now reside"* Within the diving community the PARAS Report (HSE, 1997)substantiated this point when it states having looked at the incidents that "***All** fatalities were associated with at least one procedural error"*. These points are also confirmed when reviewing the summary of the statistics in Edmond's publication Diving and Sub Aquatic Medicine.

1.6.12 As I have discussed, open circuit diving is far simpler and requires far less discipline than rebreather diving. Thus similarities between the recreational diver accident statistics in the US, the UK and Australia seem to show that there is a real possibility that procedural errors could be a major contributing factor towards the cause of the fatalities of divers using closed circuit rebreather.

1.6.13 Further research using recreational diving statistics has shown that equipment failure is the primary cause of only a small number of diving fatalities. The PARAS Report (HSE, 1997)[17] quantified the likelihood of equipment failure being the primary factor in diver fatalities for the years 1991-1995. The study concluded that only **4%** of these deaths could be directly attributable to equipment failure. This figure is substantiated by Edmond's & Lowry's research (*Diving and Sub Aquatic Medicine,* Reed Educational and Professional Publishing, 1992) in which they reviewed data published by the National Underwater Accident Data Centre (NUADC) in Rhode Island. At the time of their review NUADC had looked at 2600 fatalities and yet only **9.5%** of the deaths were due to equipment failure. On this basis, it is possible that only one of the UK rebreather fatalities to date is as a result of equipment failure[18].

1.6.14 In light of the discussion above, it is submitted that the only other possible explanation for the high level of fatal accidents is human error.

1.6.15 The PARAS Report states that the current fatal accident rate for adventure sports is about 1 in 5000 participants. The current rate for closed circuit rebreathers since their inception in the U.K. in 1995 is approximately 1 in 2000 dives (figures provided by TDI UK Ltd).

[17] A research project compiled on behalf of HSE which investigated the root cause of 286 diving fatalities
[18] As one of the investigating officers of a number of these fatalities due to pending legal action I cannot enter into any further discussion because of legal reasons and disclosure

1.6.16 In the remainder of this dissertation, I intend to explore these issues try to establish whether or not these errors are consistent with the standards of training and experience and provide the reader with a number of recommendations that could significantly improved diver safety when using rebreather technology

Chapter 2 – An overview of the possible causes of rebreather incidents

2.1 Introduction

2.1.1 Since the introduction of rebreather technology in 1995 there has been significant number of incidents and fatalities in divers using these technologies. The statistics relating to these occurrences are discussed at length in Chapter 3. This chapter is dedicated to identifying the possible causes of the incidents, in particular those that lead to diving fatalities, as discerned from the available literature. The aim of this chapter is not to draw any concrete conclusions but rather to present an overview of what the rebreather diver must face when using recreating technology in terms of equipment, knowledge, experience and training as well as meeting the legal requirements of the activity. The possible ways in which the causes of the fatalities can be eliminated will be dealt with in Chapter 5.

2.1.2 The following quotation contains all but one cause that I have identified as being the basis of rebreather fatalities.

"The majority of rebreather accidents are caused by breather [diver] error: improper use, poor maintenance, inadequate preparation, failure to monitor warning signals and a general inattention to detail (such as forgetting to open the oxygen valve. The key to successful rebreather operations is the unlearning of ingrained open circuit techniques and the mastering of closed circuit rebreather skills" (Gentile, Gentile Productions, 1998)

The missing potential cause is equipment failure.

2.1.3 As the following analysis of the literature will demonstrate, it is difficult to extricate single causes. Each cause has a potential knock on effect to another and consequently there is much overlap in discussing individual factors. However, I have attempted to categorise each cause and discuss them in turn. The categories are as follows:

- Equipment failure
- Diver's inexperience
- Diver error
- Inadequate training

2.2 Equipment failure

2.2.1 As indicated in Chapter 1, equipment failure has largely been discredited as a major cause of rebreather fatalities. This study is largely dedicated to finding possible alternative causes in light of the PARAS Report (HSE, 1997). The following table is largely self-explanatory as to why this decision has been taken.

Summary of the principal causes of fatal accidents in divers

Principle Cause	Number of fatalities	%
Procedural	97	69
Medical	80	27.9
Equipment	9	3.1
Total	**286**	**100**

Figure 2.1 PARAS (HSE, 1997)

2.2.2 Whilst based on SCUBA experience the likelihood of, equipment failure would represent only a small percentage of rebreather fatalities. The majority are caused by procedural errors and medical problems. Therefore, although it is recognised that a small minority of deaths are caused by such failures it is outside the limitations of this study to analyse further what these equipment failures are. However, it may be appropriate to reiterate the sentiments of an astronaut waiting to be launched into space, "the rocket beneath his seat was constructed of more than 10,000 parts, each of which was supplied by the lowest bidder" (Gentile, Gentile Productions 1998).

2.3 Diver's inexperience

2.3.1 At first glance, the minimum entry level for closed circuit rebreather training appears impressive. The primary training agencies, the International Association of Nitrox and Technical Divers (IANTD) and Technical Diving International (TDI), demand the minimum of a 100 dives as well as holding advanced diving qualifications in the use of Nitrox, oxygen enriched air. A diver with this level of experience is able to undergo instructor level training and is viewed by the diving industry as an experienced diver. The literature begs the questions as to whether they are experienced enough.

2.3.2 One of the unique features of diving, and one that divers find most attractive, is the wide variety of diving experiences that a diver can achieve. This means that divers embarking on a course of advanced instruction may meet the entry requirement of a 100 dives, at the required minimum of depth and yet have varying degrees of experience. For example, experiences in warm water can be very different from those in cold water and each diver will have encountered different forms of emergencies that they have learnt to deal with. Therefore, on paper each diver will appear to have the same level of experience but in practice some divers may be completely unprepared for rebreather diving. Further, where they apply, this also means that a diver embarking on rebreather diving may also fall well below the legal definition of 'competence'. This issue of diver competence is explored further in this chapter.

2.4 Diver Error

2.4.1 Reason defines error as being "a generic term to encompass all actions in which a planned sequence of mental or physical actions fail to achieve the desired outcome and…these failures cannot be attributed to the intervention of some chance agency" (Cambridge, 1990). Such errors can be further broken down into 'skill based, rule based and knowledge-based errors' (Hurst, 1998).

2.4.2 The literature makes it clear that the possibility of human error must be taken into account when using rebreather technology. "If a system involves humans no complete risk assessment can be undertaken unless some method is used for introducing the possibility of human error" (Hurst, 1998). This becomes particularly pertinent when it is remembered that rebreather diving is relatively new. As Hurst again states, "we simply do not know how all the things that people do (or do not do) can effect the system".

2.4.3 When a diver trains and becomes experienced, the majority of the basic skills he learns become instinctive and the diver will normally respond to a given situation automatically. It is submitted that this automatic process could hold the key to the reason why experienced divers suffer fatalities whilst using rebreather technology. As already discussed, the minimum level of entry for rebreather training means that divers embarking on rebreather training will be experienced open circuit SCUBA divers. The majority of conditions that a diver will encounter will be familiar to them, only the equipment is different. However, when faced with an emergency, a diver could easily make skill-based errors. They will automatically react as a SCUBA diver, not as a rebreather diver. The consequences of this will be discussed in Chapter 4 but suffice to say here that this could have fatal consequences.

2.4.4 Many of the actions or inactions in rebreather operations are based solely on the diver's ability to respond to a given situation and react correctly. In reality he is the only barrier to the risk. His response to a situation will be based on his experience, the perception of the risk and his response as a result of his training. The issue of training is therefore the next logical factor to look at.

2.5 Training

2.5.1 Within health and safety, training is generally seen as a 'low order' risk control measure (HSE, 1997). However, within the diving industry, training is in most cases, the sole barrier to risk that exists. Thus majority of diver training is focused on dealing with survival drills and exercises that are built up through a course to enable the diver to become totally familiar with foreseeable emergency and operational situations and allow him to operate safely at depth. In the light of section 2.4, when converted and experienced diver from one piece of technology to another this will do little to eliminate the risk of automatically reacting inappropriately to emergency situations.

2.5.2 The key issue is not only how that training is delivered, but also that the quality and quantity of the training meets the requirements of the user. Rasmussen has identified three key areas that must be addressed and reinforced to make training effective (Reason, 1997). These are:

1. Providing training for skill to eliminate errors

2. To ensure that divers thoroughly understand the rules on how to conduct a specific task by improving the diver's knowledge

3. To make divers aware of the risks associated with skill based errors

The implications of Reasons work are that if a rebreather diver responds incorrectly to a given situation by using his previous or stronger open circuit training he could be exacerbating the problem not solving it. We will look in detail at the possibilities in Chapter 4.

2.5.3 The author has identified that little formal research has been conducted on these types of diver-based errors. However, it is apparent that training programmes must be developed to meet the requirements of rebreather divers who are coming from an experienced SCBUA background.

2.5.4 To create an effective training programme it is essential that the elements of risk are clearly understood. There are two key areas associated with risk. Firstly, the actual risk, i.e. the chance that an event will actually occur. Secondly, the perceived risk the diver's perception that an event might actually occur. These two, actual risk and perceived risk could be significantly different in divers mind depending on his experience and the location and depth of the dive. For example, in a given area the statistical risk of being murdered would be X but the perceived risk, i.e. what people feel the risk to be, could be higher or lower than the actual risk depending on where the individual was. A diver must be trained to recognise what the actual risk is and how to react accordingly, not to perceived risk which if the diver responded to, could exacerbate the problem not correct it. To reach this ultimate degree of training, more research must be conducted into what a diver perceives the risk to be. Only then can a training system be developed to educate a diver away from mistaken perceptions and towards dealing with the actual risks.

2.5.5 One of the key aspects in a training programme is evaluation (HSG (65)). This is a blatant omission in diver training. The student leaves the training school and practices their skills outside the control of their school or instructor. Little or no feedback takes place between the student and training agency or instructor other than for quality control purposes. The only real feedback measure on performance that the training agencies receive on the effectiveness of their training is through the published statistics gathered on the number of incidents and fatalities that occur. In the majority of countries the collection of this data is poor due to the lack of technical knowledge during the investigation or the lack of a central system of recording.

2.5.6 The inadequacy of this evaluation system is obvious. By the time a diver succumbs to inadequate training he has already been injured or will be dead. Cooper further analyses the inadequacies of looking at accident statistics as a performance measure to the effectiveness of training (Cooper, 1995). They include:

- Failure, not success is being measured
- There is no account for random fluctuations in annual diving participants. In the UK, for example, the weather or major sporting events can effect any consistency
- There is a time lag in judging success
- Long term ill health is not assessed

- Evidence of previous failures may not predict future ones, a key point in the diving industry as the technology is changing rapidly
- There is an under reporting of accidents.

In addition from my experience within the industry the there is virtually no formal near miss reporting, so all this experience is lost.

2.5.7 Therefore, not only should the quality and quantity of training be improved to meet the needs of rebreather divers, the training should also be continuously evaluated to ensure that the aims of training programmes are being met. In reality it is too late to wait for the fatalities to occur but this is clearly not the case.

2.6 Legal requirements

2.6.1 One further aspect, which needs to be considered, is whether the legal requirements for diver training are being fulfilled and enforced or whether tighter controls need to be developed.

2.6.2 Rebreathers are now being used in a variety of work places in the UK. For example: diving instructors who are undertaking training using rebreathers; the military; the police; the media and the scientific community, are all using rebreathers in the course of their work activities. Therefore, their activities fall within the scope of *The Health and Safety at Work etc. Act 1974* (HSW 1974) and the corresponding regulations.

2.6.3 The HSW 1974 prescribes the general duties on employers and the self-employed. Two of the most wide-ranging sections are Sections 2 and 3. Section 2 details the general duty to employers: "It shall be the duty of every employer to ensure, so far as reasonably practicable, the health, safety and welfare of all his employees". The term 'reasonably practicable' was defined in the case of *Edwards v National Coal Board* [1949]. The quantum of risk is placed on one scale and the sacrifice, whether in terms of time, money or trouble, is placed on the other. If it is shown that the cost of averting the risk is disproportionate to the sacrifice, then the necessary aversion is deemed not to be 'reasonably practicable' and the employer escapes having to make any adjustments in their working practices. This becomes pertinent when the issue of training is addressed.

2.6.4 Section 2(2)(c) details the requirements for training extending the employer's duty to "the provision of such information, instruction and training as is necessary to ensure, so far as reasonably practicable, the health and safety at work of his employees. Therefore, training is subject to what is considered 'reasonably practicable'.

2.6.5 Regulation 13 of the *Management of Health and Safety at Work Regulations 1999*, (1999 Regulations), entitled 'Capabilities and Training', states that 'Every employer shall ensure that his employees are provided with adequate health and safety training'. The guidance for Regulation 13 goes on to say that 'training and competence needs will have to be reviewed if the work activity a person is involved in or the working environment changes. This may include…the introduction of new equipment, processes or tasks' (HMSO 2000). This would clearly include the introduction of rebreather technology.

2.6.6 In 1997 the U.K. Government issued a new set of Diving Regulations called the Diving at Work Regulations 1997 supported by 6 ACOPs (Approved Codes of Practice which we will look at later). These regulations replaced the for more prescriptive Divining Operations at Work Regulations which by 1997 had become dated and were now, due to the prescriptive nature stifling the growth of the diving industry due to the advent of new technologies like rebreathers. These regulations were wide reaching and changed the focus from being prescriptive to goal setting and were based on the premise of risk assessment and project planning thus dramatically opening the scope for deeper more adventurous diving.

2.6.7 In addition the 1992 Management Regulations had been used to form the basis of the risk assessment portion of The Diving at Work Regulations 1997 (DWR 1997). DWR 1997 Regulation 12, entitled Duties and Restrictions on Divers, prescribes that 'no person shall dive a diving project unless he [holds] an approved qualification which is valid for any activity he may reasonably expect to carry out'. Further, DWR 1997 Regulation 13 goes on to say that 'no person shall dive in a project…unless he is competent to carry out safely and without risk to health'. The competency of a rebreather diver is again called into question as regards the level of training, risk awareness and evaluation he has been exposed to.

2.6.8 The issue of competency in general terms has been discussed at length in case law emanating from HSW 1974 breaches. In *Gibson v Skibs A/S Marina Limited* [1966] ALL ER 476, it was decided that 'a competent person is one who is a practical and reasonable man, who knows what to look for and how to recognise it when he sees it'. Following the analysis of the legal requirements, and for the purposes of this study, I have defined a competent person as being an individual with all the skills, training and knowledge to safely conduct an operation within a given set of parameters. It is questionable whether many rebreather divers could fulfil this definition.

2.6.9 The DWR 1997 are supported by 6 ACOP's. The Media and Recreation Diving Projects ACOP (HMSO, 1998) gives the guidance that; "in order to dive using mixed gasses or rebreathers an appropriate qualification is needed. Diving using rebreathers not only requires a qualification in the general understanding of the dive technique but an additional qualification in the specific type of rebreather endorsed by the manufacturer". The advice notes for the Scientific and Archaeological ACOP (HMSO, 1998) goes on to state that 'no rebreather diving, or supervision of that diving, may be carried out unless having previously attended an approved rebreather course'.

Chapter 2 – An overview of the possible causes of rebreather incidents

2.7 Conclusions

2.7.1 The reliability of modern diving equipment appears to be good. In the majority of diving accidents equipment failure is not directly attributable to the death.

2.7.2 It is clear that the HSW Act 1974, the 1999 Regulations and the DWR 1997 place a fundamental requirement on employers, the self-employed and divers to ensure that they are adequately trained and competent to carry out any diving operations without risk to the health and safety of those taking part. However, the legal requirements fall short of defining the standards of performance a competent person should not reach, nor does it outline a training programme, which will ensure that a person is competent.

2.7.3 In practice however the onus is generally placed on the individual to limit his own activities to within his own level of competence, however that in itself creates its own problems.

2.7.4 There is no formal feedback or near miss reporting system within the rebreather diving community to influence the diver's training and thus the lessons learned during the use of the equipment are being lost unless they result in a fatal accident.

Chapter 3 – The Evolution of Recreational Diving Instruction

3.1 Introduction

3.1.1 The evolution of recreational diving has not been without its price. As the industry developed in terms of knowledge, equipment and size it began to recognise that training was an essential element if it wanted to reduce the growing accident rate. In this section I look at the evolution of the industry both within the United States and the U.K. I have used both the U.K. and U.S because the evolution in the United States has been longer (since the late 1940's) and there is far more information and statistics available about the industry's growth and development. Within the U.K. the growth of the industry has only really taken place since the early 80's and the statistics and information is limited. Using statistics from both the United States and the U.K. I have tried to establish what effect the development of an effective diver-training programme has had on the accident rate.

3.2 Background History

3.2.1 In the late 1940s, the introduction of SCUBA diving equipment to the public by *U.S. Divers* and *North-hill*[19] in America, and *Spiro technique*[20] in Europe, led to the launch of a new sport, recreational diving. Until this time undersea exploration had only been the privilege of the military and the scientific community, it had never been widely introduced to the general population. SCUBA diving really began to blossom after the Second World War when military divers returned to civilian life and wished to continue their diving activities. The equipment was now available but in the early

[19]U.S Divers and North-Hill were breathing equipment manufacturers that began producing diving equipment in the United States just after the war

[20] Spiro technique were one of the first a diving equipment manufacturers based in France

years no formal training was required to obtain or operate it. (PADI Course Directors Manual, PADI 1995)

3.2.2 During the late 1940s and early 1950s the majority of the diving population were males between the ages of 20 and 40. These were people in search of new adventures (The Undersea Journal, PADI 1968, Course Directors Manual, PADI 1995) and who thrived on facing adversity (Skin Diver Magazine Volume 49 No. 10). They had the requisite high standard of fitness required to cope with the crude nature of the equipment and their high-risk tolerance becomes significant when I examine the birth of rebreather divers 50 years later.

3.2.3 By the mid-1950s, Cousteau had published the *Silent World,* the first publication that dealt with the aqualung which later went on to become the basis for recreational SCUBA and Hans Hass' exploits were now beginning to become well known. Hans Hass was an Austrian scientist who produced a number of early trailers for the movies, which were seen worldwide. In the late 50's the first James Bond movies depicting diving had also been released. This led to the public becoming aware of the possibility for underwater exploration as a sport. By the mid 70's simultaneously, the US saw the launch of *Sea Hunt* and *Carter Primus*, two TV series featuring the exploits of divers, which was eventually followed, by the NBC T.V. series *The Undersea Adventures of Jacque Cousteau.* The result was a dramatic growth in the interest in recreational diving by the general population.

3.2.4 As the industry evolved, members of the public who were curious about diving could now learn from a number of ex-military divers. The courses were tough, the drop out rate was high and because of the crude nature of the equipment, tremendous stamina was required just to breathe on the equipment. Divers who could not meet the physical demands of the sport did not survive and left the sport. Therefore, diving began to acquire a reputation, probably somewhat deserved, as a difficult, male orientated, dangerous activity.

3.2.5 Diving technology was also in its infancy. For example, there was no way to determine the air left in a diver's tank and they had to rely on a mechanical reserve that allowed a diver sufficient air to return safely to the surface, providing it worked. Incidents and fatalities were high. The statistics relating to these incidents are analysed in the relevant section below.

3.3 The growth of the recreational diving industry

3.3.1 As the sport evolved, the public perception began to change and so did the consumer. The industry was beginning to mature. By 1996, according to statistics compiled by the Recreational SCUBA Training Council (RSTC Europe1997), within Europe there were 3.2 million qualified divers spending in the region of 4.6 billion DM on travel, training and equipment every year; a significant industry. According to statistics published by PADI in 1995 (PADI, 1995) there was an estimated 20 million qualified divers worldwide. PADI also reported that in 1999 they qualified 1,000,000 divers in one year (Diver Magazine, Feb 2000).

Chapter 3 – The Evolution of Recreational Diving Instruction

3.3.2 By the mid-1970s recreational diver training had continued to develop as new equipment entered the market, more co-ordinated information about the risks of diving became available and instructional techniques evolved. Although it is outside the scope of this study to discuss in detail every aspect of the recreational diving industry, it is worth mentioning that other influences on its evolution have included:

i) Popularity

ii) The miniaturised computer technology

iii) Improved information on the physics and physiology of the general population

iv) Improved diver safety

v) Government legislation

vi) Civil Liability

vii) The ease of International Travel

viii) Media

ix) The increased level of disposable income

3.3.3 The point to note is that despite the continuous growth of the sport, the fatality rate decreased. The remainder of this chapter is devoted to presenting and analysing accident statistics from both the US and the UK and identifying potential reasons for the decrease in the number of incidents.

Chapter 3 – The Evolution of Recreational Diving Instruction

3.4 Early Accident Statistics

3.4.1 The lack of a co-ordinated system of reporting fatal accidents before the 1970s means there is little information about such incidents. However, some States in the U.S. like Michigan, which had a high level of recreational diving activity due to its proximity to the Great Lakes, had begun to compile some information about diving fatalities prior to 1970. It is form this data they were able to begin to establish some of the root causes of the accidents which were: "that divers without training were more likely to suffer an accident whilst diving" (JAMA April 1965 Vol 192. No 3)

Annual Distribution of SCUBA Diving Deaths in Michigan 1959-1965 from statistics complied by the Vital Statistic Bureau Michigan, Department of Health. (JAMA April 1965 Vol 192. No 3)

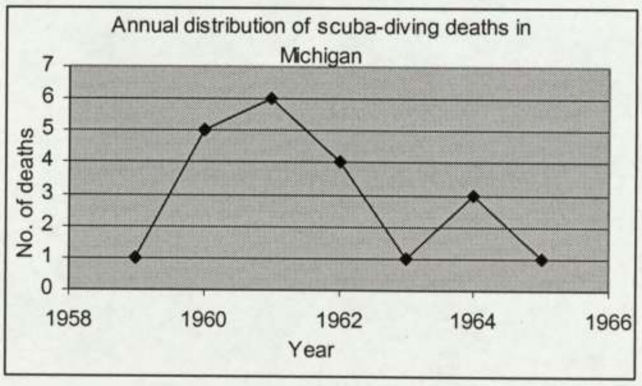

Figure 3.4

3.4.2 The figures published looked at 21 deaths over a 5-year period, 20 males and one female. 20 of the deaths occurred in less that 14 metres of water. Only one of these incidents occurred at depths that could be described as deep.

3.4.2 In comparison, despite the current capability for deep technical diving, the year 2000 saw the investigations by the HSE's Southern Diving Inspection Team[21] of five diving fatalities. Four of these investigations involved recreational divers and only one of these accidents occurred at a depth greater than 25 feet (8 metres). These statistics, coupled with my investigative experience, raises serious doubts about the perception of both divers and the general public that depth denotes risk. The majority of divers perceive the risks in diving increase the deeper you go because of nature of the environment and physics associated with diving. In my opinion and from my experience as divers gain experience their perception of risk changes and they become complacent, as they no longer sees shallow diving as risky. Statistics show that this is not the case.

3.5 Later Accident Statistics

3.5.1 According to the Diving Accident Network (DAN), by the late 1960s and early 1970s the recreational diving community was suffering on average 123 fatalities per year (PADI, 1995). However, by the mid-1980s this figure had fallen to 104 fatalities per annum in spite of a dramatic growth in recreational diving participants and more effective accident reporting.

3.5.2 In the UK, according to figures published in the National Diving Council (A Council established by the British Sub Aqua Club) the Diving Accident Report 1999 (BSAC,

[21] HSE's Southern Diving Inspection team is responsible for the investigation of a work related diving accidents along the south coast of England and Wales

2000), shows that in the 1960s the fatal accident rate was on average about 1 in 4000 participants per year for those as members of the BSAC. However, for those who were not members and believed to be untrained he rate was a staggering 1 in 689 participants (BSAC 2000). Using these figures it is clear that those receiving training through their branches in the 60's as members of BSAC stood a better chance of survival that those who were not.

3.5.3 By the late 1990s the average accident rate had fallen to 1 in 7000 participants for members of BSAC and 1 in 1300 for divers who were not (NDC Diving Incident Report, 2000). However, this figure now included deep, technical and rebreather fatalities that are in most cases outside the "scope of recreational diving". (PADI define "recreational diving" as diving above 40 metres with no decompression) This must be taken into account when make direct comparisons.

3.5.4 In figures presented in the Diving Officer's Conference in December 2000 and published in the NDC Diving Incidents Report 2000 (BSAC, 2000) the National diving officer presented a summary of the fatal accidents since 1975 as presented in **Figure 3.5**. One of the points he noted that since 1985 the fatal accident rate has fallen continuously.

Chapter 3 – The Evolution of Recreational Diving Instruction

BSAC Fatalities 1975-2000 (BSAC 2001)

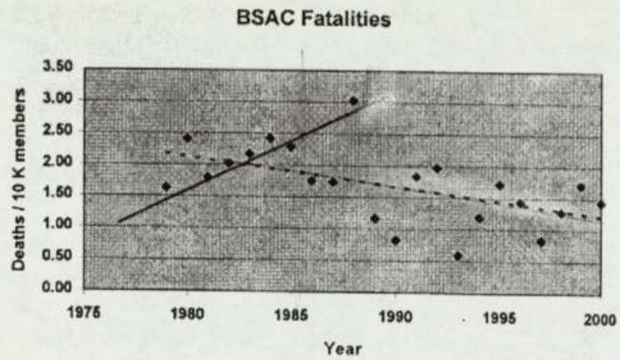

Figure 3.5(a)

3.5.5 The same pattern can be seen in relation to the US.

Yearly US recreational diving fatalities 1970-1992

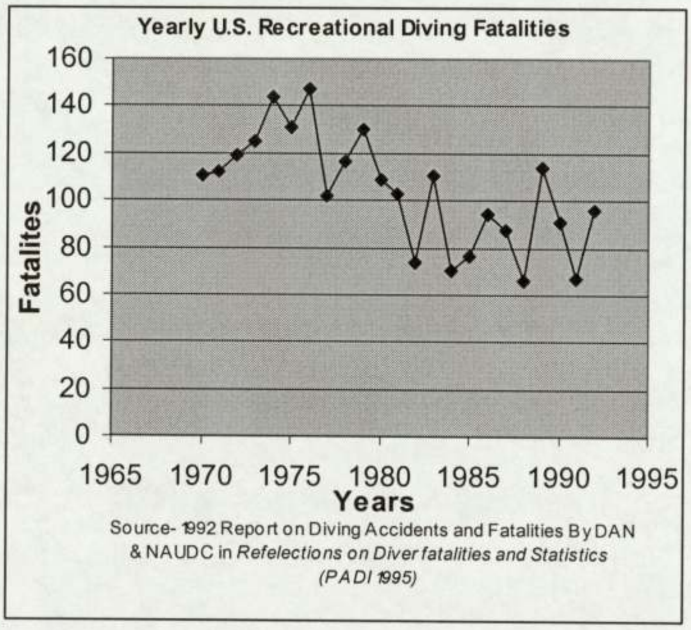

Figure 3.5(b)

3.5.6 However, this fall in accidents should be looked at in relation to better accident reporting, better and more effective means of collecting data and a dramatic rise in the number of participants as well as improved reliability and performance of equipment.

Chapter 3 – The Evolution of Recreational Diving Instruction

3.5.7 The fall in fatal accidents despite the continuous growth of the sport needs to be analysed. I have identified a number of significant factors that should be read in conjunction with **Appendix 3**. They are as follows:

i) The change in consumer demographics

ii) The recognition of the importance of diver education, particularly as regards the risks involved in diving

iii) The introduction of a formalised diver training including the training of diving instructors

iv) Better understanding of the physiology of the general diving public including emergency support facilities to support them

v) Improvements and developments in diving equipment. This is not discussed as an individual topic in this chapter as this study is concerned mainly with rebreather technology that has been discussed elsewhere.

3.6 Consumer change

3.6.1 The industry and the consumer have changed since recreational diving's introduction in the late 1940s. In the early years, the diving consumer focused solely on diving as his primary activity. Those who focus solely on diving are now in the minority. The recreational diver of today considers diving to be

one of his many activities that they pursue simultaneously with other activity based pastimes. (PADI, 1995)

Chapter 3 – The Evolution of Recreational Diving Instruction

3.6.2 The result has been a competition by the diving industry for potential divers with other "adventure sports" such as windsurfing, rock climbing and sailing. To meet these changes and attract more participants diving has had to change its image and try to become a more family orientated activity. The result has meant that the diving industry has recently lowered the entry level age from 15 to 10, and in some cases to 8, in an effort to try and entice more family participation. Significant changes have had to occur in diver training programmes to cater for these younger divers. The consequences of these changes have yet to be revealed and are outside of the scope of this study.

3.6.3 The issue of consumer change is inextricably linked with the development of diver education and training as discussed below.

3.7 The Role of Training

3.7.1 One of the key factors that influences diving accidents and fatalities is inadequate training. This lack of training will directly influence the diver's ability to understand the risks and cope effectively in the event of an emergency. This point is further reinforced when the statistics in **Figure 3.4** are further analysed. Only 6 of the divers (28%) had completed any formal diving instruction at all.

3.7.2 However, by the late 1950s the industry was beginning to recognise that there was a need for diver training due to the complexity of the equipment and the harshness of the environment. The high level of fatalities compounded these factors. The one key element that was beginning to emerge from the limited accident information that was available at the time was that people with little or no training were far more likely to suffer a fatal accident than those who had. The people who had been trained, all be it "crudely", were at least aware of the risks and were able to begin to develop the skills and psychology to operate safely.

3.7.3 It was clear that as the industry began to evolve, to survive it had to modernise widen its consumer base and reduce the level of fatalities.

3.7.4 Within the diving industry, the requirement to train has been incorporated into both *The Health and Safety at Work etc. Act 1974* and *The Management Regulations 1999.* Lord Cullen, the then Chairman of the Health and Safety Commission, stated that:

"Inadequate training is a significant factor in almost a fifth of all fatal Accidents……." (HSE, 1991)

3.7.5 The key problem, however, is that in most cases people get involved in recreational diving as a past time and are prepared to accept lower levels of safety for their recreational activities than they are for work. By training an individual you begin to provide him with the experience to operate effectively within a given set of parameters. The problem comes when people perceive that they have sufficient knowledge and begin to operate outside of the parameters of their training.

Unfortunately, as discussed elsewhere in this study, this has been the case in a number of rebreather fatalities. (See Chapter 1)

3.7.6 Cooper defines training "as a modification of attitudes, knowledge or skills to achieve pre determined standards through a planned process of instruction and practice" (Health and Safety Training, 1995). The problem within the recreational industry was that there were no real pre-determined national standards until the mid-1970s. Until that point diving instructors created their own courses based on experience and their local environment. As a result there was a significant inconsistency between instructors, courses and areas. Event though a national training standard had been established in Britain in 1954 this was being delivered by untrained and inexperienced instructors with little national consistency.

3.8 The development of diver education

3.8.1 One of the key questions to ask is whether the standard of diver education has fallen in an effort to attract more participants. Water is a hazardous environment. In training, it is essential that realism be created for student divers to ensure that they understand and experiences the risks, albeit in a controlled situation. However, in order to survive, the recreational diving industry must attract more divers. This creates the danger that it will play down the significance of these risks in an effort to develop. This particular issue is outside the scope of this study but it does emphasise the fact that more obvious factors, such as training, is not the only influence on diver safety.

3.8.2 In 1978 PADI introduced the Open Water Diver Course, a systems based diver training course broke down into the key components that are required to teach a diver to operate safely to a depth of 18 metres. The aim of this course was to provide the diver with the knowledge, skills and experience to look after himself. Further training was then required to allow the diver to dive to a depth of up to 40 meters. The programme focused totally on skills for the diver himself. Shortly after, the National Association of Underwater Instructors (NAUI) and Scuba Systems International (SSI), two alternative American based training organisations, also developed similar programs.

3.8.3 As a result of the introduction of these systems based courses two things began to occur:

i) There was a fall in the number of fatal diving accidents

ii) The reduction of the "macho" approach to diver education and the introduction of new small equipment and simplified training program began to attract a wider range of ages and female divers. By 1980 about 40% of all new entrants to diver education were female as opposed to about 10% in the 1960s (PADI, 1995).

The issue of how these new participants were to be trained is next addressed.

Chapter 3 – The Evolution of Recreational Diving Instruction

3.9 Diver Instructor Training and the Introduction of the New Diver Training Scheme

3.9.1 By the early 1960s the YMCA (Young Man's Christian Association) and the NAUI (National Association of Underwater Instructors) had established national training standards, which included the training of SCUBA instructors. The first formal training manual was released entitled *"The New Science of Skin and SCUBA Diving"(1965).* This manual was to serve as the industry's training manual until 1978 when PADI introduced the *Open Water Diver Manual* (PADI, 1977). In 1981, PADI ran the first instructor-training programme in the UK and were beginning to establish diver training schools using their own system of education throughout Europe.

3.9.3 Until 1981 BSAC had had a virtual monopoly on recreational diver training within the UK. It then realised that in order to compete with PADI they would have to modernise and improve their training programmes.

3.9.4 In 1983 the then National Diving Officer, Tony Dix, announced that the National Diving Committee would be conducting a review of current BSAC diver training programme after 30 years of using the same standards and diver grades (Diver Officers Conference, 1983). The New Diver Training Scheme was introduced in 1984 together with training manuals and instructor support materials, something that had never been available to BSAC instructors before. In addition, Tony Dix announced that he would like to see a nationally qualified instructor in every branch of recreational diving schools.

3.9.5 The initial training scheme had been developed so that someone at 3rd Class could train a novice diver, and a 2nd Class Diver could train a 3rd Class and so on. This was after having been deemed suitable as a Branch Instructor by the Branch's Diving Officer. However, this meant that there was no input form outside the branch as to the standards or requirements for divers. The training and qualification of divers was left solely to the Branch Diving Officer and the Committee. Details of the appointment and structure of the Branch were detailed in the Diving Officers Handbook, which provided details of how to run your branch (BSAC 1998).

3.9.6 In 1978 I came to Britain and was recruited by a recreational diver training school on the South Coast (Plymouth Ocean Projects) the first commercial recreational diver training school in Britain. Part of my responsibilities was to assist in the training of BSAC divers. Early on it became apparent that there was a wide range of standards and skill levels, which were dependent on the branch the divers came from and the standard of instructors who trained them. The need for nationally enforced standards was as much in need then as it was when the industry first began evolving. In 1983 the National Diving Council of the BSAC announced the introduction of a complete new training program together with a new series of diver grades. These grades fell in with the requirement and standards of the World Underwater Federation based in France (CMAS). This federation was made up from representatives from a number of countries worldwide and set a minimum international standard for divers, which the BSAC based their new diver-training program on.

Chapter 3 – The Evolution of Recreational Diving Instruction

3.10. The development of emergency support facilities

3.10.1 The main factors, which have had an influence on decreasing the fatality rates, have now been discussed. This chapter has made clear that there are many other issues, which have also had a role to play but are outside the scope of this study. One further issue is that the reduction in fatalities and serious injuries in diving within the U.K. is also due in part to the development of emergency support facilities for the changed consumer.

3.10.2 Myron states, "by 1962 eight out of ten serious diving injuries treated in US Naval recompression chambers were civilians rather than military" (Under Sea Journal PADI 1968). Most decompression tables at that time were designed for fit, military divers. They were never designed to be used in a "recreational mode" and had a "incident rate" for which the military were prepared to accept as an occupational hazard and for which they were equipped. It was not until the mid-1970s that tables were specifically designed and tested for the recreational diving community. This by itself would improve a recreational diver's chances of survival and reduce the risk of a decompression accident.

3.11 Conclusion

3.11.1 At the time of the introduction of the New Diver Training programme in 1984 the fatal accident rate in the UK was 2.65 per 10,000 divers (NDC Diving Incidents Report 2000). The effect of the new training programme was dramatic and by the close of

1985 the fatal accident rate for BSAC divers began to fall. This trend has continued to date. By the year 2000 the BSAC fatality rate had fallen to 1 in 7,000 participants for those who were BSAC members. There is no question that the introduction of the new/revised BSAC Diver Training programme along with changes in instructor standards has made a significant impact on the reducing the fatal accident rate within recreational divers in the UK.

3.11.2 Worldwide the introduction of national standards enforced by the training agencies has gone a considerable way to radically reduce the fatal accident rate in the industry. It is clear however that the lessons that were initially learned by the industry do not currently appear to have been transferred to the rebreather training agencies, as evidenced by the current high incident rate. There is no question that it appears that the rebreather training agencies could benefit from the experience gained by the recreational diver training agencies in course design and the systems approach to diver education.

Chapter 4 Research/Results

4.1 Introduction

4.1.1 Having looked at a number of fatal accidents that have occurred to divers using rebreathers (**Appendix 2**) it was clear in my opinion that some form of human error was occurring. Chapter 2 and 3 has established that:

- today's modern diving equipment is extremely reliable even though it is used in the harsh environment of the sea
- human reliability and poor training were initially key issues in recreational SCUBA fatalities
- as the training regimes have improved the fatal accident rates began to fall

4.1.2 Further, it has also been established that all the rebreathers currently sold in the U.K. have undergone thorough testing and examination prior to receiving their CE marking. In order to accomplish this, a rebreather supplier must put together a "technical file" which includes the test data of all the component parts and the system as a whole. Both the semi closed and fully closed rebreathers on sale within the U.K. have been tested and examined. Given that the reliability of SCUBA equipment is well known and documented, it is submitted that equipment failure has had no significant impact on the accidents reported in Appendix 2.

4.1.3 The question then remains, why were these experienced divers dying using this new technology? Having ruled out technical failure it is apparent that there must be some other failure method at work, namely human error. To identify the possible types of human error, I have looked at the differences between a diver's already learned skills in SCUBA diving and the new skills a diver would require to operate a rebreather. The aim was to see if there are some SCUBA skills that could create problems when inadvertently used or ignored by a rebreather diver. Following the identification of these differences, I have then tried to identify the potential human errors that could cause the problems and analyse the consequences that might result from such a deviation.

4.2 Specific Methodology

4.2.1 On 22 February 2001 I undertook a rebreather diver's course run by Andark Diving (Southampton) under the sanction ship of Technical Divers International (UK), (TDI). This course enabled me to gain first hand experience of the differences between SCUBA and rebreather diving. My findings are also based on my previous thirty years recreational and commercial diving experience and the knowledge of two other rebreather divers, Richard Stevenson (an experienced closed circuit rebreather diver) and John Parlour (an experienced semi closed circuit diver).

4.2.2 In any activity in order to gain understanding of the possible human failures it is essential to have a comprehensive understanding of the task. In order to evaluate a task I broke a dive down the components that make it into a number of steps and then using Task Analysis broke down a descent into all its component parts looking for the differences between Scuba, semi closed and closed circuit rebreather diving in an effort to confirm my findings. The results are presented in **Appendix 4.**

Chapter 4 Research/Results

4.2.3 In order to logically categorise my research I broke a dive into the following steps under the following headings and each are dealt with separately in sections 4.4 – 4.15:

- On the surface
- Descent
- On the bottom
- Ascent

4.2.4 The rebreather course also enabled me to explore and experience the possible human errors that could combine with the above differences in technology. These differences, in my opinion, could if poorly managed to result in the fatalities. I have broadly categorised the potential errors as follows:

- Failure rate of humans due to stress, and
- Strong habit intrusions leading to skill based errors.

The latter ranges of errors are as result of two related situations. Firstly, it must be recognised that an applicant for rebreather training must be a diver with nitrox training experience and hold a BSAC Dive Leader qualification or equivalent. This means that by the time a diver embarks on rebreather training he will be an experienced SCUBA diver with strong SCBUA habits intrusions thus majority of his skills will be instinctive. Secondly, during the course of a diving season a most divers will use both SCUBA and rebreathers depending on the dive being planned. This requires a diver to switch between technologies with his habits and instincts on SCUBA being reinforced as the season progresses.

Chapter 4 Research/Results

4.3 The differences between SCUBA and Rebreather techniques

4.3.1 To analyse the differences between SCUBA and rebreather techniques I drew up the dive profile contained in Figure 4.3.

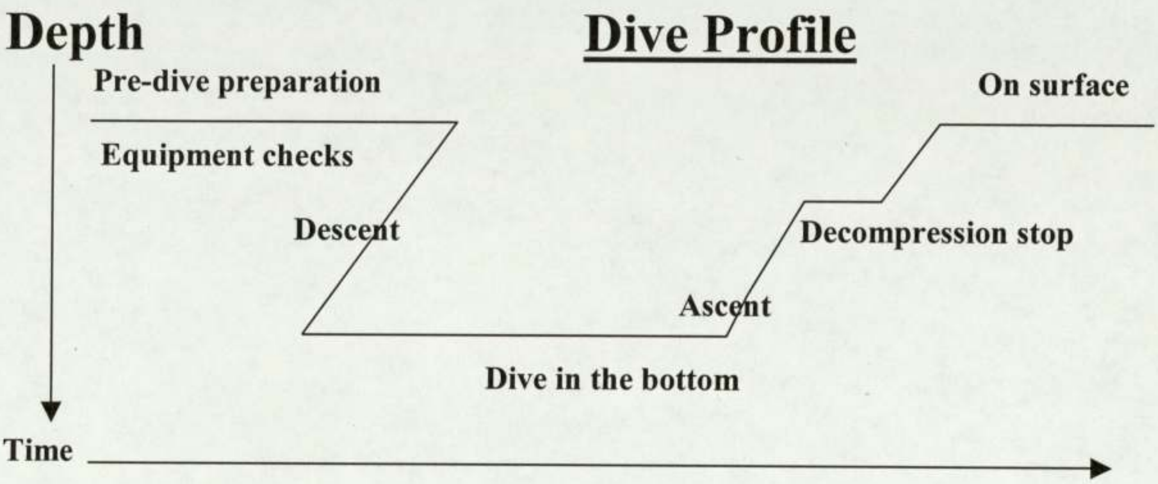

Figure 4.3

4.3.2 The dive profile enabled me to focus on the various stages of the dive. I have only concentrated on areas where a diver using his experience as a SCUBA diver and acting in a "SCUBA way" would produce a different result when using a rebreather. In all cases the SCUBA response would cause significant difficulties to a diver using a rebreather and could lead to him being task loaded, which could lead to further difficulties. It is submitted that some of the fatal accidents reported in **Appendix 2** were as a direct result of some of the failings outlined below.

4.3.3 4.4. On the Surface – failure to turn the set on

4.4.1 There are a number of key issues that relate solely to the rebreather's preparation that could cause problems before the dive. However, I will look only at problems common between the two types of equipment

4.4.2 The first key area starts at the beginning of the dive. If a diver fails to turn the set on using SCUBA equipment it is instantly apparent. On the surface, the diver would either take one or two breaths as the hose and regulator is charged or would get no gas at all. The diver would either then turn his set on or ask his dive buddy to turn it on for him. The problem is easily identified and resolved.

4.4.3 It could, however, have disastrous effects for a SCUBA diver if he is in the water before he takes his first breath. Most SCUBA divers control their buoyancy during the dive by the use of a power inflator. The gas contained in a diving cylinder powers this inflator. If the air is not turned on at the start of the dive the diver is unable to establish buoyancy on the surface and could sink without air to the seabed.

4.4.4 However, in a rebreather the gas is contained within a breathing loop. As the diver exhales, his exhaled gas goes through the loop and is returned to him. He would start his initial breathing sequence on the boat or shore prior to entering the water. There would be no indication if he had failed to turn the gas on prior to the start of the dive other than no reading on his pressure gauge. As the diver breathes on his breathing loop he would begin to consume the oxygen in his set. At some point, dependent on his oxygen usage, there would come a point when there would be insufficient oxygen available to sustain life. The diver would lapse into unconsciousness and probably drown if he had entered the water by this point. This would not take very long as the loop only contains between 2 to 5 litres of gas. He might get some warning in the form of dizziness and confusion but by the time this occurred it is unlikely he would be able to establish the cause.

4.4.5 If the rebreather diver had entered the water quickly and had started his descent, he would eventually collapse the counter lung and would be unable to get any air. He would then have the same problem as a SCUBA diver in that it could be difficult to establish sufficient buoyancy to get to the surface. The risk is foreseeable and relies on the diver performing his basic checks correctly and a good thorough buddy check. In my experience proper buddy checks are rarely done. Figure 4.4 contains a summary of these differences and their consequences.

Failure to turn the set on

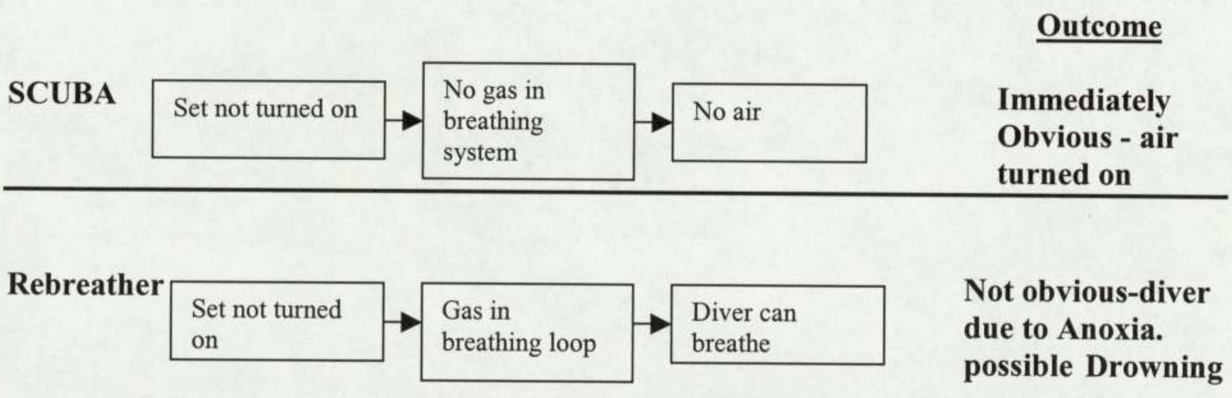

Figure 4.4

4.5 Changes in Buoyancy

4.5.1 During a dive there are three states of buoyancy that a diver could employ by altering his displacement: positive; negative; and neutral.

4.5.2 **Positive:** In order to remain on the surface before and after a dive, a diver uses positive buoyancy. To accomplish this the diver increases his displacement by either adding air to his BCD or by adding air to his suit when he is using a dry suit. This makes him positive and he floats on the surface.

4.5.3 **Negative**: In order to start a dive or to descend at any point during a dive, the diver must become negative. In order to accomplish this a diver can become negative by altering his displacement by letting the air out of his BCD or dry suit until he sinks. For minor modifications during a dive on SCUBA he can just exhale sharply reducing his displacement until he descends. Once this process starts the diver will continue to descend until he halts his descent by either becoming neutral or by increasing his displacement and becoming positive.

4.5.4 **Neutral**: This is the ideal for a diver at all points during a dive except ascent or descent. It is at this point that a diver is in equilibrium. The diver neither sinks nor floats. For a diver on SCUBA, this is constantly changing as the diver inhales and exhales and is usually controlled by his fin and arm movements.

4.6 The descent - change in buoyancy

4.6.1 As the diver descends the air trapped in his suit and buoyancy control device jacket (BCD) is compressed thereby increasing his rate of descent to the seabed. With SCUBA, in order to gain some control of this descent, the diver would inhale deeply from his SCUBA unit and with his chest expansion would increase his displacement and thus slow or stop his descent. At this point the diver would add air to his BCD and trim his buoyancy so that he was neutral in the water i.e. he would not sink or float (see 4.6.2).

4.6.2 However, as the rebreather diver begins his descent the air inside his suit, counter lung and BCD is compressed thus increasing his descent rate. As the diver goes deeper this rate increases. If the diver were to use his SCUBA skill of inflating his chest by inhaling to slow his descent, a common practice in open circuit divers, nothing would happen. This is because as the rebreather diver inhales the gas in his counter lung and it is drawn into his lungs, there is no change in his buoyancy as the gas is still contained within the breathing loop. The only way for a rebreather diver to change his displacement and alter his descent rate is to add air to his BCD or suit. As a result of this failure it is foreseeable that a diver on a rebreather could loose control of his descent, collapse the rebreather's counter lung and get into severe difficulties before recognising the problem.

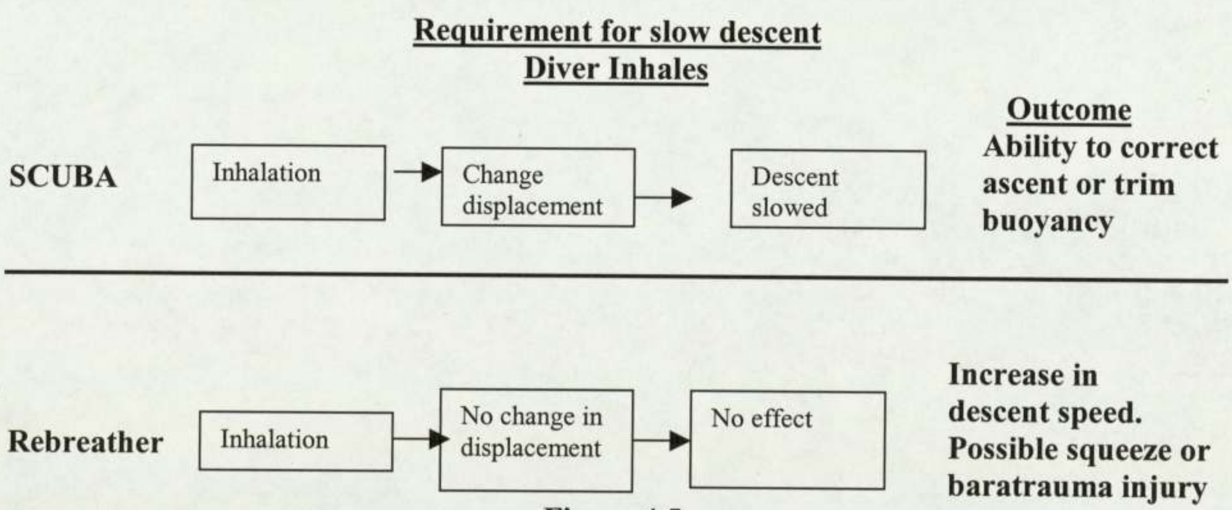

Figure 4.5

4.7 On the Bottom - Buoyancy Changes during a Shallow Dive

4.7.1 Buoyancy during a dive for a rebreather diver is generally far better than for a SCUBA diver. Providing the diver remains at a constant depth and once the diver has established neutral buoyancy his buoyancy will not change. However, it is extremely difficult to maintain a constant depth at any point during the dive. Minor changes in depth result in continuous changes in buoyancy. As Boyles Law states "the volume of gas will vary with the absolute pressure" (U.S. Navy,1993). Therefore, as a diver changes depth his buoyancy also will change. In SCUBA, to compensate for these minor changes, the diver can make small alterations to his buoyancy by breathing either in or out. An experienced diver will do this all the time subconsciously throughout the entire dive. For a rebreather diver, due to the nature of the system, breathing will result in no change in buoyancy. He must physically alter his buoyancy throughout the dive.

4.7.2 At a depth of less than 10 metres, where the pressure volume change is more dramatic, the need to make alterations occurs more quickly and radically. Should a diver fail to control his buoyancy at this depth it is conceivable that the diver can easily suffer a run away ascent with its associated problems such as gas expansion injuries like air/gas embolism, which can ultimately prove fatal. These changes in buoyancy make diving rebreathers at shallow depth more difficult and increase the diver's task loading.

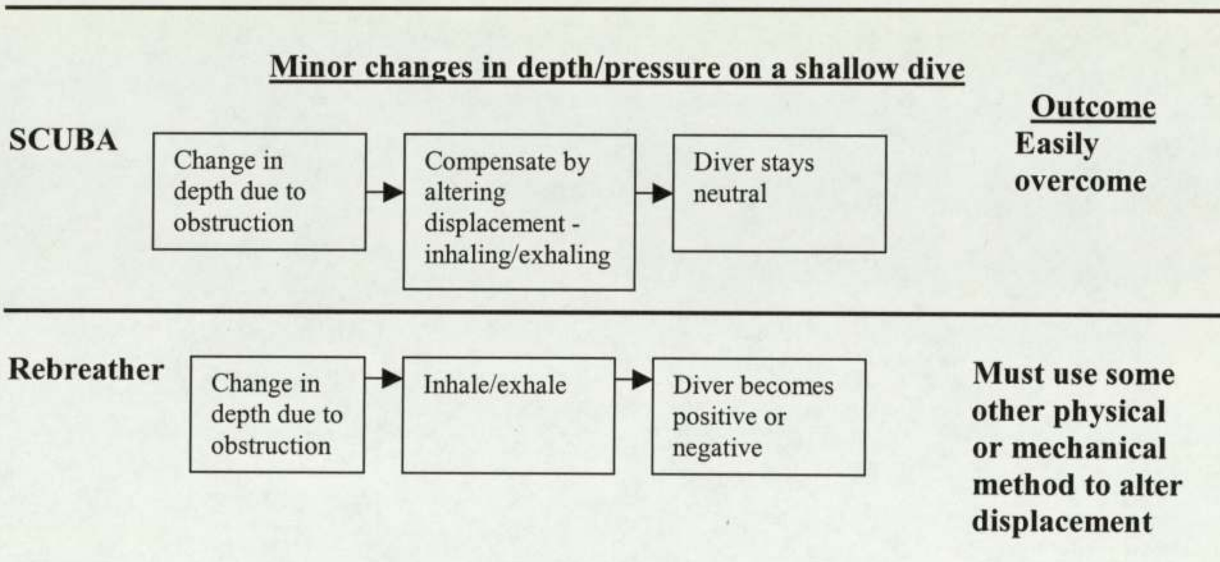

Figure 4.6

4.8 On the bottom - Accidental loss of mouthpiece under water

4.8.1 The loss of a SCUBA mouthpiece during a dive is a drill taught very early on in a SCUBA diver's training. The skill involves the removal, replacement and clearing of the SCUBA mouthpiece. The only consequence of an incident can be a run away free flow, which creates noise and bubbles. The regulator usually drops down due to its weight making it easy for the diver to find and recover the mouthpiece. The recovery drill is simple and following its replacement in the diver's mouth, the diver will exhale sharply so he can breathe again and carry on with the dive.

4.8.2 With rebreathers, the loss of a mouthpiece is far more serious. Once the mouthpiece is dislodged the following occurs:

1. The mouth and hoses piece floats up above the diver
2. The mouth piece free flows with the loss of gas from the breathing loop
3. The system begins to flood which can result in a chemical reaction with the absorbent creating a caustic soda
4. The diver's buoyancy changes to a negative position with the loss of gas from within the breathing loop.

4.8.3 Providing the diver recovers from the loss of his mouthpiece it is likely the diver will have to abort the dive and bailout using his emergency system, usually an open circuit SCUBA device.

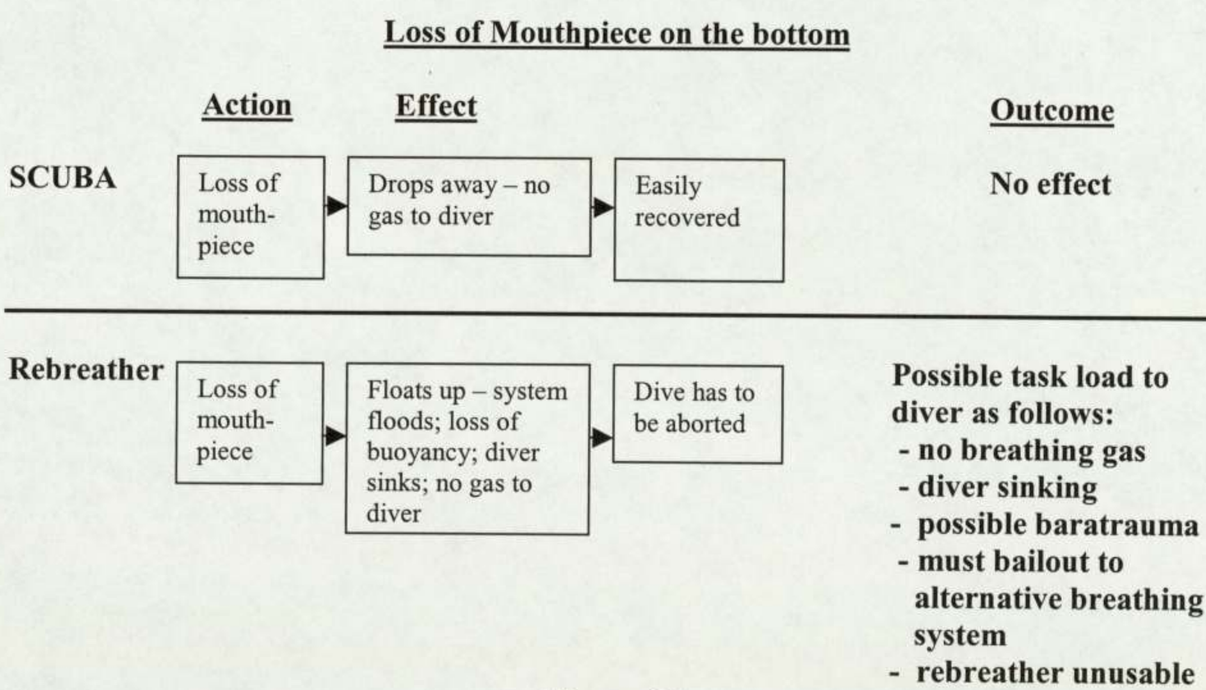

Figure 4.7

Chapter 4 Research/Results

4.9 On the bottom - Exhaling through the nose

4.9.1 The SCUBA system is designed so that exhaled gas can be vented through the SCUBA regulator. After time it is common that some experienced divers exhale through their nose as opposed the their mouths. This eases exhalation resistance and reduces the risk of mask squeeze during the dive that can occur in the air filled space contained inside the diver's mask. It makes absolutely no difference to a SCUBA diver how he exhales the gas. Many experienced divers do this as a matter of course.

4.9.2 However, for a rebreather diver, the exhalation sequence is more critical. It is absolutely crucial that the breathing loop remains intact for it to work effectively and that the exhaled gas remains within it. Should a diver forget and exhale through his nose during the dive he reduces the amount of gas within the breathing loop and thus reduces the benefits and efficiency of the rebreather system. If this continues a rebreather diver will very quickly run out of breathing gas at depth.

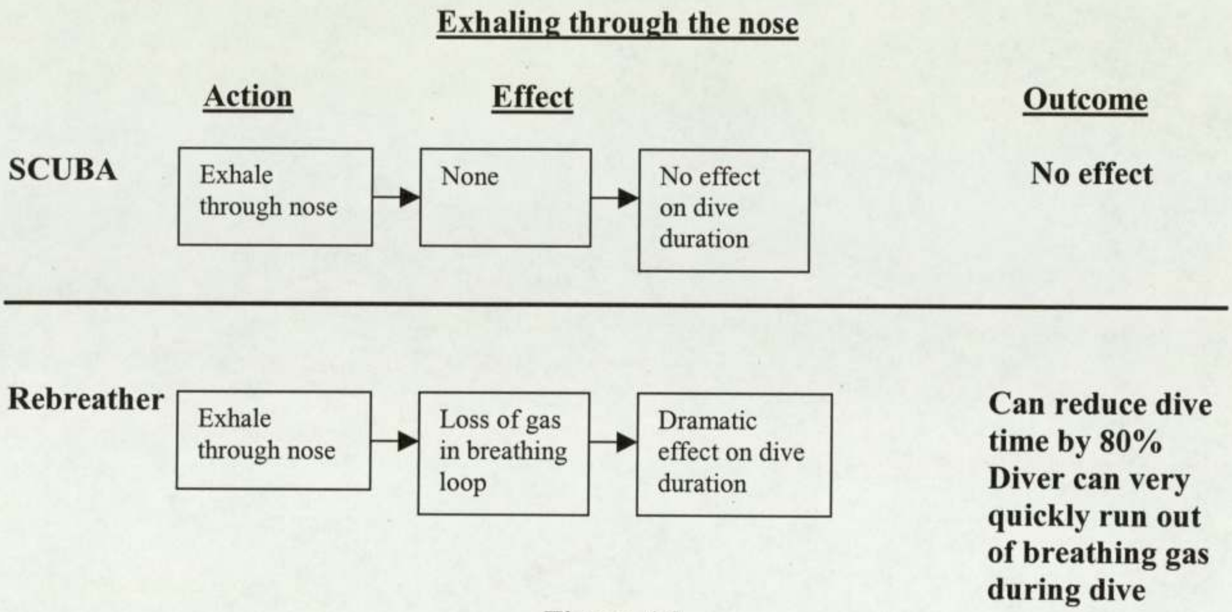

Figure 4.8

4.10 System flood due to component failure

4.10.1 In SCUBA a system flood is unlikely with the exception of a mouthpiece failure when it comes away from the breathing system. This is extremely rare and unlikely in a well-maintained SCUBA system.

4.10.2 In rebreathers, the components that make up a breathing loop are by nature dynamic to enable them to cope with the breathing cycle. The majority of these components are large in bore and in volume to reduce resistance during breathing, especially at depth when the density of the gas increases. In addition, the breathing loop must be capable of disassembly so that the diver can clean and maintain the system after use. This creates problems in that components can be damaged during assembly or during the course of a dive. Some manufacturers, but by no means all, have taken measures to protect the sensitive components by putting shrouds or covers over them.

4.10.3 It is therefore essential for the diver to test the system's integrity during the set up. However, even if these checks are performed, the system could still fail if it has been incorrectly assembled. As discussed in 4.7, the loss of integrity of the breathing loop will lead to a catastrophic failure and the diver will be forced to abort the dive. Other difficulties can include loss of buoyancy, caustic cocktail and the inability to breath due to a flooded breathing loop. Potentially the diver would be required to cope with all of these problems simultaneously.

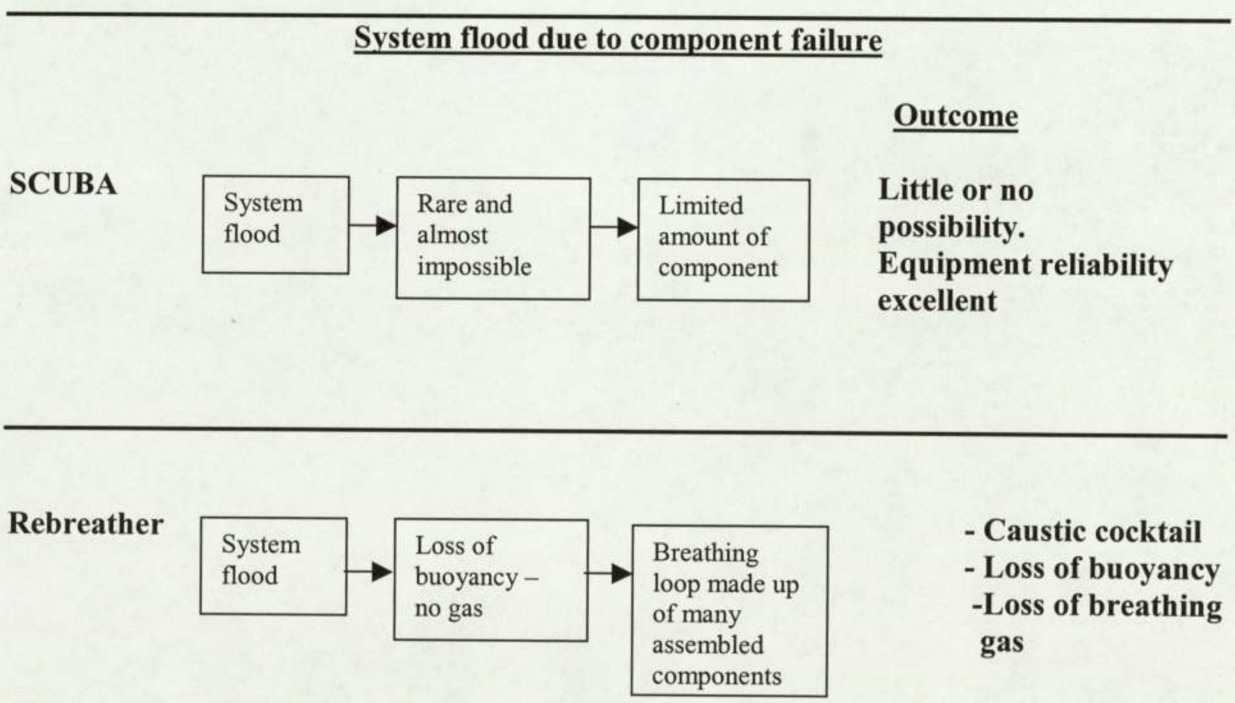

Figure 4.9

4.11 On the bottom - Oxygen poisoning

4.11.1 During a dive on closed circuit rebreathers divers can be exposed to high levels of oxygen for long periods of time. These exposures can lead to oxygen poisoning.

4.11.2 There are two forms of oxygen poisoning that a diver must be aware when conducting operations involving elevated partial pressures of oxygen commonly found in closed circuit rebreathers. These are acute oxygen poisoning which can lead to immediate convulsions, which can prove fatal if they occur underwater due to drowning or chronic oxygen poisoning. Chronic oxygen poisoning is often referred to as Central Nervous System (CNS) toxicity. This is the result of being exposed for long periods to high partial pressures of oxygen. The longer a diver is exposed to these pressures the greater the risk of oxygen poisoning.

4.11.3 By their very nature, closed circuit rebreathers expose a diver to an elevated oxygen partial pressure throughout the dive thereby dramatically increasing the risk of chronic oxygen poisoning. With SCUBA, the risk is controllable as the mix constantly changes when the diver alters his depth. With divers on closed circuit rebreathers the oxygen in the breathing loop can and often does run beyond the maximum permitted limit of tolerance.

Oxygen Poisoning

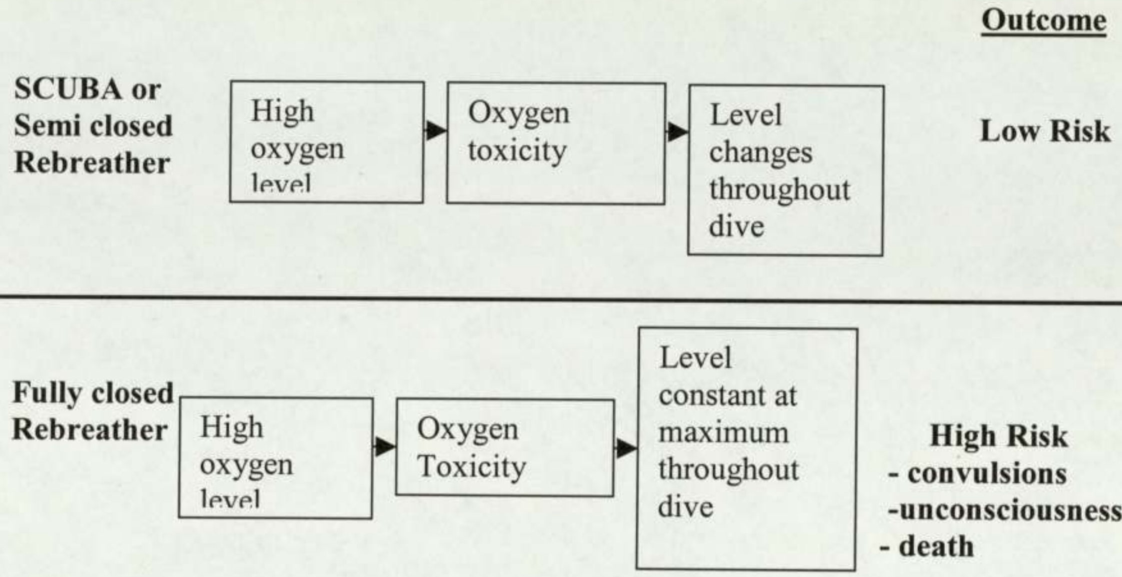

Figure 4.10

4.12 Ascent - Change in Buoyancy

4.12.1 As a diver begins to ascend his buoyancy is likely to change from neutral to positive. As a rebreather diver ascends the pressure exerted on the gas contained inside the confined spaces of his suit, BCD and his counter lung will reduce causing the equipment to begin to expand. This alters his displacement from neutral to positive and it will become more positive as the pressure decreases if it is not addressed as he ascends. The ascent is a critical portion of a dive and it must be gauged to allow the body to release nitrogen in a controlled manner. An excess of nitrogen will cause decompression sickness. Should a diver lose control during ascent, he will dramatically increase his risk of explosive decompression sickness. Further, a diver may suffer from a burst lung injury, which could easily lead to a fatal accident.

4.12.2 A SCUBA diver need only contend with 2 confined spaces, his suit and his BCD. In my experience most divers can easily control their buoyancy control device and their dry suit (two confined spaces) easily during ascent. A rebreather diver must give careful thought before he begins his ascent due to the increase number of confined spaces he must control or the consequences could be fatal. It is possible that a rebreather diver can become "task loaded" during ascent due to the increased number of confined airs spaces expanding during ascent. Should the diver loose control of these during ascent the consequences could prove fatal.

Change in buoyancy on ascent

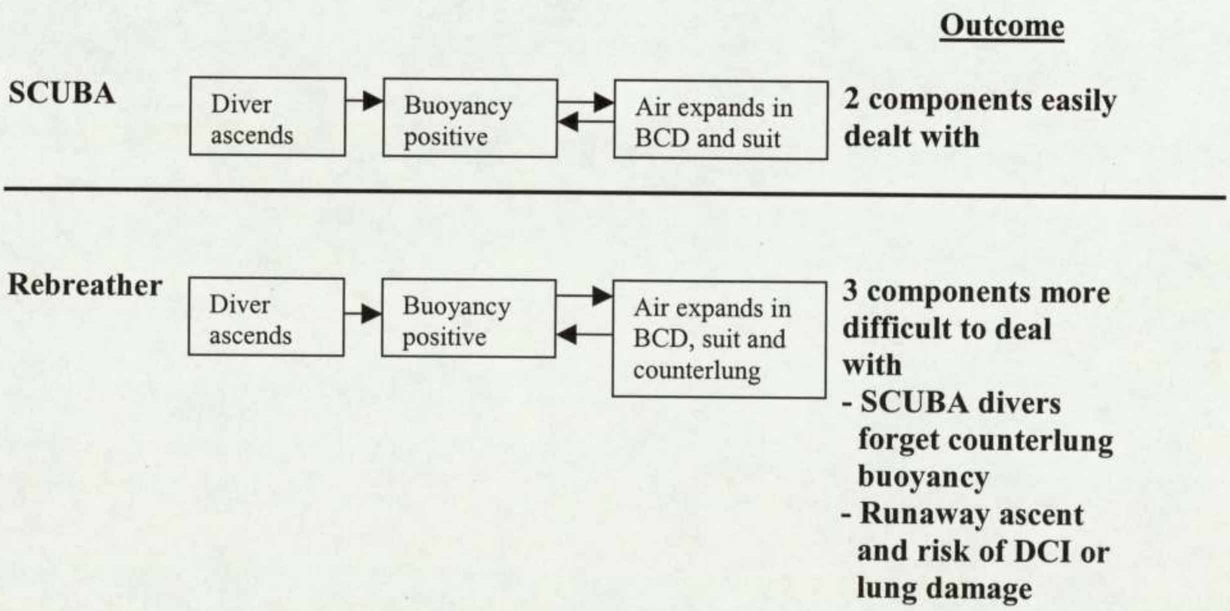

Figure 4.11

Chapter 4 Research/Results

4.13 The Ascent - Falling Oxygen Levels

4.13.1 During ascent the partial pressure of oxygen falls. This is a result of the physics involved in diving. The gas law that relates to this is Daltons' Law of Partial Pressure (U.S. Navy, 1993). This problem only occurs to divers who are operating a semi closed circuit rebreather. As the diver starts his ascent the partial pressure of oxygen in the breathing loop begins to fall. If the partial pressure falls, the diver can black out. This is called shallow water blackout caused by a drop in the oxygen level in the breathing loop. The blackout occurs suddenly and without warning and could lead to drowning. In order to prevent this ailment the diver must flush through the breathing loop prior to his ascent. This raises the partial pressure of oxygen in the system. This is done by the diver inhaling normally but exhaling through his nose thus raising the partial pressure of oxygen in his breathing mixture.

4.13.2 Within open circuit diving the diver is constantly taking a fresh breath from the regulator and whilst the partial pressure of oxygen will fall it will never fall to below a safe level and thus is of no concern to an open circuit diver. The closed circuit rebreather diver's system maintains a constant partial pressure through out the dive even on ascent thus is not a problem for a diver using this type of technology.

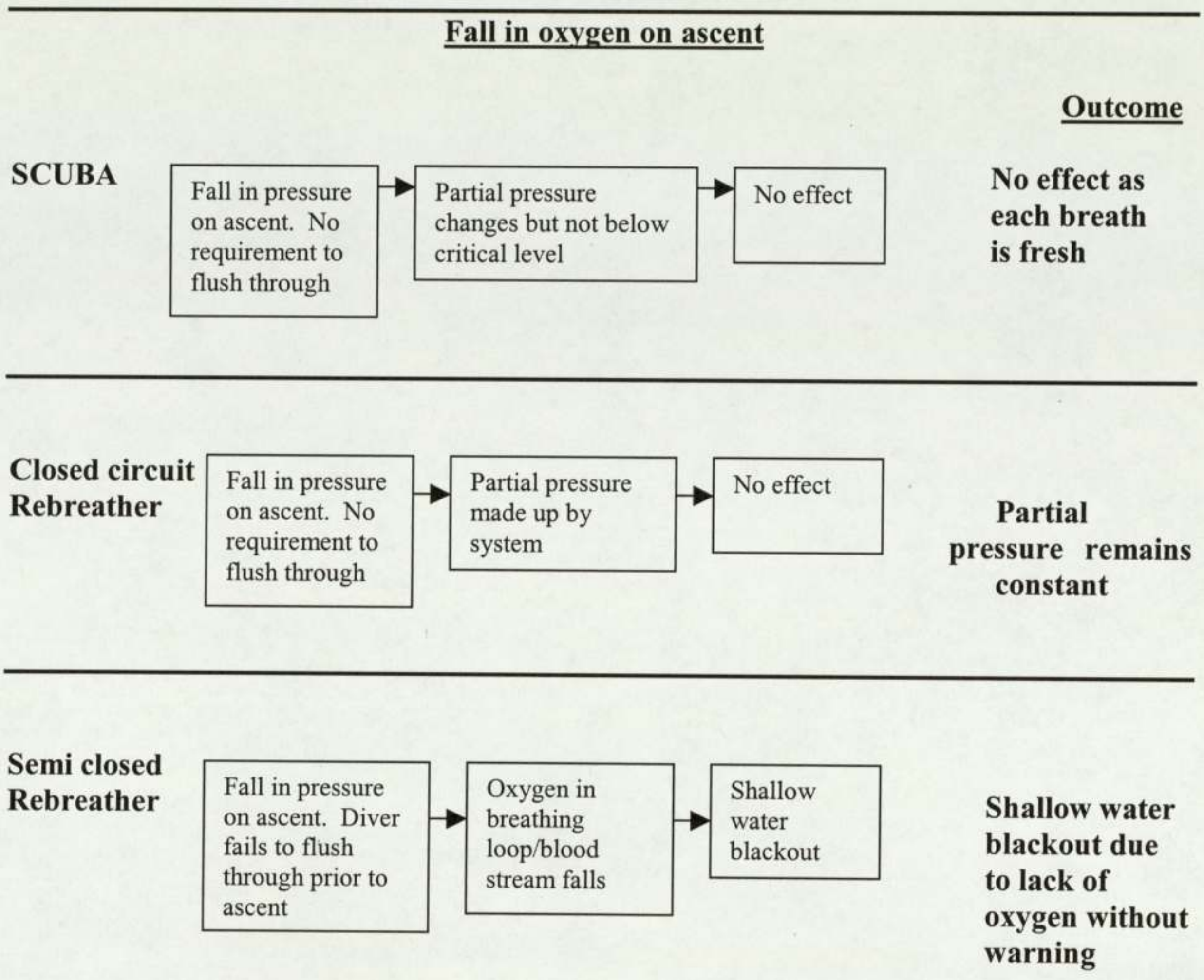

Figure 4.12

4.14 The Ascent - Diver Rescue

4.14.1 All through a SCUBA diver's career he is taught various techniques to rescue a SCUBA diver in distress not only on the surface but at depth as well. As demonstrated above, there are a number of additional problems that could occur in rebreather diving that a SCUBA diver would not normally encounter. As a result a SCUBA diver would require a specialist briefing and possibly training prior to diving with a rebreather diver. Most divers are familiar with techniques for rescue under water including out of air emergencies, loss of buoyancy, and equipment failure or problems. However, they would have no experience in oxygen toxicity, carbon dioxide poisoning, system floods, unconsciousness and loss of buoyancy due to system failure. As a result it is unlikely that a poorly briefed dive buddy would be able to react appropriately to a rebreather emergency outside of his technical training and experience.

4.15 On the surface - Loss of mouthpiece

4.15.1 On the surface after a dive it is common with a SCUBA diver to remove the mouthpiece to talk to their buddy, conserve gas and to swim back to the boat.

4.15.2 However, whilst using a rebreather this action can be catastrophic to the diver. If the diver fails to isolate the mouthpiece prior to removing it the ambient water pressure collapses the counter lung, floods the system and the diver suffers immediate loss of buoyancy. This means that it is possible for the diver to sink beneath the surface as he loses the positive buoyancy of the counter lung. He would also be without breathing gas as the system is now flooded. The rebreather diver must then remember to find his bailout regulator and establish positive buoyancy using some other method.

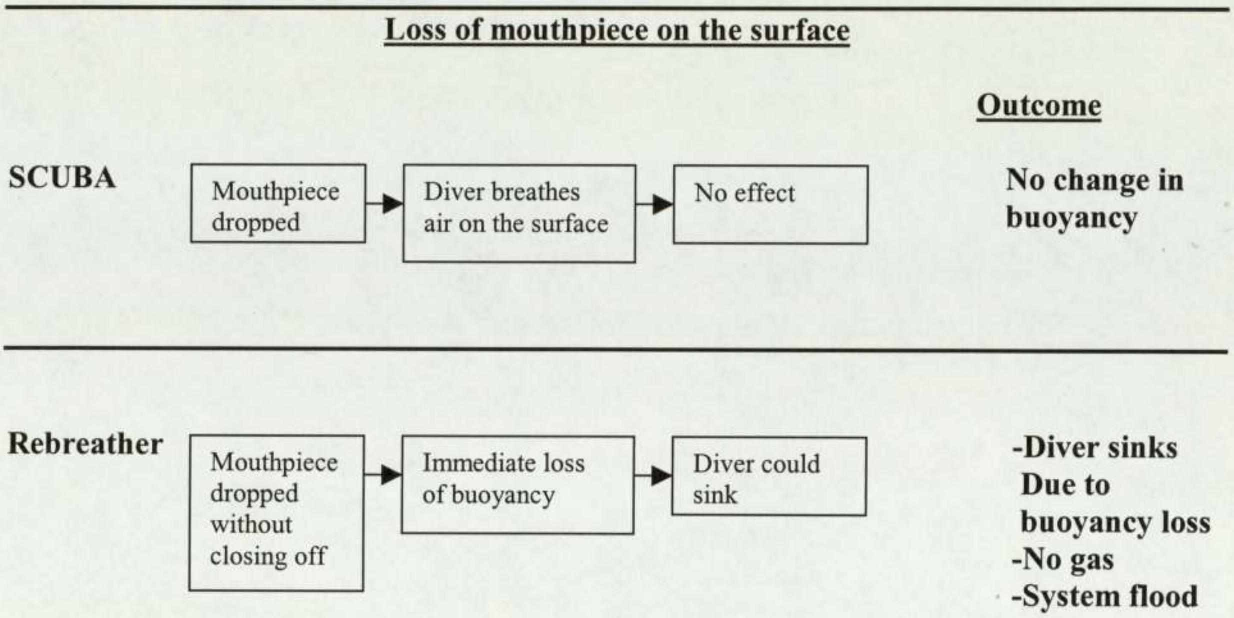

Figure 4.13

(Psychological aspect of SCUBA divers reacting under stress and by instinct)

4.16 Conclusion

4.16.1 It is clear that proper training and constant practice in the use and application of rebreathers would eliminate the majority, if not all, of the problems I have identified.

4.16.2 For my first year of rebreather diving I made a conscious decision to dive on only my rebreather system so that I would not "unlearn" my rebreather experience. In 2002 I was forced to return to SCUBA and spent 6 days conducting 17 dives using open circuit technology. About 1 month later I returned to rebreather diving. It was clear that I had relearned some of my open circuit skills and I started making some basic rebreather mistakes such as failing to close the mouthpiece off after a dive or failing to perform the more complex pre-dive checks correctly. It is my opinion and from the research I have conducted for this dissertation I have concluded that the strong habit intrusions from my open circuit experience led me to make these simple skill based errors.

Chapter 5 Conclusions and Recommendations

5.1 Summary

5.1.1 In future the application and number of divers using rebreather technology will increase due to its benefits. Today, dives are being planned using this technology to depths and locations that were only dreams 5 years ago. However, not every diver will want to use a rebreather. The system has developed a reputation for being extremely dangerous and complex. As submitted in this study, this reputation is largely unearned and incidents are more likely to be the fault of the diver rather than the system.

5.1.2 In order to use rebreather technology divers must learn and master new skills making the training of these divers critical to their survival. It is also clear that previously learned SCUBA skills could prove detrimental to that training process as well as for their future diving. Richard Pyle (Proceedings of Rebreather Forum 2.0 1996), Richard Stevenson (990 Publications, 1998) and Gary Gentile (Gentile Productions, 1998) all explain that rebreathers require more training and discipline than scuba and the unlearning of ingrained open circuit skills is essential in order to operate them successfully. This view is reinforced by the military's safety record with regard to this type of diving as I discussed in Chapter 1. It is submitted that the military's good safety record is the result of an excellent training regime, discipline, knowledge and continuous ongoing practice, all essential requirements for a successful rebreather diver. These benefits however are not always available to the military's civilian counterparts.

Chapter 5 Conclusions and Recommendations

5.1.3 The root causes of diving accidents have been broken down in the PARAS report, *Quantified Risk Assessment* (HSE 1997). Of the 269 fatalities reviewed, 93% were a result of :

- Procedural error
- Environmental conditions
- Decompression considerations
- Out of air conditions

All of these causes are directly attributable to human error at some point in the dive and are directly avoidable by the application of appropriate diving skills; skills, which are introduced during a diver's, initial training

5.1.3 History also appears to be repeating itself and the industry is failing to take on the early lessons identified from its SCUBA experience. Could this mean that as the technology improves, the rebreather industry develops and matures the fatal accident rates will fall off. At this point it is to early to tell. However despite the development and massive expansion of recreational SCUBA diving in the UK and US since the 1950's, in the last few years the accident rate has fallen off. The evidence suggests that the rate falls as technology evolves and improvements in training take place. We discussed these points in Chapter 3.

5.1.4 Over the past 5 years rebreather training has also changed. To embark on a fully closed circuit training programme using mixed gas, a diver must now undergo a 5 day basic training course and then proceed to carry out over 50 hours of rebreather diving before has can do the second, mixed gas stage of training. In 1993 the same course was only half a day. During 2002 there was only 1 reported rebreather fatality in the U.K.

Chapter 5 Conclusions and Recommendations

5.1.5 Could this be as a result of these changes or as a result of poor weather or other unknown factors? It is likely however that at this early stage in rebreather diving as we have seen in recreational scuba diving that factors out with diving have influenced the fall in this years statistics.

5.2 The Technology

5.2.1 All rebreathers being sold within the U.K. must now have a C.E. marking. In order to achieve this standard they must have undergone thorough testing. However, one of the problems with testing is that at present there are no common standards for rebreathers within Europe. Manufactures have in the past written their own based on experience or other similar standards. Irrespective of this, it is submitted that rebreather diving technology is extremely reliable. In both PARAS (HSE 1997) and other documents cited in this dissertation and Bennett and Elliott (1995) The Physiology and Medicine of Diving, illustrate the fact that SCUBA equipment has only been the primary cause of diving accidents in between 4% and 9.5% of the cases. Rebreather's incorporate a large amount of existing SCUBA technology thereby indicating a safe system. This reinforces HSE's findings that 93% of fatal accidents are as a result of procedural errors made by the diver's themselves. However, are there other aspects of the equipment that could be improved that would influence diver safety?

5.2.2 In some research I conducted for an essay The Role of Ergonomics in Securing Healthy and Safe Working Environment with Respect to the Inspiration Rebreather during my post graduate course I looked at a number of ergonomic issues involving the design of rebreathers that could lead a diver under stress to make catastrophic mistakes. In my essay I concluded that "it appears little or no consideration has been taken of the ergonomics of design of the inlet control valves and their location on the rebreather". These valves control the introduction of pure oxygen and diluent into the breathing loop. In fact Dr Ed Thalman when referring to the Mk 16 US Navy Rebreather trials stated that " we haven't touched ergonomics at all... their (the evaluators) only concern was to ensure that the bloody thing would perform the way it was supposed to perform" (Proceedings of the Rebreather Forum 2.0, 1996). It is submitted that this is one key area that could benefit from further research and improvements in design. The man/machine interface is critical for diver safety. Only a limited amount of study has been dedicated to this aspect of diving, particularly in relation to working in a dynamic three-dimensional environment such as water. Some research has been undertaken by Bachrak and Egstrom using frames in tanks (Best, 1995) but this was only in relation to open circuit divers in confined water and no parallel research appears to have been done in relation to rebreather diving.

5.2.3 Equipment relating to the recirculatory or breathing loop aspect of rebreather diving could also be improved to prevent the diver developing breathing difficulties. These incidents can be caused by the failure of the sofnolime or sodasorb to effectively remove the carbon dioxide within the breathing loop resulting in the diving suffering from carbon dioxide poisoning. This can be as a result of over use, incorrect packing of the canister and "tracking" (gas tracking occurs when the gas tracks though in small channels the Carbon dioxide absorbing chemicals. As a result of the gas tracking the absorbent life is dramatically reduced) though the canister. In these events, the results can lead to carbon dioxide poisoning. The onset of CO_2 poisoning within the breathing loop is usually very slow and can hard to detect due to mental confusion it creates. In extreme cases however CO_2 poisoning can prove. The ability to monitor CO_2 in a gas mix is available in a wide range of industrial applications on the surface however there is currently is no warning system on the market available that works underwater in a self contained rebreather. This could be an area for future development.

5.2.4 Other improvements in the systems design within the breathing loop could also be made. For example, the list of rebreather fatalities in Appendix 1 demonstrates that a number of divers have arrived on the surface safely only to sink back down again. As identified in Chapter 4, the failure to *close off the mouthpiece* prior to removing it from your mouth results in an instant loss of buoyancy of between 2 to 3 kilos. This could result in the diver sinking back to the seabed and the increased risk of the system /breathing loop, flooding thus rendering the rebreather unusable for the diver. During a diver's basic training on SCUBA, he is always taught to establish positive buoyancy on the surface prior to removing any equipment. With rebreathers failure to follow this basic rule has undoubtedly lead to a number of accidents. In view of this experience, work should be done to either fit a warning device to the breathing loop or some form of automatic shut off valve. These however must not interfere with the passage of gas through the breathing loop whilst the system is in use. There is no question, however, that these simple modifications would go some way to dramatically improve the safety of the system whilst the diver is on the surface.

5.2.4 The incorrect assembly of the system by the diver also appears to be another area of risk. With SCUBA, mistakes are easily spotted before a dive since the majority of divers are familiar with the equipment and it is far less complex. With rebreathers, most manufacturers provide the diver with a checklist to ensure that the checks are done properly. However, the checklist must be followed and it is far more difficult to identify problems with the system as a larger number of the critical components hidden from view except during assembly. It is submitted that a review of this portion of the diver-training programme should be undertaken to ensure that safety critical components are correctly assembled and checked prior to the dive.

5.3 Training

5.3.3 Training and the diver's ability to respond to a given problem or error message is generally the **only** barrier to ensure the diver's health and safety whilst the system is in use. Thus the only real protection to a diver during a dive is his safe system of work. It is absolutely essential that prior to a diver undertaking dives without the direct supervision of his instructor on his own, he must be competent. The definition of competence is discussed in Chapter 2. It is not just a legal issue; it is the key to ensuring a diver's safety when using this piece of equipment. The rebreather diver, when he completes his training, is still only as good as the instructor who trains him. Thus high standards of competence are required by the training staff to ensure adequate training for the diver. The selection and training of the instructor is a critical link in the chain to ensure the survival of the rebreather diver.

5.3.4 Another problem associated with training in a hazardous environment is the teaching of an individual how to react correctly to an emergency situation without actually placing him at risk. Ideally divers should undergo initial training across the full range of depths as well as potential problems they would expect to experience during the early stages of their rebreather diving career. Later when they embark on mixed gas training it is not be possible to create all the problems due to limitations of time and depth. However, divers need to be fully conversant with the planning and requirements for any dive within the depth range they are qualified for. Unless the diver has experienced the fears and apprehension of the dive, learned how to control them during training, there is a potential risk he could get into difficult circumstances later without an instructor's supervision and react incorrectly. Therefore, it is critical for the instructor to create a safe learning environment to allow the student diver to experience the emergency fear and apprehension without placing either the diver or the instructor in actual risk.

5.3.5 Once a diver is trained it is also critical that he maintains his skills. BSAC Accident statistics for any year show that usually around Easter time there is a rise in accidents as divers, having had a winter lay off return, to diving and get into difficulties as illustrated in the BSAC Incident Reports (BSAC 2001). Part of the problem is likely to be skill degradation during the winter months or long periods of inactivity. During this time, if a rebreather diver fails to maintain his skill level he will start the following year with a reduced level of a capability. As already discussed in Chapter 1, most rebreather divers are experienced SCUBA divers to start with. During this lay off and prior to the next season's diving, divers are likely to "forget" some of their rebreather skills and when they return to the water the strong habit intrusion of SCUBA will take over thus increasing the risk to the diver in the early part of the season. Therefore, it is essential that divers maintain their rebreather skill level out of season by either regular pool practice or continuing to dive in the off-season.

5.3.4 Another key issue is the high level of diving experience required to embark on rebreather training. Part of the reason for this is that the current rebreather-training course does not allow for basic or initial diver training within its programme. The result is that all divers embarking on rebreather training start with strong SCUBA habits as a result of previously learned and practiced skills. To eliminate the problem it would be safer to train a diver with no previous diving experience than it would be to train an already trained and experienced SCUBA diver. This would ensure that he would have none of the strong SCUBA habits that could put the diver at risk during the dive. The training would then take a diver from innocence to experience but only on rebreathers.

5.3.5 In the preparation of Appendix 3 Task Analysis it became apparent that most divers following their initial training seem to forget or change the way they operate to suit their ability/personal preference. This means there is little or no standardisation in the way divers operate and dive rebreathers. A higher degree of standardisation could lead to improvements in the way divers operate rebreather equipment. For example, the military's high degree of discipline and standardisation ultimately contributes towards their high safety standards. Using their safety record as an example it is clear that there could be further safety benefits from a higher degree of standardisation during operations by rebreather divers.

5.4 Instructor/Diver Requalification

5.4.1 Another way to ensure that divers and instructors maintain their skills is to require them to requalify after a number of years unless they could provide evidence of relevant ongoing experience. This requirement for retraining appears in other aspects of the industry such as in the First Aid at Work Regulations 1981. Regulation 3 states that "first aid certificates are only valid for the length of time HSE decides (currently 3 years), employers need to arrange refresher training with retesting of competence before certificates expire"(HMSO ,1997). Such requalification courses may go some way to ensure the instructor's ongoing competence. It is likely however that most active diving instructors would regularly practice his skills during training so the skill degradation would not be as great as it would be in first aid. However, an additional benefit to the instructor would be to allow for him to update regularly on any new techniques or skills, a practice which is not undertaken at present. Fort he diver there would be some benefits however he would know that prior to embarking on a course of instruction his instructor was:

- up to date,

- well practiced,
- regularly assessed,
- competent

The key problem with this issue from an industry perspective is who would administer the assessment, how would it be conducted and would the additional costs and difficulties outweigh the benefits the assessment would achieve .

5.5 Information Distribution

Another problem associated with the diving industry as a whole is the way the industry is fragmented into sectors i.e. recreational, military, police, media etc. and by its location. There are a number of divers within the industry prefer it this way as it allows them to operate with little reference to others, including authorities such as the HSE. However, the fragmentation of the industry also means that it is extremely difficult to capture information about good or bad practice. Within the MOD, however due to the nature of the organisation, information about good practice disseminates very quickly along with details of near misses and accidents. This allows the military to modify it's training or working practices when problems are identified. With rebreathers and the diving community as a whole this is not the case. With the exception of a few user websites run by manufacturers near misses are not reported to any central location. As a result, changes to the training programme only occur following fatal accidents. This is a major failing within the industry and the lessons learned are not be "captured" by the users until they prove fatal when it is too late. As discussed in Chapter 1, this was the same problem in the early days of SCUBA training. Information was held by the military and commercial industry but it was not transferred to the SCUBA community. They had to relearn the same lessons through their own costly errors and mistakes. This explains why it took so long for the safety record within the SCUBA community to improve. Even today, in most cases divers generally only hear of anecdotal evidence of accidents and never really get the full story.

5.6 Diver Perception of Risk

As a diver increases in experience his perception of the risk associated with diving changes. It is submitted that the actual statistical risk changes very little for a given level of experience but a diver's perception does. There is little or no research undertaken into this complex area of diving. It is made more complex because the risk to a diver will change during a dive due to the environmental influences of it such as depth, light, duration, narcosis, task etc. There is no question that this is an area of diving requires significant research in order to improve its safety. If any training programme is to be effective it must address all the risks either actual or perceived by the diver.

5.7 Oxygen Toxicity

5.7.1 During the course of my research for this thesis I have looked at many of the possible causes for fatal accidents involving rebreather divers. Another area in which limited research has been undertaken is the problems associated with oxygen toxicity. During the course of a dive a diver breathes at a constant partial pressure a mixture of gasses including oxygen. It is well known that long exposure to oxygen at high partial pressures can lead to chronic oxygen poisoning. However, little information or research has been conducted into the effect of oxygen "spiking". Oxygen spiking could occur when a diver has for some reason a problem with either the solinoid valve controlling the oxygen supply to the breathing loop or the controlling software. The result could be an oxygen spike that would result in a dramatic rise in the oxygen partial pressure to above permitted limits within the breathing mixture. The results of this phenomenon are unknown but it is conceivable that further difficulties could occur to the diver as a result. These difficulties could include acute oxygen poisoning as a result of this spike. This could be extremely dangerous for a diver during the dive as the likely outcome is for the diver to fit. Research needs to be undertaken in this area as the increased use of oxygen in all breathing mixtures is becoming more wide spread across the whole of the diving industry not just with rebreather divers.

5.8 Conclusion

5.8.1 It is clear that most divers currently using rebreathers are experienced SCUBA divers with strong scuba habit intrusions as a result. These habit intrusions mean that a diver who is under pressure (stress) is likely to revert to well-rehearsed automatic SCUBA behaviours to respond to a problem. As we have seen in Chapter 4 these behaviours could lead in some cases to skill-based errors that could, if unchecked, lead to a serious or fatal accident. Part of the difficulty for a diver is determining at what point or what action during the event does a problem become serious enough to take further action. In all cases this decision will be based solely on his training, his previous experience from both scuba and rebreathers and his perception of the risk. Further, the factors effecting his decisions are also constantly changing throughout the dive and from dive to dive.

5.8.2 It is submitted that to dive safely using a rebreather a diver must have the following;

- Good initial training
- Extreme self-discipline
- Regular practice of skills
- Focus on one and one only diving method so previously learned skills are not reinforced
- A gradual building up of experience

I feel that this dissertation substantiates Gentiles comments in *The Technical Diving Hand Book* (Gentile Productions, 2002) when he discusses rebreather fatalities.

> "The key to successful rebreather operations is the unlearning of ingrained open circuit techniques and the mastering of closed circuit rebreather skills" (Gentile, Gentile Productions, 1998)

It is foreseeable that strong habit intrusion due to the high level of SCUBA experience can lead to the potential of skill-based errors in rebreather divers and that for the training to be successful they must be "trained out". Stress is also acknowledged to be an important factor affecting human performance. A diver who rapidly experiences task overloading as a result of a crisis, like running out of gas, is more liable to make an error. Divers who regularly use both SCUBA and rebreathers continuously reinforce both patterns of behaviour and increase the likelihood of making a mistake. Only constant training and practice in one method at the cost of the other will help reduce the risk of skill based errors in rebreather divers in the long term.

Appendix 1

A Summary of the Published Information on Closed Circuit Rebreather Fatalities 1998-2001

May 1998 (UK)

A diver failed to surface after a 75 metre dive on a tri-mix rebreather dive. The two other divers surfaced without incident. Sub surface and surface searches were unsuccessful and a team of technical divers were called in. On the second day of searching located and raised the diver. (Coastguard & RNLI Report as sighted in the 1998 NDC Diving Incidents Report) Age 33

June 1998 (UK)

Three divers conducted a wreck dive to 34 metres. After about 17 minutes and at a depth of 25 metres they agreed to start their ascent. At about 20 metres the dive leader could see the other two divers in front of him. He then reached for a pocket in his suit and deployed a delayed SMB. When he looked back from this one of his divers was missing. Neither of them had seen the third diver go. They looked around and concluded that he had ascended. They completed their ascent. At the surface they were recovered into their boat and discovered that the third diver was missing. They conducted a search and then alerted the Coastguard. An extensive surface search involving 5 lifeboats, 3 helicopters and many other surface craft failed to find the missing diver. A strong current prevented other divers from returning to the wreck. Later navy divers searched the site, but the missing diver was not found. This diver had been using a rebreather, the other two, normal open circuit sets. (1998 NDC Diving Incidents Report) Age 62

September 1998 (UK)

Three divers completed a dive, one using a rebreather. As the dive was ending when one of the divers dropped a reel, and the diver on the rebreather went down to recover it. He did not return and the emergency services were alerted. Other divers conducted a search but kelp and increasing darkness prevented them from finding the missing diver. His body was later recovered the following day from a depth of 3 metres. His mouthpiece was still in place, the oxygen cylinder is reported to have been turn off. Death was found to be due to drowning. (1998 NDC Diving Incidents Report)

Age 44

July 1998 (Cork, Eire)

A diver died while diving on a wreck, the Kowloon Bridge. The incident occurred at 24 metres. (Dive International, Volume 4 No. 11) Age 43

May 1999 (UK)

A diver commenced a solo dive to a wreck in a depth of 55 metres. He returned to the surface rapidly 4 minutes later. At the surface he was unconscious. There was only one person in the boat and recovering him into the boat was difficult. Assistance was requested and a helicopter took the casualty to the hospital where he was found dead. This diver was using a rebreather. It is believed that his dry suit became over inflated, although no subsequent fault was found with the inflation equipment. This diver had suffered from a rupture of his lings. (1999 NDC Diving Incidents Report) Age late 40's

August 1999 (UK)

A diver using a rebreather entered the water to commence a dive. He was found to be unconscious on the surface and other divers went to his aid. The Coastguard was alerted and a helicopter took the diver to the hospital. Resuscitation attempts were made but the diver did not recover. (1999 NDC Diving Incidents Report)

Age 32

June 2000 (UK)

A diver, using a closed circuit rebreather, surfaced unconscious, from a wreck dive. The dive boat broadcast a "Mayday". The casualty was airlifted to hospital by a Coastguard helicopter. The diver was certified dead at the hospital. (Coastguard & RNLI Report as sighted in the 2000 NDC Diving Incidents Report)

Age unknown

August 2000 (UK)

Two divers had completed a wreck dive to a maximum depth of 82 metres using rebreathers. They were completing their decompression stops at 6 metres when on of the pair suddenly spat out his mouthpiece and made a rush for the surface. His buddy lost sight of him at 3 metres due to the poor underwater visibility near the surface. The buddy completed his stops and surfaced. It was then discovered that the other diver was missing. An extensive search was made involving two helicopters, two lifeboats and other craft. The diver was not found.

Age 32

August 2000 (Germany)

A diver suffered a rapid ascent after becoming entangled in a lift bag as he deployed it. His depth was not known, but he was 80 minutes into a dive the required a decompression stop. After surfacing the diver the diver was conscious and asked his buddy a rebreather instructor to remove his weight belt. He couldn't and was unable keep himself buoyant and sank from view. His buddy could not get him back to the surface and by the time he was recovered from 42 metres the diver had drowned.

Age 72

February 2001 (UK)

The Police were notified of a missing diver. His vehicle was located near a dive site; it had been there since the previous day. Police and Coastguards attended the scene and conducted a search. The diver's body was recovered from the seabed. It is believed that he had been diving alone. Age unknown (BSAC NDC Incidents Report 2001)

June 2001 (over seas)

An instructor was teaching on a rebreather course. He dived to a depth of 35 metres and was reported to have suffered a convulsion as he made his ascent. He died as a result of this event. Age unknown. (BSAC NDC Incidents Report 2001)

July 2001 (UK)

A group of divers planned a dive to 130 metres. The diver having established the correct shot descended and subsequently failed to surface. The diver was on a closed circuit rebreather and his body was recovered 4 weeks later. It is alleged that the diver had only about 5 hours experience on the system. Age unknown. (BSAC NDC Incidents Report 2001)

July 2001 (UK)

Two divers were ascending from a dive reported to be 30 metres. One diver became tangled in the delayed Surface Marker Buoy and the divers became separated. One diver surfaced and raised the alarm. Following an extensive search the second diver was not located. At the time of the accident the divers were diving on semi-closed rebreathers. Age unknown. (BSAC NDC Incidents Report 2001)

May 2002 (UK)

A diver surfaced following a dive to 60 metres using a rebreather. He was seen to sink back down and did not resurface. An extensive search was conducted however he was not found. Age unknown. (BSAC NDC Incidents Report 2002)

Appendix 2

The Evolution of Recreational Diving: A Time Line

1942	Cousteau invents the aqua-lung the for runner to modern day SCUBA
1946	La Spirotechnique of France begins to manufacture and market the Aqualung to the public
1948	Production of the Aqua-lung begins in Canada under licence
1949	First recorded open water SCUBA dive in the USA
1952	According the Madsen's book on Cousteau by 1952 1,000,000 SCUBA sets had been sold in the USA
1953	The British Sub-Aqua Club is formed to promote the growth of the sport and to provide information on how to modify military surplus equipment for use in diving
1954	The first recreational diver training program is created by L.A. Country Parks and Recreation Department
1959	The YMCA offer the first nationwide sport diver training program
1966	The Professional Association of Diving Instructors (PADI) is formed to promote diver training and continuing education
1978	PADI introduce the first standardised modular SCUBA course based on the "systems based approach".
1985	In an effort to maintain market share the BSAC changes its system of education to a systems based approach

1989 The introduction of Nitrox and Trimix into recreational diving allowing divers to go deeper and stay longer at depth

1994 Draeger releases the Draeger Dolphin the first semi closed rebreather to the recreational market

1998 A.P. Valves of Cornwall and CIS Lunar introduce the first mass market closed circuit mixed gas rebreather to the recreational community.

Royal Navy begin conversion course on (Clearance Diver Breathing Apparatus) CDBA a closed circuit electronically controlled rebreather.

Appendix 3

Time Line of Key Recreational Diver Issues

Date	Equipment	Instruction	Consumer Demographics
1945	Prototypical and crude design	No Civilian training programs	Exclusively Military
1960	A few sport diving companies come into existence. Equipment still designed for "survival" rather than energy saving	Formalised training begins Adopt courses similar to military	Mostly ex-military or those with extensive aquatic background Predominantly male
1967	A few changes and innovations including the introduction of under water pressure gauges to monitor air and single hose regulators Larger manufacturing base	No significant change Little attention paid to changes in either equipment technology or consumer demographics	More variety in the type of participants Many due to television beginning to see diving as not difficult as they once believed
1977	More energy saving devices More comfortable equipment in a variety of colours and sizes Divers can now dive with their brains not the backs	Still no real change Programmes needlessly weed out prospective participants	Much broader consumer base including any more females Accident rate still high
1978	Equipment and diving technology improving	PADI introduce the systems approach to diving training "The Open Water Diver Course" Course made easier by focusing on diver's requirements in line with new Technology	Consumer base begins to widen The blockbuster movie "The Deep" is released creating a large consumer interest
1984	The recreational diving market begins to mature Small lighter better design More attractive	BSAC introduce new diver training programme to meet the change in market demand	Wide range of participants Dramatic fall in accident rates in the USA

1994	"Nitrox" oxygen enriched air becomes widely available in the U.K. Dive computers to monitor decompression profiles for every diver cheap and readily available Introduction of the Draeger Dolphin Semi Close Circuit rebreather	Changes to diving instructor occur regularly to meet changes in technology	Accident statistics within the UK are falling the US begins to hit ar all time low Lusitania Expedition Technical divers operating to depths of 98 metres. Depths not thought of 5 years earlier
1995	Improved equipment design, wider choices better performance at depth	Introduction of "Technical Diving" in the U.K. allows divers to go deeper than ever before using alternative breathing mixtures	Whilst fatal accidents within the recreational community remair low. Fatalities within the technical diving community climb.
1997	Introduction of Closed Circuit Rebreathers to the recreational diving community	Limited to the experience of the designers	Fatalities begin to occur withir divers using this technology at ar alarming rate

Appendix 4

Task Analysis of a Descent looking at Open Circuit (Scuba), Semi Closed Circuit (SCR) and Closed Circuit Rebreather (CCR)

In any activity in order to gain understanding of the failures it is essential to have a comprehensive understanding of the task. As we have discussed we are looking for differences between the strong open circuit experience of a diver and the different skills needed during rebreather diving. The majority of descent tasks with time will become automatic. It is when the diver is on "autopilot" and reacts using the either wrong skill or forgets a step that the skill based errors evolve. As I have pointed out in my text it is my belief that these failures as a result of strong habit intrusion case incidents. Sadly we will never likely know how many times they have occurred and divers have "got away with it".

In order to gain a better understanding of these differences I have used *Task Analysis* in an effort to break down the task into a number of steps and to look for differences. Some of these difference could, if unchecked lead to difficulties during a dive.

I have, for the purposes of this dissertation I have only broken down in detail one aspect of a dive. However, it is this process, albeit mentally I used to look at all the failures I identified in Chapter 4. In all cases I have had both the task analysis and errors reviewed by other experienced divers.

As I have discussed in Chapter 4 a dive is made up of a number of distinct phases, which can be broken down into a number of steps, for example;

- **Surface.** On the surface, which covers planning, equipment preparation, equipment checks, buddy checks and entering the water prior to the descent.
- **Descent.** Starting the dive, noting time, orientation, venting, bubbles check, adjusting buoyancy, monitoring buddy, eliminating baratrauma due to squeeze and arriving on the bottom
- **Dive on the Bottom.** Monitoring depth and time, monitoring oxygen level if applicable, watching you buddy, checking and adjusting buoyancy and monitoring breathing gas supply, conducting the task.
- **Ascent.** Monitoring oxygen level, monitoring ascent rate, checking time and depth, checking buoyancy, venting expanding gas to prevent a rapid ascent, preparing if applicable for decompression stop and watching buddy. Thinking about gas switching if applicable.

- **Decompression stop.** Monitoring depth and time, checking and controlling buoyancy, and watching buddy.

- **On surface**. Establishing positive buoyancy, checking buddy for any unusual signs or symptoms. Shutting down and maintaining equipment

Task Analysis

Descent

No.	Open Circuit (Scuba)	Semi Closed Circuit (SCR)	Closed Circuit Rebreather (CCR)
1.	Thumb down	Thumb down	Thumb Down
2.		Check Oxygen Level in Bag*	
3.	Note Time	Note Time	Note time
4.	Orientate Feet	Orientate Feet	Orientate Feet
5.	Vent suit or Buoyancy device	Vent suit or Buoyancy device	Vent suit or Buoyancy device
6.	Begin Descent	Begin Descent	Begin Descent
7.	Equalise ears	Equalise ears	Equalise ears
8	Breath normally exhaling either through mouth or nose	Breath normally exhaling by mouth only	Breath normally exhaling by mouth only
9.	Monitor mask squeeze, exhale through nose as appropriate	Monitor mask squeeze, exhale through nose as appropriate being careful to maintain the breathing loop	Monitor mask squeeze, exhale through nose as appropriate being careful to maintain the breathing loop
10.		Check Oxygen Level in Bag*	Check hand sets to monitor Oxygen Partial Pressure
11			Manually top up breathing loop as required to optimum level of about 1 full breath using dilutant
12	Monitor and slow descent by either deep breaths or adding gas to either suit or buoyancy control device	Monitor and slow descent by adding gas to either suit or buoyancy control device	Monitor and slow descent by adding gas to either suit or buoyancy control device
13.	Continue descent at appropriate descent rate	At 5 metres stop and bubble check buddy then continue the descent at the appropriate descent rate	At 5 metres stop and bubble check buddy listen for solenoid valve toping up gas (unlikely though during descent) Continue descent
14.	Repeat Steps 7,8,9,10	Repeat Steps 2, 7,8,9,10	Repeat Steps 7,8,9,10,11

15.			At about 15 metres change set point on hand sets to upper limit
16.	On approaching bottom take a deep breath, slow descent and then using either suit or buoyancy devices trim for neutral buoyancy	On approaching bottom take a deep breath slow descent and then using either suit or buoyancy devices trim for neutral buoyancy	On approaching bottom take a deep breath slow descent and then using either suit or buoyancy devices trim for neutral buoyancy
17.	Check Gas supply	Check Gas supply Check Oxygen Level in Bag*	Check Gas supply, Check hand sets

Text in RED highlight operating differences between the systems

* Is an optional piece of equipment that my or may not be fitted to the breathing loop on semi closed circuit rebreathers

Each of the steps could be further broken down into a number of sub-steps identifying how each action could be conducted however this would show little additional information for the purposes of illustrating the differences.

For the purposes of this dissertation I have a used Job Orientated Task Analysis (Task Analysis Strategies and Practice, Bettina Lankard Brown, 1998) because is highly specific and looks at each distinct task required for the descent.

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Glossary of Technical Terms

Absorbent

A Chemical compound used to remove carbon dioxide from a diver's breathing gas in a rebreather. The compound is contained within the canister and forms part of the breathing loop. The primary ingredient is soda lime and as a result of its reaction with CO2 produces moisture and heat. Sometimes referred to as Sofnolime or Soda Sorb which are product brand names.

Ambient Pressure

The pressure surrounding the diver. The rough pressure change is plus or minus 1 bar for each 10 metres of depth in the water column.

Approved Code of Practice (ACOP)

An approved code of practice is a document prepared to give practical advice to industry on how to comply with the law.

Automatic Dump Valve

A valve designed to release air beyond a pre-set pressure. Such valves are often fitted to dry diving suits to prevent over-inflation of the suit or used as vent valves for semi closed circuit rebreathers.

Bailout System

A backup system used by divers in case their primary system fails. In most cases it is a completely redundant scuba unit capable of bringing a diver back to the surface safely if his primary breathing system fails.

Breathing Bag

A flexible bag that form part of a rebreather's breathing loop and serves as a reservoir for breathing gas.

Breathing Loop

The entire breathing pathway including the divers lungs, airways and well as the rebreather's breathing components including the breathing bag, canister, mouthpiece and hoses.

Barotrauma

Pressure related ailments that may occur in the air filled cavities of the body if fundamental principals of the interaction between pressure changes and body organs are ignored and are no equalised.

Bar

A measurement of pressure 1 bar being the equivalent of about 14.7 pounds per square inch or roughly 1 atmosphere.

Bottom Time

The total elapsed time from when the diver leaves the surface in descent to the time (next whole minute) that he begins his direct ascent.

Buoyancy Control Device (BCD)

A device worn by a diver containing a bag, which can be inflated or vented by him as, required in order to vary his buoyancy. A free swimming diver will seek to maintain a situation of neutral buoyancy at all times in order to swim easily, change depth and "hover" in mid-water during a dive.

Canister

The device within the breathing loop used to hold the carbon dioxide absorbent.

Contents Gauge

A pressure gauge attached to the gas supply of divers, which provides the diver with a constant read-out of the amount of gas remaining in his/her cylinder(s).

Closed Circuit Rebreather

A self-contained diving system that allows the diver to rebreath his exhaled gas having removed the contaminates through a chemical scrubber. The system is more gas efficient than scuba and allows divers to travel to deeper depths and carry considerably less gas than an open circuit diver would need. It can however be far more complex and difficult to dive and requires specialist training.

Decompression Obligation

A term used to define the fact that a diver has built up a requirement to decompress during a dive and this is related to the time the diver spends at depth and the depth of the dive. In order to meet this obligation the diver must perform a series of timed stops a various depths to release inert gas, the gas that causes decompression sickness.

Decompression Sickness

A condition that results from the formation of bubbles in the blood or body tissue, caused by inadequate decompression following a dive or other exposure to high pressure.

Decompression Stops

Specified depths at which a diver must remain for a specified length of time to eliminate inert gases from his body, thus preventing the onset of decompression sickness.

Decompression Tables

Decompression tables are used by divers for diving. They provide the diver with a depth timetable to allow him to plan his dive. It is from these tables that the diver would calculate his decompression obligation. They can be computer generated or can be a series of published tabulated tables listing the no decompression limits, decompression obligation and ascent rates for a variety of times and depths.

Depth Gauge

A gauge worn by SCUBA divers to provide a continuous read-out of the diver's current depth during the dive.

Distance Line

A reference line that is connected to the shot line at the seabed and is usually contained on a reel. As the diver swims away he pays out the line and then recovers it on his return this enabling him to return to the shot or anchor line for the purposes of ascent and decompression.

Dive Computer

A device worn on a divers arm or high-pressure hose that continuously monitors the diver's depth, time and subsequently automatically calculates his decompression obligation.

Diving Regulators (or Demand Valves)

The purpose of a diving regulator is to reduce the high-pressure air in the diver's cylinders (typically 200 bars) to a pressure, which can be breathed by the diver and to deliver the air as required at a sufficient flow rate. This is usually achieved in two stages. In the first stage, high-pressure air from the cylinder is reduced by a regulator to level approximately 8 to 11 bars above ambient (this figure varies between manufacturers). In the second stage contains a moveable diaphragm, which is linked to a low-pressure valve by a lever mechanism. When the diver breathes in through the mouthpiece on the second stage this arrangement feeds gas "on demand" to the diver at the appropriate pressure and at the appropriate rate. These systems are also used as the basis to provide gas to the diver's breathing loop on a rebreather.

Dry Suits

This type of diving suit is designed to prevent the ingress of cold water so encasing the diver's body in a warm, insulated environment. Dry suits are usually fitted with attached boots and tight seals at the wrists and neck and through the suit inflation whip have a method of introducing gas into them to prevent "squeeze". Squeeze is as a result of the air filled spaces in a suit becoming compressed at depth.

Half Mask

A mask designed to protect the face and nose of the diver from the water and to provide maximum visibility by putting a layer of air between the lens of the eye and the water, thus permitting the eye to focus underwater.

Hypercapnia/ Carbon Dioxide Poisoning (CO_2 poisoning)

An excess of carbon dioxide that can be caused by a number of things including poor diving technique, failure of the absorbent to remove carbon dioxide. In can lead to mental confusion and ultimately death

Line Reel

A reel used by divers with about 30 to 100 metres of line to assure a known exit path. It can be used by a diver for decompression diving by supplying a guideline back to the anchor or shot line.

Manifold Twin Cylinders

When two cylinders containing breathing gas are used by SCUBA divers these are generally joined together by a manifold of pipe work so that both cylinders can have their supplies of gas routed to the diver through a single diving regulator.

Nitrogen Narcosis

When increased partial pressures of nitrogen gas are breathed by divers, symptoms of narcosis or anaesthesia are induced. Effects are similar to those of alcohol consumption (slowing of mental function, amnesia, fixation of ideas, slowing of reaction time, general euphoria, disregard for personal safety). The higher the partial pressure of nitrogen the more pronounced are the effects.

Normoxic Trimix

A breathing gas that contains a mixture of helium oxygen and nitrogen used for deep diving. The oxygen percentage is based on air i.e. at about 21%, which means in theory that the gas is only safe to 62 metres due to the potential risk of oxygen toxicity.

Omitted Decompression

When a diver surfaces without completing all of his decompression stoppages it is likely that his body tissue will still contain an excessive loading of inert gas. The danger is that at surface pressure this excess gas will come out of solution in the body and cause decompression sickness. Divers who have omitted some or all of their decompression stoppages need to be recompressed (usually in a recompression chamber) as soon as possible in order to avoid the possible onset of decompression sickness.

Oxygen Cells

Cells or sensors that are used to monitor the level of oxygen in the breathing loop.

Oxygen Fitting, Oxygen Toxicity, Oxygen Poisoning

High partial pressures of oxygen are also capable of producing toxic effects. An extreme case of oxygen toxicity can cause fits (an extremely dangerous occurrence for any diver), with drowning being the almost inevitable result for a SCUBA diver. It also posses a serious hazard for in rebreather divers whose mix is incorrect. HSE recommends a maximum partial pressure for oxygen of 1.5 atmospheres for surface supplied diving. This partial pressure of oxygen is achieved when air is breathed at a depth of 62 metres.

Partial Pressure

Dalton's law states that in a mixture of ideal gases, the partial pressure of each gas component is the same as the pressure would be if the single component were alone and occupied the total volume. The total pressure of a mixture is therefore the sum of the partial pressures of each gas component. For example at 1 bar pressure air (21% oxygen and 79% nitrogen) has a partial pressure of oxygen equal to 0.21 bars, and a partial pressure of nitrogen equal to 0.79 bars. At 2 bars pressure air has a partial pressure of oxygen equal to 0.42 bars, and a partial pressure of nitrogen equal to 1.58 bars (the sum of these partial pressures totalling the 2 bars of pressure).

Pony Cylinder

A small diving cylinder, which usually contains about 600 litres of free gas. Divers use the cylinder for decompression or as a bailout in the event of an emergency from moderate depths. These cylinders are also used as the main gas supply for closed circuit rebreathers and also used for bailout systems on rebreathers.

Recompression Chamber

Divers who have omitted to carry out necessary decompression or who have symptoms of decompression sickness must be recompressed to prevent or reduce the formation of bubbles in their bodies. Recompression chambers are surface facilities that can be pressurised with people inside them and will allow controlled return to surface pressure in closely supervised circumstances. This is the only effective treatment for decompression illness.

SCUBA

An acronym for Self-Contained Underwater Breathing Apparatus. SCUBA divers carry all the necessary gas to survive underwater with them.

Semi closed Circuit Rebreather

A Semi Closed Circuit rebreather (sometimes referred as **SCR**), is very simpler by nature as it has no electronic control system, units continuously feeds the diver between 4 and 10 litres per minute with a pre-set breathing mixture dependent on the maximum depth of his dive. The majority of the gas is kept within the breathing loop thus radically reducing the gas wastage that SCUBA has and dramatically increasing a diver's potential endurance.

Set Point

The pre-selected setting at which the oxygen controller (software) maintains the oxygen level (PPO2) within the breathing loop. In the cases of some rebreathers this set point can be changed manually during the dive.

Sofnolime/Sodasorb

Brand name chemical compounds that are used to remove carbon dioxide from the breathing loop. These chemicals are contained within the canister.

Stage Cylinder

These are extra scuba cylinders generally used by the diver to carry out decompression, independent from a boat or decompression stage.

Standby Diver

A diver on the surface kept in full readiness to dive should he be required to render assistance to a diver or divers in the water.