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SEA SYSTEMS COMMAND

DEPARTMENT OF THE NAVY
EXPERIMENTAL DIVING UNIT

Navy Experimental Diving Unit

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FOREWORD

The spectacular rise of self-contained diving in recent years has left authoritative Naval literature far behind in the subject. Several large gaps now appear in the material which can be assembled readily to provide basic information and comprehensive coverage of the field. Incidental to a revision of the Diving section of the Manual of Submarine Medical Practice, these reports were written to fill some of the gaps. Because of its origins, the series has a special format and contains many specific medical references. However, it covers the field of self-contained diving as completely as possible.

Considerations of printing costs made it desirable to coalesce the reports into a single volume instead of reprinting eleven separate reports. Consequently, the following changes have been made.

(1) Individual report cover sheets and forewords have been eliminated in favor of a single cover sheet and this foreword.

(2) Errata listed in the original explanatory notes have been corrected in this revision, and the list has been dropped.

(3) All other changes in written material have been clearly labeled "Change #1". This change is effective as of February 1955.

(4) Changes in form, such as rearrangement of figures and captions, have not been labeled.

The original forewords invited anyone who found discrepancies either in form or in substance to submit his findings and criticisms to the Experimental Diving Unit, so that the appropriate changes can be incorporated in subsequent revisions. Despite a widespread distribution of the reports, no specific criticisms were made. Changes in written material are therefore minor, reflecting only information arising from recent EDU studies. Nevertheless the invitation to criticize remains open.

Change #1

EXPERIMENTAL DIVING UNIT
SPECIAL REPORTS 1-54 THROUGH 11-54

"SELF-CONTAINED UNDERWATER BREATHING APPARATUS"

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PREFACE

"DIVING WITH SELF-CONTAINED UNDERWATER BREATHING APPARATUS"
(Special Report Series - 1954)

Special Reports 1-54 through 11-54 have been assembled to provide coverage for a specialized field in diving which to date has not been surveyed adequately in any authoritative publication. These reports are being incorporated almost unaltered into the Manual of Submarine Medicine Practice (NavPers 10838), and are currently being rewritten in a less medical vein to fill the need for a training manual on self-contained diving. Although the reports are intended to be unbiased, they may contain controversial material in those sections where policies have not been formulated because of a lack of information. Wherever possible, those sections are slanted strongly toward the side of safety.

These reports are not a substitute for the Bureau of Ships Diving Manual. They are purely secondary to the Diving Manual, and any discrepancy must be resolved in favor of that publication. The Bureau of Ships is preparing a section on self-contained diving, for incorporation into the Diving Manual. Its promulgation will then put the Bureau of Ships authoritative stamp of approval on any material from these reports which is incorporated into the Diving Manual.

The overall table of contents preceding this section of the introduction lists the titles of all the reports, and the number and heading of each section; it does not list the number and heading of any sub-section. Sub-section listings can be found in the individual table of contents for each report.

In the remaining section of this introduction, the acknowledgments give credit to those persons who assisted in preparing the reports. The explanatory notes clarify the system of numbering and the method of referencing. The corrections do not include typing or spelling errors which are obviously such and which do not affect the context.

ACKNOWLEDGMENTS

"DIVING WITH SELF-CONTAINED APPARATUS"
(Special Report Series - 1954)

Production of the finished reports involved many manhours of labor, consultation, and research not apparent in the assembled work. Typing of several rough drafts, a smooth copy, and a finished hecto master preceded duplication of the typewritten pages. Rough sketches, pencil layouts, and inked drawings preceded duplication of most of the figures. These acknowledgments place the credit for these operations where credit is due - directly on the Yeoman and Draftsman attached to the Experimental Diving Unit. Their patience in re-doing finished work to match a change in information was remarkable and highly commendable. Without their able help these reports would still be months away from completion.

EXPLANATORY NOTES

"DIVING WITH SELF-CONTAINED APPARATUS"
(Special Report Series - 1954)

1. Chapter and section numbers:

The series consists of eleven special reports (1-54 through 11-54), each constituting a "chapter" on a given aspect of the subject. The chapters are broken down into sections and sub-sections by a "decimal" numbering system. In this system the first number shows the chapter; the second, the section, the third, the sub-section.

Example: 6.3.2 (Chapter 6, Section 3, Sub-section 2).

2. References:

An attempt was made to assist the reader by providing as many useful references as possible. These are of several types and can be distinguished by the numbering used:

a. Cross-references within this series. These are designated by the regular section numbers as discussed above.

Examples: 9.0.0 (Chapter 9)
11.4.0 (Chapter 11, Section 4)
2.1.3 (Chapter 2, Section 1, Sub-section 3)

b. References to other parts of "Submarine Medicine Practice". Because this series was intended for incorporation as a section of "Submarine Medicine Practice", the existing sections were categorized into IA (Diving and Underwater Medicine Practice) and II (Submarine Medicine Practice), so that this series could be inserted as IB (Medical Aspects of Self-Contained Diving). The references therefore indicate one of the existing sections, the chapter number in that section, and the sub-chapter. In this system "(IA-2B)" is a reference to the section on diving Chapter 2, Sub-Chapter B (Physiology of Diving). Although the references were originally intended to apply to the revised edition of the book, the chapter numbers themselves were revised before the book went to press, so that the references no longer apply. However, the material is generally in the chapter indicated. Since the revised edition contains this entire report series, anyone who has a copy of the new edition should refer to it exclusively.

c. References to the Diving Manual. These are indicated by the letters "DM", followed by the appropriate article number.

d. References to other sources. A list of such references is provided at the end of many of the chapters. An individual reference is designated by a small letter preceded by the number of the chapter in which it is found.

Example: (6m) (Reference "m", listed at the end of Chapter 6.)

3. Figures, tables, and formulas:

These are designated by numbers such as "Figure 6-2" or "Formula 9-2". The first number is that of the chapter, the second is that of the figure, table, or formula in order of its appearance in the chapter.

4. Page numbers.

Originally the pages of each report were numbered separately, however, they have been changed to read consecutively.

Conflicting policy matters required judicious decisions from the senior officers, who gave unstintingly of their time in lengthy consultations and conferences. In all their decisions, they ascertained that the conflicting material was brought into line with established Navy policy as specified in the Diving Manual, the Bureau of Ships Manual, the Manual of the Medical Department, and the Bureau of Naval Personnel Manual. In those areas where Navy policy is not yet established, they insured that conflicts were resolved on the side of safety.

One acknowledgment which is especially necessary is the extensive use of an existing publication as a basic guide for one of the reports. Special Report 4-54, "Safety Considerations in the Use of SCUBA", is in large part an expansion of the National Research Council Publication 274 "On Using Self-Contained Underwater Breathing Apparatus", by Walter A. Hahn and Christian J. Lambertsen. The National Research Council Panel on Underwater Swimmers, of which Dr. Lambertsen is the chairman, is currently preparing a more comprehensive manual on self-contained diving, which will ultimately supersede Publication 274.

The following people deserve special mention:

LCDR Walter K. WILSON, U. S. NAVY: Former Officer in Charge

CDR Moffitt K. HOLLER (MC), U S. NAVY; Senior Medical Officer

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Harry G. HENLEY, DMSN, U. S. NAVY; Draftsman

CHAPTER 1

DIVING WITH SELF-CONTAINED UNDERWATER BREATHING APPARATUS

CONTENTS

CHAPTER 1

DIVING WITH SELF-CONTAINED UNDERWATER BREATHING APPARATUS

1.1 IMPORTANCE IN MODERN DIVING

Self-contained underwater breathing apparatus was invented and used in various forms long before World War II. Widespread appreciation of its general potentialities and military applications did not occur, however, until events of that conflict and subsequent developments focused attention upon the unusual capabilities of divers who need no connection to the surface.

Italian Navy "limpeteers" were able to inflict severe damage on elements of the British fleet in supposedly safe anchorages. Subsequently, the British adopted similar techniques. They found self-contained apparatus useful in such operations as clearing mines from harbors, and they were able to damage the German battle cruiser TIRPITZ, which had been relatively immune to other forms of attack, in a Norwegian fjord. By equipping operational swimmers of the Office of Strategic Services with Lambertsen Amphibious Respiratory Units, the United States demonstrated the value of free diving in reconnaisance and in demolition of underwater obstacles.

Meanwhile, during the occupation of France, Cousteau and Gagnan, working toward a practical method of using compressed air in self-contained apparatus, developed the Aqua-Lung. This equipment was used extensively in underwater exploration and photography. Wide publication of accounts and photographs of these developments attracted much interest to this field. An increase of general interest in "skin diving" with mask and swim-fins for spearfishing and such activities paved the way for eager acceptance of underwater breathing devices among sportsmen.

The importance of self-contained underwater breathing apparatus, which has come to be referred to as "SCUBA" for the sake of convenience, lies only to a minor degree in its ability to replace standard deep sea and lightweight diving gear. These remain superior in many of the jobs for which they have long been used. The great contribution of SCUBA has been the opening-up of vast new fields of underwater activity.

The potentialities of self-contained diving equipment have received increasing recognition in recent years. Consequent expansion of the applications and use of such gear has, in effect, profoundly altered the total aspect of diving. Diving has become not only an effective offensive weapon and a necessary element of defense but also a valuable adjunct to scientific work, a familiar activity of sportsmen, and in some areas even a popular pastime. As a result, diving medicine has acquired a new significance, new problems, and new responsibilities.

1.2 IMPLICATIONS IN DIVING MEDICINE

While the use of self-contained breathing apparatus permits a man to enter the underwater environment with unaccustomed freedom, his liberation from heavy equipment and from the necessity of surface connections does not exempt him from any of the physical and physiological realities of diving.

Development of SCUBA has therefore solved none of the basic problems of diving medicine; instead it has given considerable importance to clinical and physiological factors which could once largely be neglected. These demand extensive study if the ultimate capabilities of SCUBA are to be realized and if the safety of users is to receive due attention.

The practice of diving medicine is also becoming more demanding and more difficult. For example; personnel selection has assumed new importance since diving now includes activities requiring large numbers of men with exceptional physical, mental, and emotional qualifications. Diving has heretofore been confined to a relatively small group of trained and qualified men doing a circumscribed number of jobs under close supervision. Medical personnel and facilities for the treatment of casualties have generally been available. Now, a quite different situation must be foreseen: large numbers of men engaged in diving activities of diverse types; jobs having unique problems; greater difficulty in providing sufficiently extensive and specific training; and undertakings in which close supervision and control from the surface is, by definition, impossible. It will also be impossible to provide recompression chambers and other facilities for many such operations.

Although the vast increase in diving activity among civilians is not the direct concern of Naval medical personnel, it does present problems which deserve mention. In general, the essentials of good diving condition, training, and supervision all tend to be overlooked in the deception of ease and simplicity which surrounds SCUBA diving. Provisions for treatment of casualties are seldom adequate. Authoritative publications on the whole subject have been essentially non-existent. In particular, there are few qualified individuals who can provide accurate information.

The most crucial factors in safe SCUBA diving are clearly medical in nature, yet the average physician understandably knows little or nothing about diving medicine. No civilian medical specialty encompasses more than a fragment of the field. Physiologist are rarely acquainted with more than a few diving problems. Naval medical officers trained in diving medicine are thus almost alone in their ability to offer competent guidance. In turn, they must realize that SCUBA diving presents problems not encountered in standard diving operations, that it has many aspects of a new field, and that continued development must be expected. Such medical officers should be willing to give all practicable advice and assistance to civilian institutions and organizations which employ SCUBA diving and which are trying conscientiously to improve their practices and regulations from the standpoint of safety.

1.3 OBJECTIVES

The section on medical aspects of diving with self-contained apparatus was included in this edition of Submarine Medicine Practice with the intention of providing, as well as possible, a compilation of the essentials of present knowledge in this field. Its coverage is by no means exhaustive, and it is not intended as an instruction manual in the use of SCUBA.

The material has been compiled at an unfortunate time in the sense that the field it covers is at an early stage of development in all respects. In many connections, it can do no more than state that a problem exists and that study is required. New problems are bound to arise or to be recognized. More applications of SCUBA diving will be found, and these will necessitate additional investigations. Improvements in apparatus and techniques are inevitable. In a sense, however, it may be that this is the stage of development at which a compilation of this sort can be most valuable.

1.4 COMPARISON WITH CONVENTIONAL EQUIPMENT

1.4.1 Advantages

Elimination of the need for connections between the diver and the surface gives self-contained apparatus one great advantage over conventional gear: mobility. Elimination of heavy equipment either underwater or at the surface also contributes to this advantage.

The SCUBA diver cannot only be free of hose and line but he may maintain neutral buoyancy if he desires and then propel himself in any direction underwater by swimming. This mobility means that he can cover considerable distances underwater. Furthermore, if necessary, he may submerge in one area, work in another, and return without surfacing at any time. Propulsive devices or submersible craft can extend the range of his activities to a remarkable degree. A man using SCUBA can also change or maintain depth at will, and thus, he can work at mid-depths without rigging. He can enter spaces which may be inaccessible to divers in standard dress. His equipment is such that his bodily movements are essentially unencumbered.

What might be called "topside mobility" also has important aspects. Setting up a diving operation with SCUBA requires little more than providing the breathing apparatus, which is readily transported to the scene.

Mobility is clearly desirable in many underwater operations and is essential in some. From the military standpoint, the underwater mobility of SCUBA is particularly important because it allows stealthy entrance into otherwise unapproachable areas.

1.4.2 Disadvantages

The superiority of SCUBA over conventional gear requires little elaboration where mobility and its adjuncts are of major consequence, but there are other considerations.

Two important and interrelated factors which may constitute serious disadvantages in SCUBA are duration and depth. There is obviously a limit to the amount of gas which a diver can carry. This limit exceeds a man's normal ability to remain underwater only in oxygen closed-circuit systems (2.2.0); but here, unfortunately, the depth to which the diver may go is strictly limited by the danger of oxygen poisoning (8.0.0). With an open-circuit air-demand system (2.1.2), the hazards of nitrogen narcosis (5.8.0) impose the primary limit on depth. However, the duration of air supply becomes vanishingly short at greater depths, and the added necessity of decompression stops on ascent may reduce the available bottom time to nothing unless special arrangements for decompression are made (7.3.1). Working dives of significant duration are generally impractical with such gear beyond 130 feet.

The use of mixed-gas apparatus (9.0.0) permits relatively deep diving with definite decompression advantages, but the possibility of oxygen poisoning imposes limits on both depth and duration of exposure. Although gas is conserved by rebreathing, the available supply may also prove restrictive.

The prized mobility of a SCUBA diver may be a positive disadvantage in numerous situations. Some jobs require heavy work in one spot or considerable stability for various reasons. These tasks necessitate special rigging, additional weights, or both. In strong tides or currents, the SCUBA diver may be useless or even in actual danger without such aids as a lifeline, descending line, and weights. Where visibility is poor or non-existent, the necessary arrangements for searching and similar jobs may differ little from those used with conventional gear. Communication - the ability to transmit and receive information readily - is frequently crucial and is most easily attained by direct telephone connections. Because of the depth-duration limits of SCUBA, many situations requiring deep or prolonged dives will favor use of the familiar accessories of conventional diving.

If the underwater mobility of SCUBA must be severely limited in order to accomplish the purpose of a dive or to safeguard the diver, it will often be wiser to use conventional gear. In some situations, however, the advantage of mobility at the surface may govern. If an adequately equipped diving vessel is not readily available, SCUBA may have to be used even though conventional gear would be preferable.

Although the ability of SCUBA divers to do hard work has often been questioned, one of their most frequent activities, underwater swimming, can involve as great oxygen consumption and ventilation as is encountered in any form of work (6.1.0). However, breathing resistance (6.7.0) is inevitable to some extent in SCUBA and represents a serious problem in many available models. This factor does unquestionably set a limit on the extent of a man's exertion in SCUBA. In standard deep-sea dress, the man has free access to the air in his helmet without any interposed valves or tubing, and the supply from the surface is essentially unlimited. Here breathing resistance is minimal. Breathing resistance is an important consideration at greater depths, where the increased density of air produces noticeable difficulty in breathing, even without apparatus. The problem of carbon dioxide absorption may also limit work in some SCUBA types.

These considerations do not of themselves make a clear case for the use of suit and helmet wherever work is involved. A large part of the work of many diving jobs may be attributed to the equipment rather than to the necessities of the situation. For example, searching on a muddy bottom is extremely hard work for a diver in deep-sea dress. The same search made by a SCUBA diver swimming just above the bottom, or walking with light shoes and barely negative buoyancy, would require much less work. The same principle applies in other situations where cumbersome gear increases the effort without making a positive contribution to the job.

1.4.3 Relative Merits

Many arguments arise about the relative merits of standard equipment and self-contained gear where either might be used. Most of these appropriately center about the safety of the diver. They concern such matters as the reliability of an air hose as opposed to cylinders carried by the diver, or the protection afforded by a heavy suit in contrast to greater mobility and the possibility of ascending to the surface without equipment in an emergency. A need to enter confined spaces is bound to raise the question of whether a lifeline and air-hose are a real safeguard or a positive hazard in such circumstances. Such questions cannot usually be answered except within the framework of specific situations. There, if an appreciable difference in safety exists, the answer will generally be clear. In some such cases the answer will depend upon the SCUBA available. Where the type has certain inherent hazards, minor disadvantages of standard gear would almost always be accepted in preference.

The lightweight diving outfit, which consists basically of a hose-supplied facemask, deserves special consideration since it embodies advantages and disadvantages of both standard and self-contained apparatus. It requires connections to the surface, but it retains a considerable degree of mobility and freedom of body movement. The diver does not have to wear the suit which is provided, except as protection against cold or contaminated water and similar adverse conditions. Because it is not inflated, the suit has little excess buoyancy. The weights are relatively light and are attached to a belt secured by a quick-release buckle. Although its use is currently limited to relatively shallow water, optimum development of this type of equipment would probably result in a rig which, when used with an air-hose, could supplant present suit-and-helmet gear to great advantage. Minor modifications would permit use of a self-contained gas supply with this outfit.

The concept of such a rig at least serves to emphasize the fallacy which underlies many current discussions of the relative merits of air-hose and self-contained gear. The term "self-contained" implies only that the supply of respirable gas is independent of surface connections. The additional connotation of great mobility and lack of stability is quite accidental. In reality, a diver using modern SCUBA and non-inflated suit can achieve greater stability with less weight than can a man in deep-sea rig. This is true because the uninflated suit requires practically none of the weight to compensate excess buoyancy and because it presents a much smaller total surface area to tide and currents.

There is no compelling reason that a SCUBA diver cannot have good stability where it is required nor that a diver who uses an air-hose cannot have either reasonable local mobility or stability, depending on the situation. And in neither case does stability have to involve extreme clumsiness.

1.5 MILITARY APPLICATIONS

A growing number of diving operations, particularly those of military importance, are beyond the capabilities of conventional gear either because they must be conducted in the face of the enemy without detection, because the limitation of mobility by surface connections cannot be tolerated, or because logistic problems require highly portable equipment.

1.5.1 Offensive operations

Many of the characteristic operations of Underwater Demolition Teams can be conducted without SCUBA, but the ability to approach enemy beaches without surfacing is highly advantageous. In bottom reconnaisance or in location and demolition of underwater obstacles, the operations are primarily diving tasks. Development of surface detection equipment may preclude the use of surface swimmers for these tasks on account of the danger to the men and because of the probability of compromising a projected invasion. With SCUBA, detection is less probable, and the swimmers retain the advantages of freedom and direct observations.

Direct attacks on ships will require SCUBA for work beneath the ships as well as for undetected approach and safe departure. Landing parties with the ability to approach submerged can make successful raids even on closely guarded installations.

1.5.2 Defensive operations

Adequate defense may require SCUBA even though it does not directly involve the problem of detection. SCUBA divers may prove to be the only effective defense against direct attacks on shipping. Interception by underwater swimmers and hand-to-hand combat are only remote possibilities, but periodic ship-bottom search may be essential. The slow progress of a diver encumbered with surface connections may make self-contained apparatus mandatory for that job.

Locating and inactivating mines may present similar problems. If the type of mine or its position precludes working from the surface, diving may be the only alternative. Then the limitations of speed and mobility imposed by surface connections may dictate the use of SCUBA.

1.5.3 Miscellaneous operations

In the rare situation where proximity to the enemy would expose a surface vessel to undue danger, SCUBA may provide the only way to accomplish a job, even when mobility or stealth are unimportant and conventional equipment is more suitable. Sometimes portability may be the determining factor, particularly in small Naval vessels with infrequent requirements for diving. Occasionally logistic problems alone may necessitate SCUBA, as in bridge construction by mobile land forces.

1.6 CHOICE OF EQUIPMENT

The specific situation will generally determine the choice of equipment. A need for mobility or stealth will require SCUBA. Special requirements of depth and duration may dictate conventional gear. Occasionally the choice may not be clear-cut. Requirements for standard diving accessories largely cancel out the advantages of self-contained apparatus. The safety of the diver is always the prime consideration. Conventional gear usually meets safety requirements best, although not invariably.

Those responsible for the safety of divers must be well aware of the factors affecting safety. In a given situation the characteristics of the different types of SCUBA (2.0.0) will generally influence the decision. No dogmatic rules will cover all situations, but the following will help in selecting the type of gear for a given job. Most of the factors mentioned affect each other to some extent, and the list does not cover all circumstances.

1) Job requirements

a) For ability to cover considerable distances or to move easily from place to place underwater, SCUBA is required.

b) For ability to move freely but over short distances, SCUBA is desirable and lightweight gear is suitable.

c) For freedom of bodily movement, SCUBA or lightweight gear is suitable.

d) For stability in one spot, SCUBA can be used only with weights, and a lifeline and other rigging may be required; conventional gear is usually preferable.

e) For entry into enclosed spaces, SCUBA may be required. A lifeline is desirable, and close tending by another SCUBA diver is mandatory. Depending on the danger of fouling, air-hose equipment may be preferable.

2) Extent of exertion

a) For light work, SCUBA is suitable.

b) For heavy work, SCUBA is not generally desirable. The lightweight outfit may serve, but the deep-sea rig is probably preferable.

3) Depth and duration

a) For any reasonable duration at depths beyond 200 feet, SCUBA is unsuitable.

b) Between 130 and 200 feet:

(1) For long durations SCUBA is unsuitable.

(2) For short durations the deep-sea rig is generally preferable. SCUBA is usable if absolutely necessary (air-demand open-circuit gear for very short durations, and mixed-gas closed or semi-closed circuit gear for moderate durations). Decompression is the principal complication.

c) Between 60 and 130 feet:

(1) For very long durations SCUBA is unsuitable.

(2) For moderate durations air-demand or mixed-gas SCUBA is satisfactory.

d) Between 30 and 60 feet:

(1) For long durations SCUBA may be used.

(2) For moderate durations SCUBA is satisfactory.

(3) For brief duration SCUBA may be preferable.

e) Between 0 to 30 feet for reasonable duration all types of SCUBA are suitable.

4) Summary

a) For any duration beyond 200 feet SCUBA is unsuitable.

b) Between 130 and 200 feet SCUBA should be avoided when possible, although air-demand and mixed-gas apparatus may be used for some short-duration dives.

c) Between 30 and 130 feet air-demand and mixed-gas SCUBA is satisfactory for moderate duration dives.

d) Between surface and 30 feet SCUBA has maximum usefulness.

CHAPTER 2

TYPES OF SELF-CONTAINED UNDERWATER BREATHING APPARATUS

CONTENTS

CHAPTER 2

TYPES OF SELF-CONTAINED UNDERWATER BREATHING APPARATUS

The variety of available underwater breathing units is increasing constantly. Individual characteristics of the different types not only influence their suitability for various purposes but also present varied physiological considerations. Responsible personnel should be fully acquainted with the distinguishing features of the classes into which the units fall.

Classification of self-contained apparatus may be approached in several ways. In general, the most important question is whether the system involves rebreathing of the respired gas.

2.1 OPEN-CIRCUIT SYSTEMS

In an open-circuit system, rebreathing does not occur unless poor design gives the system some dead space (6.5.0). In a well-designed apparatus, the lungs take in a given volume of breathing medium only once. At least two arrangements have this characteristic.

2.1.1 Open-circuit continuous flow system

This system is merely a self-contained substitute for the ordinary air hose with continuous flow. A simple example is a shallow-water facemask furnished with air from cylinders carried by the diver rather than from a surface supply through an air hose. Since the flow has to meet the demands of inspiration, and since it continues during expiration, the cylinders must provide at least twice the diver's minute volume of respiration. The waste will soon exhaust any reasonably portable cylinders. A reservoir bag to accumulate incoming air during the expiratory phase can reduce waste. However, in either arrangement the flow has to be adjusted to meet changes in the man's respiration. Such systems have been used, but they are generally impractical.

2.1.2 Open-circuit demand system

Release of the compressed gas to meet only inspiratory requirements yields maximum conservation of the gas supply. A "demand" valve controls the release automatically. This is a special low-pressure regulator which maintains the breathing system at ambient depth pressure, opening to a slight negative pressure at the start of inspiration and remaining open only until the end of inspiration. Figure 2-1 illustrates the basic principle used by almost all demand valves.

Successful adaptation of a demand valve to diving apparatus is not so simple as it might seem (6.7.3). It is a relatively recent development which was almost revolutionary because it made the use of compressed air in self-contained apparatus really practicable for the first time. Demand systems are virtually the only type of open-circuit apparatus in use.

2.1.3 Demand system components

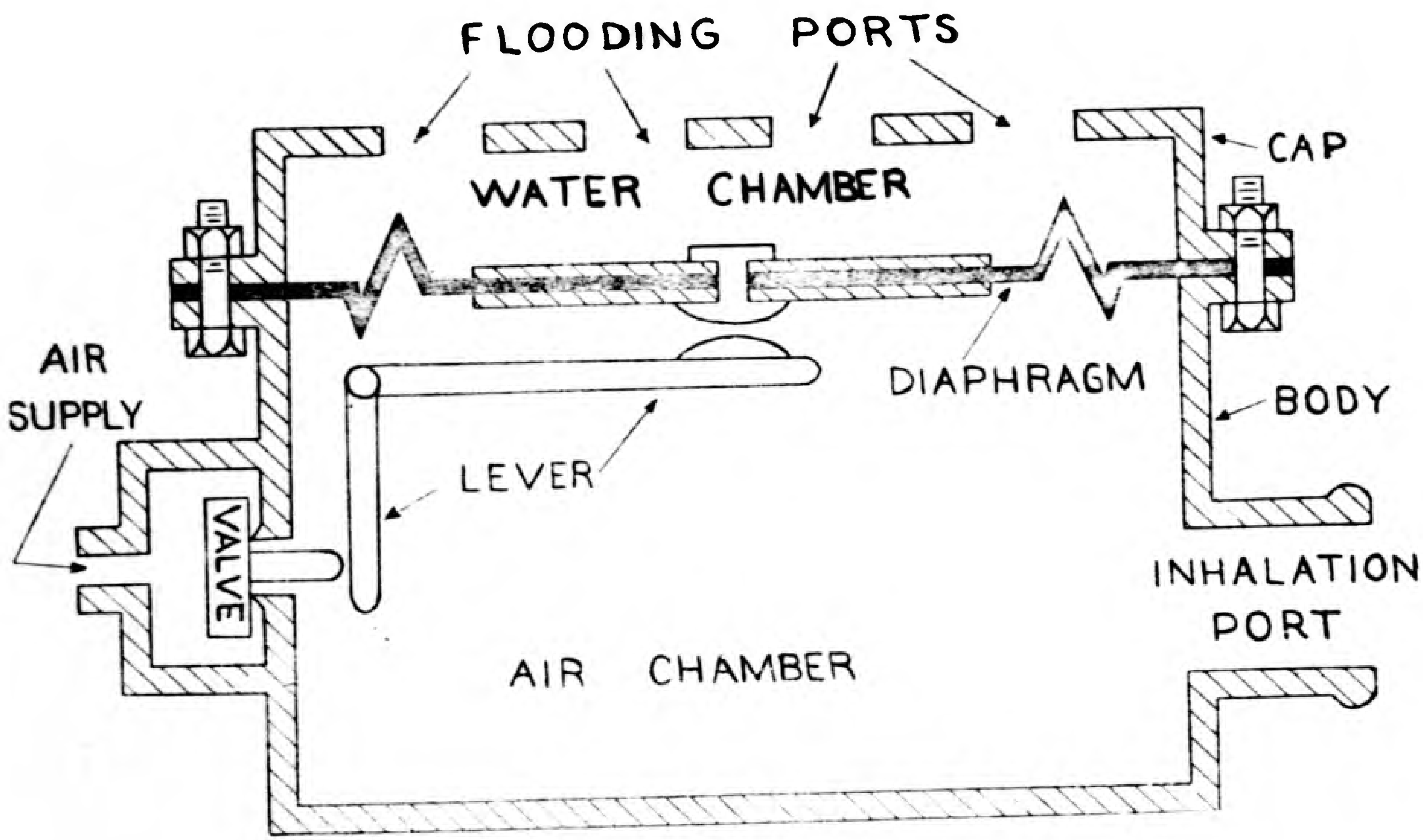
The schematic diaphragms in Figures 2-2 and 2-3 show the basic components of two common open-circuit demand systems. One or more cylinders supply compressed gas to the demand valve. The cylinder charging pressure is usually 1800 psi or more, but most demand valves are designed to operate at a lower pressure, near 100 psi. For these, a first-stage regulator provides the necessary reduction in pressure. The demand valve furnishes the breathing medium to the diver through a mask or mouthpiece. An exhaust valve discharges the exhalation directly to the water.

The actual arrangement of the components varies considerably among the different makes of demand apparatus. In the Cousteau-Gagnan "Aqua-Lung" (Figure 2-4), the reducing valve, demand valve and exhaust valve form an integral unit mounted on the high pressure manifold. The cylinders are worn on the back with the manifold up, so that the demand unit rides near the nape of the neck. A corrugated rubber hose supplies gas from the demand valve to a mouthpiece. Another corrugated hose carries the exhaled gas to the exhaust valve, which discharges the gas to the water. The position of the exhaust valve close to the demand valve diaphragm minimizes the hydrostatic pressure differential between the two valves, so that inhalation and exhalation occur at nearly identical hydrostatic pressures.(6.7.3).

The Northill experimental "Air-Lung" (Figure 2-5) uses the same arrangement of components. However, it has no intermediate-pressure regulator because the demand valve is designed to work directly from cylinder pressure. Furthermore, the exhaust valve is integral with the demand valve diaphragm, and exhaust occurs through the diaphragm from a chamber which is isolated from the demand valve itself. This arrangement subjects the demand and exhaust valves to exactly the same hydrostatic level.

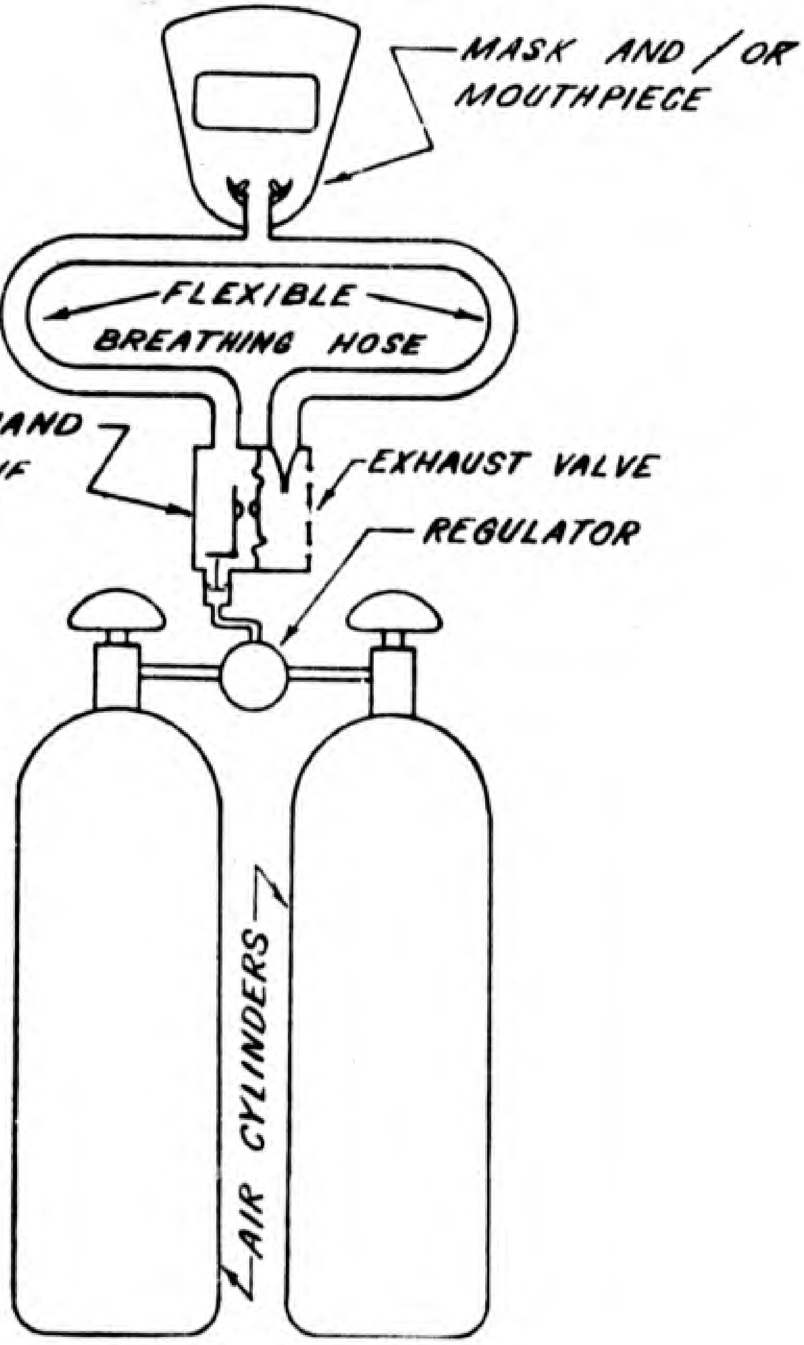
The Scott Aviation Corporation "Hydro-Pak" (Figure 2-6) uses a completely different arrangement of the components. The cylinders, secured to a backplate, can be worn with the stop valves up or down. The first-stage regulator is integral with the high-pressure manifold. Flexible rubber tubing supplies low-pressure air to the demand valve. This valve is molded directly into the right side of the mask, which replaces the mouthpiece. The exhaust valve, molded into the left side of the mask, discharges the exhaled gas to the water. A special pressure-balancing mechanism subjects the exhaust valve to demand valve pressure and compensates for hydrostatic differentials between the two valves.

In addition to the basic essentials, open-circuit systems should include two important safety features: a low-pressure warning device and a means of clearing water from the breathing system. Each of the apparatuses described above has a spring-loaded "air-reserve" valve. When cylinder pressure drops to about 500 psi, this valve restricts the air flow, causing an increase in breathing resistance which signals approaching exhaustion of the gas supply. The air-reserve valve has a manual release so that the remaining gas supply is available for surfacing.



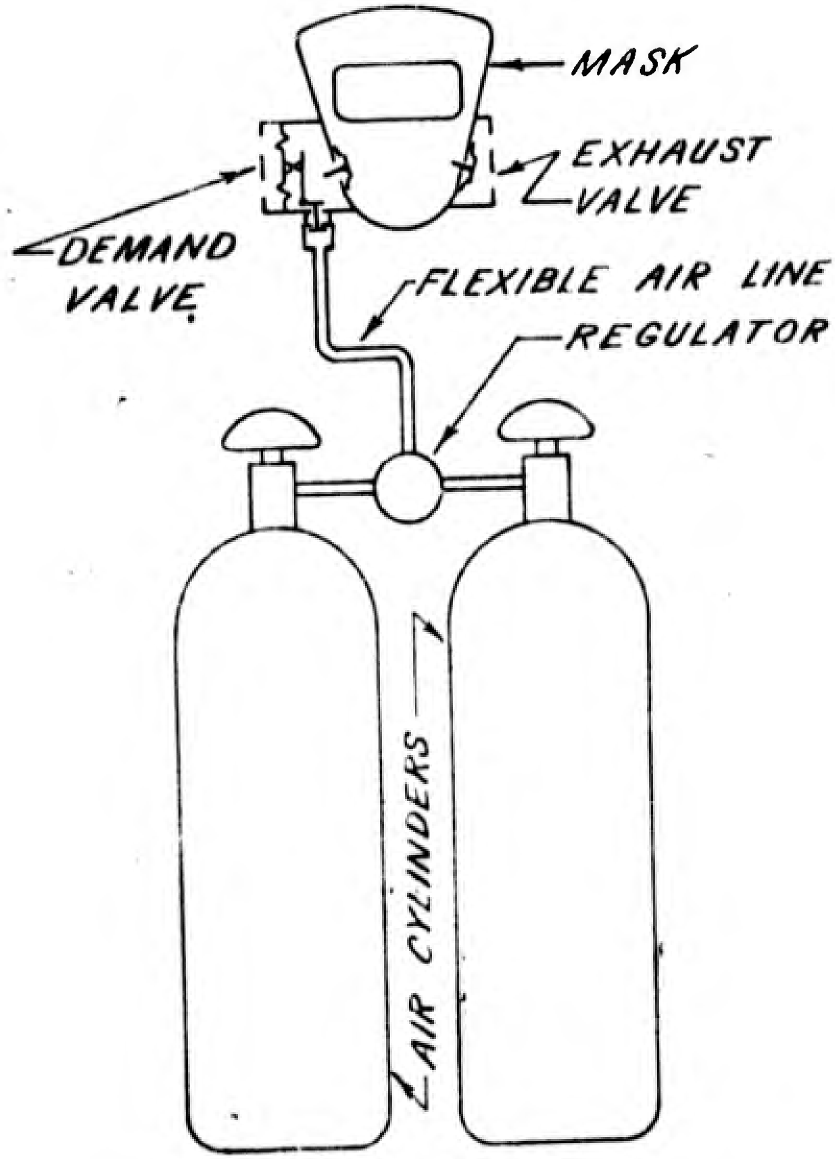
2-1 BASIC DEMAND VALVE MECHANISM

When inhalation reduces the pressure in the air chamber below the pressure in the surrounding water, the diaphragm deflects toward the air chamber, depressing the lever and opening the valve on the air supply. As long as inhalation continues, the valve remains open and admits air to the system. When inhalation ceases, rising pressure in the air chamber returns the diaphragm to its original position and the air-supply valve closes.



2-2 OPEN-CIRCUIT AIR-DEMAND SYSTEM with cylinder-mounted valve 2.1.3

Mounting the demand valve on the air-cylinder manifold conveniently minimizes high-pressure tubing. In the swimming position the few inches of hydrostatic differential pressure between the demand valve and the eupneic point make inhalation slightly difficult until the body acclimatizes. Use of a mask without a mouthpiece is uncomfortable in the swimming position, because the hydrostatic differential places the entire face under a slight squeeze, to which the face adapts far less easily than the lungs. In the diving position the differential is negligible, and breathing is restricted only by the resistance of the valves. Use of a mask without a mouthpiece is uncomfortable in the diving position because the higher air pressure at the face tends to blow the mask off the face. Most systems using a cylinder-mounted demand valve also use a mouthpiece, although this may be incorporated into a face mask.



2-3 OPEN-CIRCUIT AIR-DEMAND SYSTEM 2.1.3
with mask-mounted demand valve

Mounting the demand valve on the face mask minimizes the hydrostatic differential between the valve and the face, so that the mask does not tend to squeeze nor to inflate. The mouthpiece can be eliminated altogether. In the swimming position, the demand valve is very close to the eupneic level, and breathing is restricted only by the resistance of the valves. In the diving position the differential pressure makes inhalation slightly difficult until the body acclimatizes.

2-4 U.S. DIVERS "AQUA-LUNG" (Cousteau-Gagnon process) 2.1.3

This apparatus uses a cylinder-mounted demand valve. Note the mouthpiece and separate swim mask.

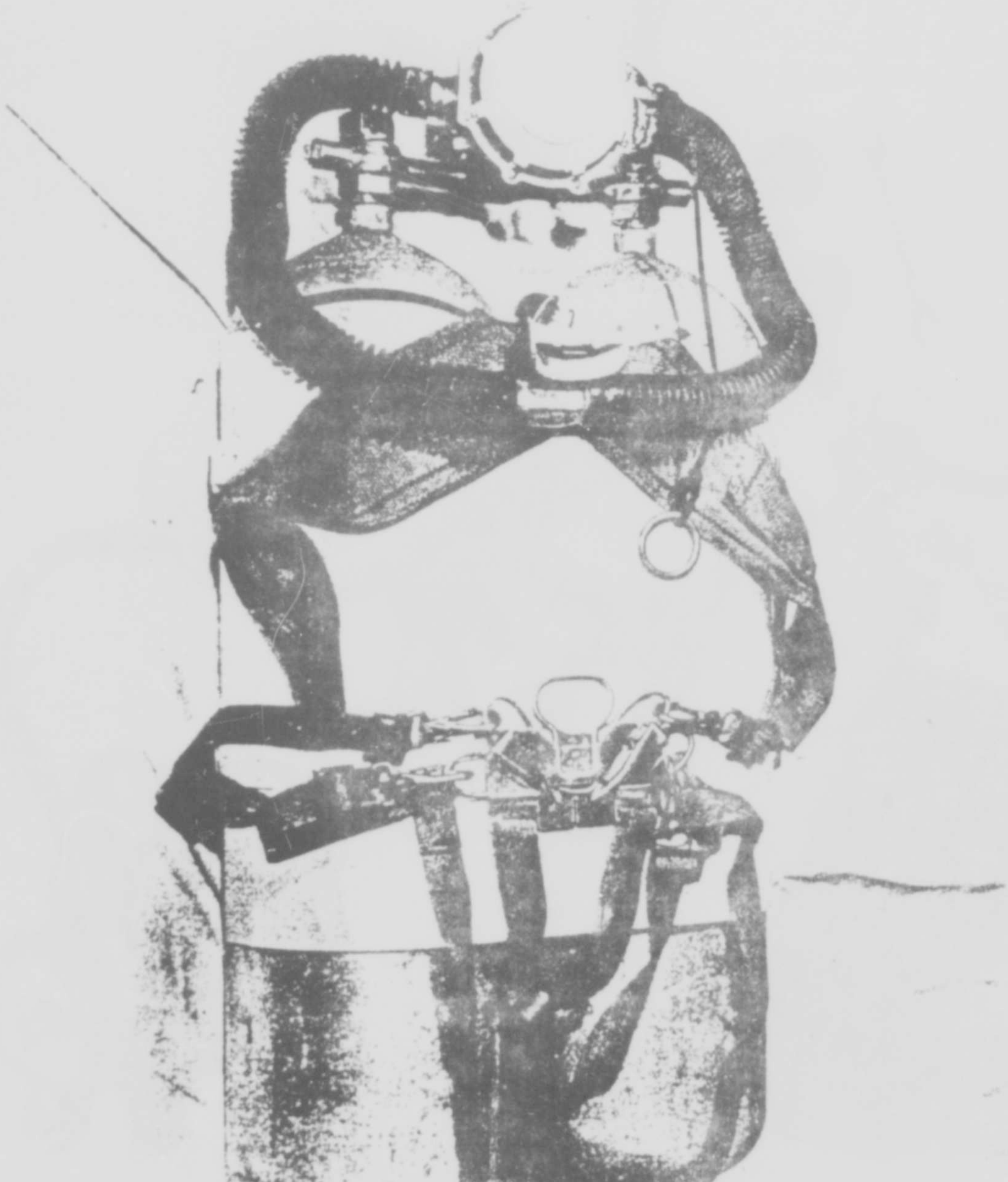


FIGURE 2-5

2-5 NORTHILL "AIR-LUNG" (pre-production model) 2.1.3

This apparatus also uses a cylinder-mounted demand valve and a mouthpiece. The level on the demand valve assembly operates the air-reserve valve.

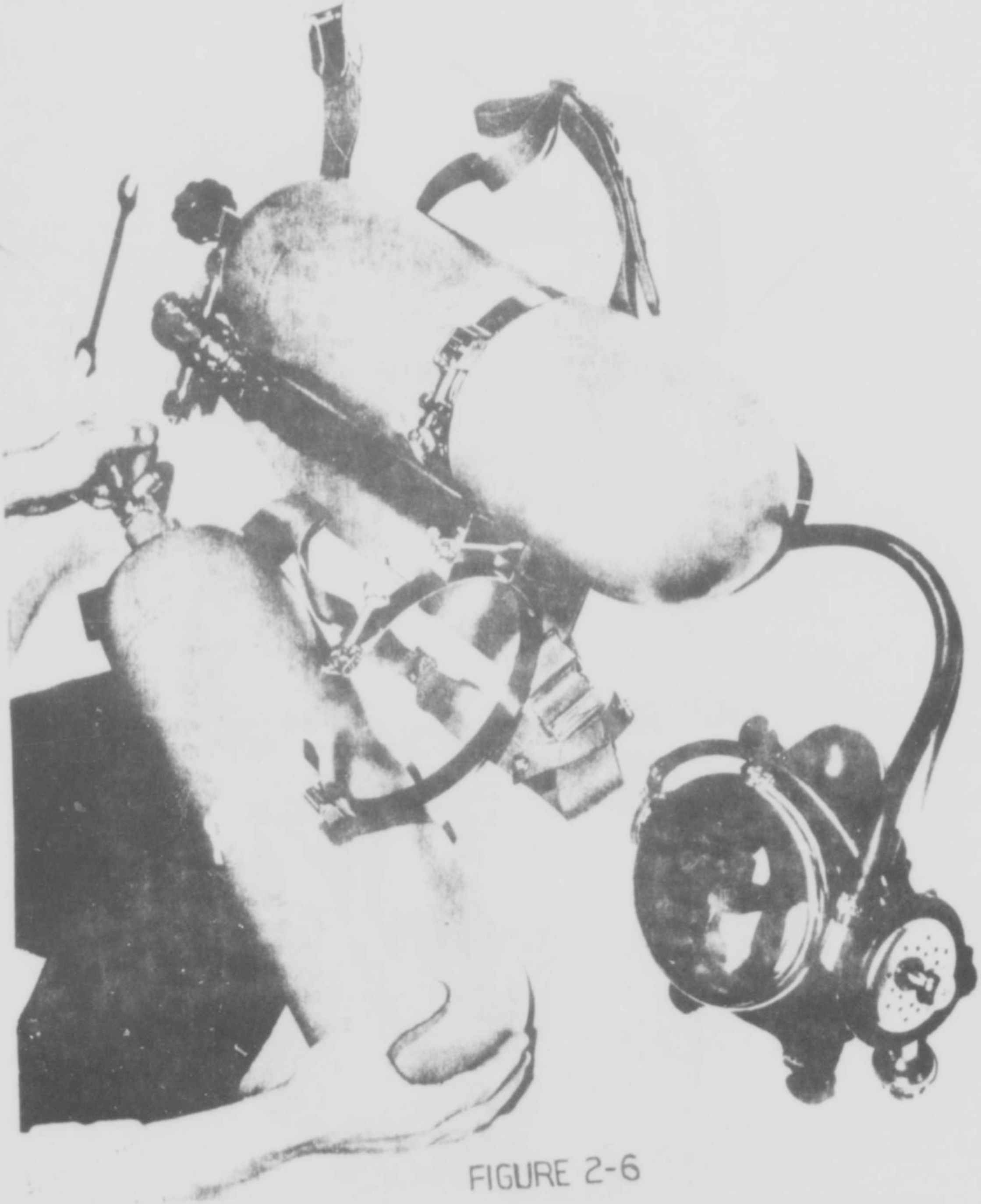


FIGURE 2-6

2-6 SCOTT"HYDRO-PAK" 2.1.3

This apparatus uses a mask-mounted demand valve. The button on the demand valve cover can depress the diaphragm independently of breathing, pressurizing the mask for rapid ejection of water. The tube between the demand valve and the exhaust valve forms part of the pressure balancing mechanism. The low-pressure regulator is integral with the high-pressure manifold and incorporates the air-reserve valve, operated by a knurled knob on the regulator.

In case of flooding, a relatively simple sequence of maneuvers can clear water from the Aqua-Lung and Air Lung breathing tubes. Pressing a button on the demand valve cover gives a free flow of air to clear the Hydro Pak mask. In any system the method of clearing must be second nature to the diver if it is to be effective in a real emergency.

2.1.4 Breathing media

Theoretically, any respirable gas or gas mixture can be the breathing medium in open-circuit demand systems. In practice, for all but very unusual circumstances, only compressed air is satisfactory. Ironically, it may sometimes be easier and cheaper to obtain oxygen, which is highly undesirable for two reasons. First, previous charging with air may have left a residue of oil vapor which will cause an explosion when charging with oxygen. Second, oxygen toxicity imposes stringent depth limits which are not normally associated with open-circuit equipment and may therefore tend to be ignored.

Most of the advantages of special gas mixtures occur at greater depths (9.0.0). These advantages are largely nullified by the effect of depth on duration of the gas supply in open-circuit equipment (2.1.6). The volumes of gas required are so large and the advantages are so reduced that it is usually difficult to justify the labor of making mixtures or the expense of buying them.

To be satisfactory breathing medium compressed air must, of course, be free from carbon monoxide, carbon dioxide, oil vapors, and other impurities. In some areas it may be difficult to obtain unlimited quantities of satisfactory high-pressure air outside of Naval facilities. Companies which supply compressed oxygen can usually supply compressed air. In many cities a satisfactory source of high-pressure air is a charging station for the compressed-air breathing apparatus used by fire departments.

2.1.5 Gas utilization

The body utilizes only about one-fourth of the oxygen available in each breath of air at the surface, and increasingly less at greater depths. Furthermore, the actual mass of gas in a given breath increases directly with the absolute pressure of the depth. Demand systems are therefore inherently wasteful because all of the unutilized gas drawn from the demand valve during inhalation is discharged into the water during exhalation.

2.1.6 Gas-supply duration

As a consequence of the increased mass of gas required for each breath at depth (7.2.2), the total time available from a given gas supply at a constant volumetric breathing rate diminishes inversely with the absolute pressure. For example, at 100 feet (4 atmospheres) a gas supply gives only one-fourth of the time that the same supply gives at the surface.

Although variations between individuals may be considerable, for any one man the primary factor in respiratory requirements is physical exertion (6.3.0). Since the work rate can vary greatly from dive to dive, the duration of a given gas supply can also vary greatly. For rough calculations an average requirement by a man performing moderately hard work is one cubic foot of air a minute, measured at the depth.

2.1.7 Operating limits

Depth is the primary factor which determines the operating limits of air-demand apparatus. It reduces the air-supply duration (7.2.2), and produces nitrogen narcosis (5.8.0), the possibility of oxygen toxicity (8.0.0), and decompression problems (7.2.1). The normal limits are established within the depths and times requiring no stage decompression (7.5.4), with a strong recommendation that the limits also include an allowance for ascent time at 25 feet a minute.

2.1.8 Military considerations

Exhaust of each breath directly to the water creates an inevitable trail of bubbles. From any significant depth, these bubbles expand considerably by the time they reach the surface. Because of this telltale factor, open-circuit gear is not always suitable for military operations involving stealth. In addition, the air passing through the demand valve and the bubbles escaping through the exhaust valve create periodic noises which are frequently audible underwater for considerable distances. These noises may expose a man's presence to underwater detection devices. More disastrously, they may detonate acoustically activated ordnance.

2.1.9 Medical aspects

Open-circuit equipment has some physiological advantages over other types of breathing apparatus. As long as the breathing medium lasts there is no possibility of anoxia. If dead space is minimal there is no probability of carbon-dioxide poisoning. If the breathing medium is air there is no danger of oxygen toxicity. Except for these advantages, all the physiological considerations which apply to self-contained diving (5.0.0), particularly the problem of decompression, also apply to open-circuit apparatus.

2.2 CLOSED-CIRCUIT SYSTEMS

In a closed-circuit system rebreathing occurs continuously. There is no loss of gas to the surrounding water unless expansion during ascent creates an excess. Rebreathing necessitates provision for two special needs: addition of oxygen and removal of carbon dioxide.

2.2.1 Basic components

A closed-circuit breathing apparatus must include an oxygen supply, an oxygen control valve, a rebreathing bag, a mask or a mouthpiece, a carbon-dioxide absorption canister, and the breathing system hose. Details and arrangements of these components vary considerably among the available models of closed-circuit equipment. However, all of the units fall into two general categories: the "recirculating" system shown in Figure 2-7, and the "pendulum" system shown in Figure 2-8.

The physician will recognize the closed-circuit principle in almost all metabolism equipment and in most gas anesthesia systems. He generally refers to the recirculating and pendulum systems as "circle" and "to-and-fro" respectively.

2.2.2 Closed-circuit recirculating system

The recirculating system predominates in American and German closed-circuit apparatus design. Respiratory check valves maintain unidirectional flow of the breathing medium, to insure that rebreathing does not occur until the exhaled gas has passed through the carbon dioxide absorbent.

2.2.3 Closed-circuit pendulum system

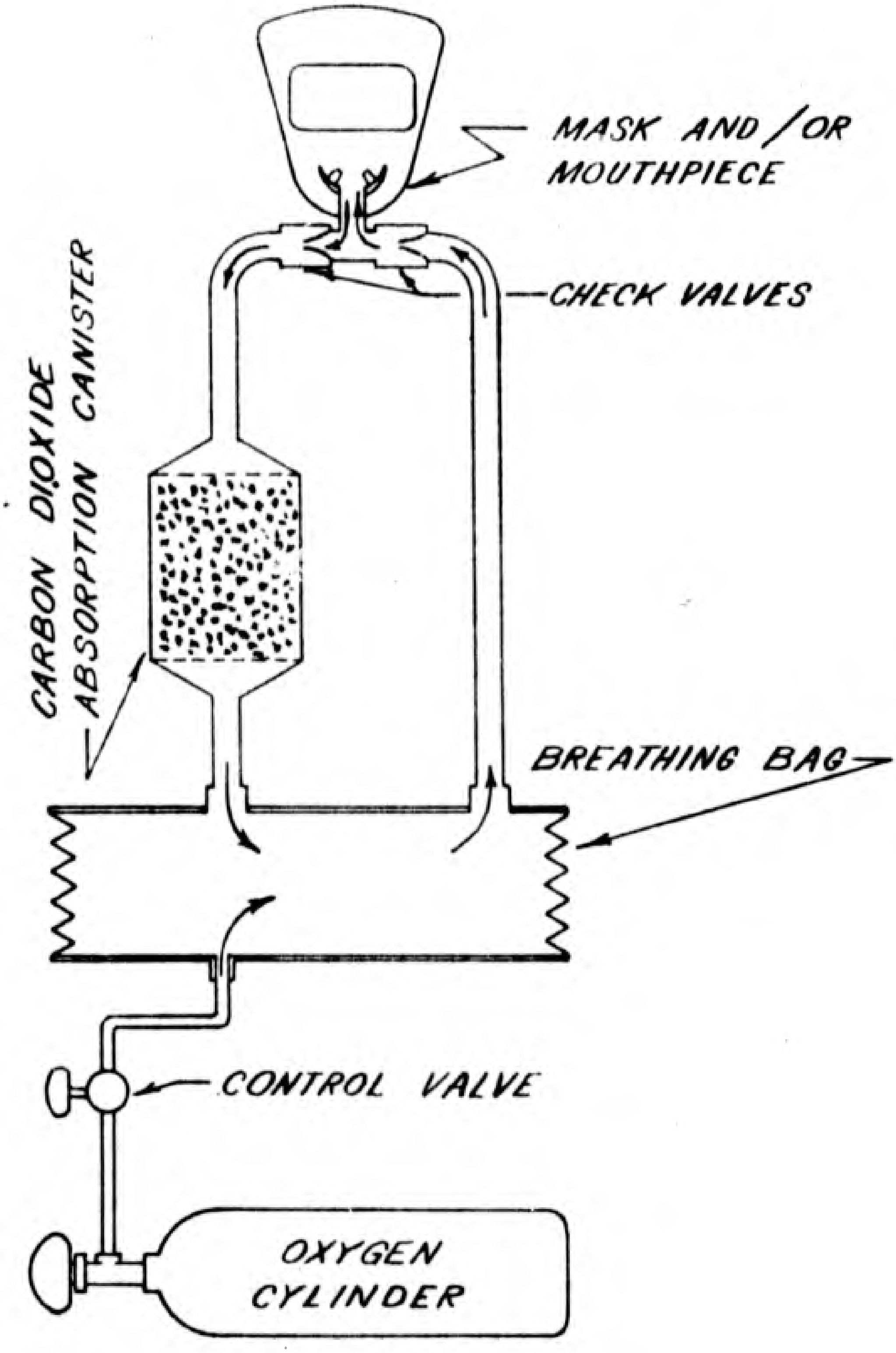
The pendulum system predominates in British and Italian design. Placement of the canister between the mouth and the breathing bag simplifies the design by eliminating the respiratory check valves. At least part of the gas in a pendulum system passes through the absorbent twice on its way to and from the bag. The claim that a pendulum system therefore gives a marked increase in canister efficiency is not definitely proven.

2.2.4 Dead space

Any space from which exhaled gas is re-inhaled without passing through the absorbent is dead space (6.5.0). The body itself has a certain unavoidable amount of "anatomical dead space" in the respiratory tract. The single breathing tube between the mouth and the canister in a pendulum system is entirely dead space. For this reason the design almost invariably includes a mouthpiece, because the internal volume of a full facemask would add considerably to the dead space.

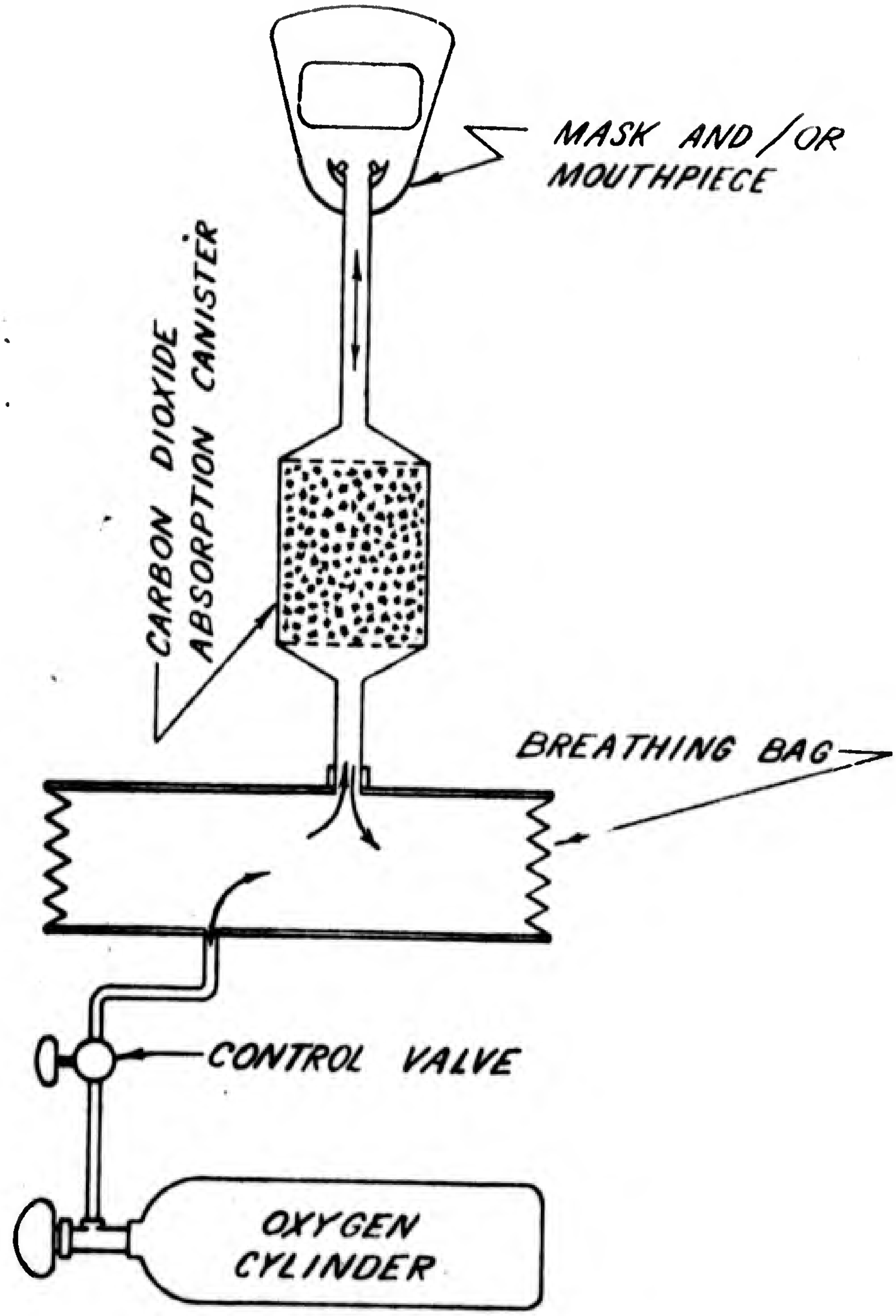
The physiologically permissible volume of dead space in breathing systems has not been adequately studied. With shallow breathing in a pendulum system, however, a large part of each inspiration can be dead space gas having a high carbon dioxide content. Furthermore, as the absorbent exhausts, the increasing volume of inactivated absorbent adds to the dead space.

The entire canister can form an "oxygen dead space". This fact has no consequence in an oxygen pendulum system, but it may have a very serious effect in a mixed-gas pendulum system where depletion of oxygen in the dead space gas at low tidal volumes can cause a large accretion of nitrogen, even to the point of anoxia.



2-7 CLOSED-CIRCUIT OXYGEN RECIRCULATING SYSTEM 2.2.2

This figure shows the basic components of the system. Details and arrangements of these components vary considerably among the available models. This system is common in American, French and German.



2-8 CLOSED-CIRCUIT OXYGEN PENDULUM SYSTEM 2.2.3

This figure shows the basic components of the system. Details and arrangements of these components vary considerably among the available models. This system is common in British and Italian design.

2.2.5 Breathing media

In any simple closed-circuit equipment the gas supply is always oxygen. Deliberate flushing of the apparatus and the lungs with oxygen prior to entering the water purges most of the nitrogen from the breathing medium. A small amount of nitrogen in the system will not cause trouble, and it does provide a slight margin of safety from oxygen toxicity. In a prolonged dive, the nitrogen present as an impurity in the oxygen supply (usually less than 1%) and the nitrogen eliminated from the body (probably less than 1 liter) can produce a measurable accretion of nitrogen in the breathing medium.

Proper initial purge of the system is the most important preventive for the possibility of anoxia from nitrogen accretion, but some authorities recommend occasional purges during operation. Calculations indicate that there is little possibility of nitrogen attaining excessive levels in well-purged apparatus with average volumes within one hour of normal use but that the possibility may exist beyond that time. Consequently, additional purges appear desirable at approximately one hour intervals during use.

In a complex closed-circuit apparatus for mixed-gas diving (9.2.3) the gas supply may include oxygen and nitrogen, or a mixture of both. The composition desired in the breathing medium depends on depth, time, decompression, and oxygen tolerance (9.1.0). Maintenance of proper nitrogen-oxygen proportions in the breathing system is a function of automatic equipment with adequate safety devices to warn the diver of failure. Operation of such an apparatus is a specialized skill which must be acquired by thorough training. Practical equipment of this type is not available at present.

2.2.6 Gas-supply control

When utilization of oxygen in a simple closed-circuit system causes the breathing bag volume to become less than the tidal volume, the sudden cut-off at the end of inhalation signals the need for replenishment. Sometimes an evident loss of buoyancy gives warning before inhalation cut-off occurs.

Various arrangements can control admission of oxygen to the system. The simplest is a manually-operated needle valve such as World War II Lambertsen equipment has. A more complicated arrangement uses an adjustable continuous-flow metering valve to approximate the diver's oxygen consumption, such as Pirelli and some Bureau of Ships developmental units use. One of the most satisfactory is an automatic demand valve actuated by flattening of the bag, such as in Cressi and 1952 Lambertsen apparatus. Any arrangement except a manually-operated valve must also have a manual by-pass to give rapid admission of additional oxygen whenever necessary.

2.2.7 Gas utilization

All of the oxygen added to a simple closed-circuit system is consumed. Waste occurs only on ascent when expansion of the gas exceeds the consumption, or at any time when gas is used for ejection of water from the system. The gas needed for a given dive in closed-circuit equipment is approximately 5% of the amount needed for the same time in open-circuit equipment at the surface.

2.2.8 Gas-supply duration

Oxygen consumption, depending mainly on the work rate, is the primary determinant of gas-supply duration in closed-circuit gear. The diving depth makes no significant difference in duration because oxygen consumption appears to be independent of depth. A man can easily carry enough oxygen to last longer than his physical endurance at work underwater.

2.2.9 Apparatus duration

With present absorbents and canisters the primary factor limiting apparatus duration is carbon-dioxide absorption. Good design can provide adequate absorptive capacity for dives of considerable duration, but the field of absorbents and canister design remains relatively uncovered. (6.4.0)

2.2.10 Operating limits

Oxygen toxicity severely limits the safe depth of operation for oxygen closed-circuit equipment. Extensive operations are not safe at depths beyond 30 feet, and even limited operations at greater depths are very hazardous (8.0.0). Normal limits are presently set at 30 feet and 30 minutes. Although many diving jobs suitable for self-contained equipment occur in depths safe for oxygen apparatus, the depth limitation is an unfortunate disadvantage of oxygen closed-circuit equipment.

2.2.11 Military considerations

Except for the depth limitation, closed-circuit apparatus is ideal for military purposes. Leaks and spillage are the only source of bubbles. The apparatus is the most nearly silent of all types of diving equipment. It is compact and easily portable. Charging the canister with absorbent requires very little time. The gas supply is not a large logistic problem.

Maintenance is somewhat demanding because of the numerous parts and connections which must be kept completely watertight. In operation, well-maintained units are generally reliable. The principal source of failure is inactivation of the absorbent by water leakage into the canister.

2.2.12 Medical aspects

Oxygen poisoning is the greatest potential physiological problem in closed-circuit equipment, but observation of safe depth-time limits should adequately forestall its occurrence. With proper purging of simple oxygen systems and with proper operation of automatic mixed-gas systems, anoxia should never occur in closed-circuit equipment. The most common mishap is carbon-dioxide accumulation, which can happen for a number of reasons (6.4.0). Except for the extremely remote possibility of "oxygen bends", decompression sickness is no problem in closed-circuit oxygen apparatus and is only a slight problem in closed-circuit mixed-gas apparatus. Other physiological considerations which apply to self-contained diving also apply to closed-circuit equipment (6.0.0).

2.3 SEMI-CLOSED CIRCUIT SYSTEMS

In a semi-closed circuit system partial rebreathing effects conservation of the gas supply; however, a certain amount of the breathing medium is intentionally discharged from the system continually. This type of apparatus is generally designed exclusively for use with nitrogen-oxygen mixtures on a continuous or intermittent low-flow basis.

2.3.1 Basic components

The semi-closed circuit breathing apparatus must have a mixed-gas supply and all the basic components of a closed-circuit apparatus (2.2.1). In addition it needs two special components: a reliable automatic injection system for the mixed gas, and an adjustable exhaust valve for the excess breathing medium. Fundamentally the semi-closed system is a special closed system which utilizes a continuous purge to permit substitution of mixed gas for oxygen (2.2.5). The most common adaptation of the semi-closed circuit uses continuous injection and exhaust.

2.3.2 Semi-closed circuit continuous flow system

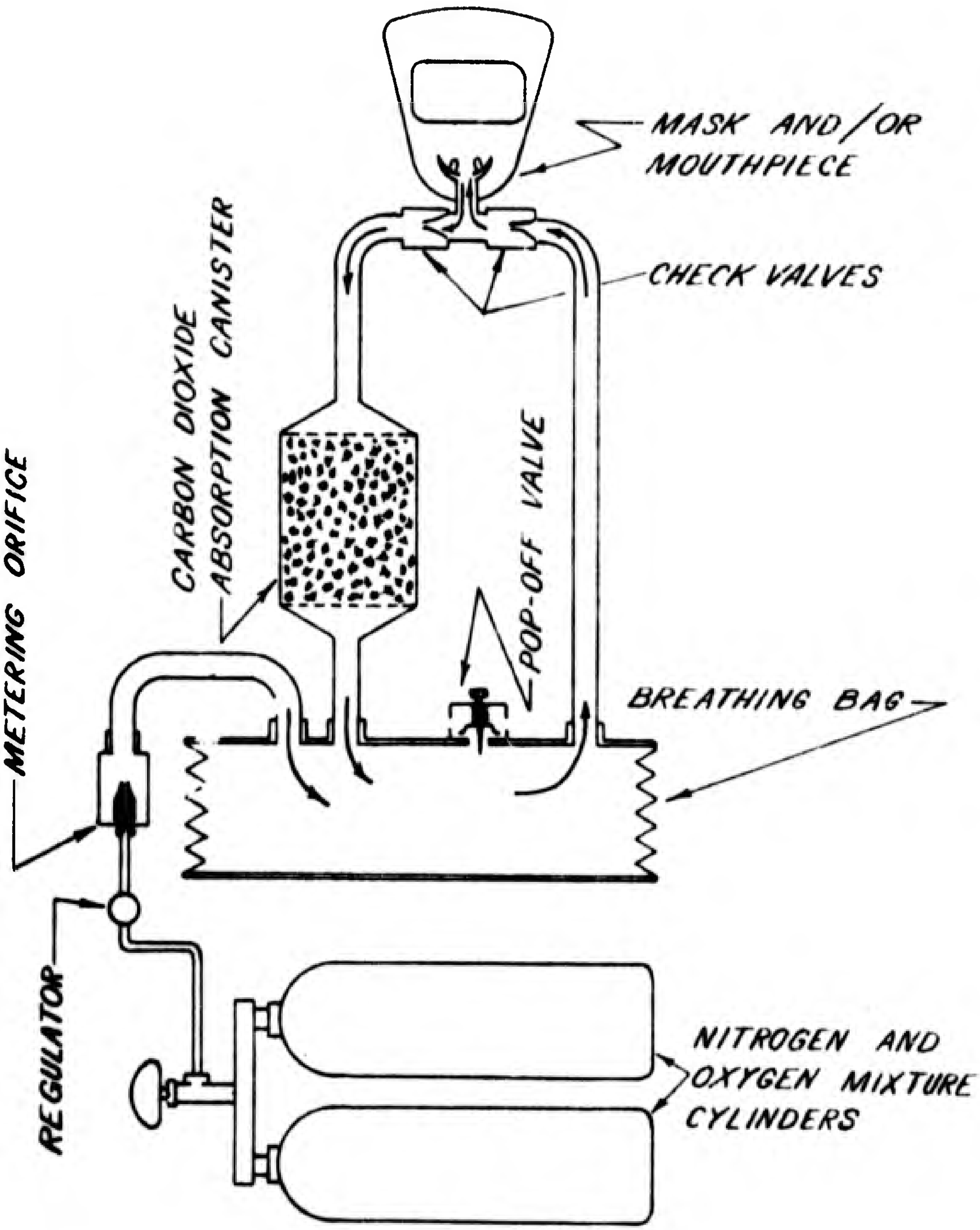
Although a very successful British apparatus design employs the pendulum system (2.2.3), considerations of dead-space effects (2.2.4) lead American designs to employ the recirculating system. Figure 2-9 shows the most frequent arrangement of this design for a continuous flow system. A constant mass-flow injector supplies the breathing medium with mixed gas. Since the injection is at a constant rate of mass flow, the volumetric flow diminishes with depth. The design must provide oxygen at a rate greater than the probable maximum oxygen consumption. Excess gas is discharged from the system through the "pop-off" valve, which is adjustable to meet buoyancy and breathing pressure requirements. This system is well adapted to mathematical analysis for design considerations (9.2.0).

2.3.3 Breathing media

Depending on operational requirements, semi-closed equipment design can provide for a gas supply of various nitrogen-oxygen mixtures range from pure oxygen to air. The principal considerations in the choice of a mixture are depth, time, decompression and oxygen tolerance (9.1.0). The choice may also depend on certain apparatus characteristics which influence the composition of the breathing medium (9.1.0).

2.3.4 Gas-supply control

The possible effects of manual control are too hazardous to risk (9.2.3). All semi-closed systems therefore have some automatic means of introducing more than enough mixture to meet the probable oxygen consumption. Excess gas serves to flush the system, to prevent nitrogen accumulation.



2-9 SEMI CLOSED-CIRCUIT MIXED-GAS RECIRCULATING SYSTEM 2.3.2
with injection and pop-off.

This system has all the basic components of the closed-circuit oxygen recirculating system. In addition, it has two special components: a reliable automatic injection system for mixed gas, and an adjustable exhaust valve for the excess breathing medium.

2.3.5 Gas utilization

Over an extended dive, the average oxygen consumption will seldom exceed 2 liters a minute. A representative injection rate for mixed gas is 6 liters a minute. On this basis the maximum gas utilization will be 35%. However, with a constant mass-flow injector the gas utilization is independent of the depth. Consequently, the semi-closed system conserves the gas supply far better than the open-circuit system, where the utilization is about 5% at best and decreases greatly with depth.

2.3.6 Gas-supply duration

In a semi-closed apparatus with constant-mass injection, the gas-supply duration is reliably predictable. An allowance of 10% of the supply for volumetric requirements on descent and of another 10% for a safety factor will cover most contingencies. With an injection of 6 liters a minute, a 750-liter supply will provide at least 90 minutes of diving time.

2.3.7 Apparatus duration

In general, good design will provide the semi-closed apparatus with satisfactory carbon-dioxide absorption capacity, so that the apparatus duration will always be the gas-supply duration (2.2.9).

2.3.8 Operating limits

The large variation of breathing medium composition possible during operation of semi-closed systems with a given mixed-gas supply presents complex considerations in establishing operating limits (9.1.6). For greatest safety, the present limits are set so that the highest probable nitrogen percentage governs decompression and the highest probable oxygen percentage governs maximum allowable diving time (9.1.5).

2.3.9 Military considerations

With proper design, operating depths for semi-closed systems can be extended far beyond the 30 foot limit which applies to simple oxygen closed-circuit equipment. Although the intentional flushing creates an undesirable bubble trail, it is much less detectable than the bubble trail in open-circuit gear. It is compact and easily portable. Charging the canister with absorbent requires very little time. Supply of various gas mixtures can be a serious logistic problem.

Maintenance is even more demanding for semi-closed circuit equipment than it is for closed-circuit equipment. The injection and exhaust apparatus, together with various safety warning devices, all require special attention. In operation, well-maintained units are reasonably reliable. The principal source of trouble is failure of the injector. Any good design must include a device to warn of injector malfunction.

2.3.10 Medical aspects

Anoxia is the greatest potential physiological problem in semi-closed circuit equipment. Poor design, improper use of low-oxygen mixtures, or failure of the injector can cause severely anoxic levels in the breathing medium. At greater depths, the oxygen partial pressure may be high enough that a very low oxygen percentage goes unnoticed until anoxia occurs during ascent. Even if actual anoxia does not occur, the nitrogen percentage may be high enough to produce severe decompression sickness. So long as the safe depth for the supply mixture is not exceeded, oxygen toxicity is not probable. However, accidental use of a high-oxygen mixture can have serious consequences. As in closed-circuit equipment, carbon-dioxide accumulation can happen for a number of reasons (6.4.0). In a properly functioning apparatus decompression sickness is possible, but is unlikely with proper decompression. Other physiological considerations which apply to self-contained diving also apply to semi-closed circuit equipment (5.0.0).

2.4 MISCELLANEOUS SYSTEMS

The foregoing classifications cover all self-contained diving equipment known to be in use at this time. Future developments will probably fall within these categories, although there is one proposed system which does not. The term "semi-open circuit" would place it in proper perspective. Basically it is a special open-circuit demand system which utilizes an "air saver" to conserve the gas supply by allowing controlled partial rebreathing. The air saver is a device which traps the first portion of each exhalation, with its low carbon-dioxide content, and presents the trapped gas for the first part of the next inhalation. Theoretically, a worthwhile extension of the air-supply duration is possible. Actually, the physiological factors in rebreathing are too uncertain (2.2.4) to create an unquestionably satisfactory design, and even a good design could give a large percentage of dead space at low tidal volumes.

A practical automatic control for the oxygen level in a full rebreathing system will permit use of mixtures in a closed-circuit apparatus (2.2.5). Such an apparatus will be a true closed-circuit system. However, it must inevitably bubble upon ascent because the expanding nitrogen in the system cannot be metabolized. The physiological considerations of mixed-gas diving (9.1.0) will apply to such an apparatus.

2.5 SELF-CONTAINED APPARATUS FOR STANDARD DEEP-SEA SUITS

The descriptions in this chapter have referred primarily to self-contained equipment which can be used for swimming and diving with or without a suit. However, the earliest self-contained systems were essentially a replacement for the surface gas supply in a standard deep-sea diving suit. The first and simplest of these were merely oxygen closed-circuit systems. There was no breathing bag because the suit itself served the purpose, but the diver had to use a mouthpiece and tubing to direct his exhalation through a carbon-dioxide absorbent.

Later, the mouthpiece was eliminated by a venturi recirculator system which drew the breathing medium from the helmet and forced it thorugh the canister. The continuous injection of gas to operate the venturi made this a semi-closed system, and gas mixtures frequently replaced oxygen. Some of these self-contained deep-sea outfits are still in use today.

Although these systems differ in appearance and detail from the U. S. Navy helium-oxygen rig, the basic principle is exactly the same except that the diver carries this own gas supply. Equipping a helium-oxygen rig for semi-open circuit operation with a self-contained gas supply is entirely feasible, although not necessarily practical. Development of a reliable automatic control for oxygen partial pressure would offer the greatest possibilities for equipping a helium-oxygen rig with a self-contained gas supply.

An open-circuit demand arrangment would not be too satisfactory in a deep-sea suit because the diver would still require a mask or a mouthpiece and therefore would have the helmet as an unnecessary burden. An open-circuit continuous flow arrangement would be completely impractical because of the enormous volumes of air required to provide adequate ventilation of the helmet.

Even more remote from the usual concept of self-contained diving apparatus are the Italian and German "armored suits", which have a completely self-contained breathing system. The armored suit is designed to withstand the pressures of considerable depths (as much as 700 feet) while keeping the man inside at one atmosphere. Suspended from a ship by a steel cable, the suit has no air hose. A self-contained supply of compressed oxygen provides for breathing through a mouthpiece and canister arrangment, and also provides for blowing the ballast tanks.

2.6 SUMMARY

The comparative characteristics of the three basic categories of self-contained gear described in this chapter are summarized in Table 2-1. The remarks apply to currently available equipment under usual conditions of use, except in the column headed 'closed circuit (mixed gas)'. Practical equipment of this type is still in the developmental stage.

FACTOR	SYSTEM AND GAS SUPPLY OPEN-CIRCUIT (AIR)	CLOSED-CIRCUIT (OXYGEN)	CLOSED-CIRCUIT (MIXED GAS)	SEMI-CLOSED CIRCUIT(MIXED)
GAS-SUPPLY DURATION	Limited (2.1.6)	Maximal (2.2.8)	Maximal (2.2.5)	Moderate (2.3.6)
DEPTH EFFECT ON GAS-SUPPLY DURATION	Marked (2.1.6)	Minimal (2.2.8)	Minimal (2.4.0)	Variable (2.3.6)
FACTORS LIMITING DIVING DEPTH	Gas supply Decompression Nitrogen Narcosis	Oxygen toxicity	Oxygen toxicity Decompression	Oxygen toxicity Decompression
PRACTICAL DIVING DEPTH	Moderate (2.1.7	Limited (2.2.10)	Maximal (2.3.9)	Moderate (2.3.9)
BUBBLING	MAXIMAL (2.1.8)	Minimal (2.2.11)	Minimal (2.4.0)	Moderate (2.3.9)
HAZARD OF ANOXIA	Minimal (2.1.9)	Minimal (2.2.5)	Moderate (2.2.5)	Maximal (2.3.10)
HAZARD OF OXYGEN TOXICITY	Minimal (2.1.4)	Maximal (2.2.10)	Moderate (2.2.10)	Moderate (2.3.10)
HAZARD OF CARBON DIOXIDE POISONING	Minimal (2.1.9)	Moderate (2.2.12)	Moderate (2.2.12)	Moderate (2.3.10)
HAZARD OF DECOMPRESSION SICKNESS	Maximal (2.1.7)	Minimal (2.2.12)	Moderate (2.3.10)	Moderate (2.3.10)
SIMPLICITY OF MAINTENANCE	Maximal	Moderate (2.2.11)	Minimal (2.2.5)	Moderate (2.3.9)
SIMPLICITY OF USE	Maximal	Moderate (2.2.11)	Moderate	Moderate

TABLE 2-1

CHAPTER 3

SELECTION AND TRAINING FOR THE USE OF SELF-CONTAINED UNDER-WATER BREATHING APPARATUS

CONTENTS

CHAPTER 3

SELECTION AND TRAINING FOR THE USE OF SELF-CONTAINED UNDERWATER BREATHING APPARATUS

3.1 PERSONNEL SELECTION

3.1.1 General considerations

The use of self-contained apparatus does not diminsh the physical demands of diving. The SCUBA diver will escape some of the familiar labors of the helmet diver, but the demands of his own activities may be equal or greater (6.1.0). His cardio-vascular-respiratory system is further burdened by the breathing resistance of self-contained apparatus. Diving with SCUBA involves the usual primary effects of pressure (IA-2C), and exposure to excess carbon dioxide (IA-20, 6.6.0) or to high partial pressures of oxygen (8.0.0) may intensify the secondary effects (IA-20).

The psychological implications of diving with self-contained apparatus are also significant. Not only is the SCUBA diver exposed more directly to the underwater environment than the man in a suit and helmet, but he will seldom have any contact with the surface by lifeline or through telephone communication. He is completely dependent upon his breathing apparatus. Even when accompanied by another diver, a basic rule, he must face most of his problems alone.

SCUBA diving frequently requires a high order of general intelligence and mechanical aptitude. In addition, the physical and psychological demands imposed by such special activities as underwater demolition and explosive ordnance disposal work are formidable.

3.1.2 Present standards

The manual of the medical department makes no special provision for divers who use self-contained apparatus, and the requirements for members of the Underwater Demolition Teams are the same as those for first class divers. The applicable section (IA-1/I) provides as satisfactory a basis for selection as is presently available anywhere else. The requirement that the candidate must be a volunteer is particularly important.

3.1.3 Screening

A man is unlikely to be effective, or safe, unless he actually enjoys this form of diving and feels at ease in the underwater environment, but the beginner, regardless of his aptitude, may be concerned primarily with remaining alive until he becomes familiar with the apparatus and its use. Without previous experience, the crucial factor of liking or disliking the work may remain an unknown until he is well into his training. "Test dives" may therefore be of little predictive value, although they can eliminate the panicky individual. Deferment of fine screening until the candidates become familiar with the work should allow the medical officer and the instructors to reach reliable conclusions about whether a man is at ease underwater and whether he has sufficient ability and confidence.

3.1.4 Psychiatric aspects

Superficial observation divulges little about the essential psychodynamics of a successful SCUBA diver. It does, however, reveal certain apparent paradoxes. This man is able to work in darkness, isolation, and in the presence of numerous seen and unseen hazards, and he does so with relative equanimity. On the other hand, he has a healthy respect for danger and is capable of normal fear reactions. While he carries out orders conscientiously and does not violate them except in extraordinary circumstances, he can readily formulate sound plans of action when orders cease to be applicable. He is well-informed about an operation as a whole without stressing his own role in it. He frequently represents the essence of teamwork, but he is equally capable of working alone.

Paradoxical as these qualities may seem, they do not differ much from those found in any "good fighting man." The crucial factors determining particular suitability for SCUBA diving may lie beyond these qualities. Being at ease underwater probable overshadows all others in importance; however, this quality is not determined by aptitude alone but by training as well.

There is no room for the exhibitionistic or egocentric individual in a situation which demands teamwork. Emotional stability is a prime requirement since a single "break" may endanger the life of the diver and many others. One unstable diver can ruin an entire operation.

Aside from claustrophobia as a distinct entity, the sense of confinement caused by absence of light, lack of communication, and awareness of solitude can certainly elicity strong reactions in susceptible men, Unfortunately, few of the fundamental facts on the psychiatric aspects of selection are actually known.

3.1.5 Miscellaneous factors

SCUBA diving subtends the range from simple operations under favorable conditions to complex jobs under hazardous circumstances. Although men assigned to operations like simple repair work or ship-bottom search will not generally receive training in specialized tasks like underwater demolition or explosive ordnance disposal, selection of these men cannot be slipshod, and their training must still be thorough. Consequently, where the selection problem becomes more acute, for advanced training and difficult assignments, careful observations made during basic training and elementary operations can provide guidance more effectively than any other consideration.

Any measure to increase the pool of volunteers will simplify the process of selection. One measure in which Naval diving personnel can play an important part is to increase the availability of young civilian free-diving enthusiasts. To do this, diving personnel must help the Navy assume its proper role as a prime source of useful, authoritative information in the diving field. The trained medical officer is a logical agent for this endeavor.

Such measures as provision of incentive pay, recognition of SCUBA diving as a specialty, and authorization of distinctive insignia can greatly influence the number of volunteers. Most important is development of an "elite corps" spirit among groups engaged in SCUBA diving. For officers and enlisted men alike, the work must make an acceptable Naval career which can ultimately compare favorably with submarine duty.

3.2 ELEMENTS OF TRAINING

3.2.1 Considerations

The use of SCUBA appears easy; in fact, it is possible to don some self-contained units and dive with no training whatever. This approach, used by many civilian enthusiasts, will probably account for a large proportion of any deaths reported. Deceptive ease largely conceals the great difference between mere ability to use the equipment and real competence. Competence involves not only proficiency in normal operation but also familiarity with the basic safety precautions, ability to avoid and recognize danger, and ability to cope with perilous situations in which training determines the outcome: life or death.

Instruction manuals and lists of rules can fulfill the necessities of training only in small part. There is no substitute for competent personal instruction, nor for extensive drill in procedures which must be second nature.

Many competent helmet divers are not particularly at ease in the water except in diving dress; a few are not even able to swim. In contrast, SCUBA diving demands not only confidence underwater but also special swimming ability, which is a prerequisite for successful use of SCUBA. Training programs should begin with the development of this proficiency.

3.2.2 Instruction

In addition to the mechanical and operational aspects of SCUBA, classroom instruction must provide a firm background in the physics and physiology of diving. Students must know the symptoms of oxygen poisoning, anoxia, and carbon dioxide excess and the methods of avoiding and coping with these hazards. Since these conditions represent serious potential problems, it is desirable to supplement classroom material with demonstrations under controlled conditions so that the student can note his own sensation and reactions. Oxygen poisoning cannot reasonably be presented in this way, but the student can experience anoxia and carbon dioxide excess with little risk. With closed-circuit apparatus he can rebreath air through an absorbent until evidence of anoxia appears, and rebreath oxygen without an absorbent to produce carbon dioxide accumulation. Figure 3-1 illustrates a safer and more graphic method for the demonstration. A recording spirometer clearly indicates the respiratory changes. Continuous gas analyzers give correlation of the actual oxygen and carbon dioxide levels with the observed effects and permit stopping the demonstration before the levels become hazardous. An ear-oximeter would also be useful for showing anoxia. A medical officer must supervise all such demonstrations.

Instruction in decompression tables must include particular emphasis on the special decompression problems arising from the use of SCUBA (7.4.0). Students must be thoroughly familiar with the symptoms and treatment of decompression sickness, air embolism, and other accidents or illnesses associated with diving. They must receive indoctrination in the safety precautions and regulations applicable to SCUBA and in the general principles of good diving practice.

If diving with gas mixtures is probable, the trainees must receive thorough instruction in the additional complexities involved.

Shop training should lead to proficiency in the maintenance and repair of all apparatus which may be used. Practical instruction should cover the maintenance and repair of suits, accessory gear, compressors, and related equipment, as well as the proper handling of compressed gases.

3.2.3 Introduction to SCUBA

Upon achieving a reasonable degree of swimming ability the student should start the actual use of self-contained apparatus. He should concentrate on one type of apparatus at first, becoming proficient in the particular techniques involved in its use. In this process, he will also become familiar with the methods and operations common to most types of apparatus and to the majority of SCUBA activities.

This phase of training should begin in a swimming pool or in other shallow water with good visibility and comfortable temperature. These conditions will allow close supervision of all instruction and familiarization with emergency techniques and will not entail real danger.

Individual observation of trainees is essential, especially when training extends to distance swimming and work in deeper water. Properly manned boats, ideally with provision for underwater observation, are necessary when training is conducted in open water. Instructors should accompany trainees when they are underwater.

Training should next proceed to instruction and experience with all types of equipment which the trainees may have to use. In particular, drill in the emergency procedures applicable to each apparatus must be extensive enough so that students can handle difficult situations without panic.

Training in the technique of free ascent is highly desirable but must be conducted in one of the submarine escape training tanks or in a situation which provides fully equivalent safeguards.

3.2.4 Application of techniques

The final phase of instruction covers the application of SCUBA techniques to specific underwater activities. In the Navy, SCUBA diving is rarely an end in itself. Its most important applications are in fields such as underwater demolition and explosive ordnance disposal. The ability to use self-contained apparatus is essential to many phases of these jobs but SCUBA instruction itself represents only a small part of the total training required.

3.2.5 Ultimate proficiency

Adequate basic training in SCUBA diving can be provided in a course of reasonable length, but the development of ultimate proficiency and full realization of the potentialities of the technique may require many months of specific application. This fact is often overlooked.

Another frequent error is the assumption that a capable helmet diver should be able to use self-contained apparatus equally well with little special training or experience. This rarely proves to be the case. A solid background in conventional techniques represents a real advantage, but the profound differences between the two forms of diving must be recognized.

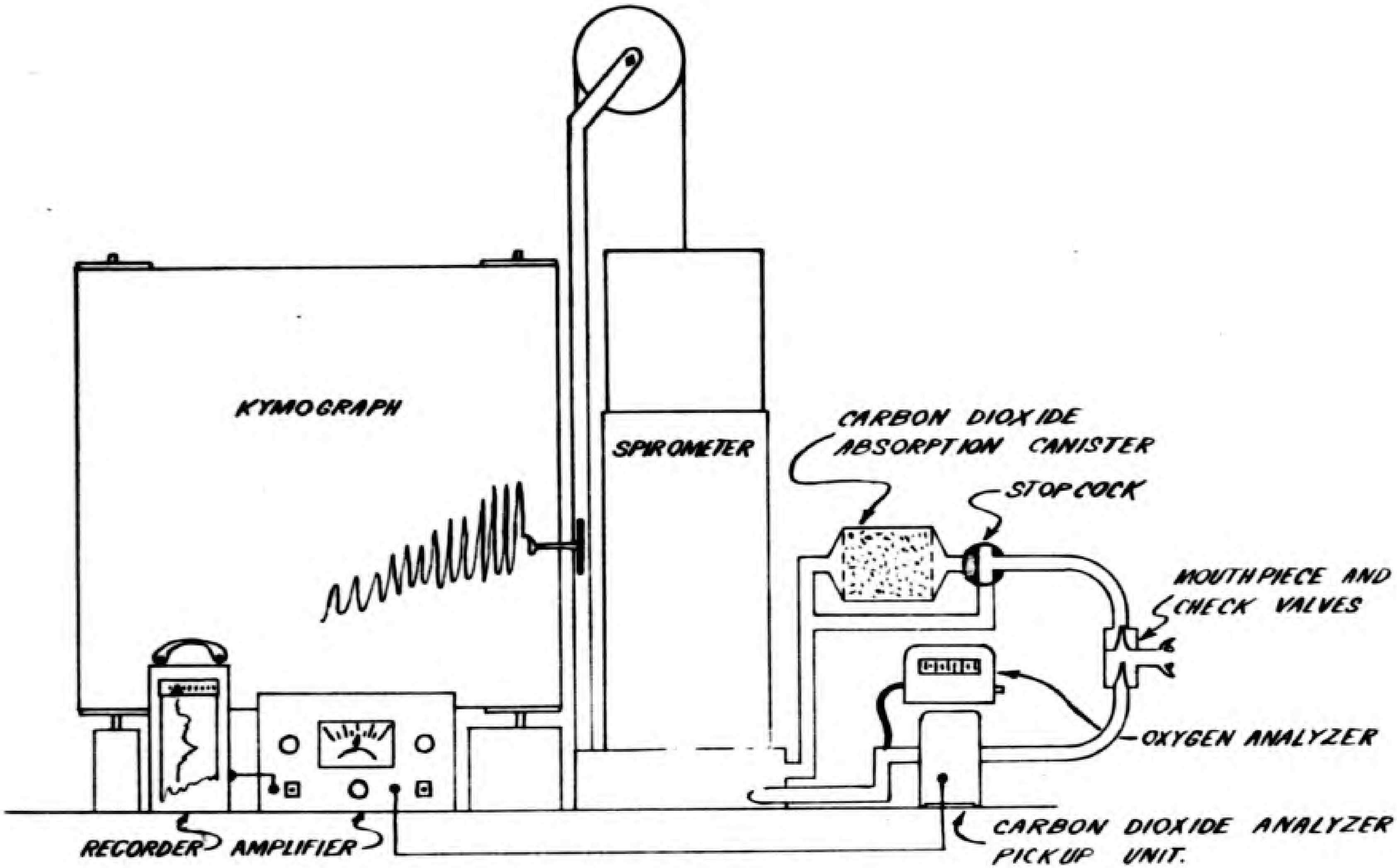

KYMOGRAPH
SPIROMETER
CARBON DIOXIDE ABSORPTION CANISTER
STOPCOCK
MOUTHPIECE AND CHECK VALVES
OXYGEN ANALYZER
CARBON DIOXIDE ANALYZER PICKUP UNIT.
RECORDER
AMPLIFIER

FIGURE 3-1

FIGURE CAPTIONS - SPECIAL REPORT 3-54

FIGURE	DESCRIPTION	SECTION
3-1	LABORATORY DEMONSTRATION APPARATUS for low oxygen and high carbon dioxide effects.	3.2.2

Basically, the apparatus is a closed-circuit oxygen recirculating system (Figure 2-7) in which a recording spirometer replaces the breathing bag. The gas analyzers allow continuous determination of oxygen and carbon dioxide levels in the inspired breathing medium at any time. The full inhalation passes through the carbon dioxide analyzer pick-up unit. A small pump (not shown) draws a portion of the inhalation through the oxygen analyzer and returns the sample to the system. The stopcock permits deliberately bypassing exhalation around the canister. A medical officers must supervise all demonstrations, and must assure that the analyzers are in accurate calibration.

In the demonstration of low oxygen (anoxia) effects, filling the system with air simulates failure to purge a closed-circuit SCUBA. By rebreathing through the canister, the subject reduces the oxygen level without raising the carbon dioxide level. When the oxygen falls to 10% or very slightly below, the medical supervisor stops the demonstration. At this low level the subject almost always shows distinct mental impairment. However, the kymograph record rarely indicates any noticeable change in the rate and depth of breathing, and the subject has no sense of labored breathing.

In the demonstration of high carbon dioxide (hypercapnia) effects, filling the system with oxygen simulates a properly purged closed-circuit SCUBA. After the subject has established a baseline respiratory record by rebreathing through the canister, bypassing the canister with the stopcock simulates complete canister failure. By rebreathing directly to the spirometer, the subject raises the carbon dioxide level in the system. When the carbon dioxide approaches 10%, the medical supervisor should stop the demonstration. Frequently the subject will become so uncomfortable that he will insist on stopping at some lower level. Most subjects show a marked increase in rate and depth of respiration, but not all of them complain of difficulty in breathing. A few show only a slight increase of respiration, with no sense of increased breathing. However, on approaching 10%, almost all subjects show mental changes similar to those which occur in anoxia.

Since the system is actually a large version of a basal metabolism apparatus, it can also serve to determine oxygen consumption during various activities at the surface, by using oxygen with the absorbent canister in the circuit.

CHAPTER 4

SAFETY CONSIDERATIONS IN THE USE OF SCUBA

CONTENTS

CHAPTER 4

SAFETY CONSIDERATIONS IN THE USE OF SCUBA

Diving with self-contained gear carries with it most of the risks of the conventional methods. It also introduces other hazards which stems from the potentialities as well as from the limitations of the equipment. Furthermore, the ease of using most SCUBA invites the uninformed and untrained to expose themselves to danger unnecessarily and may encourage carelessness even among qualified personnel.

On the other hand, SCUBA diving can be reasonably safe if a few logical requirements are met: The diver must be qualified, physically and otherwise. He must be cognizant of the potential dangers and of his own limitations. He must be trained in the techniques of SCUBA diving and in the avoidance, recognition, and handling of hazardous situations. He must use appropriate apparatus which is in optimum condition. He must observe all the principles of good diving practice as applied to SCUBA. Specific situations require various rules and precautions, check lists, and other aids. The details necessarily depend on the type of SCUBA used and on the nature of the operations. The considerations listed may be regarded as basic. Disregarding them can rarely be justified except by urgent military necessity.

Most of the matters discussed under this heading are non-medical in nature, and the medical officer will rarely have primary responsibility in such diverse areas as apparatus maintenance and the details of diving procedure. He does, however, have obvious concern for the safety of personnel under his care; and this places all safety considerations squarely in his province. He must have a thorough understanding of the subject, be capable of discerning unsafe practices and omissions, and be able to provide competent advice and relevant suggestions. He may frequently find himself the final arbiter in these matters.

(Where the points mentioned are discussed more fully elsewhere in the text, section numbers are given).

4.1 CONDITION OF THE DIVER

4.1.1 Initial examination and assessment

Ascertain that the diver is physically, mentally, and psycholigically qualified (3.1.0).

4.1.2 Periodic re-examination

Give particular attention to the cardio-vascular and respiratory systems. Examine the ears, nose and throat thoroughly. Assess psychological adjustment to diving and to specific duties.

4.1.3 Condition at time of dive

Examination before each dive is generally impractical, but the men should know the importance of reporting significant symptoms and other factors. (In this, the personal relationship between divers and their Medical Officer or Corpsman is important). The following should be considered:

(1) Avoid diving in the presence of upper respiratory or middle ear disease, of skin or external ear infections, or of any evident illness.

(2) Determine that the diver feels fit.

(3) Prohibit diving with any degree of alcoholic intoxication or evidence of its aftereffects.

(4) Assure adequate sleep where possible.

(5) Instruct divers neither to eat heavily nor to miss meals before diving.

(6) Maintain a high degree of physical fitness for optimum performance. Utilize regular exercises which favor endurance, such as running, swimming with fins, skin-diving, and active water sports.

(7) Do not force a man to dive when, for any reason, he seriously desires not to do so. Avoid penalties or ridicule in this connection. However, disqualify any man who evidently dislikes diving or often demurs for insufficient reasons.

4.2 TRAINING AND QUALIFICATION OF THE DIVER

The objectives and elements of training are discussed more fully in section 3.2.0 but may be summarized in the following prerequisites for diving without direct supervision.

(1) Proficiency in swimming with fins.

(2) Adequate basic knowledge of diving.

(3) General proficiency in SCUBA diving.

(4) Specific training in type of SCUBA to be used.

(5) Actual drill in handling emergency situations, including drill with the specific type of SCUBA to be used in a given operation.

(6) Recognition of own physical limits; ability to avoid over exertion.

(7) Ability to recognize symptoms of diver's maladies.

(8) Facility in the use of auxiliary equipment.

(9) Proficiency in hand or visual signals and any other method of communication to be used.

4.3 EQUIPMENT - MAINTENANCE AND HANDLING

4.3.1 Approved equipment

No breathing equipment should be used in operations unless it has received official evaluation and approval. Trials of experimental gear and new products of reputable manufacturers are permissible but should be conducted only with adequate safeguards.

4.3.2 Maintenance

Maintain equipment in optimum condition at all times:

(1) Set up routines of periodic inspection and preventive maintenance. Adhere to them rigidly. Keep records on all complete units and major components. Correct all noted defects, however minor, before using equipment.

(2) Cover all components of breathing apparatus in the routine harness and other adjuncts as well as the breathing circuit.

(3) Give reducing valves, demand valves, and air reserve devices particular attention. Field maintenance of these is not always practical.

(4) Insure that face masks, suits, flotation gear, knives, compasses, and other accessories also receive proper maintenance and handling.

(5) Inspect cylinders for bulges, strains, and other signs of impending failure. Have them tested hydrostatically at intervals depending on the type and on the conditions of use.

(6) Inspect all high pressure connections frequently and give them hydrostatic tests periodically. Be sure to include charging connections, which may be a particular hazard.

(7) Calibrate gauges periodically to insure accuracy.

(8) Give compressors and associated equipment for charging SCUBA diligent maintenance. Operate them carefully. Their output must be free of dust, excess moisture, excess oil vapor, and toxic gases (5.11.0). Periodic analysis of air samples is mandatory.

(9) Provide check-off lists for pre-dive inspection and tests of breathing apparatus by individual divers. Include tests for gas and water leaks, operation and position of controls, determination of cylinder pressure, and any special procedures for specific apparatus.

(10) Have any defects noted during the operation of an apparatus reported immediately. Make certain that they are corrected before the apparatus is used again.

(11) The principle of making each man responsible for his own equipment is very sound. However, where special skills are required for maintenance and repair, as is the case with some valves and other intricate mechanisms, utilize trained maintenance personnel in the field or establish a central repair shop.

(12) Increase safety of operations by providing an adequate supply of spare parts in order to forestall hazardous makeshifts.

4.3.3 Handling

Handling and stowage of apparatus should receive adequate attention:

(1) Breathing apparatus is particularly prone to damage. Handle it carefully in use or in transport, and stow it properly in a dry place away from excessive heat.

(2) Prevent corrosion of metal parts and rapid deterioration of rubber parts by washing with fresh water and drying thoroughly after use.

(3) Handle cylinders carefully to prevent any kind of damage. treat aluminum and alloy cylinders with particular respect. Remember that a dropped cylinder with its valve broken off becomes a rocket.

(4) Charge cylinders carefully. Charging connections require cautious use to avoid kinking or rupture. A flexible charging connection with high-pressure gas escaping from the distal end may become a deadly whip. Cylinders should be charged slowly to prevent overheating and should never be charged above the rated pressure.

(5) Keep charged cylinders from excessive heat. Do not leave charged bottles in direct sun. Store cylinders with valves closed and with some pressure remaining inside. Before charging or attaching a cylinder to an apparatus, crack its valve slightly to blow out any dirt which may have entered the open end.

(6) Use open-end wrenches of proper size in preference to the adjustable type. Never force a fitting.

(7) Exercise extreme care to prevent oil or other organic materials from coming in contact with oxygen under high pressure (or with high-pressure streams of escaping oxygen) because of the danger of explosion or fire. Such contact may occur in numerous ways, all of which must be carefully avoided.

Cylinders, valves, guages, and fittings not specifically intended for use with oxygen frequently contain oil. Oily residues may be left in any parts which have previously been used with compressed air. Attempts to clean such equipment by using volatile solvents are hazardous. Maintenance operations on valves and reducers may leave oil from tools or fingers if precautions are not taken. Handling of connections or use of oily or dirty wrenches may deposit oil or expose oil to escaping oxygen. Uninstructed personnel may deliberately lubricate valves and fittings with disastrous results. Mixing oxygen and compressed air or other gases under pressure is hazardous unless the air or gas is water-pumped and oil free.

The precautions regarding oil also apply to grease, graphite-base lubricants, pipe-dope not intended for oxygen fittings, and most paints and enamels. There is no objection to normal lubrication of apparatus exposed to oxygen under near atmospheric pressure, but volatile materials should be avoided.

4.4 DIVING CONDITIONS

Safety in SCUBA diving depends in large part upon the environmental conditions and upon the suitability of arrangements made for diving under these conditions. In some circumstances the use of SCUBA may be completely inappropriate unless demanded by military necessity.

4.4.1 Underwater visibility

Dark or murky water puts self-contained apparatus at a serious disadvantage. Except in special operations, poor visibility demands the use of such aids as a lifeline, descending line, and circling line. Conventional gear may be much more suited to the task. Wherever possible, avoid SCUBA diving at night.

4.4.2 Tides and currents

Even with swim-fins, the SCUBA diver has little ability to maintain position or to make progress against tides and currents. A 1 knot current can require all his propulsive effort. Consequently, such conditions may necessitate use of weights and lines with self-contained gear. These conditions often favor employment of conventional equipment instead.

4.4.3 Water temperature

Cold water demands adequate protective clothing (10.0.0). This in turn, may limit freedom of movement and frequently introduces difficulty of buoyancy control. Limitation of useful diving time and reduction of manual dexterity must be expected as consequences of cold.

4.4.4 Contaminated water

Most rivers and harbors are heavily polluted, requiring use of closed rubber suits. In such circumstances, avoid the use of SCUBA with an exposed mouthpiece.

4.4.5 Surface conditions

Any circumstance which precludes use of appropriate diving craft or other suitable surface arrangements argues strongly against SCUBA diving. Any situation is unfavorable if the diver must cover a considerable distance on the surface before reaching safety in case of an emergency. This is particularly true in rough water, heavy surf, or strong currents. Such circumstances must, of course, often be accepted in military situations.

4.5 GENERAL ARRANGEMENTS

4.5.1 With few exceptions, SCUBA divers should work in pairs. This is probably the greatest single aid toward SCUBA safety especially under unfavorable conditions. The divers should remain in sight of each other. In poor visibility, they should use a "buddy line" six to ten feet long. These divers should have confidence in each other's ability, and they must recognize their responsibility for each other's safety. The following rules are important:

(1) Always signal before ascent, descent, or change of direction.

(2) Upon losing visual contact, first listen for breathing noises; then try audible signals such as banging the SCUBA cylinders with a piece of metal.

(3) If contact is completely lost, surface immediately. Inform the tenders, look for bubble trails, and resume the search.

Where feasible, paint breathing apparatuses distinctively to assist visual contact. When more than two divers are working together, distinguishing markings will aid identification and reduce confusion.

If possible, use an apparatus which permits underwater voice communications without complex electronic equipment. A full face mask with a speaking diaphragm is desirable.

An exception to the "buddy" rule may be made when the diver is using a lifeline or is plainly visible from the surface in shallow water. In this case, a competent diver must be in the boat, with breathing equipment at hand for immediate use.

4.5.2 <u>Surface craft</u>

For the immediate base of SCUBA diving operations, locate a small power carft as near as possible to the scene, and moor it, preferably to an anchored buoy. Keep the craft free to cast off immediately for recovery of any diver surfacing in trouble at a distance. Where descending lines are in use or lifelines are being tended, provide a second craft for emergency assistance.

Enable the diver to enter the water or to return aboard without difficulty. If necessary, provide a ladder or a small stage.

Whenever possible, avoid diving directly from shore or large vessels or from piers or similar installations. The mobility of a small craft and the possibility of reaching the diver directly from it may save life.

4.5.3 Personnel and organization

Man the diving boat with sufficient qualified personnel to handle the situation adequately, with particular regard to the number of divers in the water. Place one competent man in clear charge of each operation, with full responsibility for the divers' safety. He should be a qualified diver, but should not be in the water during the operation.

Arrange sound signals or other communications, at least to order surfacing. Allow no diver to disobey such signals. The divers must heed immediately any command to surface, proceeding at the normal rate of ascent and taking any applicable decompression.

4.5.4 Planning

Every operation should be carefully planned, and all personnel should understand the plans thoroughly. Select the depth and time by considering the type of apparatus, the available gas supply, and the limits which diving physiology imposes. Make instructions for the divers extremely clear and definite.

Except in cases of absolute necessity, avoid dives requiring decompression. The procedures of decompression add greatly to the complexity and hazards of SCUBA diving. However, when it is necessary, or could become necessary through unforeseen circumstances, make adequate provisions to decompress the divers (7.0.0).

Apply ample safety margins in estimating gas supply duration and in setting depth and time limits. When a man must dive more than once in a 24-hour period, give thorough consideration to the cumulative aspects of exposure in repetitive dives (7.0.0).

4.5.5 Unusual diving conditions

Wherever necessary for unusual conditions, provide lifelines, descending lines, additional weights for divers, and any other special equipment which may be desirable.

4.5.6 Emergency measures

Have at least one extra breathing unit available for emergency use.

Train all personnel in the approved method of manual artificial respiration (IA-6A6). Having a mechanical resuscitator at hand is worthwhile, but do not let the presence of such equipment obscure the value of the manual method or the urgency of applying it.

Always know the location of the nearest recompression chamber and the most rapid means of reaching it. Wherever possible, make advance arrangements for summoning help, and for providing rapid transportation in emergency.

The possibility of successful treatment of decompression sickness by water recompression with SCUBA is remote.

Provide a medical kit for handling minor injuries and giving first aid.

4.5.7 Diving with negative buoyancy

As has been mentioned, certain jobs and diving conditions demand the use of extra weights, lines, and other accessories in conjunction with techniques characteristic of suit-and-helmet diving. It has also been pointed out that these techniques are not particularly adaptable to SCUBA diving and that use of standard gear would generally be more suitable.

It is important to remember that where these accessories and techniques are used with SCUBA, the operation takes on most of the aspects of air-hose diving. The tenders and other surface personnel have corresponding responsibilities. These are discussed in the Diving Manual and should be familiar.

4.6 PERSONAL EQUIPMENT

4.6.1 Breathing apparatus

The type of SCUBA must be appropriate for the operation (2.0.0) and in first rate condition (4.3.0). Its harness or vest must permit immediate removal.

4.6.2 Accessories

A number of accessories are necessary in virtually every dive. These include:

(1) Swim-fins. The diver should use an efficient type to which he is accustomed. He will need different sizes for use with and without a suit. They should fit well.

(2) Face-mask. If a separate swim-mask is used it should be comfortable, seal well, and have a retrieving lanyard.

(3) Weight belt. Weights will generally be required for adjustment of buoyancy. They should be on a belt and not on the breathing apparatus unless the apparatus is specifically designed to receive weights and provides ready means for dropping them. The belt fastening must permit rapid removal with a single movement of one hand. A ring buckle with the free end of the belt passed back through to permit unfastening with one pull is suitable.

(4) Flotation gear. A life preserver of compact design which can be inflated with carbon dioxide cartridges may be of life-saving importance. It should automatically keep the wearer afloat in the proper position at the surface. A vest-type preserver specifically designed for this purpose is most desirable. In certain types of SCUBA, such arrangements can be an integral part of the apparatus.

(5) Knife. The diver should always have a knife, worn so that it can be unsheathed quickly and easily. A double-edge type is preferable, with one edge sharp and the other saw-toothed.

(6) Depth gauge. Except in shallow water where depth is known, the diver should be able to check his depth at any time. Several models of wrist depth gauges are available. These should be calibrated regularly to insure accuracy.

(7) Watch. The diver should keep track of his own time even when surface personnel have responsibility for doing so. Pressure-proof watches or watch enclosures can be obtained.

(8) Noseclip. Although opinions differ as to its desirability, many divers find a noseclip helpful in equalizing pressure and in decreasing the annoyance of small amounts of water in the swim-mask. It is particularly valuable upon losing or flooding the mask. A properly adjusted noseclip should be comfortable and will not interfere with equalizing pressure in the mask or with expelling water.

NOTE: Never use goggles or ear-plugs (5.3.5).

4.6.3 Additional equipment

Diving conditions or specific jobs may favor use of certain accessories.

(1) A lifeline is highly desirable when it does not interfere with the dive; it is essential in some circumstances. Attach the lifeline to the diver's body, not to the SCUBA or the weight belt.

(2) A floatline may be valuable when a lifeline is not practical. The line extends from the diver to a float on the surface. The buoy or flotation bag shows the diver's position at all times, but does not restrict his freedom. It can also be used for signalling.

(3) Protective clothing such as a rubber exposure suit is required in water of 60°F or less. Wool underwear may suffice above that temperature. Use a suit in contaminated water. Consider a suit for protection against marine life, jagged edges, and other contact hazards. Furnish gloves when necessary, and provide positive foot protection when needed as for working on the bottom, for diving around coral, or for emerging on shore. When using fins, protect the heels when necessary.

(4) A compass is essential in most attack, reconnaisance, and search operations. It is valuable in any SCUBA diving operation especially if visibility is poor.

(5) A plastic slate and a pencil permit the diver to carry written instructions and to record observations.

(6) In night dives, an underwater flashlight is valuable for illuminating work and for signaling. During daylight, it may prove useful for close work in murky water.

(7) Use extra weights to provide negative buoyancy when working on the bottom in heavy currents or under other conditions requiring exceptional stability. Secure the weights only to a belt which has a quick release fastening. Weighted shoes are hazardous. Always use a ligeline when carrying extra weights.

4.6.4 Complications of accessory gear

Much of the personal equipment of the SCUBA diver is essential to his safety or to his work, but the aggregate may constitute a distinct encumbrance. Keep the number of non-vital accessories to a practical minimum. Insure that the SCUBA, the weight belt, and the lifeline are all readily and separately removable. Diving in cold water or working with gloves may greatly reduce tactile sense and dexterity. Keep the fastenings and arrangements of all equipment separate, distinctive, and accessible.

4.7 THE DIVE

4.7.1 Preliminaries

Certain procedures should be observed habitually before any dive. The following are particularly important.

(1) Use a check-off list in testing and inspecting the apparatus before entering the water. Such a list should cover all essential points related to the particular gear and accessories. Cylinder pressure should always be determined.

(2) Don the apparatus and accessories. Be sure all quick-release fastenings are operative. Put the mask in place and check the seal by inhaling. The faceplate or eyeports must be clean. Reduce fogging by smearing the inside with saliva and rinsing lightly with water. Purge oxygen rebreathing gear at this point (2.2.5). Manipulate other types of gear as necessary.

(3) Enter the water. Use assistance if needed. Do not jump from boat.

(4) Check the apparatus for leaks and for satisfactory operation while just beneath the surface.

(5) Adjust buoyancy for swimming. The technique depends on the type of apparatus. With closed-circuit equipment, fill the breathing bag to a comfortable degree and add weights until buoyancy is neutral. With open-circuit equipment, adjust buoyancy so that the diver rises on full inspiration and sinks on full expiration. When the diver uses a suit, vent the air thoroughly before adjusting buoyancy.

4.7.2 The descent

In descent, use a descending line or swim down headfirst. Do not rush. Be sure that pressure equalizing in the middle ears and sinuses. Stop the descent if significant discomfort develops. Do not continue descent unless it subsides. Remain level or ascend slightly until the pressure equalizes. Discontinue dive if the pressure does not equalize; never force the issue. Consider the possibility of "suit-squeeze" if ear discomfort persists in spite of equalization (5.3.8). Remember the consequences of ear drum rupture in cold water (5.3.4). If diving to decompression depths, note time carefully at beginning of descent.

4.7.3 The dive

While submerged, watch depth and time carefully. Keep the buddy within sight and observe him frequently. Maintain slow, deep respiration. Avoid overexertion. Keep physical activity to practically minimum. At the first sign of shortness of breath or fatigue, slow down or stop. If fighting a current prevents slowing down, terminate the dive. Know the characteristics of the type of SCUBA used, and be alert for signs of apparatus failure, exhaustion of gas, or any symptoms which may indicate trouble. Avoid hazards of entanglement in kelp, wreckage, or lines. Extend hands in front, if swimming where visibility is poor.

4.7.4 The ascent

Before ascent, signal the buddy and wait until he replies. Ascend leisurely at a pace not exceeding 25 feet a minute. "Do not pass the smallest visible bubble" is a useful rule of thumb for this rate. Swimming slowly in a wide spiral is often a satisfactory method of ascent. Continue breathing throughout ascent. Consult the watch and stop at appropriate depth if decompression is required. End "diving time" upon breaking surface or upon starting the first decompression stop. If decompression is indicated, surface personnel should have rigged a stage or marker (7.0.0). Make the proper stops, if required, before surfacing.

4.7.5 Surfacing

Upon surfacing, the diver may be extremely fatigued. Make sure that surface personnel render all possible assistance, including removal of heavy SCUBA while diver is still in the water if this will facilitate climbing into boat. Guard against falling. Have diver dry himself promptly. Provide warm, dry clothes when surface temprature is low. Observe routing established for care of ears (5.16.2).

4.7.6 Equipment care

At the earliest opportunity, rinse the equipment completely with fresh water, dry, and provide proper stowage. Report immediately any defects noted, and insure prompt correction.

4.8 UNDERWATER EMERGENCIES

4.8.1 General

Very few situations underwater are so desperate as to require instantaneous action. Taking even a few seconds to think will pay dividends. Instinctive actions are seldom the right ones; but adequate training will prepare the diver for almost all emergencies, provided that he keeps his head.

4.8.2 Gas-supply exhaustion

Running out of gas should not be a serious situation except with open-circuit apparatus if the air reserve warning device (a mandatory feature) fails. Even in this case, the increase of breathing resistance prior to exhaustion generally gives some warning. In closed-circuit apparatus, the gas in the breathing bag will be adequate for ascent at a normal rate. (Certain types of mixed gas apparatus may be an exception to this rule, however). In any type of apparatus the reduction in pressure on ascent should provide at least a small amount of additional gas volume.

4.8.3 Loss or flood-out of swim mask

The diver should learn to dive without a mask. This is particularly easy if he has used a noseclip which has remained in place. With the lanyard he can retrieve a swim mask and replace it. He can readily clear the mask by tilting his head backward to place the lower edge of the mask at the lowest position, holding the upper part of the mask tight on his face, and exhaling through the nose. The water will drain effectively.

4.8.4 Flood-out of mouthpiece or facemask

This is a more serious problem, but every acceptable apparatus should have means of rectifying it. The technique of clearing will depend on the apparatus used. Training should make the technique second nature.

4.8.5 Entanglement

This situation generally requires more thought than action. The diver should try to figure out what is holding him, and use his knife where indicated. A swim-buddy is most useful here. Only as a last resort should the diver remove the breathing apparatus and make a "free ascent."

4.8.6 The role of the buddy

The diver should signal his buddy at the earliest inkling of trouble if he has time. If the two are watching each other properly, neither should have difficulty seeing when the other is in trouble. The buddy must attempt to discern the nature of the problem and do what he can. His hardest job will be in the presence of panic. Here, and in unconsciousness, he may be able to do little more than get the man to the surface, attempting to keep the mask or mouthpiece in place in the process. In ascent, the possibility of air embolism exists. It is probably not a serious problem in unconsciousness, but it is acute in panic. It may be necessary to use direct measures to get the man to exhale. A vigorous punch in the abdomen or bear-hugging about the chest from behind has been suggested.

4.8.7 Emergency ascent

Learning the technique of "free ascent" is a valuable part of training although it should not be practiced except under ideal conditions (3.2.3,II). However, such ascent should not be regarded as the first thing to do in all emergencies. It is inherently hazardous and is unusually difficult to accomplish safely in situations of stress. However, if the breathing apparatus is not usable and the situation cannot be rectified readily, there is of course no alternative.

Unless the breathing apparatus is entangled, the diver should keep it on even though it is useless. He should drop the weights, if any. If the diver then has positive buoyancy, he will begin to ascend. When he does so, he should not accelerate the process by swimming. If he does not ascend spontaneously, he must swim. In either case, he should consciously exhale throughout ascent. If exhalation causes loss of buoyancy, a few kicks will cause enough ascent to produce expansion of gas and restore buoyancy. The diver should not pass his exhalation bubbles on ascent. He can slow ascent by increasing the rate of exhalation and by extending the arms to the side. Any sensation of pressure in the chest should prompt the diver to increase his exhalation.

The foregoing represents the generally accepted doctrine of free ascent. An alternative method has been suggested which may deserve consideration. It calls for:

(1) Near-maximum exhalation early in the ascent and continued exhalation thereafter, and

(2) Ascent in the shortest possible time.

Quick ascent pre-supposes the use of flotation equipment by SCUBA divers. The carbon-dioxide cartridges would be "pulled" at the bottom but since the vest would not be completely inflated until reaching the surface, the ascent would be initiated by a few kicks simultaneous with initial exhalation.

4.8.8 Surfacing

On reaching the surface, the diver should remove the breathing apparatus if it is of the air-demand type since the cylinders will tend to hold him down in the water. (Most such apparatus has slight positive buoyancy when completely submerged. Although this would assist the diver at the surface if he turned on his back, the effect is slight. In any position, the cylinders will become negatively buoyant as soon as any part breaks surface). Most apparatus with breathing bag may be left on if the bag can be inflated. Otherwise, it too should be removed. Flotation gear will be of great advantage to the surfaced diver especially in choppy water.

4.8.9 Summary

Panic and ill-considered actions are the greatest hazards when untoward events occur in the use of self-contained apparatus. There are few situations from which the diver cannot extricate himself if he keeps his wits about him and acts appropriately. His ability to do so will depend largely upon the adequacy of his training and preparation.

NOTE: Safety considerations related to various specific hazards are discussed in Chapter 5.

CHAPTER 5

SPECIFIC MEDICAL PROBLEMS IN THE USE OF SCUBA

CONTENTS

CHAPTER 5

SPECIFIC MEDICAL PROBLEMS IN THE USE OF SCUBA

Among the accidents, untoward physiological reactions, and related difficulties arising in the use of SCUBA, few are peculiar to that form of diving. Most of them have long been familiar in diving medicine and are described in Submarine Medicine Practice. However, the significance of many of these entities is sufficiently different in SCUBA diving to warrant further discussion here.

5.1 DROWNING

Drowning is believed to be the most frequent cause of death in SCUBA diving accidents.

The SCUBA diver is exposed to all of the potential hazards inherent in swimming; in addition his ability to remain underwater leads him into precarious situations that a surface swimmer would seldom encounter. So long as the breathing apparatus functions properly he is relatively safe. But if the apparatus floods, exhausts its gas supply or otherwise fails, he is in immediate peril. Loss of his mask or mouthpiece threatens him with drowning if he does not act promptly. Under some circumstances the apparatus itself can become a serious handicap - when, for example, a diver tries to surface but finds himself held down by an apparatus which he cannot remove.

Although some mishaps occur so suddenly that the diver can do nothing, training should equip him to handle most situations. A trained diver should not panic. Panic can change even a minor mishap into a drowning.

Fatality statistics in SCUBA are undoubtedly misleading. Where drowning is reported as the cause of death, some other accident such as air embolism may have gone unrecognized even on the autopsy table. In some cases, drowning may be the end result of an entirely different incident. Oxygen convulsions may lead to drowning. Anoxia or hypercapnia may produce unconsciousness which can result in drowning. Desperate dyspnea from overexertion may generate panic which will end in drowning. In many cases, the breathing apparatus has no bearing on the drowning except that its possession encouraged the victim to place himself in a dangerous situation.

Always bear in mind and be prepared for the possibility of drowning in SCUBA diving. Go at once to the aid of any diver who surfaces unexpectedly in any kind of trouble. Be ready to administer artificial respiration (IA-6A6).

5.2 EXCESSIVE INTRAPULMONARY PRESSURE (Air Embolism and Related Phenomena)

If a man suddenly loses his air supply underwater, his overwhelming instinct is to hold his breath and surface immediately. Restriction of expanding gas in the lungs during this ascent will produce overdistension and excessive intrapulmonary pressure. Such pressure may also occur during a normal ascent if the diver fails to breathe continuously. Theoretically, the phenomenon can occur on a local basis if an area of the lung filled with air under pressure becomes obstructed prior to ascent.

Air embolism (IA-6A1) is a frequent result of excessive intrapulmonary pressure, and is probably the second most common cause of SCUBA fatalities. Mediastinal and subcutaneous emphysema, rupture of the lung, and possibly pneumothorax are other consequences of over-pressurization of the lungs.

5.2.1 Mechanisms of damage

Studies indicate that an excised lung begins to leak air at about 35 mmHg pressure. In an intact lung in situ, air leakage through the connective tissues of the bronchioles has occurred between 40 and 50 mmHg, producing mediastinal or subcutaneous emphysema. Pressures between 60 and 100 mmHg have been known to rupture intact lungs. Pressures between 80 and 100 mmHg will produce leakage of air into the pulmonary circulation with resultant air embolism.

Experimental animals tolerate much higher intrapulmonary pressures when the thorax and abdomen are wrapped to prevent overexpansion of the lungs. This is believed to explain why high pressures produced by voluntary effort against a closed glottis rarely produce harm - the muscular effort "splints" the lung and prevents overexpansion.

Time relationships are probably important. During overpressurization, air leakage may require some time to reach serious proportions. Hence, a sudden application of pressure may cause lung rupture without air embolism. Leakage into the pulmonary circulation may occur through stomata between the alveolar air spaces and the capillaries. These, if present as postulated, would normally be closed; but would open with overexpansion of the lungs and permit leakage without any mechanical trauma.

Studies conducted with animals suggest the following"

(a) Overpressurization of the lungs may have at least three consequences.

(1) Either mediastinal or subcutaneous emphysema, or both.

(2) Air embolism.

(3) Lung rupture.

(b) Overexpansion is a pre-condition for air embolism.

While the most crucial experiments have not been repeated in man, the results would apparently be about the same.

5.2.2 Application to diving situations

Up to a point, the body can accommodate expansion of gas in the pulmonary system by corresponding expansion of the lungs. If voluntary inspiratory effort assists this expansion, intrapulmonary pressure will not rise above external pressure until the lungs attain the maximum inspiratory position. Without an inspiratory effort, rising intrapulmonary pressure alone will expand the lungs, and when the net pressure is about 20 mm of mercury they will reach position of maximum inspiration. Beyond this point, the intrapulmonary pressure increase should correspond to the external pressure decrease caused by continuing ascent. In this connection it is interesting to note that 100 mm of mercury is equivalent to about 4 1/2 feet of water.

These observations lead to two conclusions. If voluntary effort assists the compensatory expansion of the lungs, an additional ascent of only 4 1/2 feet can produce an air embolism, once the point of maximal expansion is reached. If rising intrapulmonary pressure alone has produced the lung expansion, the additional ascent need only be about 3 feet.

When a significant amount of air is in the lungs, the ascent required to produce air embolism may be very small. Even a brief interruption of normal respiration or of exhalation during a rapid ascent can then have fatal consequences.

A minimum volume of gas in the lungs gives the greatest margin of safety. Here, expansion of the lungs accommodates expansion of the gas for a considerable distance of ascent, somewhat the reverse of the familiar pearl diver problem. However, this observation is not much help in free ascent because, as generally practiced, such ascents require use of intrapulmonary gas for buoyancy. Furthermore, near-maximal expiration would not appeal to a diver unless he had an external source of buoyancy to assure rapid ascent.

A blocked segment of lung, surrounded by normally ventilating lung, should have about the same characteristics as isolated lung. Since 35 mm of mercury (about 18 inches of water) can cause leakage in an isolated lung, a blocked segment appears to have lethal possibilities. However, this seems a likely explanation in few, if any, reported cases of air embolism.

Although rare in diving, spontaneous pneumothorax is occasionally seen. Its usual mechanism is probably rupture of a temporarily occluded peripheral bleb during ascent. Short of frank rupture of the lung, pneumothorax due to overpressurization of the whole lung is improbable.

5.2.3 Prevention

Unhurried ascent and continuous normal breathing are very important in SCUBA operations. The mandatory exhalation in emergency ascent requires not only emphasis but also practice, to make it automatic in stress situations. Training requires every safeguard possible against the hazards of breath holding (II).

The possibility of trouble from occluded segments of lung, while remote, necessitates disqualification of divers with asthma or similar conditions, and supports the wisdom of avoiding diving during chest colds or bronchitis.

5.2.4 Treatment

Air embolism (IA-6A1) requires prompt recompression. Of itself, recompression will not aggravate the emphysematous conditions or pneumothorax; and it will usually provide at least temporary relief. In pneumothorax, however, subsequent ascent may necessitate management for tension pneumothorax. Ordinarily, treatment of the emphysemas is conservative; treatment of pneumothorax depends on its extent and course.

Hemoptysis (blood-stained sputum), alone or in association with any other symptoms, suggests actual lung damage. Treatment depends on the evident extent of damage and on the patient's general condition. Sound medical judgment is required. (See reference 5j).

5.3 BAROTRAUMA ("SQUEEZE")

Although "squeeze" is a colloquialism, it is an excellent descriptive term for all of the phenomena which occur when a closed space within the body or on its surface fails to equalize with external pressure.

5.3.1 Mechanism of squeeze

The unbalanced pressure quite literally squeezes the adjacent tissues into the space. The major response to the unbalanced pressure occurs in the mobile fluids of the body (blood and extracellular fluid). The tissues themselves tend to resist the squeezing force and are consequently damaged by the pressure within and behind them.

Tissue edema and capillary dilation are the earliest and mildest consequences of squeeze. As the process continues, capillary leakage results in extravasation of blood by hemorrhage into the tissues. Beyond this, breakdown of the tissue surface permits exudation and hemorrhage into the space. Actual disruption of the tissue may follow.

Most of the specific situations in which this basic mechanism operates are familiar, although a variety of other terms may be applied to them. The following list of situations is of interest.

5.3.2 Situations involving squeeze

(a) Middle ear: Blockage of eustachean tube.

(b) Sinuses: Occlusion of ostia.

(c) External auditory canal and external ear:

(1) Use of ear plugs.

(2) Seal of suit material over external ear.

(3) Use of hood with no means of equalization.

(d) Eyes: Use of goggles.

(e) Face:

(1) Use of swim mask without equalization of pressure through nose.

(2) Use of full mask with various mishaps (see Lungs).

(f) Lungs:

(1) Going too deep while holding breath.

(2) Failure of demand-type SCUBA during descent.

(3) Failure to add gas to closed-circuit SCUBA.

(4) Malposition of SCUBA components.

(5) Failure of supply to air-hose equipment during descent.

(6) Venting of air-hose equipment to surface.

(7) Falling to greater depths.

(g) Head and shoulders (in suit and helmet):

(1) Failure of non-return valve with rupture of air hose or loss of supply.

(2) Falling to greater depths.

(h) Skin surface: Presence of folds or rigid air spaces in non-inflated suit without means of equalization (10.3.0).

Although the SCUBA diver need not be concerned about the classic "buried in his helmet" type of squeeze, he is in many ways vulnerable to the same basic mechanism. Some of the possibilities deserve specific mention.

5.3.3 Middle ear squeeze

This is the most frequent and troublesome difficulty related to squeeze. Many individuals up to 10% of an unselected group) consistently have trouble and must be eliminated from diving. Others experience difficulty until they learn the technique of opening the eustachean tubes. Many successful divers are disabled by blocked eustachean tubes during upper respiratory infections.

Other methods of grading will be encountered, and the observations may not always fall neatly into place. Do not dismiss a simple description of what is seen. Keep the divers' ears free from excess cerumen as a routine procedure; this will significantly help visibility when damage occurs. Avoid syringing and instrumentation if rupture is suspected, regardless of the obstruction of vision.

Symptoms vary considerably. The damage itself and the irritation of extravasated blood may either cause discomfort for some hours or be almost negligible. An increase in pain is not common; it may signify development of infection. External bleeding is not seen except with rupture of the drum. When free blood from the middle ear drains down the eustachean tube, the patient may spit traces of blood or find blood in his nasal secretions. View with suspicion any significant drainage through the external auditory canal after the first few hours of rupture.

Experience in submarine and diving medicine indicates that the best treatment of ear barotrauma is a strict "hands-off" policy unless complications develop. In the absence of rupture, keep the patient out of the water for at least 24 hours, or until the membrane regains a reasonably normal appearance. Do not let him dive as long as he may have further difficulty in equalizing. Beyond use of local vaso-constrictors in the nose, and a dose of mild analgesic, he will need no active treatment in the absence of infection.

In the presence of rupture, aim primarily at keeping all extraneous matter out of the ear. Do not attempt to clean the area by swabbing, and particularly avoid syringing. Use no local medicaments in the ear. Have the diver avoid diving and swimming of all kinds until healing is evident. Give him particular instructions to keep water out of his ears. Warn him to exercise caution even in showering and washing.

Use of cotton plugs in the ears appears inadvisable. If some protection is desirable, place a piece of gauze over the external ear.

Some medical officers employ prophylactic antibiotic therapy. Since the patient should be watched closely and instructed to report any increased pain, drainage, or other abnormality, employment of such therapy at the earliest signs of infection should be adequate.

5.3.4 Eardrum rupture in cold water

Dizziness and nausea caused by caloric vestibular stimulation which results from entry of cold water into the middle ear presents a specific problem when the eardrum ruptures in cold water. The effect may be intense, and although it subsides rapidly as the water is warmed, it presents a serious potential hazard. The diver becomes completely disoriented and frequently is violently nauseated. Vomiting in the breathing apparatus may severely complicate the situation. Any consequent panic is not surprising.

Every SCUBA diver should be thoroughly aware of the possibility of this accident and of the fact that the symptoms will subside. (It might even be well to demonstrate the effect by giving the familiar caloric test).

It is not always easy to find the cause of the difficulty, which may range from congenital defects through malposition of the mandible to an excess of local lymphoid tissue. In the last case, a course of radium treatments to the area may be very beneficial. However, it requires time, and the initial response usually makes the situation more acute. The treatment is rarely practical when a man presents himself for diving training.

For temporary conditions, inhalers, nasal sprays, or drops may assist equalization by causing local vaso-constriction. Keep in mind the possibility of further difficulty from a "rebound" effect.

Aids to equalization of the eustachean tube include swallowing, yawning, moving the jaws from side to side, blowing against closed nostrils, and various muscular movements not readily described. Certain individuals have nearly voluntary muscular control over the orifices, and apparently most experienced divers unconsciously develop some degree of voluntary control. The opening acts much like a check valve. It rarely prevents escape of air during ascent, but it may "slam shut" when a man fails to keep pace with rapidly increasing pressure during descent. In this case the diver may have to ascend a few feet to allow the orifice to reopen.

In failure to equalize, discomfort is almost immediately apparent, and pain soon follows. A 10 foot descent without equalization is enough to rupture the tympanic membrane. In a few individuals rupture may occur without significant warning pain.

A diver should know how to "pop his ears" at the surface, by blowing against closed nostrils. He can use this procedure before entering the water, to ascertain the possibility of difficulty on a dive.

SCUBA divers may at first experience increased difficulty in equalization while inverted, or while using certain types of apparatus. Generally they overcome the difficulty quickly. The ability to close the nostrils for blowing to clear the ears depends on the equipment used. When the apparatus precludes closing the nostrils by pinching, a noseclip is extremely helpful.

Degrees of damage, as observed with the otoscope, may be graded according to the sequence of events previously discussed (5.3.1).

GRADE	EVIDENCE OF DAMAGE
I	Injection of membrane (capillary dilation, etc.); edema.
II	Marked injection of membrane with small hemorrhages; edema.
III	Gross hemorrhage within membrane.
IV	Gross hemorrhage plus evidence of free blood in the middle ear.
V	Gross hemorrhage plus rupture of membrane.

Instruct divers not to attempt to surface during this reaction. Explain that the best thing to do is simply to hang onto something until it passes. Hugging himself may help the victim when there is nothing else to grasp. To give a specific instruction of this sort is desirable in any event.

Prognosis is almost invariably good. Trauma short of rupture almost never causes trouble, and a ruptured tympanic membrane generally heals ineventfully in a matter of weeks. However, the possibility of hearing-loss or of infection and its sequel, even though unlikely, demands that barotrauma of the ear should neither be risked unnecessarily nor taken lightly.

5.3.5 External ear squeeze

Creation of a closed space external to the tympanic membrane by any of the factors listed above (5.3.2) can cause injury of the membrane similar to that seen in eustachean tube blockage. Here, hemorrhage within the membrane may appear as a blood-filled bleb on the external surface. This may rupture and produce external bleeding without actual perforation of the drum. In this particular situation, external bleeding is not pathognomonic of rupture, although in the more common situation it is. Avoid ear squeeze while using non-inflated suits with hoods by admitting air to the hood during descent. The diver can frequently do this simply by holding the facemask firmly and blowing. Some divers will have to pinch up a fold of suit at the junction between the mask and the face-seal of the suit in order to do this.

Generally, admission of air to the hood by one of these methods will relieve the ear-sensation. It may not do so if the suit material is such that it can effectively seal over the external ear. This can be prevented by lining the suit at that point with a patch of flannel or other porous material. The diver must exercise care in blowing air into the suit when he is in the inverted position. He may retain some sensation of squeeze after this maneuver. Introducing more air into the suit will not necessarily help. However, excess air will work toward his feet, where the increased buoyancy may hold him in the inverted position.

The use of ear-plugs is very hazardous not only because of the probability of forming a closed space but because of the possibility of forcing the plug against the drum. If the diver then fails to equalize pressure in the closed space and in the middle ear as well, the plug may be forced in far enough to destroy the tympanic membrane and the ossicles.

5.3.6 Sinusitis

If a sinus fails to equalize, the diver will generally be aware of a sensation of pressure which is followed by pain. If descent is continued, collapse of the space is extremely unlikely; but severe trauma of the lining membrane is possible. Exudate and hemorrhage will eventually fill the space to the point that compression of the trapped air equalizes the pressure.

Expansion of the trapped air upon ascent may produce a dramatic expulsion of material from the sinus. If sinusitis was already present, a considerable amount of purulent material may be removed in this way. Some enthusiasts claim a considerable relief of sinusitis from deliberately risking sinus squeeze. It is seriously questionable whether the possibility or relief ever warrants the trauma which may occur. In fact, it is quite probable that a purulent sinusitis will be the outcome of continued descent when equalization is difficult or impossible.

5.3.7 Bleeding

A diver who coughs up or spits out blood following a dive, or who apparently has a nosebleed, presents a diagnostic problem. Bleeding from the ear is a more obvious situation.

The appearance of fresh blood in the nose or nasopharynx is usually the result of drainage from the middle ear or bleeding from a traumatized sinus. In most cases, the man will recall some difficulty equalizing pressure, although a few individuals will bleed from the nose without any previously apparent indication of trouble. Investigate the possibility of epistaxis from causes not directly related to diving. If the investigation does not localize the source of bleeding, or if the man is clearly coughing up bloody or blood-tinged sputum, suspect a pulmonary source. Two basic causes related to diving are possible: pulmonary squeeze for one of the reasons mentioned (5.3.2), and over-pressurization of the lung (5.2.0). A relevant history may not be obtained in either case.

5.3.8 Suit squeeze

SCUBA divers who use rubber suits which are not designed on the constant volume principle (10.4.0) observe that the suit "clings tighter and tighter" during descent. On entering the water, most divers deliberately vent all excess air from the suit. This venting produces a clinging sensation. The remaining air trapped in folds of the suit, or in the interstices of the underwear, is compressed by descent. In most areas, this presents no problem other than an increase in the clinging sensation. The possible effect on the ears has been described (5.3.4). Occasionally, a fold of material or a fitting will pinch, producing an area of local edema, petechiae, or ecchymosis, and resulting in acute discomfort. This development is unlikely unless the space can seal itself against the bare skin. To prevent a seal, as well as to gain cold-protection, wearing some form of long underwear under a rubber suit is indicated.

The compressed folds of the suit can severely limit motion, particularly of the legs, because the folds may be too stiff for free movement. Attempts to pull the folds apart may result only in a pinch, which can be particularly uncomfortable at the groin. Suit-squeeze may be relieved by the same technique of admitting air as described for external ear squeeze, and the same precautions should be observed.

5.4 OVEREXERTION

5.4.1 Respiratory response

The hyperpnea of muscular exercise and the accompanying sense of dyspnea are probably the most familiar limiting factors of exertion. The respiratory response to a burst of activity may be so delayed that it does not adequately warn a man when he is exceeding his powers. Ultimate production then will force him to cease his exertion and pant furiously for some minutes. This dyspneic state can occur readily even with free access to air, and it is unpleasant enough under ideal conditions. If breathing is hampered in any way, the state not only occurs sooner than usual but can become a terrifying experience.

The SCUBA diver may frequently have to work very hard. On occasion, a few moments of extreme activity may mean the difference between life and death. Even with minimal breathing resistance (6.7.0), SCUBA will hamper respiration to some degree. It is surprising to note, in currently available units, how readily noticeable dyspnea may occur and how little warning such sensations as muscular fatigue offer.

5.4.2 Limitations

A trained diver must be clearly aware of the limitations of his own lung power and of his apparatus in this regard. He should avoid overexertion which may produce severe dyspnea. When he must overexert in an emergency, he must also expect the consequent shortness of breath. Untrained individuals, especially inefficient swimmers, tend to panic under these conditions. The only real solution to the problem is to provide a SCUBA with the best possible breathing characteristics.

5.5 ANOXIA

5.5.1 Mechanisms

Defined as lack of sufficient oxygen for the metabolic needs of the tissues, anoxia can result from interference with any phase of the uptake, transport, and utilization of oxygen. The only common cause in diving, aside from complete exhaustion of air supply or drowning, is insufficient oxygen in the inspired gas. Normal oxygenation depends upon the presence of an adequate partial pressure of oxygen. A partial pressure of 0.21 atmospheres, equivalent to the oxygen content of air (20.94% oxygen) at the surface, is ample. Thus, theoretically, 5% oxygen would be ample at 99 feet (0.05 x 4 atm. = 0.2), but ascent from that depth on such a mixture would promptly result in anoxia.

5.5.2 Consequences

The consequences of reduced oxygen content are summarized in table 5-1 below. Note that these data are derived from uncomplicated situations with healthy subjects essentially at rest.

TABLE 5-1

CONSEQUENCES OF REDUCTION OF OXYGEN CONTENT OF INSPIRED GAS

Surface Oxygen Percentage	Condition of Subject
16 to 21	No detectable change.
12 to 16	Ability to concentrate decreased; fine muscular control impaired. Pulse and respiration slightly increased.
10 to 12	Muscular function impaired, judgement faulty, emotions unstable, fainting common, moderate degree of analgesia, gait unsteady. Pulse and respiration moderately increased.
Below 10	Eventual unconsciousness, subsequent death.

5.5.3 Symptoms

Among the symptoms of anoxia, none is likely to give adequate warming to a diver. The anoxic change in respiration is not sufficient to produce noticeable dyspnea. The pulse change is not notable. Cyanosis, an unreliable index under any circumstances, would certainly not be observed. A man who kept the possibility of anoxia in mind might detect the impairment of his mental function or dexterity in time to remedy the situation. But the mental effects of anoxia resemble those of alcohol. They are not unpleasant, and once they are evident, much of the will and ability to take action is gone. Its insidious nature makes anoxia one of the most serious hazards which can be encountered in diving.

The relative danger of anoxia has been discussed together with the other characteristics of various types of SCUBA (2.0.0).

5.5.4 Prevention

Anoxia is prevented primarily through careful maintenance, adequate testing, and proper use of apparatus in which anoxia is possible. Awareness of the possibility and familiarity with the symptoms may enable a diver to recognize its onset. He must have his course of action well rehearsed and carry it out promptly.

5.5.5 Treatment

The main requirement is that the victim be given access to air if he is still breathing. If he is not, artificial respiration is obviously necessary. After-effects are usually negligible, but prolonged anoxia can produce organic brain damage.

5.6 CARBON DIOXIDE EXCESS

5.6.1 Occurrence

Carbon dioxide accumulation may occur for a variety of reasons (6.4.0, 6.5.0) - most often in rebreathing systems, due to frank failure of the absorption system or exceeding its capacity through overexertion.

5.6.2 Shallow-water blackout

The prevalent idea that carbon dioxide accumulation in closed-circuit SCUBA entails little real danger is a serious misconception. It is based on the belief that recognizable symptoms always are present before serious effects occur. This is not reliably true. In shallow water blackout, carbon dioxide causes the diver to lose consciousness without the usual warning of dyspnea or of other symptoms such as headache, nausea, dizziness, or weakness. (See section 6.6.0).

5.6.3 Prevention

Carbon dioxide accumulation requires careful attention to the design and proper use of absorption canisters, and avoidance of overexertion.

5.6.4 Recognition

Ability to recognize warning symptoms if they occur is important. If these are mild, they may pass if the diver rests and allows his canister to recover. It is better for him to surface.

5.6.5 Treatment

Treatment is simple, provided that the affected diver, who may be unconscious, is reached before drowning supervenes. Exposure to air is all that is required if he is still breathing. The after-effects in uncomplicated cases rarely include more than headache, nausea, and fatigue.

The carbon dioxide problem is discussed more fully in sections 6.4.0, 6.5.0 and 6.6.0.

5.7 OXYGEN TOXICITY

Oxygen poisoning represents a potential danger in the use of certain types of SCUBA (2.2.0, 2.3.0, 9.0.0). A general discussion of the problem will be found in IA-6A12. Its particular significance in SCUBA diving is discussed in 8.0.0.

5.7.1 Occurrence

The most important point to be remembered is that oxygen poisoning is not confined to diving on pure oxygen. It can occur whenever the oxygen partial pressure and the exposure time exceed acceptable limits.

5.7.2 <u>Prevention</u>

Prevention is achieved by remaining within the specified limits of partial pressure and time (8.0.0). Ability to recognize warning symptoms when these occur is important (IA-6A12), since lowering the partial pressure of oxygen by ascent or other means may abort convulsion.

5.7.3 <u>Treatment</u>

Two major considerations affect treatment. The first is prevention of drowning and injury during convulsion; the second is lowering the partial pressure of oxygen.

5.8 NITROGEN NARCOSIS (Compressed Air Intoxication)

Occurrence of central nervous system depression when breathing air at greater depths has been known for many years (IA-2C). This effect has set the maximum practical depth of air diving at 300 feet and may seriously hinder diving operations at lesser depths. It provided the major impetus for the development of helium-oxygen diving, by which the anesthetic action is avoided.

These factors not withstanding, the same entity, under the name "Rapture of the Depths", was greeted as a new discovery in some SCUBA circles. Here it provides a good illustration for the statement that liberation from surface connections does not grant exemption from the "facts of life" of diving.

5.8.1 <u>Symptoms</u>

The loss of judgment and skill, and the euphoria characteristic of nitrogen narcosis, (IA-2C) have been fully appreciated as hazards to the safety of the helmet diver. He, however, has the advantage of continuous communication with the surface which permits his tenders to assess his condition and give him specific instructions. If the situation requires, the helmet diver may usually be hauled up. The SCUBA diver has no such safeguards. His life is entirely in his own hands, and the number of lethal mistakes he can make under nitrogen narcosis is impressive.

Nitrogen narcosis and alcohol intoxication have much in common. The general effects are similar, and the degree of individual difference in sensitivity and type of response is comparable. A man who expects to do deep diving with air SCUBA should become acquainted with his own response through exposure in a recompression chamber. Tolerance must not be overestimated, and resistance must not be considered equivalent to immunity.

5.8.2 <u>Diving Limits</u>

The maximum depth for diving on air is 300 feet for the deep sea rig. When nitrogen narcosis, air supply duration, and decompression are considered together, it is reasonable that the maximum depth for diving on air be set at 200 feet for SCUBA. Very few useful dives are prevented by this limit. As explained elsewhere (2.1.0, 7.1.1), the practical limiting depth for air SCUBA is 130 feet in most circumstances.

5.8.3 Prevention

Avoidance of excessive partial pressures of nitrogen is the only preventive measure. Using helium in SCUBA is not practical at present (9.3.0), and reducing the nitrogen partial pressure by increasing the oxygen content introduces the danger of oxygen poisoning (8.0.0). Therefore, the SCUBA diver has no alternative but to stay out of the depths where nitrogen narcosis is a problem.

5.8.4 Treatment

Because the effect disappears as the diver ascends special treatment is unnecessary.

5.9 DECOMPRESSION SICKNESS

The problems of decompression have too often received little consideration in the use of self-contained apparatus. A man who uses air-demand SCUBA is subject to the same risk of decompression sickness as the man who makes a similar dive with conventional gear; yet this fact has been frequently disregarded.

It is widely believed that air supply exhaustion in SCUBA will terminate the dive before decompression becomes necessary. At certain depths, this can be true (7.0.0), but it is no guarantee against decompression sickness following the use of such gear. This false assumption, plus general unawareness of the possibility, has resulted in an unknown number of cases of bends, unrecognized as such and attributed to non-specific trauma. In such cases, the probability of permanent injury from delay or lack of treatment is a cuase for considerable concern. The average physician will seldom recongize decompression sickness, especially if the patient gives him no history except that he has "been swimming".

Individuals who have clearly violated the decompression table without evident retribution have created another source of confusion. Such violations have led to another misconception: that the table is extremely conservative and contains large built-in safety factors. For "average" individuals under optimum circumstances this approaches being true but in the total picture it is clearly false.

In the first place, individuals vary widely in their susceptibility to decompression sickness; and a given man will vary in his susceptibility from day to day. The amount of exertion makes a large difference in the probability of bends. The influence of diving conditions and other factors is great and frequently unpredictable. The decompression table takes this range of variability into account to a certain extent, but to make the table completely safe would almost preclude diving. It is clearly more practical to have, and treat, some cases of decompression sickness than to burden the vast majority of dives with unnecessarily long decompression stops. This philosophy is somewhat less reasonable in SCUBA diving, since treatment facilities are often unavailable.

The present decompression table was developed and tested with literally hundreds of actual dives. The tests were conducted to determine the adequacy of the specified decompression stops and the non-decompression limits. A ZERO incidence of bends clearly could not serve as the criterion of adequacy. The incidence actually used as a criterion approached 5% in some regions of the table. It was frankly admitted that "any series of decompression tables which is intended to be adequate for divers in good physical condition is bound to be deficient for approximately 2 to 3% of the average Navy divers" (5a).

It is true that the actual incidence of decompression sickness in Navy diving since the table was adopted is closer to 1% and that some of these cases involved plain violation of the table. However, this does not prove existence of an excessive safety factor for two reasons. First, in actual diving practice, dives are rarely made to the exact depths and times specified by the table. A dive for 63 minutes to 92 feet for example, takes the decompression specified for 75 minutes at 100 feet. This introduces a considerable and possibly unnecessary margin of safety, but interpolation of the tables is neither practical nor permissible, in the field. Second, under conditions involving exceptionally hard work, extremely cold water, or questionable depth measurement, decompression is taken for the tabulated depth or time beyond that which would normally be used. This is not a large margin of safety; allowance for those conditions is necessary.

If dives were made to exact depths and times, the overall incidence of bends would probably approach 5%. In some regions of the table, it might possibly be higher. In spite of good diving practice, many cases of bends occur after decompression that should have been more than ample. This fact simply indicates the extent of variations in susceptibility and the unpredictable influence of diving conditions.

A 5% incidence of decompression sickness is acceptable, although undesirable, in standard Navy diving where treatment facilities are immediately available. It is completely intolerable where such facilities are remote or lacking, or where large numbers of men are diving simultaneously, circumstances which are likely to exist in SCUBA applications. Air-diving with SCUBA offers no excuse for taking gross liberties with the decompression table or even for cutting it close. Small portable recompression chambers would constitute a considerable asset for SCUBA activities not having access to standard installations.

The general subjects of decompression and decompression sickness are discussed in an earlier section (IA-6A), and further discussion of the problem of decompression in the use of SCUBA will be found below (7.0.0).

5.10 CARBON MONOXIDE POISONING

5.10.1 Sources

Intoxication with carbon monoxide represents a serious potential hazard in diving with compressed air. The source of monoxide in the breathing medium is usually one of the following:

(1) Entrance of the exhaust gases into the air intake is an obvious possibility in the use of portable gasoline driven compressors, but contamination of intake air from any source of exhaust gas can also occur.

(2) In certain types of high-pressure compressors cylinder temperatures may become high enough to promote partial combustion of lubricating oil.

5.10.2 Compressors

The suitability of a given compressor as a source of high-pressure air for diving deserves thorough investigation. Analysis of air samples for carbon monoxide is mandatory in most cases and should generally be repeated periodically. Scrupulous attention to proper maintenance and operation of compressors is required, and the use of special equipment for the removal of carbon monoxide may be indicated. In some situations, it may be extremely difficult to obtain air which is free of all traces of carbon monoxide. The problem of allowable concentrations thus becomes important. Figures for safe limits of exposure at the surface may not be directly applicable.

5.10.3 Mechanisms

Although the possibility of other harmful actions of carbon monoxide has not been ruled out, the primary effects are those of anoxia. These are a consequence of the fact that carbon monoxide combines with hemoglobin. Hemoglobin so combined loses its normal function, and inadequate transportation of oxygen results. The symptoms are proportional to the amount of hemoglobin which has been inactivated in this way but are more severe than those accompanying comparable inactivation or loss of hemoglobin in other conditions. This is probably explained by the accompanying left-shift of the dissociation curve of the remaining oxyhemoglobin (oxygen is less readily given up to the tissues). The possibility of some interference with cellular enzyme systems has been suggested. Individual differences in susceptibility are significant, but Table 5-2 represents a good approximation of the relationship between the proportion of inactivated hemoglobin and symptoms in carbon monoxide poisoning:

TABLE 5-2 Symptoms accompanying various percentages of carboxyhemoglobin in circulating blood.

Percentage of Carboxyhemoglobin	Symptoms observed at one (1) atmosphere.
7%	Generally asymptomatic
10 - 20%	Headaches, mild symptoms and impairment
20 - 30%	Headache, weakness, dizziness, shortness of breath, faintness, nausea
30 - 50%	Severe mental confusion, muscular effort nearly impossible. Victim essentially helpless.
50%	Rapid loss of consciousness.

5.10.4 Formation of carbon monoxide hemoglobin

The amount of carboxyhemoglobin formed, at equilibrium under surface conditions, has been shown to depend upon the ratio between the partial pressures of oxygen and carbon monoxide - not upon the partial pressure of carbon monoxide alone (5b). The law governing the reaction can be expressed in the following formula:

$$\frac{\%\ HbCO}{\%\ HbO2} = 210 \times \frac{pCO}{pO2} \qquad (5\text{-}1)$$

where % HbCO and % HbO2 represent the percentages of hemoglobin combined with the two gases and when pCO and pO2 are the partial pressures for the gases. The figure 210 is the experimentally-determined proportionality constant which sets forth, in effect, the fact that the affinity of hemoglobin for carbon monoxide is 210 times greater than that for oxygen.

5.10.5 Effect of depth

The apparent fact that carboxyhemoglobin formation depends upon the ratio between carbon monoxide andooxygen is very important in considering carbon monoxide as a hazard in aviation. It means that a given percentage of carbon monoxide will cause virtually the same amount of carboxyhemoglobin to be formed regardless of altitude. The lowering of the partial pressure of carbon monoxide by ascent does not reduce its toxicity. The partial pressure of oxygen is lowered at the same time, and the ratio thus remains the same. That this relationship actually exists has been quite well established in aviation.

The toxicity of carbon monoxide under increased pressure - such as in diving - appears never to have received specific study. It seems possible that the same type of relationship would exist here and that the equilibrium amount of carbon monoxide produced by a given percentage of the gas should be no greater than at depth than at the surface. Unfortunately, there is too much at stake to permit assuming this to be the case without direct evidence.

5.10.6 Rate of formation

Whatever may be the case about the equilibrium concentration of carboxyhemoglobin, its rate of formation is also of interest. Until the blood has taken up about one-third of the equilibrium amount of carbon monoxide, the rate of formation (in terms of the increasing percentage of carboxyhemoglobin appears to be a function of two factors: (1) the total amount of hemoglobin present and (2) the rate at which carbon monoxide molecules are delivered to the blood. In a given individual at the surface, the most important factors determining the rate of carboxyhemoglobin formation are thus simply the concentration of the gas and the respiratory minute volume.

The equations of Forbes, et al. (5c) provide a convenient means for making a rough estimate of the increase in carboxyhemoglobin which can be expected in a given exposure: Increase in %HbCO = K x % CO x minutes of exposure where K is a factor representing the respiratory and circulatory state of the individual, related to exertion. The values for K range from rest to 11 for "heavy work". Heavy work is defined as producing a 30-liter respiratory minute volume and can thus be considered average work for a swimmer.

Accepting the concept that the rate of carboxyhemoglobin formation at this stage depends mainly upon the "number of molecules delivered per minute," a factor for the number of atmospheres of pressure should be inserted as a multiplier in the formula.

The formula, so modified, can be rearranged in several ways and used to determine such things as the minutes required to produce a given %HbCO in a given situation or the tolerable percentage for a given duration of exposure.

5.10.7 Recommended limits

Lambertsen and Bascom (5d), using a similar approach, concluded that the maximum safe amount of carbon monoxide for air-diving within the zero decompression limits (7.4.1) was slightly under 40 parts per million (0.004%). They recommend "that no air be used in underwater breathing devices which contains more than 20 parts per million (0.002%) CO." This limit percentage is one-fifth of that (100 ppm = 0.01%) considered safe for exposure of up to eight hours per day at the surface, so it is clear that assuming an increase of toxicity with depth imposes very stringent limits on carbon monoxide. Otherwise, the surface limits would presumably apply. However, until adequate study can be accomplished, the 20 ppm (0.002%) limit is recommended. It can be reasoned that a compressor which is shown to produce anywhere in the vicinity of 20 ppm CO might on other occasions produce considerably more.

5.10.8 Repeated dives

The slow rate of elimination of carbon monoxide makes it necessary to be cautious about repeated exposures. Carboxyhemoglobin concentration will decrease about one-half in one to three hours under normal conditions. The fact that the increased oxygen partial pressure at depth may prevent development of symptoms until the diver ascends should be kept in mind. A diver may for this reason be completely asymptomatic at depth but severely intoxicated on approaching the surface.

5.10.9 Treatment

A victim of carbon monoxide poisoning can frequently be recognized by the pale skin and bright red lips. In the presence of apnea, artificial respiration should of course be given. In any case, administer oxygen. A mixture of oxygen and 4-7% carbon dioxide is preferable. (This is almost the only situation in which such mixtures are desirable). The oxygen speeds elimination of carbon monoxide by displacing it from the hemoglobin, the effect being much the same a that involved in formula (5-1). The carbon dioxide not only increases the respiratory minute volume but also shifts the dissociation curve for carbon monoxide in the desirable direction.

Intramuscular injection of 0.5 to 1.0 cc of 1:1000 epinephrine may throw unpoisoned red cells into the circulation by causing the spleen to contract. Partial replacement transfusion has been advocated in extremely severe cases. The use of intravenous procaine has also been recommended.

With adequate pulmonary ventilation, the administration of carbon dioxide in oxygen should cause most of the carboxyhemoglobin to be re-converted within 30 minutes. Oxygen alone will accomplish the reconversion in 30 to 90 minutes; whereas air requires about 2 hours. Coma persisting beyond these periods suggests organic brain damage as a result of anoxia.

5.11 UNDERWATER BLAST

Injury from underwater explosion is extremely important in SCUBA because so many of the military applications involve work with, or near, explosives. Blast tolerance and blast protection have been under study in the past (IA-6A11) and are receiving further investigation at the present time.

5.11.1 Current information

Apparently a submerged man is safer close to the surface during an explosion in deep water. A given explosion at a specific distance will probably produce greater damage to an individual in shallow water than in deep water. The concept that a gas-fluid interface is required for the production of physical injury is sound. The lungs are the most vulnerable part of the body, showing trauma even though damage elsewhere is minimal. The stomach and intestines (because they contain gas) and the head (because of sinus and middle-ear space) are also subject to injury.

5.11.2 Procedures

The instructions which may be given to divers who will be working with explosives are few and not especially reassuring. They may be stated as follows: "When you expect underwater explosion, head for the surface and put as much distance between yourself and the explosion as possible. Get as much of your body out of the water as possible; climb up on anything available at the surface, otherwise remain on your back and hold your head, chest, and abdomen as far out of water as possible." (If an air blast is expected, the diver should go deep).

The SCUBA diver is in a much better position to carry out these feeble measures than the man in a suit and helmet. However, the helmet diver probably derives more protection from his equipment than the SCUBA diver. The effects of underwater blast during use of self-contained equipment of various kinds have received little study in this country.

5.11.3 Protective equipment

Protective gear is of great interest. For the SCUBA diver, the bulk of material required, the resultant buoyancy, and the loss of freedom and mobility limit the possibilities rather seriously. A diver who can reach the surface will be aided by any flotation gear which helps keep the vulnerable areas out of the water.

5.11.4 Treatment

Treatment of blast injury is discussed elsewhere (IA-6A11). Be alert for the earliest indications of necessity for surgical intervention in gut injury. Any diver who has been exposed to an underwater blast deserves careful examination and observation regardless of his immediate symptoms.

5.12 WATER TEMPERATURE

Excessive cold can impair the performance of a diver and his ability to remain underwater more readily than almost any other factor. The SCUBA diver is unusually susceptible to cold because the bulk and buoyancy of insulating material limits the protective clothing he can wear. He has a particular problem in maintenance of tactile sense and manual dexterity.

Loss of body heat occasions an increase in metabolism and a consequent drain on the available supply of respirable gas. An uncomfortably cold diver, especially if shivering, will consume much more gas than one who is comfortable. There is some evidence that ventilation (RMV) is increased out of proportion to the oxygen consumption under these conditions; so the effects may be more acute in demand type apparatus than in other SCUBA.

A degree of chilling may be experienced in water as warm as 80°F if prolonged immersion without vigorous exercise is involved. Ordinarily 68°F may be tolerable for a reasonable period without protection if the diver is active. Down to about 60°F, a suit of woolen underwear may alone suffice for a working diver. Below this temperature, or at rest, more extensive protection is required.

Several approaches to the problems of cold water protection are possible. These are discussed elsewhere (10.0.0).

A diver who emerges from a chilling dive should be enabled to dry himself and put on warm, dry clothes at once. Hot soup and coffee are the best warming agents to use after such a dive. Avoid alcohol if the diver may continue to lose body heat because he cannot get warm at once. Otherwise, the use of alcohol in small amounts is unobjectionable.

A diver with persistent shivering should try a brief period of vigorous exercise after he has donned dry clothes.

Excessively warm water is rarely encountered, and is therefore a less serious problem. However, exercise in water warmer than 86°F will cause overheating, and rest in water at 96°F is the maximum tolerable for any length of time. Water temperatures in this range do occur and they impose serious limitations on SCUBA diving. Providing practical protection is very difficult.

5.13 SURFACE EXPOSURE

As is often the case in diving, personnel at the surface may suffer more from exposure than the submerged diver, and the plans for an operation should take this into account.

<u>Sunburn</u> can be a serious problem in SCUBA operations, particularly if the men have not had the benefit of gradual exposure. It causes great loss of efficiency and may produce actual illness. Prevention is a responsibility of the medical officer and of each individual.

Wearing shirt and pants when on the surface is an obvious solution and gradual exposure can be arranged by stripping to trunks for periods of increasing length over several days or weeks. The face, neck, and hands may require sunburn protective ointment. The shoulders, back, and thighs should also be protected if the body cannot be kept covered. The usual brilliant white ointment may be undesirable as a detection risk.

5.14 MARINE LIFE

Of the myriad forms of underwater animal and vegetable life, only a very few constitute a recognizable hazard to the diver. The number of genuinely serious or fatal accidents involving marine life is extremely small.

5.14.1 <u>Vegetable Life</u>

The diver has little concern with vegetation aside from the possibility of entanglement in such forms as kelp. This can be a serious possibility where such growth is plentiful and dense. Such accidents as the loss of mouthpiece or facemask may occur in this connection.

5.14.2 Coral

Divers who must work about reefs frequently sustain cuts and abrasions from contact with coral formations. These injuries are generally superficial, but they are notoriously slow in healing and are often the chief cause of disability in SCUBA diving operations. Treat coral injuries as infected wounds from the outset. Cleanse them thoroughly with soap and water, and dress them. Have the diver remain out of the water until healing is complete.

Some types of coral produce a violent reaction. Waite (5f) has described this as follows: "The primary reaction to a coral cut, sometimes called 'coral poisoning' is characterized by the appearance of whelts, reddening and intense itching in and around the wound. This is an allergic reaction of the skin to a toxin liberated by the nematocysts or 'sting cells' of the tiny polyps that form the coral. Antihisteminic drugs given orally or applied locally to the site afford immediate relief. A coral cut or abrasion left untreated will show signs of advanced inflammation within 24 hours. The coral found in some geographic locations is more 'poisonous' than that found in others. First aid in the form of simple cleansing and the application of an antiseptic will prevent infection in most cases, but penicillin or sulfadiazine may be required for the more seriously infected wounds." Wear rubber-soled canvas shoes and gloves when working around coral, to reduce the likelihood of injury. When using swim fins, make some arrangement to protect the exposed heel.

5.14.3 Sea Urchins

These are echinoderms with long, movable spines radiating out from a round body about 10 cm in diameter. The spines are needle-sharp and are between 2 and 15 cm in length. Sea urchins are extremely common in tropical waters, being found in large numbers about coral reefs, in shallow water, and near beaches. Dark brown or black in color, they show easily against a light background. They represent a considerable hazard to swimmers and SCUBA divers. The man who steps on one experiences severe, stinging pain as the spines penetrate deeply into the tissues and break off. He may have 30 or more spines in his skin from the encounter, and since each spine has hundreds of microscopic barbs and is extremely brittle, most of them cannot be withdrawn. Fortunately, those which remain will be absorbed, leaving only a blue tattoo mark at the site of entry. After removing as many spines as possible, cleanse the area and cushion it with a large dressing. Although bacteria may have been carried deep into the tissues, infection often fails to materialize. Keep the victim out of the water for a few days and watch him for development of infection.

Lambertsen (5g) characerizes the injury as startling but not severe or incapacitating and states that the pain, which is severe at first, disappears almost completely after about 10 minutes. Provide adequate protection of the feet for work where sea urchins are numerous, particularly at night when they cannot be seen and avoided. Protection of the body is less easy to provide, although the heavier variety of rubberized fabric suit should be effective.

5.14.4 Jellyfish

The tentacles of jellyfish, Portuguese Men-of-War, and sea-nettles produce a degree of injury which depends upon the extent of contact and upon its duration. The tentacles are covered with nematocysts having sting cells which inject a toxin capable of paralyzing small fish. The local effects in man consist of a sharp, stinging pain and pruritus. A dermatitis characterized by erythema develops promptly and is followed in about 5 minutes by development of large, confluent wheals surrounded by erythema. Severe burning pain and the wheals may persist for a matter of hours.

Use a piece of cloth to remove the tentacles, to avoid spreading the lesions to other parts. Wash the area with fresh water, and apply an analgesic ointment or cold compresses. Antihistamine therapy or injection of epinephrine will reduce the urticarial reaction.

In some cases the initial pain will be so intense that it produces a shock-like state with nausea and vomiting. Many individuals will panic, and this may explain the number of drownings which have been reported in association with jellyfish stings.

The secondary or systemic reaction to the sting can be extremely severe. Wiate (5f) has discussed this eventuality: "severe secondary reaction of rapid onset is sometimes seen following a nettle sting. Pallor, sweating, muscular cramps, faintness, shortness of breath, thready pulse, and a fall in blood pressure are indicative of anaphylactic shock and emergency treatment with epinephrine given intravenously or benadryl should be administered. If angioneurotic edema appears, the air passageways should be cleared, oxygen administered, and a tracheotomy performed if necessary. There have been no authenticated medical reports of death as a result of Portuguese-man-of-war stings, although it may occur if complicated by anaphylactic shock."

Lambertsen (5g) points out that a jellyfish sting can cause failure of a mission or loss of the diver and strongly recommends that a protective garment of some kind be worn.

5.14.5 Sharks

The number of authenticated cases of attacks by sharks on men is extremely small. An enormous amount of surface swimming and SCUBA diving has been done in waters where sharks are numerous, and it is not uncommon for large sharks to approach men closely underwater without showing any inclination to attack. A number of episodes in which underwater swimmers or divers have had genuine cause for alarm have been reported, but the outcome of these appears to have been uniformly favorable. That sharks do not constitute a major problem is apparent, but regarding them with respect and avoiding them when possible is surely indicated.

The values from the diver's standpoint of various shark repellents and protective measures remains debatable, but their use should not be discouraged. More important is the avoidance of anything which is known to attract or excite sharks. The presence of blood in the water, or of dead fish and raw meat, come under this heading. An injured swimmer should not remain in the water, and killing or handling fish in the presence of sharks in unwise.

5.14.6 Barracuda

In discussing barracuda, Lambertsen (5g) says: "The chief problem in regard to the Barracuda, as with the Shark, is the adverse psychologic effect its dental structure has on the diver. Although it is rarely more than 4 or 5 feet in length, its prominent teeth make it one of the most ferocious appearing fish in the sea. The association of the operational swimmers with Barracuda has been closer than with Sharks. Rarely a day passed during the five months of training in Caribbean waters in which Barracudas were not seen.

"The Barracuda is an extremely inquisitive fish. It may approach within a foot of the working diver or follow an underwater swimmer for as much as a mile. No instance that could be construed as an attack was made by a Barracuda on a diver at any time during the training period. The same precautions regarding hemorrhage into water apply to both Sharks and Barracuda. Since Barracuda will snatch a fish off a spear it is not advisable to handle speared fish in the water. The divers were less concerned over Barracuda and Sharks at night when they could not see these fish."

5.14.7 Moray Eels

Morays may grow to as much as 8 feet in length and 10 inches in diameter. They generally live in reefs, wrecks, or underwater caves. Totally unprovoked attacks on divers are not common, but the possibility of encroaching unintentionally upon a moray's prerogatives is considerable in locations where they may be hiding. Under these circumstances, the eel is vicious. Its powerful jaws frequently maintain their grip until death, and the weight and strength of the moray may be sufficient to trap a diver underwater.

5.14.8 Sting-rays

Russell (5h) has provided a valuable discussion of sting ray injury, and the following abstract summarizes his discussion.

Sting rays may reach enormous size (700 lbs. or more), but the variety usually encountered reaches a length of about 50 cm and has a sting, located near the base of the tail, about 6 cm long. The rays may often be found lying in mud flats or sandy bottom, and stepping on them represents the chief hazard. The ray will thrust its tail and sting upward and forward into the leg or foot of the victim. Sting ray injuries are not infrequent; approximately 500 cases occurred along the Southern California coast in one 7 month period.

The toxin associated with the sting has predominantly local effects, but there is evidence that serious systemic symptoms and even death may result from it. Symptoms of primary shock, presumed due to the extreme pain, are frequently seen immediately following injury. Intravenous injection of the toxin is known to cause a fall in systemic blood pressure caused by peripheral vasodilatation, and this effect may accentuate or precipitate transient cerebral anoxia and shock.

In addition to severe local pain, victims have experienced pain in respiration, inguinal or axillary pain, and generalized cramps. Systemic symptoms described include cardiac arrhythmian, tremors, nervousness, profuse sweating, vomiting, diarrhea, and acute abdominal pain. Convulsions have also been reported.

The serrated edges of the sting may cause extensive damage on withdrawal, and part of its epidermal sheath may remain within the wound.

Prompt treatment is important. It is recommended that the victim himself wash the wound in sea water immediately. Application of a tourniquet just proximal to the stab site may be useful but requires the usual precautions. Following thorough irrigation of the wound and removal of the sheath, if present, soak the extremity in water as hot as tolerable from 30 to 60 minutes, to relieve the pain. After debridement and further cleansing, close the wound with dermal sutures if necessary and apply a sterile dressing.

An incidence of secondary infection of less than 3% is attributed to adequate early treatment. The use of prophylactic antibiotic therapy does not appear necessary under these conditions although some authorities recommend such therapy together with anti-tetanus measures. Demerol usually relieves persistent pain.

Wounds which may involve penetration of the abdominal or thoracic cavity demand immediate hospitalization. Treatment of secondary shock must be prompt and vigorous.

5.14.9 Manta-rays

The giant manta-ray is often said to be harmless to the diver. It is unlikely to take the offensive, but the enormous ize which the manta may attain is sufficient cause for respect. A diver could be severely injured merely by happening to be in the manta's path.

5.14.10 Octopus

Although the octopus may exceed 25 feet in span, those found at diving depths are generally much smaller, and are inquisitive rather than vicious. They tend to hide in underwater caves, which are best avoided for this and other reasons. The diver is chiefly in danger of being trapped underwater, even by a small octopus, if it can hang on to something with its tentacles. Clothing, such as wool underwear, hinders attachment of the suction cups. Stabbing deep between the eyes is the method of choice for killing an octopus. That the diver carry an appropriate knife for such purposes has already been suggested.

5.14.11 Miscellaneous

There are a number of other species which represent various types of hazards: electric rays, electric cells (confined to South American fresh water rivers), killer whales, certain small poisonous fish (reported in certain areas, especially in the South Pacific), and giant clams. Giant clams can trap a diver underwater. Even the abalone can trap the diver who attempts to pry one from its attachment with his fingers. Like mantas, groupers and other large fish merit respect mainly because of their size.

5.14.12 Summary

While marine life offers a number of potential hazards, there are few significant dangers which cannot be avoided by exercising proper caution. Few forms of underwater life can be charged with unprovoked attack, and most cases of such attach can be attributed to the diver being mistaken for natural prey. A diver pursuing his work underwater appears to be much safer from such hazards than a man splashing about at the surface. Certain obvious hazards such as remaining in the water in the presence of blood or dead fish can generally be avoided.

The medical officer will find injuries due to underwater life to be confined almost entirely to contact with forms such as coral, jellyfish, and sea urchins; but these can cause the loss of many man hours. Give the divers adequate instruction and insist upon caution and appropriate protection.

5.15 HAZARDS RELATED TO THE SEA ITSELF

In addition to submergence, pressure, cold water and similar entities already discussed, the SCUBA diver is directly exposed to other factors inherent in the underwater environment.

For example, the sea is usually in motion. Tides and currents can interfere with the diver's work, produce unusual fatigue, or even carry him away. Surges and surf may cause physical injury by dashing him against rocks. Rough water at the surface may put him in peril especially if his breathing apparatus is not functioning.

While seasickness is not generally a serious problem in diving, it may become one in certain SCUBA activities. Men may have to spend prolonged periods in small craft in the process of their work. At times they will have to remain at or close to the surface during dives, and in some operations there may be significant wave-motion at the diving depth. Working beneath smaller vessels in rough water may be a problem, as may be spending a period of decompression in similar circumstances.

Even mild seasickness can produce a considerable loss of efficiency, and the problem of vomiting during the use of SCUBA is practically inseparable. Men who are unusually susceptible to seasickness will generally eliminate themselves from SCUBA diving. This is a factor which may demand consideration in the selection process. The use of preventive medication may be imperative in some situations. The usual side-effects of such drugs should be considered.

5.16 SIGNIFICANT DISEASES

In addition to the diseases and conditions expected in any group, a few entities present special problems to the medical officer associated with SCUBA diving. While these conditions are by no means limited to such divers, their incidence or special significance renders them especially important in this connection.

5.16.1 Upper respiratory infections

These infections are especially important in SCUBA diving because of the problem of barotrauma (5.3.0) and because exposure and fatigue may make them unusually frequent.

Men having such conditions should avoid diving and exposure until convalescence is well along. Difficulty in equalizing pressure increases the risk of relapse and complications. Time saved by going back to full duty too soon is often lost in the end.

The necessity for keeping as many men in action as possible while observing these principles demands considerable judgment on the part of the medical officer. Be sure that men excused from diving take care of themselves and do not abuse the exemption. See that minor difficulties don't become a handy excuse for avoiding unpleasant jobs, but maintain an attitude which encourages men to report these conditions.

5.16.2 External ear infections

Infections of the external auditory canal (otitis externa) may be frequent and very troublesome in Underwater Demolition Teams and other groups of swimmers and SCUBA divers, especially those operating in warm, humid climates. The amount of discomfort and loss of time which these infections cause make prevention and prompt, effective treatment highly important.

(a) Types

(1) The chronic or subacute form is characterized by pruritus and discharge. Examination reveals desquamation, crusting, and a serous or sero-purulent exudate. Various degrees of inflamation and accompanying pain may be noted. In the phase of acute inflammation associated with this type of otitis externa, the canal may be swollen shut and the entire ear rendered exquisitely tender.

(2) A cellulitis, often called acute bacterial infection, is sometimes distinguished from the acute inflammation described above, which it closely resembles. Here, desquamation, exudate, and related signs are not seen. A small furuncle is occasionally found in the canal when the patient is examined early.

(b) Etiology

"Acute bacterial infection" has generally been attributed to streptococci.

Chronic or subacute otitis externa has often been called "otomycosis", implying that pathogenic fungi are responsible for the condition. In recent years, careful studies have failed to implicate fungi and indicated a bacterial origin in almost every case. Even where fungi may be involved, significant inflammation strongly suggests the presence of bacterial invaders.

In healthy military personnel, the most important factors favoring infection appear to be:

- Hot, humid environment
- Swimming; failure to dry the ears
- Trauma - as in scratching or attempting to clean the ears by improper methods
- Lack of cleanliness

Conditions such as seborrheic dermatitis or contact dermatitis may simulate otitis externa or favor its occurrence. Especially in diving personnel, barotrauma (5.3.0) may play a role: "squeeze" of the external ear probably can provide the trauma which leads to infection. In a few cases, barotraumatic otitis media with perforation and discharge has led to otitis externa, been mistaken for it, or been overlooked in its presence.

(c) Treatment

Whenever acute inflammation is present, it demands primary attention. Applications of moist heat and systemic administration of antibiotics or chemotherapy are indicated. When the canal is exudative, keeping wicks saturated with Burow's solution in place is helpful. Analgesics should be given as needed to control pain, which may be severe. Patients with various degrees of acute inflammation must at least be kept out of the water, and some of them will deserve bed rest. With proper treatment, acute in inflammation almost always subsides in a few days. If the inflammation appears to be superimposed on the more chronic form, appropriate local treatment should begin when it can be tolerated.

Treatment of the chronic and subacute types of otitis externa can be extremely difficult, as evidenced by the fact that nearly 300 forms of therapy have been recommended in the literature. McLaurin (51) presents a valuable discussion on the problem which suggests a number of basic principles of treatment:

(1) Cleanse the canal thoroughly and keep it clean. Be very gentle and use manual cleansing only under adequate visualization. Employ suction and irrigation where effective. Remove cerumen along with debris. (Tap water, alcohol, and slightly acid solutions are suitable for irrigation).

(2) Keep the canal dry. Except when wicks saturated with Burow's solution must be used to relieve acute inflammation, confine wet medications to intermittent application followed by drying. Dry after irrigation. (Dry cotton wicks or air are recommended in preference to swabs for drying).

(3) Use only medicinal agents which are non-irritating and not prone to cause sensitization. When possible use dusting powders or aqueous solutions in preference to ointments. Avoid substances having an alkaline pH. Avoid prolonged use of any agent, and discontinue any medication that fails to produce a favorable response in reasonable time or appears to increase inflammation. Avoid overtreatment. Stop treatment when infection [illegible] controlled.

(4) Apply specific antibacterial agents whenever possible. The rationale of using specific antibiotic and chemotherapeutic agents now that these are widely available requires little argument. However, the range of organisms which may be involved and the existance of restraint strains means that doing this properly necessitates obtaining material for culture by proper technique, identifying the organism(s), and performing in vitro sensitivity tests. These need not be formidable procedures with current methods, but they will unfortunately often be impossible for the medical officer in the field. However, McLaurin's comments on several of the specific agents at least suggest more logical approaches than the use of completely non-specific medications:

Sulfamylon (4-amino-2-methyl benzene sulfonamide HCl) and Gantrisin (sulfisoxazolc) cover a wide bacterial spectrum, have many des[illegible]ble properties, and may be regarded as drugs of choice in the absence of sensitivity tests. They are used as aqueous solutions, topically.

Neomycin is especially effective in Pseudomonas infections which are frequent and which tend to be extremely obstinate. It is used topically. Polymyxin (aerosporin) B sulfate, usually employed as an ointment, is said to share this effectiveness.

Terramycin, Aureomycin, and Chloromycetin, as dusting powders topically, are useful when indicated.

Penicillin must not be used topically because of the danger of sensitization, but it may be valuable when given intramuscularly especially when furunculosis of the canal is present.

Streptomycin is not used unless specifically indicated by sensitivity tests.

This discussion is not intended to suggest that non-specific agents, proprietary preparations, and recommended empirical regimes may not have significant utility; but these are far too numerous for comment. The medical officer will probably have his own concepts and ample opportunity for experience.

(d) Preventive measures

Since no specific agents have been shown to be especially valuable in preventing otitis externa, prevention is concerned with reducing the pre-disposing factors to a minimum.

Little can be done about an unfavorable environment of the necessity of swimming; but cleanliness, avoidance of trauma, and keeping the ears dry when possible are amenable to education and routines.

A variety of prophylactic routines have been suggested. Whatever method is adopted, the medical officer's own interests will be served by seeing that it is faithfully carried out. He should also examine the ears of divers under his charge periodically. In this way, he may detect early non-symptomatic infections, and can remove excess cerumen and any foreign matter noted. The latter is important not only from the hygienic standpoint in preventing otitis externa but because such materials interfere with visualization. Those times when visualization is most important, as following barotrouma, are rarely ideal for cleaning operations.

The maceration of tissues which may follow prolonged or repeated exposure to water is probably the prime factor predisposing to infection. Where such exposure is unavoidable, take measures to promote drying of the ears as soon as possible after exposure. Most swimmers habitually shake gross water out of the ears, but something more specific than this is required. At the present time, the procedure of instilling a few drops of 50 to 70% ethyl alcohol in each ear, then allowing it to run out, is more frequently recommended. This appears to be generally adequate and has the great advantage of simplicity - which increases the probability of its being carried out.

During Caribbean UDT operations which had previously produced a high incidence of otitis externa, Waite (5f) achieved complete prevention of the condition with a post-swim routine which consisted of (1) drying the ears thoroughly with cotton swabs, and (2) insufflation of an undecylenic acid-zinc undecylenate fungicide in powder form. If it is true that fungi play a negligible role in the condition, Waite's routine may have achieved its success because of the thorough drying which the swabbing and use of talc-base powder produced. Swabbing has been criticized as a nuisance and a potential source of trauma; and the repeated use of the powder may result in some degree of caking.

Lambertsen (5g), in his work with OSS operational swimmers, employed drying with swabs after each swim plus monthly examinations in which excess cerumen was removed and the canals treated with a solution of 5% salicylic acid and 5% tannic acid in 85% alcohol as a prophylactic measure. Otitis externa was rare in his group. It is probable that drying was the most important aspect of this routine; and if this can be achieved adequately with 50-70% alcohol drops, their use would appear to be preferable.

An alcohol-boric acid solution may be desirable for drying the ears since it would also assist in keeping the pH of the canal on the acid side, apparently a factor in normal resistance. The use of one or two drops of 95% alcohol in each ear has also been suggested as a means of drying.

5.16.3 Fungus infections

Besides "otomycosis", actual fungus infections also tend to be more frequent in swimmers and divers although they rarely constitute a major problem Infections of feet and groin are most frequent. Preventive measures are the usual ones: adequate drying and cleanliness. The men should dry themselves and change soon after a swim, and they must avoid wearing tight trunks or supporters for prolonged periods. Give treatment in accordance with sound dermotologic prinicipIes. Use wet dressings or soaks (Burow's solution, or potassium permanganate 1:10,000) for acutely inflamed, weeping lesions; use mild fungicidal and bacteriostatic agents when the inflammation has subsided.

5.17 NUCLEAR RADIATION HAZARDS

These have been discussed by Waite (5f): "An area of water can become radiologically contaminated following an air, surface, or underwater burst of an atmoic bomb. Contamination of water following an air burst is caused by the fall-out of radio-active particles, but most of the contamination following a surface or underwater burst is caused by direct radiation of the water. Because an enemy may render a beach radioactive by sowing radioactive material (fission products) at various landing points, personnel engaged in underwater demolition may encounter radiation hazards on land as well as in the water. Because the total roentgen dosage decreases rapidly, water is not usually as great a hazard as radioactive land. The factors which are responsible for this rapid decrease are natural decay, rapid dispersion of the total amount of radioactivity through a large area, and the natural dilution of the water by currents and tides. This last factor will vary with the geographic location. Most of the radioactive particles in water will settle to the bottom in from 1 to 2 weeks following an underwater burst. In such a situation a swimmer should stay away from the bottom. The fact that radioactivity can be spread by marine life presents another problem. Seaweed, algae, and plankton absorb the radioactive salts from the water. These plants in turn are eaten by fish and other forms of marine life and thus a large area could be contaminated even though it was not exposed to the initial source of radiation. Preliminary reconnaissance of an area with radiation monitoring instruments and the use of small dosimeters by the personnel are the only satisfactory preventive measures which can be offered at this time.

CHAPTER 5

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CHAPTER 6

DESIGN AND EVALUATION OF BREATHING APPARATUS

CONTENTS

CHAPTER 6

DESIGN AND EVALUATION OF BREATHING APPARATUS

The utility of breathing apparatus depends upon its ability to meet the diver's needs. In the broad sense, "needs" include a multitude of factors which must not be neglected in design or evaluation. However, the all-important function of the apparatus is to fulfill the respiratory requirements of the diver.

6.1 RESPIRATORY REQUIREMENTS

The breathing medium which the apparatus supplies must be appropriate to the diving conditions. Its nature will, in turn, usually determine the basic form which the apparatus may take (2.0.0). But whatever its type, the apparatus must meet the needs of respiration itself: sufficient oxygen for metabolic requirements, satisfactory removal of carbon dioxide, sufficient volume for pulmonary ventilation, and characteristics which permit the diver to breathe easily under all conditions.

The relative importance of these aspects of respiration depends upon the type of apparatus. In open-circuit equipment, ample pulmonary ventilation takes care of oxygen supply and carbon dioxide removal, while both of these are crucial factors in rebreathing systems. In any case, sound design and meaningful evaluation of equipment both demand quantitative data on the requirements which must be met: How much oxygen, for example, will the diver need to do his job?

Precise prediction of respiratory requirements for a given operation is far from possible, but analysis of the major forms of underwater activity can provide satisfactory approximations.

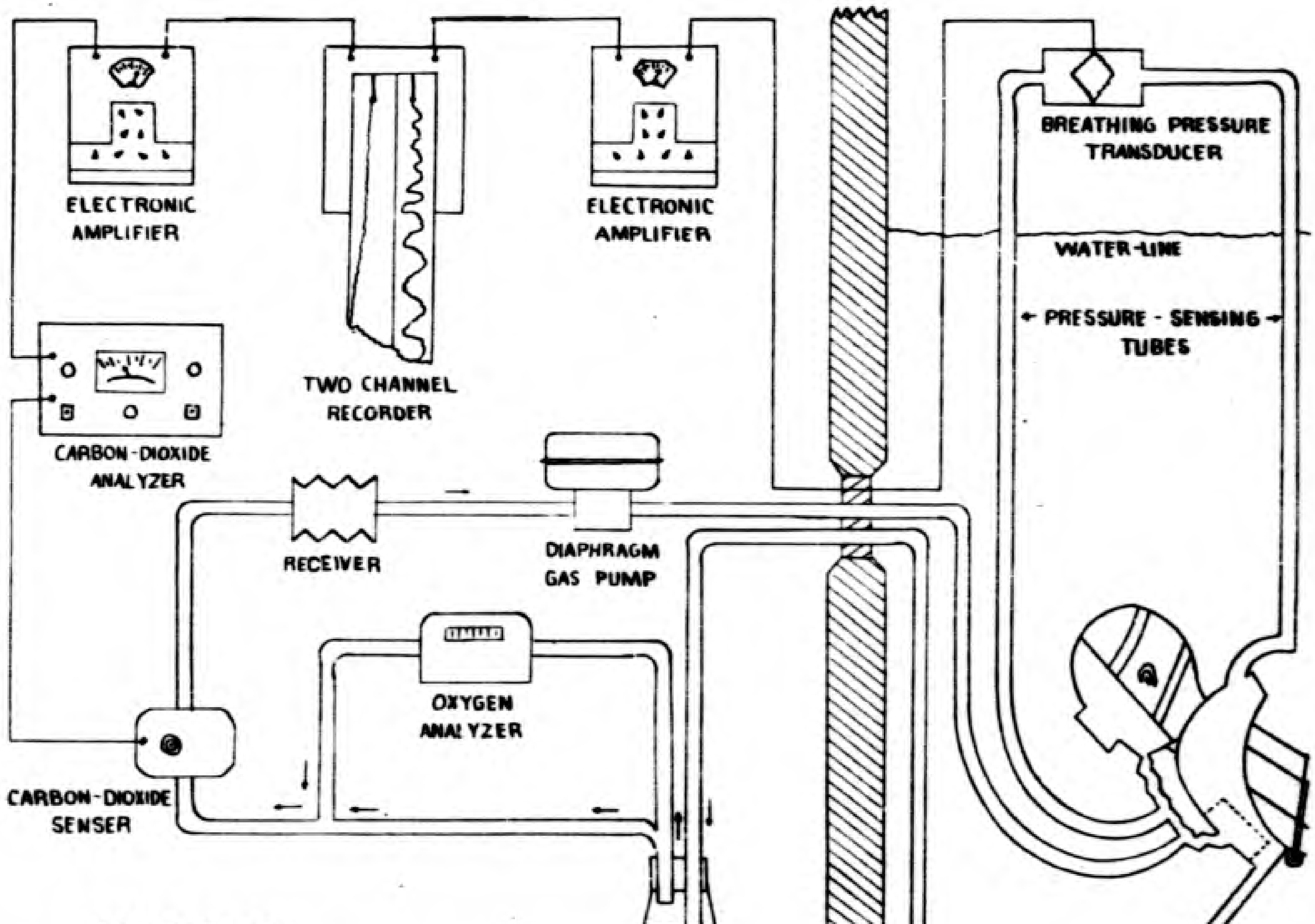
Among the factors influencing respiratory requirements the basic determinant is the amount of physical exertion -- the quantity of work -- which the diver is called upon to perform. In this connection, a measure of external work accomplished (in terms of the end result) would not be especially useful. The work which a man's body actually does (energy expended) is what influences his respiratory variables -- not what he accomplishes in the process. The latter brings the variable factor of mechanical efficiency into the picture. The mechanical efficiency of muscular work may be lower than 10% and rarely exceeds 25%. There may also be pitfalls in the process of measuring external work. In weight-lifting, for example, this seems simple enough. But the simple physical calculation of work (weight times distance) fails to account for the energy expended in sustaining the weight and in checking its fall. Such energy is certainly significant in practical situations, and accounting for it involves distinct complications.

The schematic diagram illustrates one of the many instrumentation arrangements used to study breathing apparatus performance under simulated swimming conditions at depth. The subject is shown "swimming" on the trapeze in the pressure tank.

A sampling tube delivers a continuous gas sample through a port plate to the water trap outside the tank. The sample passes through a direct-reading oxygen analyzer and then through a recording carbon-dioxide analyzer which produces a written record on one channel of the two-channel recorder. A collapsible receiver keeps the sample at atmospheric pressure, to avoid pressurizing the analyzers. A special pump returns the sample, through the port plate to the breathing apparatus, to avoid altering the balance in the breathing system itself.

The set of pressure-sensing tubes in this case applies the flow pressure (between the breathing tube and the breathing bag, across the canister) to opposite sides of a sensitive differential strain gage pressure transducer. The transducer produces an electric signal which varies with the pressure changes. After amplification, the signal appears on the second channel of the two-channel recorder.

Similar arrangements permit study of the performance of any apparatus for gas percentages and breathing resistance at various depths through a wide range of work rates. These arrangements provide a tool for objective comparison of different breathing apparatuses. (The diagram greatly exaggerates the size of the sampling and sensing tubes).



ANALYSIS OF
UNDERWATER BREATHING

FIGURE 6-8

One approach to the measurement of actual work is to determine the heat-production of the body. While this is the most basic method of quantitating the expenditure of energy the determinations are technically difficult and generally impractical. Especially in studies related to SCUBA, the best approach is to measure exertion in terms which are themselves of primary interest: the elements of respiration. (For further information concerning the physiology of muscular activity, the reader is referred to Karpovich's book on the subject (6r).

6.2 OXYGEN CONSUMPTION

The oxygen consumption of the body is an accessible and generally satisfactory measure of the metabolic cost of exertion. Besides being one of the most significant respiratory factors in itself, it can provide approximations of the associated carbon dioxide production (6.5.0) and, often, of the respiratory minute volume (6.4.0).

When a measure of the body's heat production is required (10.1.0), this can be approximated from oxygen consumption if the respiratory quotient is known.

Oxygen consumption may be expressed simply as the volume consumed (corrected to standard conditions) per unit time. It is sometimes converted to volume consumed per square meter of body surface per unit time. Occasionally, the oxygen consumption in work will be expressed in multiples of the man's basal or resting rate.

Determinations of oxygen consumption will be grossly misleading only if an oxygen debt is being incurred or repaid at the time of measurement. When the muscles are not receiving a sufficient supply of oxygen from the blood, their metabolism becomes anaerobic in nature. The products of this anaerobic metabolism, such as lactic acid, will be oxidized later when more oxygen is available. This mechanism provides a significant safety factor for emergencies. Even trained athletes can rarely take up more than 4 to 5 liters of oxygen per minute; but by building up an oxygen debt, they can briefly exert muscular effort equivalent to several times this amount. Even in trained men, however, the maximum extent of the oxygen debt is rarely as much as 20 liters; and when this limit is reached, exertion must diminish or cease.

A certain lagein respiratory and circulatory adjustment occurs even in mild exertion; so some oxygen debt is incurred during the first few minutes of work. The rate of oxygen uptake will rise gradually and then level off, generally within about 3 minutes. Unless this plateau represents the maximum rate of uptake--in which case accumulation of debt is probably continuing--the man has reached the "steady state". During steady state, the expenditure and uptake are equal; and measurements of oxygen consumption are a valid measure of exertion.

Following exercise, the oxygen debt will be repaid. Although most of the repayment will take place in the first few minutes of recovery, continued measurements for as much as 1 1/2 hours may be necessary if the full extent of the debt is to be determined following very heavy exertion.

6.2.1 Oxygen consumption in various activities

The oxygen consumption associated with various types and degrees of activity is subject to considerable individual variations, but average values are of interest for comparative purposes. Examples are presented in Table 6-1.

TABLE 6-1. Oxygen Consumption and Respiratory Minute Volume Associated With Various Degrees of Activity (Approximate average values).

Activity	Oxygen Consumption (liters/min. STPD)	Corresponding RMV (liters)
Bed rest (basal)	0.25	6
Sitting quietly	0.30	7
Standing	0.40	8
Walking, 2 mph	0.70	15
Walking, 4 mph	1.20	26
Running, 8 mph	2.00	44
Uphill running	4.00	85

Such classifications of work as "light", "moderate", and "heavy" are generally expressed in terms of oxygen consumption. Being based upon subjective impressions for the most part, the classifications tend to be arbitrary and variable.

Efforts to quantitate the energy expenditure of underwater activity have been meager by comparison with the attention given to various forms of dry-land activity. Table 6-2 summarizes data available in 1952.

TABLE 6-2 Oxygen Consumption in Underwater Work (data available in 1952)

Type of Work	Rate	Oxygen Consumption (liters/min. STPD)	Source
Walking(in tank)	minimal	0.60	(6a)
Waliing(muddy bottom)	minimal	1.10	(6a)
Walking(in tank)	maximal	1.50	(6a)
Walking(muddy bottom)	maximal	1.77	(6a)
Swimming(with fins)	0.5-0.8 kts.	1.49	(6b)
Swimming	0.8-1.0 kts.	2.17	(6a)
Swimming	1.0-1.4 kts.	3.35	(6a)
Stationary swimming	(7-9 lb.force)	1.19	(6b)

6.2.2 Oxygen consumption in underwater swimming

The necessity for more data concerning oxygen consumption in diving was particularly evident in the case of underwater swimming-the most frequent and apparently most demanding form of activity involving SCUBA. The information was needed to determine the oxygen supply a man should carry for a given job with closed-circuit oxygen equipment and to set design conditions for semi-closed circuit mixed-gas equipment. It also would provide an approximation of

FIGURE 6-1

6-1 OXYGEN CONSUMPTION STUDY 6.2.2

The picture shows an underwater swimmer equipped for determination of his oxygen consumption. The apparatus is the 1952 model of the Lambertsen Amphibious Respiratory Unit (LARU), a closed-circuit oxygen recirculating SCUBA (figure 2-7). The small, carefully calibrated supply cylinder is suspended in the harness, below the swimmer's chest. It has a pressure gage which can be read underwater at intervals by another swimmer without stopping the subject. The perforated disk on the right side of the breathing bag covers a demand-valve which admits oxygen to the breathing system as it is consumed.

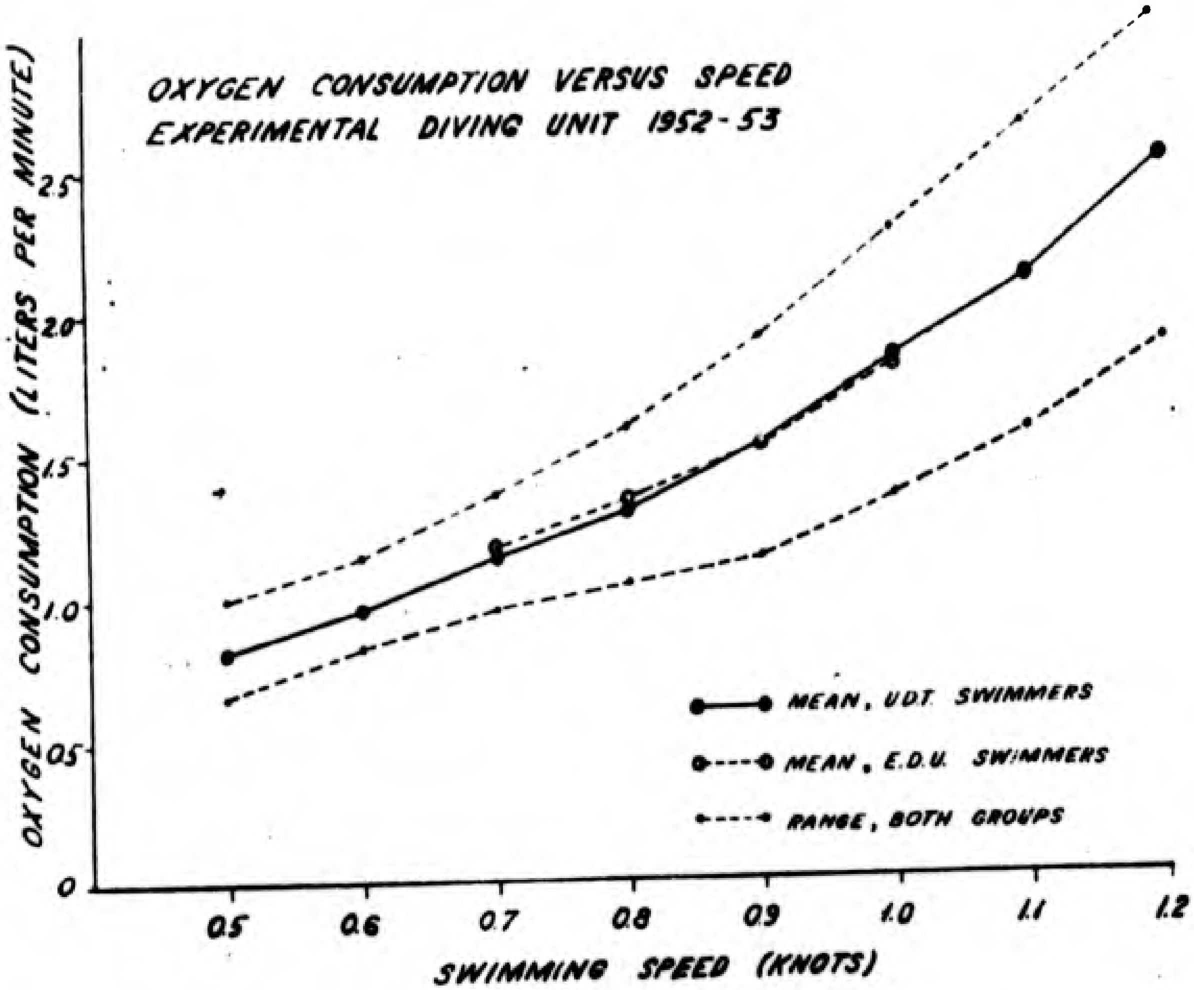


FIGURE 6-2

OXYGEN CONSUMPTION IN UNDERWATER SWIMMING 6.2.2

The figure shows the rise in oxygen consumption with an increase in swimming speed. The solid line follows the average for Underwater Demolition Team swimmers used in the study; the center broken line follows the average for Experimental Diving Unit swimmers used in the study. The outer broken lines follows the extremes for the UDT group. In general, the lower extremes were produced by small men, the higher by large men.

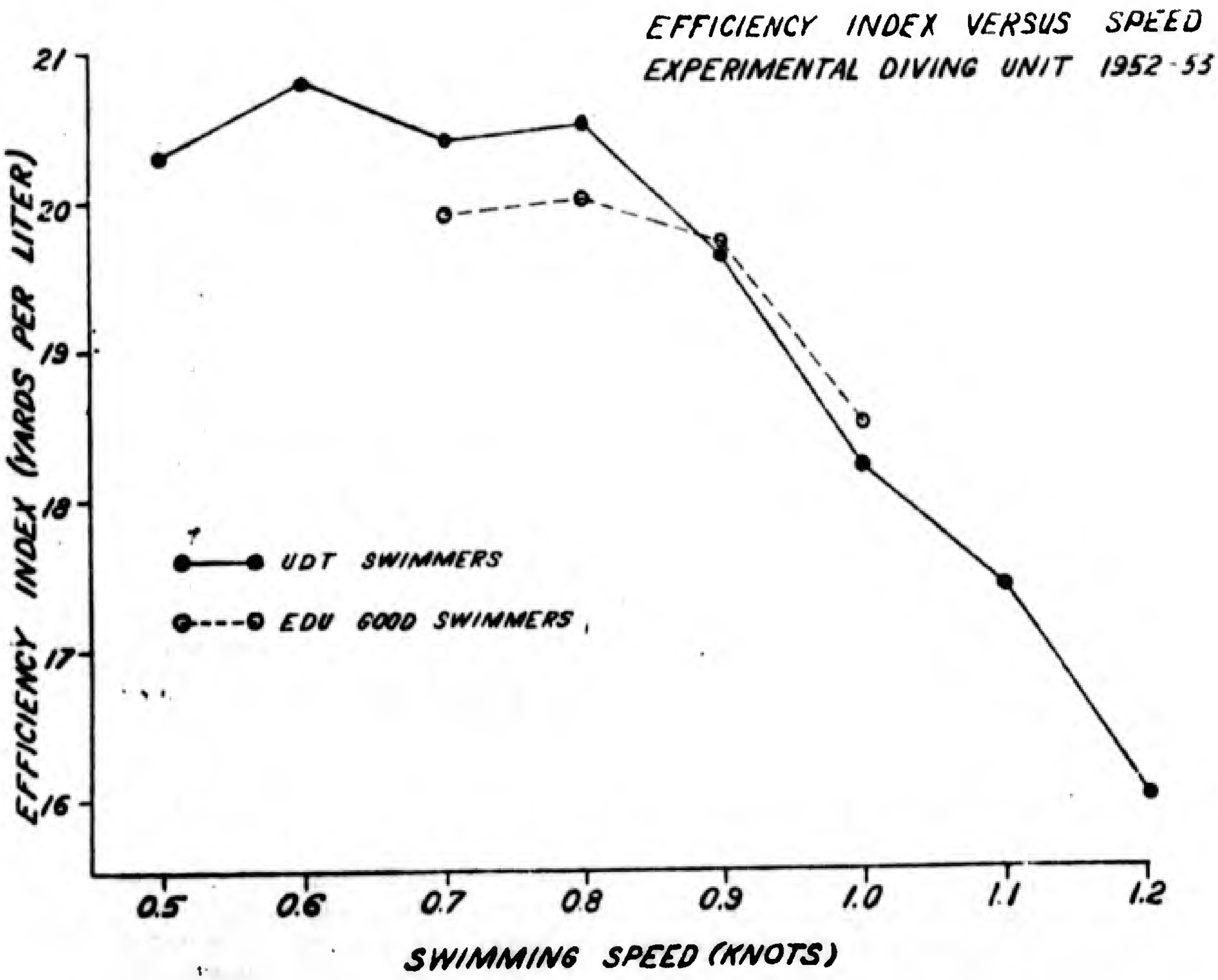


FIGURE 6-3

EFFICIENCY INDEX IN UNDERWATER SWIMMING 6.2.2

The curves show the variation of efficiency index (measured in terms of yards of swimming distance per liter of oxygen consumed) with increase in swimming speed. Note that the distance covered per liter ("gas mileage") decreases markedly as speed exceeds 0.8 knot. The solid line follows the average for the UDT swimmers; the broken line represents the EDU swimmers.

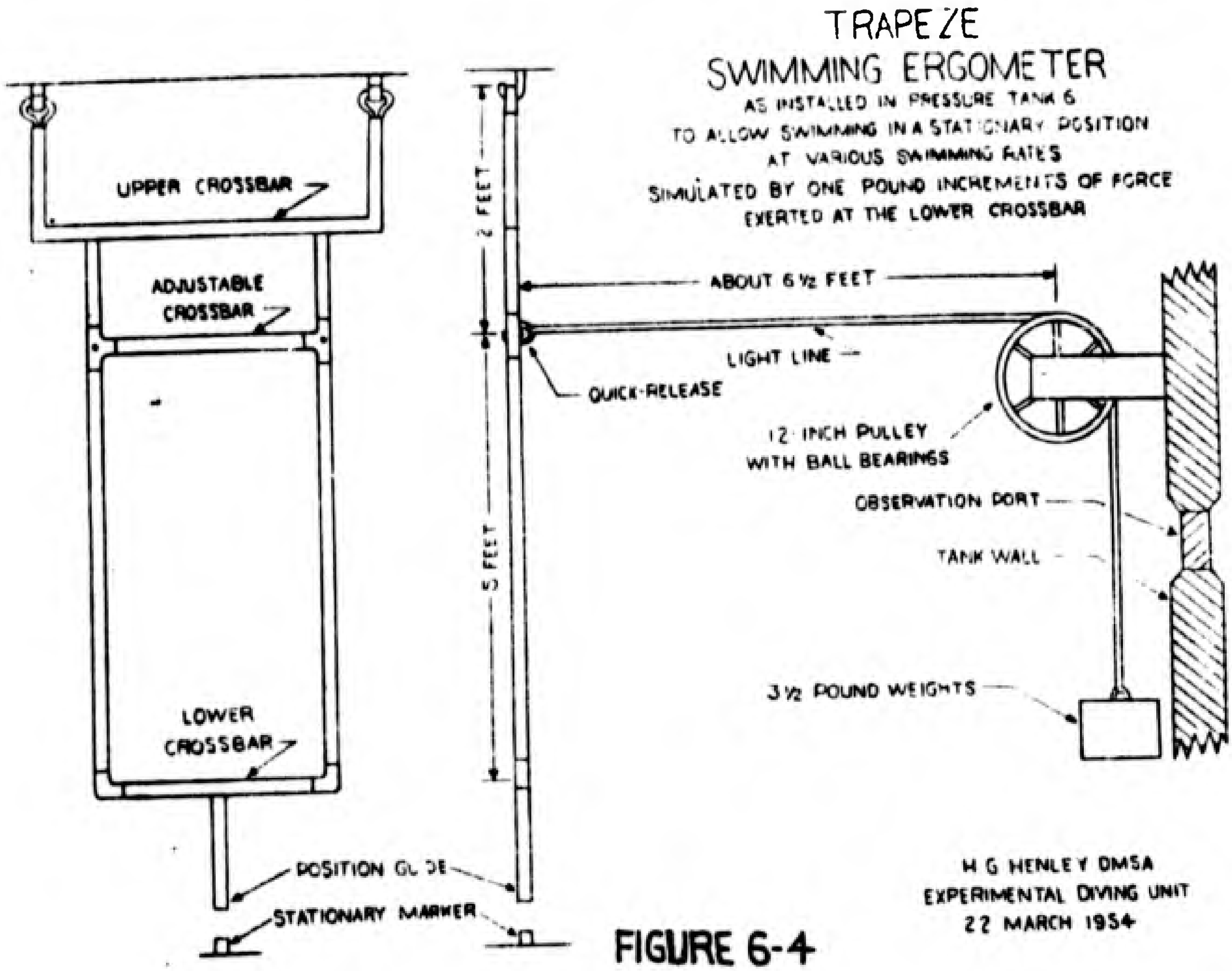


FIGURE 6-4

TRAPEZE SWIMMING ERGOMETER 6.2.2

The trapeze is constructed of galvanized 3/4-inch pipe, with a hook and ring suspension at the fulcrum as shown. The "adjustable" crossbar is now permanently fixed two feet below the fulcrum. The water line is kept about six inches below the 12-inch pulley. The swimmer lies with his chest over the lower crossbar, generally grasping the position guide to maintain stability. Loading the "adjustable" crossbar with weights on the light line produces a torque about the fulcrum. To keep the position guide directly over the stationary marker, the swimmer must generate an equal torque in the opposite direction by exerting a steady swimming force on the trapeze. Change of loading on the light line gives control of the force the swimmer must exert. The trapeze leverages are such that 3-1/2 pound increments of weight require 1-pound increments of swimming force.

of the carbon dioxide absorption capacity necessary in rebreathing systems- a factor which is difficult to measure directly (6.4.0). In the evaluation of existing apparatus, use of men not trained specifically in SCUBA swimming had placed the validity of the evaluation runs in question. Accurate knowledge could eliminate the necessity for evaluation swims designed to test the "endurance" of a given oxygen supply. Finally, there was little information on the feasible range of swimming speeds and none on the influence of speed upon the oxygen consumption and relative efficiency of underwater swimming.

Late in 1952, the Experimental Diving Unit undertook a study of oxygen consumption in underwater swimming at different speeds. The subjects were 6 experienced SCUBA divers from Underwater Demolition Teams and 9 EDU divers, 5 of whom had participated extensively in SCUBA evaluations and wore considered good underwater swimmers. The breathing apparatus used was of the closed circuit oxygen rebreathing type. Oxygen consumption was determined by measuring the pressure drops in small, carefully calibrated cylinders which supplied oxygen to the breathing systems. The cylinder pressures were read underwater at frequent intervals as the subjects swam along a 200-foot course marked out in a large swimming pool (Figure 6-1). Swimming was maintained at the desired rate by means of a system of underwater marks and sound signals. More than 120 swimming runs were conducted in this way at speeds ranging from 0.5 to 1.2 knots. The swimmers used swim fins of a standard type.

The results of this study are presented in Figure 6-2. This shows average oxygen consumption values and the range of values, obtained with the 6 UDT men and the 5 experienced swimmers of EDU. The less expert swimmers were studied only at 0.8 knots, and their average consumption at this speed corresponded to the high value for the others. No significant difference was noted between the two groups of experienced swimmers.

Figure 6-3 is based on the same data, here converted to an "efficiency index" - yards of distance covered per liter of oxygen consumed. A pronounced drop in average efficiency occurred beyond 0.8 knots. This finding correlates with the subjective impression of the swimmers, who felt that they could swim "indefinitely" at 0.8 knots but generally experienced increasing fatigue at speeds approaching 1.0 knots. The average oxygen consumption at 0.8 knots was approximately 1.3 liters per minute. Few were able to maintain 1.2 knots for more than 10-15 minutes, and it is probable that the steady state was not reached in all cases. Rates below 0.7 knots were uncomfortably slow and did not offer sufficient headway to permit depth-control by using the hands and arms as "planes".

Dyspnea was the predominant limiting factor at the higher speeds, and its onset was undoubtedly hastened by the less-than-optimal breathing characteristics of the apparatus as well as by carbon dioxide accumulation. The latter occurred almost universally at speeds of 1.0 knots and above until the canisters were enlarged. During the course of the study, three men experienced what has been called "shall-water black out" (5.6.2, 6.6.4).

No accurate comparative studies concerning the "drag" of different types of underwater breathing apparatus have yet been conducted; consequently, conclusions about the oxygen consumption involved in swimming with units of different design cannot be reached directly from this study. It is believed that the apparatus used in the study is about average in respect to drag. More drag or less would perhaps merely move the oxygen consumption vs. speed curve to the left or right to some extent. Other studies which are required to complete the investigation include tests of endurance in the practical speed-range and of the influence of fatigue on "efficiency."

The extent of individual variations, shown in Figure 6-2 was impressive. These variations correlated roughly with the size of the men, as might be expected.

During the course of this study, a means of stationary swimming against predetermined force was developed for use in the pressure tanks (Figure 6-4). With this, studies of swimming could be conducted at pressures simulating depth and with such refinements as continuous gas sampling from the breathing apparatus. This "swim ergometer" was calibrated in terms of equivalent swimming speeds by determining the oxygen consumption of the subjects as they swam against various forces, then comparing the values with those obtained in free swimming.

6.3 RESPIRATORY MINUTE VOLUME

Information concerning the minute volume of ventilation in various forms and degrees of underwater work is of vital importance especially in connection with open-circuit (demand) SCUBA. Here, the supply is necessarily limited and is further restricted by increased depth. There was little reliable information on the subject of ventilation in underwater work prior to the Cooperative Underwater Swimmer Project ("CUSP") of 1952 (6b); and to the time of this writing, practically none has been obtained since. Table 6-1 presents values for respiratory minute volume at various work rates at the surface.

6.3.1 Measurements at surface

The approach employed in CUSP was to determine the "normal" swimming speed of men using open-circuit equipment (Aqua-Lungs), and in the course of these speed trials (1/4 and 1/2 mile swims) to measure the amount of air used. The average speed was found to be 1.1 mph (approximately 0.96 k). This was considered to be a pace which the average swimmer with standard accessories could maintain to the limit of duration of his SCUBA. At this average speed, the mean respiratory minute volume was 28.2 liters.

6.3.2 Measurements at depth

It had been assumed that in diving to greater depths with open-circuit equipment, the respiratory minute volume (as measured at the depth) would remain approximately the same; that the actual air requirement would thus increase in direct proportion to the increase in absolute pressure. There was, however, reason to believe that the RMV produced by a given work load might be altered by changes in the partial pressure of oxygen or other factors.

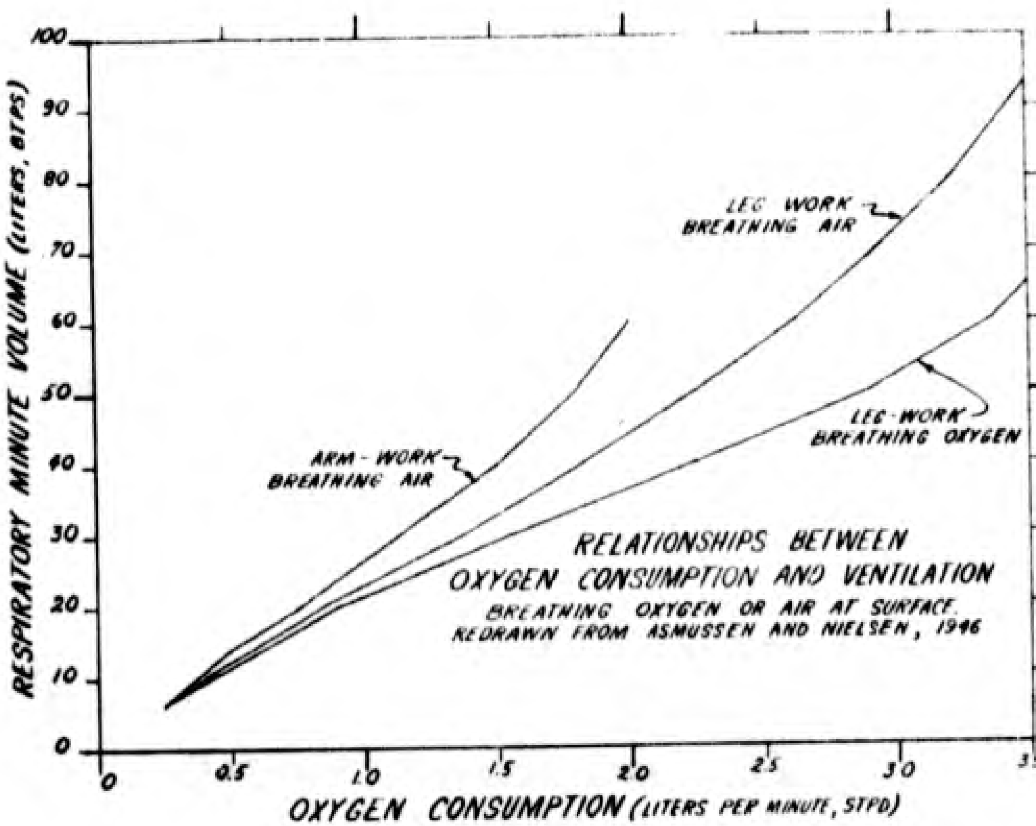


FIGURE 6-5

RELATIONSHIPS BETWEEN OXYGEN CONSUMPTION AND VENTILATION 6.3.2

The curves show the increase of respiratory minute volume with increase of oxygen consumption for arm work breathing air, and for leg work breathing air and breathing oxygen. At high oxygen consumptions for leg work, the ventilation is markedly decreased by breathing oxygen instead of air. Asmussen and Nielsen obtained these data in 1946.

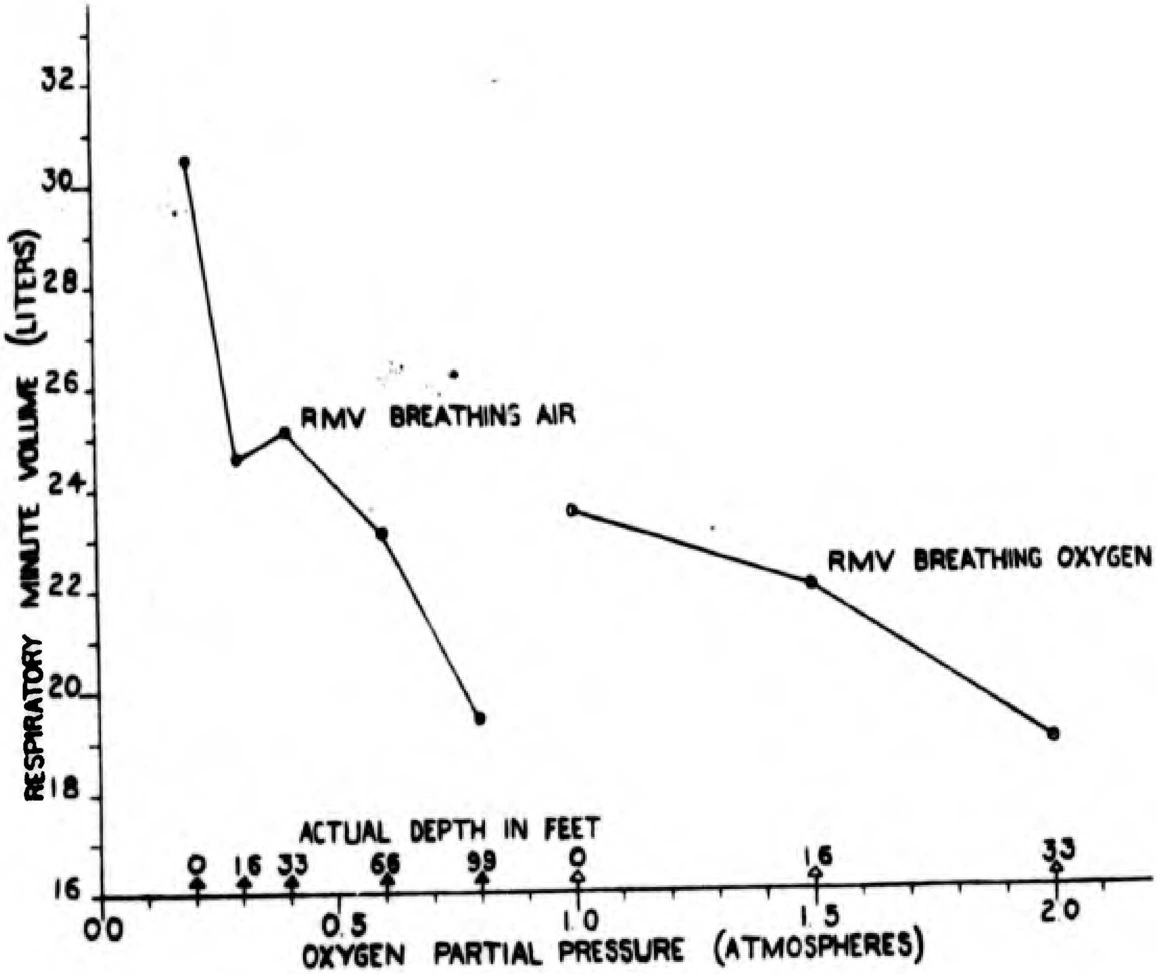


FIGURE 6-6

RELATIONSHIPS BETWEEN OXYGEN PARTIAL PRESSURE AND VENTILATION 6.3.2

The curves show the decrease of respiratory minute volume with increase of oxygen partial pressure for breathing air and for breathing oxygen at the depths indicated while "swimming" on a dynamometer against a pull of 7 to 9 pounds. An increase of partial pressure both on air and on oxygen apparently produces a marked decrease of ventilation. The decrease on air is considerably greater than the decrease on oxygen indicating the presence of some other controlling factor besides the elevated oxygen partial pressure. The Cooperative Underwater Swimmer Project (CUSP) obtained these data in 1952.

For example, Asmussen and Nielsen (6c) had shown that during heavy exertion at the surface, a given oxygen consumption is accompanied by a lower RMV when the subjects breathe oxygen than when they breathe air. Some of their results are shown in Figure 6-5. The possibility of such changes was believed sufficient to warrant investigation.

The study took two directions: (1) a comparison between the minute volumes breathing air and breathing oxygen at depths to 33 feet, and (2) measurement of RMV during air-breathing at depths to 99 feet. Rest and a constant rate of swimming were studied under these conditions. A stationary swimming device somewhat similar to that later developed by EDU (6.2.2) was used.

Studies at rest showed a barely significant decrease in ventilation with oxygen breathing and a small increase with air-breathing at greater depths.

The results under working conditions are shown in Figure 6-6. Both oxygen and increased pressure produced a significant decrease in ventilation. That observed with increased pressure was considerably greater than could be explained on the basis of the elevated partial pressure of oxygen as can be inferred from the graph. At 99 feet, the average RMV was 37% less than at the surface.

These results have never been verified under ideal conditions, and there were a number of uncontrolled factors such as temperature, currents, and apparatus breathing resistance. It is rather unlikely, however, that any of these could have accounted for such large differences. An earlier study at the Experimental Diving Unit, conducted for other purposes, shows the same trend. Individual differences were great: the decrease in ventilation ranged from an insignificant3% to as much as 50% among the 9 subjects tested. These results do not warrant the assumption that depth invariably decreases the RMV during exertion. This appears to be an individual matter and may perhaps vary in the same man from day to day. In considering duration of air supply, it remains necessary to assume that the air requirement of an individual using open-circuit gear will increase in direct proportion to the absolute pressure even though this will often not be the case.

6.3.3 Implications

The depth-change findings, if valid, raise some interesting questions concerning the influence of depth pressure upon the control of respiration. These questions may have important implications in diving. For example: if a man is doing a given amount of work, yet has only 50% of the normal RMV for such work, his carbon dioxide elimination should be impaired considerably. If so, this could have serious consequences under certain conditions (6.6.4). The problem clearly deserves study.

6.3.4 Relationships

If either oxygen consumption or RMV is known, the other may be predicted roughly if only air-breathing at the surface is involved. Under these conditions, the average oxygen consumption is approximtely 4.5% of the average RMV. Within a reasonable range of exertion, the relationship rarely varies more than between 3.5% and 5.5%.

Since such approximations are useful and frequently made, it is important to note that both increased oxygen tensions, per se, and increased depth can evidently render them invalid.

6.4 CARBON DIOXIDE

The carbon dioxide production of the body is of relatively little concern in open-circuit SCUBA, but in any apparatus in which rebreathing takes place it is of major consequence.

6.4.1 Production

The measurement of carbon dioxide output during free swimming without surface connections presents extreme difficulties. Such approaches as "before and after" titrations of the carbon dioxide absorbent have not met with much success. Determination by means of an open-circuit system with collection of the expired gas during stationary swimming on a calibrated swim-ergometer is a more promising approach but has not been undertaken at this writing.

The information is desired primarily from the standpoint of designing adequate carbon dioxide absorption systems, and it would also permit realistic evaluation of such systems by mechanical methods in which all significant variables could be controlled.

In the absence of data obtained during actual underwater work, it is probable that existing knowledge provides usable estimates: the respiratory quotient,

$$\frac{\text{CO2 output}}{\text{oxygen consumption}}$$

describes the relationship between carbon dioxide output and oxygen consumption, which is readily measured and reasonably well studied (6.3.0).

Under normal resting conditions, the respiratory quotient is determined mainly by the diet, varying from 0.7 with a total intake of fat to 1.0 on a pure carbohydrate diet. On an average diet, the value is about 0.85. The true respiratory quotient is believed to rise somewhat during exertion, but not to exceed 1. For various reasons, the apparent R.Q. may rise to 1.5 or more for brief periods during heavy exertion. The word "apparent" is used since measurements continued long enough during recovery from such exertion will show a compensatory reduction in R.Q.

Unless diving conditions introduce unexpected factors, the carbon dioxide output should average slightly less than the oxygen consumption but brief increases to nearly twice that value might be encountered.

The problem of carbon dioxide absorption has two major aspects: (1) the total amount of carbon dioxide which must be absorbed, and (2) the maximum rate of absorption required. A system which permits excessive buildup to occur in the breathing apparatus during periods of above-average exertion is inadequate even though it is capable of handling an average amount of carbon dioxide for many hours. Since the oxygen consumption of SCUBA divers can be expected to reach 3 lpm or more for brief but significant periods, the peak load of carbon dioxide might exceed 5 or 6 liters per minute in view of the possible range of apparent R.Q. Significant failure of the absorption system under such conditions could result in a very rapid rise of carbon dioxide to dangerous levels (6.6.4).

6.4.2 Carbon Dioxide Absorbents

At the present time there appears to be no better means of removing carbon dioxide from the respired gas in SCUBA than the use of the absorbents long familiar in anesthesia and similar applications: soda lime, Baralyme (R), and similar products.

All of these have the common defect of bulk and relative inefficiency. Absorbents which have much greater efficiency per unit of volume or weight are available but are unsuitable for various reasons. Shell natron, used in helium-oxygen diving (IA-5), is extremely efficient, being almost pure sodium hydroxide; but its solubility and causticity would constitute an intolerable hazard in SCUBA. The same is true of lithium hydroxide, which has the added disadvantage of highly caustic dust. Substances which take up carbon dioxide and give off oxygen, widely employed in respiratory apparatus for use in contaminated atmospheres on land, are ruled out by their tendency to react violently on contact with water.

There has, to date, been no convincing proof that any of the products which are generally used have striking superiority over the others in vital respects or that feasible modifications in the materials would greatly modify their characteristics. Further studies should nevertheless be conducted. Baralyme (R) is preferred by some diving activities because its alkali is relatively insoluble and because its pellet-form is somewhat more convenient to handle. The use of absorbents containing an indicator which changes color on exhaustion of the material is frequently desirable although the limits of accuracy of such indicators should be recognized.

All of these absorbents require careful handling to reduce dusting, and measures to remove dust in the process of filling canisters. Over-energetic screening of the material may create more dust than it removes. Winnowing is preferable if it does not involve excessive agitation or pouring the particles from an excessive height. Canisters which must be shaken vigorously to permit adequate filling guarantee the formation of dust.

Where this can be done, blowing a stream of air under slight pressure through the filled canister will remove almost all of the dust without forming more, provided that the canister is well packed. Intermittent blocking of the outflow appears to speed this process. Untoward effects due to inhalation of dust are not improbable, but this does not appear to be a frequent or serious accident.

6.4.3 Canister design

While efforts to find better absorbents should continue, attention must be concentrated on providing adequate absorption by employing the familiar materials in the most efficient way. Since the bulk of absorbent necessary for both long-term and full moment-to-moment adequacy is prohibitive, efficient utilization is essential.

Studies related to the optimum size and configuration of canisters have been directed mainly toward the needs of anesthesia, so that their application to SCUBA problems is limited. At the present time, satisfactory prediction of the total amount of absorbent required for a given load is not even possible. Figures on the abosrbing capacity of the material are meaningless unless the efficiency of utilization is known. An extensive study is required.

Figures 6-7 shows several of the most evident faults of canister design and common causes of failure. The most obvious cause, beyond complete inactivation of the absorbent, is ability of the expired gas to by-pass the active material. This may occur either through an open channel which gives a route of least resistance past the absorbent, or through early exhaustion of the absorbent in the normal path of the gas. Ideally, the canister design should cause the gas to diffuse evenly throughout. This diffusion is not easily accomplished, and arrangements of baffles which appear promising on paper frequently prove unsatisfactory because they either increase resistance to air-flow or produce new "dead" areas.

Anesthesia studies have indicated that a close match of canister intergranular space with the tidal volume gives greatest canister efficiency. This is in harmony with the concept that most effective absorption occurs when the carbon dioxide gas can remain in the canister for the longest possible time. Experience indicates that rapid passage of gas through the absorbent gives insufficient absorption and can cause failure even with fresh absorbent. This "blow-through" occurs when the intergranular space is much smaller than the tidal volume or when the gas tends to follow a small, direct path through the canister.

The range of tidal volumes encountered in SCUBA diving is such that the principle of matching intergranular space to tidal volume must be compromised. Provision of sufficient intergranular space to match high tidal volumes.would require more absorbent than enough for total absorption capacity, and would usually exceed the practical limits of bulk. The optimal solution is not currently apparent.

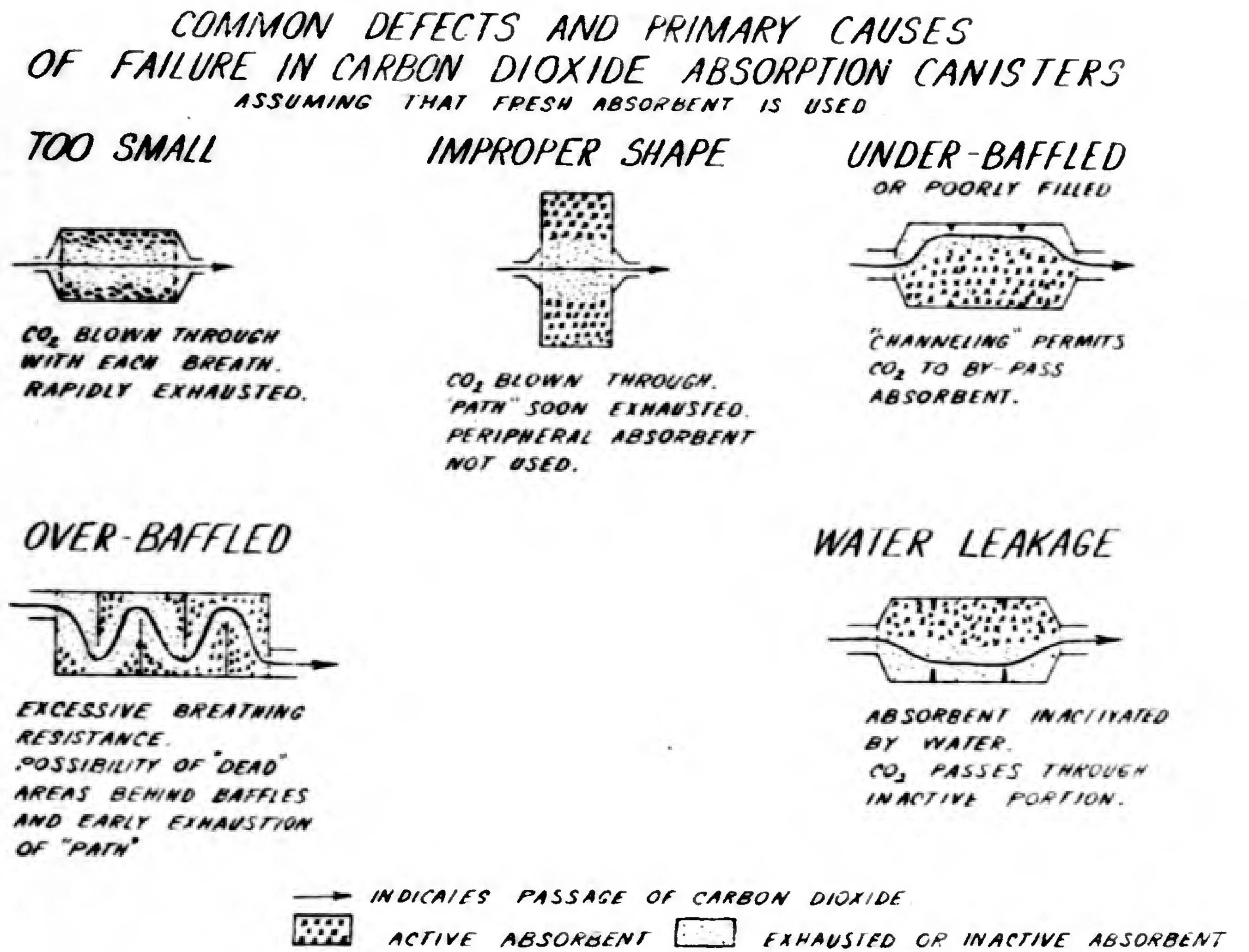


FIGURE 6-7

CARBON DIOXIDE CANISTER DEFECTS 6.4.3

The diagrams show common defects in design and other factors which can cause canisters to fail even though fresh absorbent is used.

Assuming an efficient design, several other factors must also be considered. Minimal resistance of air flow through the canister rules out an excessively long air-path and certain types of baffling. The canister must be readily filled and emptied, and the absorbent should not be able to pack down and leave open channels. All possible precautions must be taken against leakage and against entrance of moisture from saliva or condensation, because grossly wet absorbent is essentially inactive. The fact that parts of a "pendulum" canister tend to constitute dead space should be considered (6.5.0).

6.5 RESPIRATORY DEAD SPACE

The respiratory dead space of the body itself is defined as that part of the respiratory system which serves primarily as a conducting airway and in which there is no rapid exchange of oxygen and carbon dioxide. It is made up of the nose, mouth, pharynx, larynx, trachea, bronchi, and bronchioles. On expiration, these spaces are left filled with alveolar gas which is returned to the alveoli on the next inspiration. At the end of inspiration, the dead space is filled with fresh air, and this is expelled on the next expiration. The amount of fresh air reaching the alveoli on each breath (effective alveolar ventilation) is not the full tidal volume. It is the tidal volume minus the effective dead space volume. By breathing very lightly and rapidly, an individual could devote almost all of a considerable respiratory minute volume to ventilation of dead space alone.

In considering dead space, a distinction must be made between the absolute volume of the space and its "effective" volume in terms of the extent to which it actually impairs the function of respiration. This effective or "physiological" dead space is generally smaller than the "anatomical" dead space during quiet breathing, perhaps because some diffusion between alveolar gas and dead space air occurs in the terminal bronchioles. But during increased breathing, the physiological dead space may become considerably larger. In young men the physiological dead space averages about 150 cc during quiet breathing. Individual differences may be considerable, and the volume varies considerably with changes in rate and depth of breathing. Increases in the physiological dead space due to various pathological processes can seriously impair respiration.

The respiratory dead space of breathing apparatus can be considered as an extension of the dead space of the body and may be discussed in similar terms. The distinction between "anatomical" and "physiological" (that is, between volumetric and effective) dead space is important. The effective volume of dead space cannot usually be predicted accurately from inspection of the circuit and simple volumetric measurement of the parts believed to be "dead". A mask may contain space which washes out so incompletely that it is not actually dead. A unidirectional breathing tube which is not theoretically dead may collect or contribute expired gas through mixing or diffusion and thus add somewhat to effective dead space. Leakage of check valves will also contribute to effective dead space. A "to-and-fro" or "pendulum" canister which is exhausted at the proximal end will be at least partially dead, but diffusion and mixing may render the effective dead space smaller than the actual volume involved. These examples indicate that a "functional" method of measuring apparatus dead space is required.

The consequences of adding various amounts of dead space to the respiratory system depend on several factors. If the rate and depth of respiration were kept constant under given conditions of work or rest, the net alveolar ventilation provided by each breath would be reduced in proportion to the effective dead space added. Under normal circumstances, the body will attempt to compensate for added dead space by increasing the ventilation. An increase in the depth of breathing gives the most effective compensation. An increase in rate alone is relatively ineffective because much of the additional ventilation is wasted on the dead space. Increased ventilation can compensate for a considerable volume of dead space, but it cannot compensate completely. A compensatory increase of ventilation presupposes an increase of respiratory stimulus. The usual effect of added dead space is to cause an initial drop in oxygen tension and rise in carbon dioxide tension. These changes cause an increase in ventilation and a return to the tensions toward, but not to, the normal levels. In effect, the partial pressures reach a new equilibrium. However, the respiration may increase to the point of frank dyspnea, and the equilibrium levels may be such that other symptoms of elevated carbon dioxide and decreased oxygen are evident.

Any degree of compensation will draw upon the individuals respiratory reserve, decreasing his capacity for physical exertion. Since compensation depends in large part upon the respiratory response to carbon dioxide, impaired response favors accumulation of carbon dioxide, possible to toxic levels. Since certain factors in diving appear to reduce the respiratory response to carbon dioxide, the danger of excessive dead space in underwater breathing apparatus may be considerable. The anoxic aspect of apparatus dead space is not a problem in oxygen rebreathing systems, but it may be important in some types of mixed-gas gear.

The potential seriousness of the dead space problem warrants intensive study with different breathing media through a wide range of conditions of work and depth. Reliable information about the permissible volume of effective dead space in diving gear is not currently available.

6.6 EFFECTS OF CARBON DIOXIDE

Since carbon dioxide can accumulate in a breathing system because of faulty absorption or excessive dead space, its effects on the diver are of considerable consequence. The actions of carbon dioxide have been studied almost exclusively under resting conditions at the surface, and the resulting information may not be wholly applicable to diving conditions.

The customary assumption has been that carbon dioxide effects in diving are the same as those produced by corresponding partial pressures of the gas under surface conditions: a diver exposed to 2% carbon dioxide at 33 feet should react as if he were breathing 4% at the surface. Basically this is correct but it does not allow for the presence of potential modifying factors in diving situations.

6.6.1 Pressure relationships

Occasionally, confusion arises even in considering the effect of depth pressure itself upon carbon dioxide levels. If a quantity of gas containing a given percentage of carbon dioxide is taken from the surface to depth, the partial pressure of carbon dioxide will obviously increase in proportion to the ambient pressure, and the total volume of gas will decrease. But keeping the volume of a breathing system constant by adding fresh gas, as is often necessary, will cancel the increase of carbon dioxide partial pressure. Similarly, merely being under pressure does not increase the seriousness of faulty carbon dioxide absorption, and it probably does not have direct influence upon the significance of dead space. The body will produce essentially the same number of molecules of carbon dioxide at depth as it does for the same degree of exertion at the surface. Since the number of molecules present determines the partial pressure of a gas in a fixed volume, the partial pressure of carbon dioxide should not increase any more rapidly in a faulty system at depth than it does in the same system at the surface.

Another example of the relationships involved is seen in considering the diver's alveolar carbon dioxide tension. Assuming adequate carbon dioxide absorption and no change in ventilation, the tension should be independent of depth, although transient changes may appear during ascent and descent. If the partial pressure of alveolar carbon dioxide is the same as depth as at the surface, then the percentage (representing the ratio between the partial and total pressure) has to change. The following formula shows what the percentage (dry gas analysis) should be:

$$\frac{pCO2}{(760 \times A) - 47} \times 100 = \%CO2 \qquad (6\text{-}1)$$

where pCO2 - alveolar carbon dioxide partial pressure, mm.Hg
760 - (one atmosphere, mm.Hg)
A - ambient pressure, atmospheres (absolute)
47 - (water vapor pressure of alveolar gas - independent of depth).

Normal alveolar carbon dioxide tension is about 40 mm. Hg, equivalent to about 5.6% at the surface. The corresponding value at 4 atm. (99 feet) would be only 1.34%.

6.6.2 Primary actions

(a) Cardiovascular

Among the primary physiological actions of carbon dioxide, the cardiovascular effects appear to be of the least immediate importance in diving. Locally, carbon dioxide causes vasodilatation; but central stimulation of the vasomotor center also occurs and generally predominates except in the cerebral vessels. The systemic blood pressure rises moderately, and the heart rate generally increases.

Cerebral vasodilatation and increased cerebral blood flow occur. These effects have been blamed for the headaches which sometimes result from exposure to carbon dioxide, although headaches are most commonly noted on withdrawal of the gas.

Diastolic blood pressure may drop briefly but significantly on withdrawal. This effect has been explained as perhaps due to persistence of local vasodilator action after central vasomotor stimulation has been abolished. The fall in blood pressure may help to account for the exacerbation of symptoms sometimes noted in victims of carbon dioxide excess when they are given fresh air.

Circulator failure occasionally occurs as a result of carbon dioxide exposures which can normally be tolerated for short periods without serious effects. This possibility should be kept in mind especially in connection with demonstrations (3.2.2) and the like. The mechanism is not well understood.

(b) Respiratory responses

While any increase in the carbon dioxide level of inspired gas will interfere with carbon dioxide elimination and will elevate the alveolar to some extent, measureable effects rarely occur at inspired levels less than the equivalent of 1%. The average respiratory response of resting subjects at the surface to various amounts of carbon dioxide is presented in Table 6-3.

TABLE 6-3 Respiratory response to inspired carbon dioxide.

Approximate average values, adapted from Dripps and Comroe, 1946 (6d).

CARBON DIOXIDE LEVEL	RESPIRATORY MINUTE VOLUME
percent	liters
0	8
2	9
4	15
6	32
8	55
10	75

It is of interest, for the sake of comparison, to note that severe muscular exertion produces respiratory minute volumes of over 100 liters per minute and that the maximal breathing capacity of young men averages about 170 liters a minute. Carbon dioxide, alone, is not a maximal respiratory stimulus. An increase of respiration to as much as 30 or 40 liters per minute may go unnoticed, and some individuals may have a minute volume in excess of 100 liters without a sensation of actual dyspnea. A man already experiencing the hyperpnea of exertion might be unaware of a further increase in respiratory drive due to carbon dioxide, unless the increase was quite marked.

White (6e) and others have shown conclusively that the respiratory response to carbon dioxide is increased by low oxygen partial pressures and decreased by high oxygen partial pressures even at the surface. It would not be surprising to find this attenuation-effect even more marked in the presence of partial pressures of oxygen of the order found in diving.

The fact that experienced skin-divers, such as submarine escape training tank instructors, tend to have low respiratory responses to carbon dioxide has been demonstrated by Schaefer, et.al. (6f). Individual differences in response are considerable even in the general population.

The increase in ventilation caused by carbon dioxide is achieved principally by an increase in tidal volume. This is fortunate from the standpoint of compensation for excessive dead space (6.5.0).

(c) Central nervous system (CNS) depression

A variety of symptoms attributable to CNS depression have been reported. In one study (6g), lightheadedness, haziness, or sleepiness were noted shortly after the first awareness of increased respiration. Subjects who were working or who were unusually susceptible to CNS depression experienced these symptoms before noting hyperpnea. Further increase in the carbon dioxide level produced definite clouding of consciousness with impairment of vision and hearing. (This effect could be compared to light nitrous oxide anesthesia). Some working subjects continued their exertions with dogged determination and increased zeal even after losing evident contact with their surroundings.

Except for occasional brief exacerbation of symptoms or the onset of dizziness or headache on return to air, recovery is prompt. A man who loses consciousness will usually recover in less than a minute and appear quite normal in less than 15 minutes. After-effects may include headache, nausea, dizziness, or general malaise for an hour or more.

"Dose-time" relationships may have considerable influence on the symptoms and after-effects. A gradually increasing carbon dioxide level, likely in SCUBA exposures, is not strictly comparable to a sudden exposure to a similar concentration. The fact that most laboratory studies have involved abrupt administration may account for some differences. Another factor which deserves consideration is that the respiratory response to carbon dioxide tends to diminish in long exposures while the depressant effects do not. The severity of after-effects increases with duration of exposure.

Dyspnea, headache, dizziness, faintness, or fainting terminated, in less than 5 minutes, almost all of the exposures to 10.4% carbon dioxide in one study (6d). Three of 31 subjects actually lost consciousness. One of 42 subjects became unconscious after an unspecified duration of breathing only 7.4% carbon dioxide.

There are indications that CNS depression also influences the respiratory center, tending to reduce its response. In some cases, further increase in the concentration of carbon dioxide causes a drop in respiration coincident with other evidence of increased depression.

6.6.3 Causes of death

The concentration of carbon dioxide or the duration of exposure required to cause death in man remains unknown. In SCUBA diving, loss of consciousness in a man remote from assistance would probably soon result in death from other causes.

Concentrations of carbon dioxide up to 30% are used in some places for treatment of psychoneuroses. In this application, only a few breaths of the mixture are given, resulting in a violent increase in respiration, followed by loss of consciousness. Neuromuscular activity which resembles convulsion but which is more closely akin to decerebrate rigidity frequently occurs. Definite cardiac arrhythmias have been noted during those treatments (6h). No deaths have been reported, but the possibility of ventricular fibrillation has been suggested.

The occasional occurrence of circulatory failure in carbon dioxide exposures has been mentioned above.

6.6.4 Implications in diving

Respiratory stimulation from carbon dioxide can be distressing and may require discontinuing a dive; however, it is not in itself likely to be harmful. The circulatory effects are rarely impressive or dangerous. The indirect influence of carbon dioxide in oxygen poisoning is a hazard, of course, and the gas may have some role in nitrogen narcosis and decompression sickness.

The central nervous system depression which carbon dioxide can produce is a very direct and serious danger. If the diver does not become aware of the presence of carbon dioxide excess before this action renders him helpless, he will in all probability lose his life if he is not rescued. This being the case, all of the other actions and symptoms produced by the gas become insignificant except that they may warn the diver in time for him to remedy the situation.

A number of miscellaneous symptoms, ranging from headache to a general feeling of discomfort, might be listed. None of them are either reliable enough in their onset or distinctive enough in their presence to serve as a clear warning. Only respiratory distress really qualifies as an adequate danger signal - if it occurs.

At one time, the appearance of dyspnea was regarded as a highly reliable warning, and therefore the problem of carbon dioxide accumulation in SCUBA was regarded with considerable complacency.

This assurance was upset, however, during World War II when several cases of unexplained loss of consciousness underwater occurred during British operations with closed-circuit SCUBA. The phenomenon was termed "Shallow-water Black Out." Carbon dioxide was not definitely implicated until other possible causes had been ruled out and several interesting facts about responses to carbon dioxide discovered (6g).

The conclusions reached were, in brief, as follows:

(1) There are considerable individual differences in response to increased carbon dioxide. The relative degree of the depressant and respiratory stimulant effects is variable.

(2) Marked carbon-dioxide intoxication, without severe respiratory distress, can be produced in almost all individuals under certain conditions.

(3) Among conditions which favor the predominance of depression over respiratory distress are:

a. Increased oxygen tensions, and
b. Physical exertion.

These conclusions are not surprising in view of some of the facts discussed above (6.6.2), but they shed a new light on the carbon dioxide problem at the time. Since then, shallow-water blackout has become recognized as a major problem in SCUBA operations with rebreathing equipment.

In practical terms, carbon dioxide is potentially as insidious a hazard as anoxia. This fact places great importance on prevention of carbon dioxide build-up in breathing apparatus. It may mean that unusually susceptible men should be detected and kept out of certain kinds of SCUBA diving. It certainly means that instruction (3.2.2) should be aimed at helping men to recognize, when possible, the early signs of CNS depression--which may constitute their only warning.

6.6.5 Research aspects

From the standpoint of investigation, many aspects of carbon dioxide response remain to be elucidated: Is there any reliable way of screening men who are unusually prone to "blackout"? Is a low respiratory response to carbon dioxide correlated with susceptibility to oxygen poisoning (8.0.0)? What problems might this phenomenon involve in mixed-gas diving where high partial pressures of nitrogen as well as of oxygen are encountered? Will low respiratory responses impair compensation for dead space (6.5.0)?

Better understanding of carbon dioxide response phenomena should also shed new light on the mechanisms which control respiration.

6.7 BREATHING RESISTANCE

Breathing involves work even under normal conditions, and there are definite limits to an individual's ability to perform the work of breathing. Even in healthy men, heavy physical exertion can cause this limit to be reached; and when the work approaches the maximum which a man can sustain, dyspnea and limitation of activity ensue. Any form of pathology which increases the work of breathing or decreases the individual's ability to do that work will naturally decrease his capacity for physical exertion.

This is a familiar concept in clinical medicine, and it applies equally well to the problem of breathing resistance in SCUBA. To equip divers with breathing apparatus which significantly increase the work of breathing is equivalent to choosing asthmatics for diving duty. The consequences will be about the same; discomfort, loss of efficiency, low work-capacity, real peril in emergencies, and perhaps other difficulties.

Measuring the breathing resistance of SCUBA or finding its cause is not very difficult. Eliminating it is not so easy. But the real problem is to determine how much resistance a man can tolerate without serious loss of efficiency and without getting into trouble or experiencing actual harm. The main reason for the difficulty of making this determination in SCUBA is that the resistance is produced by a complicated combination of factors, each of which has its own characteristics and consequences.

The main factors causing breathing resistance in SCUBA can be discussed under separate headings, but they seldom are present alone.

6.7.1 Hydrostatic factors

When a man is submerged, the pressure of surrounding water acts upon his body and tends to produce a certain pressure in his lungs. If he is using a breathing bag, this will also be subjected to hydrostatic pressure. The lungs and bag then form a connected system with the same pressure throughout. If the bag is placed at such a level that the pressure produced in this system is equal to the pressure acting upon the chest from the outside, the man will be able to breathe to and from the bag with relatively little effort. The outside pressure is counterbalanced by the pressure in the bag. But if the bag is placed above this level, the pressure in the lung-bag system will not counterbalance the pressure acting upon the chest. The man will then have to exert continuous inspiratory effort just to keep from being deflated by the external pressure. Even greater effort will be required for inspiration from the bag. Conversely, a bag which is placed too low will subject the lungs to higher pressure than that acting from the outside; and expiratory pressure will be required to oppose it.

Imbalances of pressure caused by a breathing bag which is located too high or too low on the diver's body do not have to be very large to have undesirable consequences. Studies concerning the mechanics of breathing, such as those of Fenn and his associates (6j, 6k), shed considerable light on the implications. According to Fenn, about 60% of the normal work of breathing is done simply in the process of changing the position of the chest-lung system in order to increase and decrease the volume of the lungs. (Most of the remainder of the work goes into the actual movement of air). The amount of effort required for this volume change would be much greater were it not for the fact that the chest-lungs are very elastic and are always tending to collapse, but their enclosure is also elastic and is always tending to expand. When this balance is upset by some disease process, as by the loss of lung elasticity which occurs in emphysema, the work of breathing is greatly increased.

The point at which the normal opposing forces are perfectly balanced is the position which the system assumes when respiratory muscular effort is relaxed; the position at the end of normal expiration. At this level, the amount of air in the lungs (in addition to the residual volume) is about 30 to 40% of the vital capacity. Gas volumes and volume-changes in the lungs can be expressed readily in percentage of the vital capacity (% VC). Applying pressure to the lungs will unbalance the forces involved and will create a new position of equilibrium. For example, if a positive pressure of 20 cm below the optimum level, the new equilibrium position will be at about 80% VC. Application of an additional 20 cm of water will bring the system to equilibrium at 100% VC - the position of maximal inspiration. Negative pressures will shift the equilibrium position (sometimes called "relaxation volume") in the opposite direction; -10 cm of water will lower it to about 20% VC, while the maximal expiratory level will be reached at about -25 cm.

The amount of muscular effort required to change the volume of the system can be considered in exactly the same terms--the pressure required to produce a given change. Normal breathing takes place in the range of volumes where the least effort produces the greatest change - between the end-expiratory level (30 to 40% VC) and about 80% VC. This level is reached with an inspiratory effort of 20 cm of water which thus produces a change of 40 to 50% VC. If balance is upset by a misplaced bag, breathing may be forced to take place in a less efficient range. For example; if the bag is 20 cm too low and the resting level is thus raised to 80% VC, an inspiratory effort of 20 cm of water will then produce a change of only 20%, expiratory effort will be required as well. Furthermore, blowing air into the breathing bag will lower the gas-water interface, thus increasing the imbalance and the necessary expiratory effort even more. Meanwhile, the expiratory muscles are shortening and losing much of their power. In fact, they may not even be capable of completing a full expiration under these conditions.

The work devoted to changing the position of the chest-lung system is normally done only during the inspiratory phase. In quiet breathing, the stored energy of elastic recoil in the system is then sufficient to perform all the work of expiration. A low breathing bag not only can reverse this situation but may add a still further complication: if imbalance is marked, the positive pressure will produce forceful inflation of the lungs unless it is opposed by positive expiratory effort. Gradual relaxation of this effort is then necessary to permit inspiration. The muscles may thus be compelled not only to work harder but also to continue working throughout both phases of respiration. A bag which is too high causes very similar, though opposite, effects. These are apparently even less readily tolerated than those described.

The potential effects of mis-location of the breathing bag raise the question "What is the optimal level?" Paton and Sand (6m) investigated this question and concluded that the optimal level--the "eupneic pressure" point--is located at the suprasternal notch. They found this to be true for all positions of the body underwater except standing. Here, the level was 10 cm higher; but it dropped to the suprasternal notch in the presence of hyperpnea. Since hyperpnea accompanies exertion and is thus usual in diving, the suprasternal notch appeared to be the optimal level for all positions.

Unfortunately, it is seldom possible to locate a breathing bag exactly at this point. In any event, the "effective level" is bound to shift with varying amounts of gas in the bag. Paton and Sand found that departures from "eupneic pressure" were readily detected and could produce great discomfort, but that imbalances as great as 20 cm in either direction did not produce significant changes in breathing. (They did not measure the actual work of breathing). Subjectively, imbalances in the positive direction (with the bag too low) were much less distressing than those in the negative direction. (These investigators made many other interesting observations on the effect of submergence on breathing, but space does not permit discussing them).

The "eupneic pressure" concept has applications beyond the problems of breathing bag location. In rebreathing systems with injection and pop-off, the location of the pop-off valve is crucial. One which is too high will tend to drain the bag and the lungs while one which is too low will produce over-filling and difficulty on expiration. (Spring loading may be used to offset non-optimum location and to permit adjustment).

Hydrostatic pressure is also extremely important in connection with air-demand apparatus. Here, the elastic phenomana are not involved. Instead, the level of the demand-valve diaphragm and the level of the exhaust valve are important in that they determine the pressure which must be developed in order to obtain air on inspiration or to exhaust it on expiration.

If the diaphragm is higher than the eupneic level, the diver will be forced to develop negative intrapulmonary pressure before he receives air and to maintain this pressure throughout inspiration. If the diaphragm is too low, he will tend to be inflated continuously and will have to oppose this positive pressure with expiratory effort.

If the exhaust valve is higher than the demand valve, continuous flow of air will result. If it is lower, expiratory pressure will always be higher than inspiratory pressure, producing an unpleasant sensation. If the exhaust and demand valves are balanced but too high, the diver will not only have to produce negative pressure to get air but he will have to maintain inspiratory effort to keep from being deflated by the "suction" effect of the exhaust. If they are balanced but too low, the diver will have to produce positive pressure to exhale and he will have to maintain continuous expiratory effort to prevent inflation.

No existing air-demand system places the demand and exhaust at the suprasternal notch. The most common location is near the nape of the neck, which is about right for the upright diving position but is 10 to 20 cm too high for the prone swimming position. A "negative" sensation is distinctly noticeable in the prone position, but most users of equipment with this characteristic are able to accomodate to it without any apparent ill-effects. This type of apparatus also produces a very unpleasant sensation of inflation when used in the supine position, but working in this position is seldom necessary.

The mask-mounted type of demand valve (Figure 2-6) produces a slight "negative" (deflation) sensation in the vertical position but is almost ideal in either prone or supine horizontal positions. Free flow will occur when lying on the side with the exhaust higher than the demand valve diaphragm except where a balancing arrangement prevents this.

The bulk of the valves and the problem of connections hinder most attempts to improve the location of the demand and exhaust valves. However, there is still room for improvement particularly because it may be possible to refer the operating pressure to an optimum point without actually placing the valve there.

6.7.2. Airway resistance

Any system of tubing, connections, check-valves, and the like will present a certain amount of opposition to the passage of air, and a system which is quite appropriate for low flows at surface or altitude may prove to have a prohibitive excess of breathing resistance during hard work at depths.

In simple airway systems, such as those used in rebreathing equipment, the sources of resistance may be considered in two overlapping categories. The first is restriction to flow in the form of inadequate diameters of tubing and connections, such as check valves and stopcocks with openings which are too small to accommodate the respiratory air flows of a working man. The second is any source of turbulence, such as projecting obstructions, sudden changes in diameter or direction of the passages, and valves which cause radical re-direction of flow.

Theroretically, there are two types of gas-flow, each of which has its own characteristics in regard to flow resistance:

a) Laminar or streamline flow occurs when the gas molecules move in smooth concentric layers through a tube (laminar means "layered"). In such a system, the pressure drop between two points is directly proportional to the rate of volumetric flow per unit of cross-sectional area, that is, to the linear velocity. The ratio between the velocity and the pressure drop is defined by a constant which is dependent upon the characteristics of the particular system and the viscosity of the gas.

b) Turbulent flow occurs when the gas molecules do not move in in a laminar path. Here, the flow has no streamlined pattern -- a breath of smoke blown through such a system shows a mass of eddy currents and confusion. Turbulence is caused by such factors as projections into the stream and abrupt changes in diameter or direction, but almost any system will become turbulent when the flow is high enough. The rule traditionally applied to turbulent systems states that the pressure drop is proportional to the square of the velocity. The proportionality constant is dependent upon the characteristics of the particular system and the density of the gas. Supposedly this rule also applies to parts of a system where there are changes of diameter or direction even though flow is not frankly turbulent.

It was thought at one time that the behavior of an airway system -- such as man's own air passages or those of a breathing apparatus -- could be described simply as the sum of two distinct components representing these two types of flow. This does not appear to be strictly the case; but the concept can be used in a diagrammatic sense to present some of the most important facts about such systems from the standpoint of diving. Figure 6-9 gives schematic diagrams for various flow systems.

If a system always has perfectly laminar flow, its pressure drop will theoretically increase in direct proportion to the flow. When the flow is doubled, the driving pressure required to produce it will be doubled. If such a system is taken to depth, its pressure/flow characteristic (loosely called "resistance") will not change. The constant for laminar systems is proportional to viscosity, which does not change much with increased pressure.

In a turbulent system the driving pressure will theoretically be proportional to the square of the flow. When the flow is doubled, the driving pressure will increase four times. Density, which represents the mass of gas in a unit volume, is directly proportional to the absolute pressure. Since the constant for turbulent flow is assumed to be proportional to the density, the driving pressure necessary to produce a given flow at the surface will be doubled at 33 feet, and doubled again at 99 feet.

Although these concepts are only approximate, they give a good indication of the effect of increases in flow and increases in depth upon the resistance of a breathing system. A system which is largely

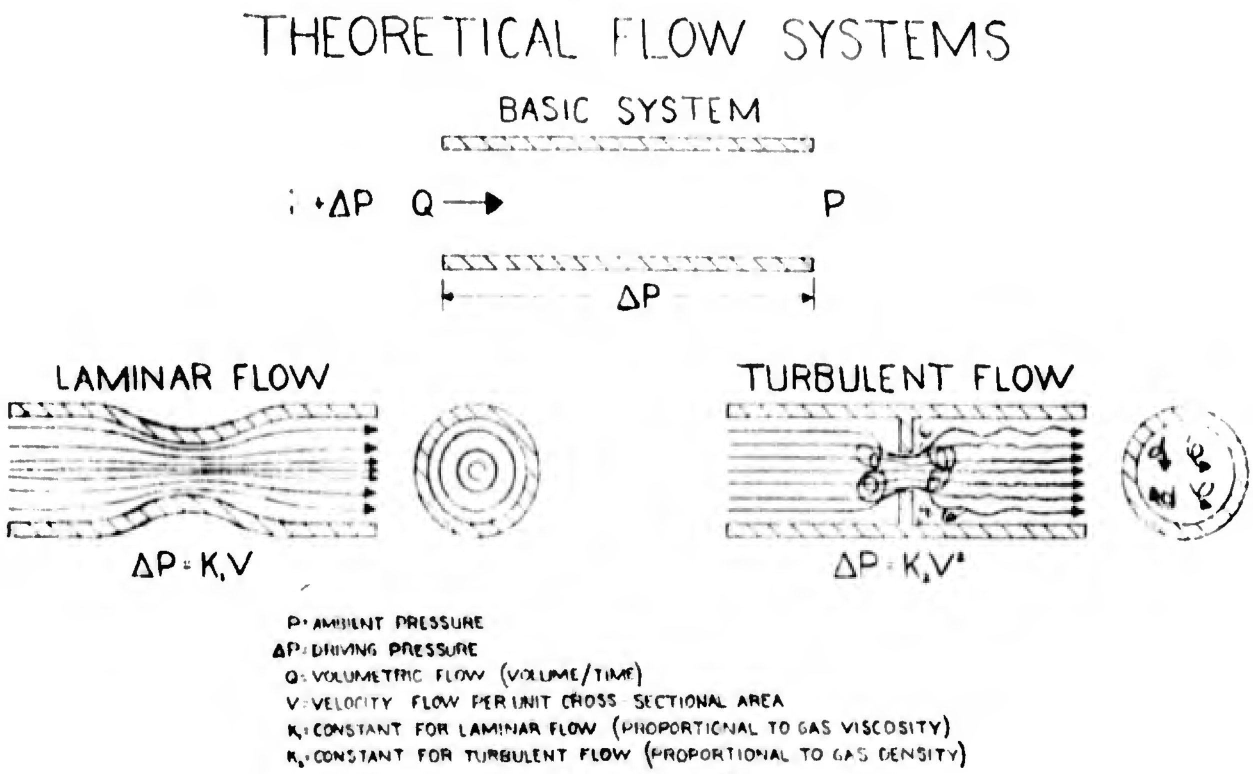


FIGURE 6-9

THEORETICAL FLOW SYSTEMS 6.7.2

The diagrams illustrate the basic fluid flow system, and the streamlines for laminar and turbulent flow. In the basic system a driving pressure which is the differential pressure between two points in the system produces a volumetric flow. Changes in the driving pressure produce corresponding changes in the volumetric flow. Conversely, a given volumetric flow necessitates a specific pressure drop.

In laminar flow for a given volumetric flow, the pressure drop is proportional directly to the velocity flow per unit cross-sectional area. The proportionality constant varies with the gas viscosity.

In turbulent flow for a given volumetric flow, the pressure drop is proportional to the square of the velocity flow per unit cross sectional area. The proportionality constant varies with the gas density.

turbulent may have low resistance when used for light work at the surface. But if an increase in work triples the air flow, the resistance may increase by as much as nine times. If the system is then taken to 165 feet, the resistance will further increase by a factor of six. In other words the resistance of such a system may then be 54 times what it is during light work at the surface. This example is not far from demonstrated fact in actual breathing systems submitted for evaluation. Tests of airway resistance mean little if they are not conducted over a range of flows and a range of ambient pressures. Barely noticeable resistance with low flows at the surface may turn into completely prohibitive obstruction under more demanding conditions.

The air flow through carbon dioxide absorption canisters is usually laminar, and the resistance is quite small. However, a canister which has a small cross-sectional area or a very long path may introduce an unnecessary amount of resistance. Over-baffling is a common cause.

6.7.3. Resistance in demand systems

Three main factors must be considered in assessing the breathing characteristics of open-circuit apparatus of the air-demand type.

1) Hydrostatic factors. These are determined by position of the demand and exhaust valves (6.7.2).

2) Opening pressure and lag of the valve. A certain amount of inspiratory negative pressure is required to open any demand valve. If this is more than a very few centimeters of water, the diver will encounter a sensation of resistance whenever he takes a breath, however small. In considering opening pressure, it is necessary to note also whether there is a time lag between the beginning of inspiration and the start of flow from the valve. Any lag will tend to upset the normal pattern of respiration by causing a sensation of having to wait for the air.

3) Inspiratory and expiratory pressures. The amount of negative or positive pressure which a man must develop in the course of the breathing cycle is the most important factor in the overall picture of demand system operation. The valve must deliver air without undue resistance during the entire respiratory cycle. In particular, the resistance must not increase markedly during the peaks of flow, which average around three times the respiratory minute volume (6.3.0), Table 6-1). Sudden increases of resistance cause discomfort and alter the respiratory pattern. To minimize peak flow resistance, the valve must deliver very high flows in its full open position, and it should open to this extent under negative pressures of a very low order.

The maximum flow of the valve is particularly important. Once the valve opens fully, the negative pressure which a man can develop will increase the flow very little. Unless the maximum flow is high enough to meet the probable maximum demand, the diver may find himself unable to obtain all the air he needs no matter how hard he "pulls". A valve which delivers a low maximum flow is highly unsatisfactory. If it has good general breathing characteristics at moderate flows, it may lull the diver into false security as he becomes familiar with it under average work conditions and will fail him when he needs it most. A valve which always meets maximum demand is preferable even if the inspiratory negative pressure becomes uncomfortably high at this flow rate and the breathing characteristics are otherwise mediocre.

Ambient pressure is the most important single factor to consider in evaluating the flow characteristics of a demand valve. A man working at 165 feet may demand respiratory volumes similar to those for the same exertion at the surface. However the gas is six times denser at that depth, and the demand valve must pass a mass of six times as many molecules for a given volumetric flow. Unless the system was carefully designed with this increased mass flow in mind, the orifices between the cylinders and the man -- in the reserve valve, the reducing valve, and the demand valve itself -- may not begin to accommodate the volumetric flow requirements. The increase of mass flow with depth constitutes an extremely difficult problem in design which few apparatuses have yet solved ideally, and it makes the problem of standards especially important (6.7.7).

Cylinder pressure is another factor to consider. A demand valve must function well throughout the range of cylinder pressures at least down to the "reserve warning" point (300 to 500 psi); otherwise the apparatus duration will be unnecessarily shortened. Below the warning pressure, the performance must be at least adequate for moderate exertion. Ideally, the apparatus should be usable almost down to zero cylinder pressure.

The exhaust valve is not nearly so difficult a problem as the demand valve. However, it must accommodate the same high flows, and it must provide a very effective barrier against inward leakage of water. Positive expiratory pressures generally increase almost directly with ambient pressure, but the actual values are usually small.

The simple airway resistance in a demand system can be discussed in the same terms as that in rebreathing systems. In general, it is negligible by comparison with the demand valve resistance; but poorly designed connections, tubes, or shut-off valves can create substantial obstructions.

6.7.4 Miscellaneous factors

With a breathing bag, overcoming stiffness of the bag material lifting an attached canister, and displacing water with gas may each involve respiratory effort. These and similar factors are rarely of much consequence by comparison with those creating hydrostatic and airway resistance, but they should be considered.

6.7.5 Consequences of excessive breathing resistance

A large number of excellent studies have been devoted to the effects of breathing resistance and of related entities such as pressure-breathing. Unfortunately, the vast majority of these studies were conducted under conditions which render attempts to transfer the data to diving situations either impossible or of very dubious validity. Only the work of Paton and Sand, already mentioned, was done with diving specifically in mind, and this covers just one main aspect of the problem. Studies in airway resistance such as those of Gain and Otis (6n) and Silverman and his associates (6p) probably apply to some extent. But even with these there is a considerable difference between the conditions studies and the comparable situation in SCUBA. The most difficult aspect of the problem in SCUBA is that all of the types of breathing resistance may be present in varying proportions at the same time.

In the absence of specific data, only general statements may be made, but the probable effects of breathing resistance can be discussed as follows without attempts at quantitation:

1) Reduction in ability to work. A man will be forced to keep his physical exertion down to the point where the associated work of breathing is tolerable. This may impair his ability to do his job and may place him in real danger when an emergency forces him into "overexertion" (5.4.0).

2) Alternations in respiratory pattern. In some types of breathing resistance, changes in the pattern of breathing will permit a degree of compensation. For example, airway resistance will be most noticeable at the peaks of flow; and to some extent, these peaks can be cut down without reducing total ventilation. The normal pattern is somewhat like a sinusoidal wave with maximum flow equal to approximately three times the RMV. If, instead, flow were to rise sharply to a sustained maximum and then fall abruptly in reversing itself, it would follow a "square wave" pattern in which maximum flow would be only twice the RMV. A complete shift to a square-wave pattern is naturally impossible, but adjustments in this direction do take place. In itself, alteration of the respiratory pattern should have no undesirable consequences; but the compensation it offers is rather limited.

3) Reduction in the respiratory minute volume (RMV). Not only are there limits to the absolute ability of the respiratory system to overcome breathing resistance, but there are also limits to its "willingness" to do so. Although the body may be able to maintain normal RMV through extreme effort, it may choose to compromise by adopting a lower rate of respiratory work and accepting the consequences. Compromise would be expecially probable in a prolonged exposure to increased resistance.

4) Impairment of respiratory exchange. A reduction in RMV must inevitably be reflecting in a lowered exchange of oxygen and carbon dioxide. Apparently, the body can increase its utilization of

oxygen in the inspired gas and accept a degree of decreased ventilation without noticeable anoxia. Markedly increased utilization would be possible with an oxygen-rich breathing mixture or with air respired at any distance beneath the surface. However, the reduced ventilation would definitely impair carbon dioxide removal, and the carbon dioxide tension of the body as a whole would rise gradually. The level would reach equilibrium when the gradient was again sufficient to remove carbon dioxide as fast as it formed. Very little information is available to indicate what this equilibrium level of carbon dioxide may be under various circumstances. It would probably depend not only upon the amount of exertion and the degree of resistance but also upon the respiratory response to carbon dioxide. This, as has been mentioned, is not only an indivudual matter but is influenced by the oxygen level. It is possible that a man who encountered heavy breathing resistance in the presence of high oxygen might have so little respiratory drive to overcome resistance that his carbon dioxide tension would climb into the depressant range. Apparatus dead space might also prove to be unusually important in the presence of excessive breathing resistance. The problem deserves careful study.

5) Circulatory impairment. The abnormal fluctuations of intrapulmonary pressure which occur in the presence of high breathing resistance will cause some interference with pulmonary blood flow and cardiac filling. The seriousness of such interference in diving situations is not known.

6) Lung damage. It has been said that a man will not voluntarily accept respiratory resistance sufficient to cause actual harm. This may be true in the acute sense, but the chance of harm in a relatively prolonged exposure to "tolerable" resistance has not been ruled out. The amount and duration of resistance required to produce pulmonary edema for example, is not known. The possibility ity of involuntary exposure to excessive resistance as in an underwater emergency requiring great physical exertion, should not be overlooked.

In actual practice, the complaint of soreness of respiratory muscles is not at all uncommon even after exposure to moderate resistance. Definite pulmonary edema or other damage has not been reported except in cases where men have tried to breathe through an open tube to the surface while submerged. Such cases actually represent thoracic squeeze; yet the pressures involved have not been much greater than those encountered in a badly designed apparatus when it is used for heavy work at depth.

6.7.6 Standards of acceptability

Acceptance standards for resistance in SCUBA have also received so little study that the problem itself remains nebulous, like the question of the consequences of excessive breathing resistance. The good work done on resistance standards in other connections is almost possible to apply to diving apparatus. In fact the best work on this subject suggests limits which can scarcely be met in SCUBA even under favorable conditions.

Current evaluations of SCUBA relative to breathing resistance are conducted mostly on a comparative basis. The evaluations include objective tests in air using a mechanical respiratory pump over a range of breathing rates and tidal volumes at various ambient pressures. They also include subjective underwater tests using men at various work rates and depths. Both types of test yield accurate recordings of inspiratory and expiratory pressures for comparative analysis. In the underwater tests, subjective reactions in the men and obvious limitations of their ability to work are important. Aside from respiratory pressures, no attempt has yet been made to quantitate factors such as changes in respiratory pattern or respiratory minute volume, work capacity, or alveolar carbon dioxide.

At moderate work rates, the average diver is reasonably comfortable for considerable periods if the inspiratory and expiratory pressures do not exceed 10 to 15 cm of water at peak flow. Subjects usually report definite discomfort when the pressures rise much above 20 cm of water. It is not definitely known how much impairment exists at such levels, or how much higher the pressures might go without deleterious effects. The foregoing figures and comments apply to demand systems and may not be valid in other types of equipment, especially where larger hydrostatic factors exist.

Absolute standards are essentially non-existent, and ideal standards would probably rule out most available equipment. Consequently, the problem has two aspects: 1) definite goals for improved apparatus, and 2) satisfactory compromises with existing realities. It may never be possible to have a man work as hard underwater as he can at the surface, even though doing so might save his life. Nevertheless considerable progress toward this end remains possible. The present problem is to determine where the line can safely be drawn, and this problem remains unsolved. Most home-made apparatus and "bargain" units of the demand type have such poor breathing characteristics that they are not really safe for use under water in any situation.

6.7.7 Resistance in man's own air passages

As has been implied by references to the work of breathing, "resistance" problems exist in man's own respiratory apparatus. These are not usually of great concern except in the presence of pathology. However, placing a man at depth and requiring him to do hard work may introduce a form of "pathology" which has received little attention.

Many divers notice a sensation of increased difficulty of breathing when working under high ambient pressures even in the dry chamber without breathing apparatus. This difficulty might be expected, because of the relation of gas density to airway resistance (6.7.2).

Some studies have been conducted at altitude and with gases of different densities in this connection (6s, 6q, 6t), but no work has been done under diving conditions. Otis and Bembower have made some interesting predictions concerning the depth effect, but these have never been checked by actual study.

The effect of depth on human respiration is important in connection with the resistance of breathing apparatus. The inescapable limitations of men's own respiratory tract may be more severe than those of breathing equipment. Consequently, the additive effect of the two sources of resistance may make it necessary to set even higher standards for apparatus than appear necessary at the present time.

Merely determining the maximal breathing capacity of men under different ambient pressures would be informative. Beyond this, recently developed techniques permit determination of the actual work of breathing at various work rates and diving depths. This information would have bearing upon the problems of submarine escape from greater depths as well as upon SCUBA problems. This method of demonstrating the effect of gas density could also provide a means of determining the source of difficulty in clinical dyspnea.

6.8 MISCELLANEOUS FACTORS IN SCUBA DESIGN

The necessary characteristics relative to gas supply, carbon dioxide absorption, and breathing resistance are just a part of the picture of an acceptable breathing apparatus. The unit must be far more than a collection of parts which happens to meet those requirements. Only a large amount of careful attention to details can make the finished product thoroughly safe and satisfactory.

It would require at least a small volume to cover the details of miscellaneous factors in design, and this section will not even present a complete outline. But the following material may be of interest if it does no more than suggest the range of matters which deserve consideration. In fairness, it must be said that some of the characteristics mentioned are hard to achieve and that no existing apparatus possesses all of them. The compilation below refers primarily to rebreathing apparatus (2.2.0), but most of the comments apply to demand apparatus as well.

6.8.1 General configuration

a. Fit and form: The SCUBA should
   1) Be adjustable to fit all divers, or have a good range of sizes.
   2) Be comfortable, having no pressure points, constriction, or chafing.
   3) Be easy to put on and take off, in or out of the water.

b. Size and shape: The SCUBA should
   1) Pass through narrow openings like submarine hatches.
   2) Be compact for storage.
   3) Have convenient carrying arrangements.
   4) Have minimum projection of hoses, valves, and corners.

c. Underwater swimming considerations: The SCUBA should
1) Be streamlined, to give minimum drag.
2) Be well balanced, automatically positioning the swimmer.
3) Be readily ballasted, with quick release for weights.
4) Have no "planning" effect.

6.8.2 Materials and components

a. Pliant parts should
1) Be of high-quality material which does not tear, abrade, or age readily.
2) Have sufficient reinforcement of stress areas.
3) Be readily patched.

b. Metal parts should
1) Be resistant to corrosion
2) Be resistant to deformation by blows and dropping.
3) Have substantial threads and connections.
4) Have standard fittings where possible.

c. Controls should
1) Have simple, positive action, with safety-lock features.
2) Be easy to identify by touch through gloves.
3) Be operated readily with cold hands or with gloves.

d. Connections should
1) Be minimum in number.
2) Have simple, quickly operated seals.
3) Have sealing surfaces protected from damage.
4) Have a low probability of leaks.
5) Tighten by hand wherever possible.

e. General: Components should
1) Have maximum accessibility of parts.
2) Be easy to maintain, repair, or replace.
3) Make full use of "unit replacement", with plentiful spares.
4) Include appropriate tools.

6.8.3 Mask considerations

a. Fit and form: The mask should
1) Be available in different sizes.
2) Be comfortable.
3) Be easily sealed against leaks.
4) Be compatible with the face seal of the suit.
5) Be easy to put on and take off.

b. Visibility: The mask should
1) Provide wide horizontal and vertical fields of vision.
2) Use clear, flat safety glass.
3) Provide for clearing condensation from the glass.

c. General: The mask should
1) Have low dead space.
2) Have a water trap.
3) Provide for ejecting water readily.
4) Permit closing the nostrils for equalizing.
5) Provide for a microphone, speaking diaphragm, or both.
6) Provide for an optional mouthpiece within the mask.

d. Special characteristics: The mask should
1) Have a faceplate which can be opened, for use when the mask is integrated into a suit.
2) Provide for breathing air at the surface.
3) Have an optional snorkel attachment.

6.8.4 Breathing system considerations

a. The breathing bag should
1) Be properly positioned hydrostatically.
2) Be big enough to accommodate extremely large tidal volumes.

b. The breathing circuit should
1) Have a positive shut-off from the mask.
2) Provide for breathing air at the surface if the mask does not.
3) Have an optional snorkel attachment if the mask does not.
4) Have readily accessible, low resistance check-valves.

c. Special characteristics: The breathing system should
1) Provide for keeping water out of the canister.
2) Provide for expelling water from the tubes.
3) Have the tubing arranged to permit full movement of the head.

6.8.5 Canister considerations

a. Size and configuration: The canister should
1) Have size compatible with desired absorbent life and moment-to-moment absorption capacity.
2) Have minimal breathing resistance from diffusers and baffles.
3) Have sufficient length to minimize blow-through.
4) Have sufficient cross-sectional area to minimize resistance.
5) Prevent collection of leakage, saliva, or condensate.

b. Filling: The canister should
1) Be readily opened.
2) Be easy to fill without excessive shaking.
3) Keep the absorbent from settling.
4) Be easy to seal, with minimum likelihood of leakage.

c: <u>Emptying</u>: The canister should
1) Be easy to empty.
2) Be easy to clean.

6.8.6 Safety devices

a. <u>Cylinder pressure</u>:
1) Rebreathing SCUBA should have a visible pressure gage or tactile pressure indicator.
2) Open-circuit SCUBA must have a reliable low-pressure warning device.

b. <u>Regulator pressure</u>: Systems should
1) Provide warning of regulator failure.
2) Have "fail-safe" features.
3) Provide a mandatory by-pass in steady-flow and demand devices.

c. <u>Flow</u>: Systems should
1) Provide warning of low flow in steady-flow devices.
2) Provide warning of high flow in oxygen metering devices.

d. <u>Flotation arrangements</u> should
1) Be integral with the apparatus.
2) Support the man properly at the surface.

6.8.7 Special characteristics

a. Some types of military use may
1) Require special acoustic properties.
2) Require special magnetic properties.

b. Use with propulsion devices may
1) Require special design of SCUBA.
2) Require special location of SCUBA components.

6.8.8 Versatility

Many parts can be used in common by more than one type of apparatus. Maximum versatility will be attained in a single basic unit provided with minimal number of conversion parts for air-hose supply, self-contained air supply, oxygen supply, or mixed-gas supply.

CHAPTER 6

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CHAPTER 7

CONTENTS

CHAPTER 7

DECOMPRESSION IN AIR DIVING WITH SELF-CONTAINED EQUIPMENT

7.1 FUNDAMENTALS

The necessity for decompression arises from exposure to increased partial pressures of nitrogen. Breathing air at a given depth exposes the body to the same nitrogen partial pressure regardless of the equipment which supplies the air. Therefore, a man who makes a dive breathing air from an open-circuit SCUBA will require the same amount of decompression as a man who makes an identical dive in suit and helmet. Plainly, then, there are no basic differences between decompression in conventional diving and decompression in self-contained diving. However, the latter does present a number of special problems.

7.1.1 Attitudes

Responsible personnel may encounter a tendency among some SCUBA divers to view the entire problem of decompression lightly. This tendency is unfortunate because it makes all of the other problems of SCUBA decompression doubly difficult to handle.

Much of this indifference about decompression stems from the widespread belief that the Navy Standard Decompression Table is so conservative and excessively safe that it can be largely ignored. This belief may be reinforced by the exploits of a few divers who violate the table with deliberate intent and apparently with monotonous impunity. But the truth of the matter is that the table is not excessively safe even though it can be violated occasionally (5.9.0).

7.1.2 Decompression sickness

One of the most striking things about decompression sickness is the great variability of the amount of decompression time required to prevent it. Consequently, decompression which is sufficient to keep the incidence of bends at less than 5 percent of all dives will inevitably be more than adequate for the majority of dives. But since a diver can never know whether he needs this "excess" for a given dive, he must follow the table in order to avoid undue and unpredictable risk. No alternative tables exist for selection of "odds". Cases of bends which do occur with proper decompression are by no means confined to unfit divers or unfavorable circumstances.

7.1.3 Safety factors

The low incidence of decompression sickness in Navy diving as a whole is frequently cited as a sign of great conservation in the table. This is a misrepresentation of the facts because it fails to take into account the fact that usual diving practice applies extraneous safety factors. A diver rarely makes a dive to the exact depth or time which the table specifies. Since interpolation is not permitted (DM 833 (2)/4), he then decompresses for the next increment of depth, time or both. In unfavorable circumstances he often adds an even greater factor of safety by decompressing for the increment beyond the next (DM 833 (2)/11). Note, however, that a considerable number of cases occur in spite of these factors, and that SCUBA decompression will often necessitate the omission of such protective extras (7.2.0).

The SCUBA diver ought to realize that the table could not very well be, was not intended to be, and is not 100% safe. He should appreciate the fact that he can achieve reasonable safety in the total picture only be accepting some apparent restrictions. He should be impressed with the fact that the absence of treatment facilities in many SCUBA operations puts an additional value on caution. Serious cases of bends (I A-6A) are not frequent, but they can occur even after ordinary dives with proper decompression.

7.2 PRACTICAL DIFFICULTIES

Far from providing any excuse for laxity in decompression, the use of SCUBA confronts the diver with several pitfalls and difficulties which the conventional diver does not share.

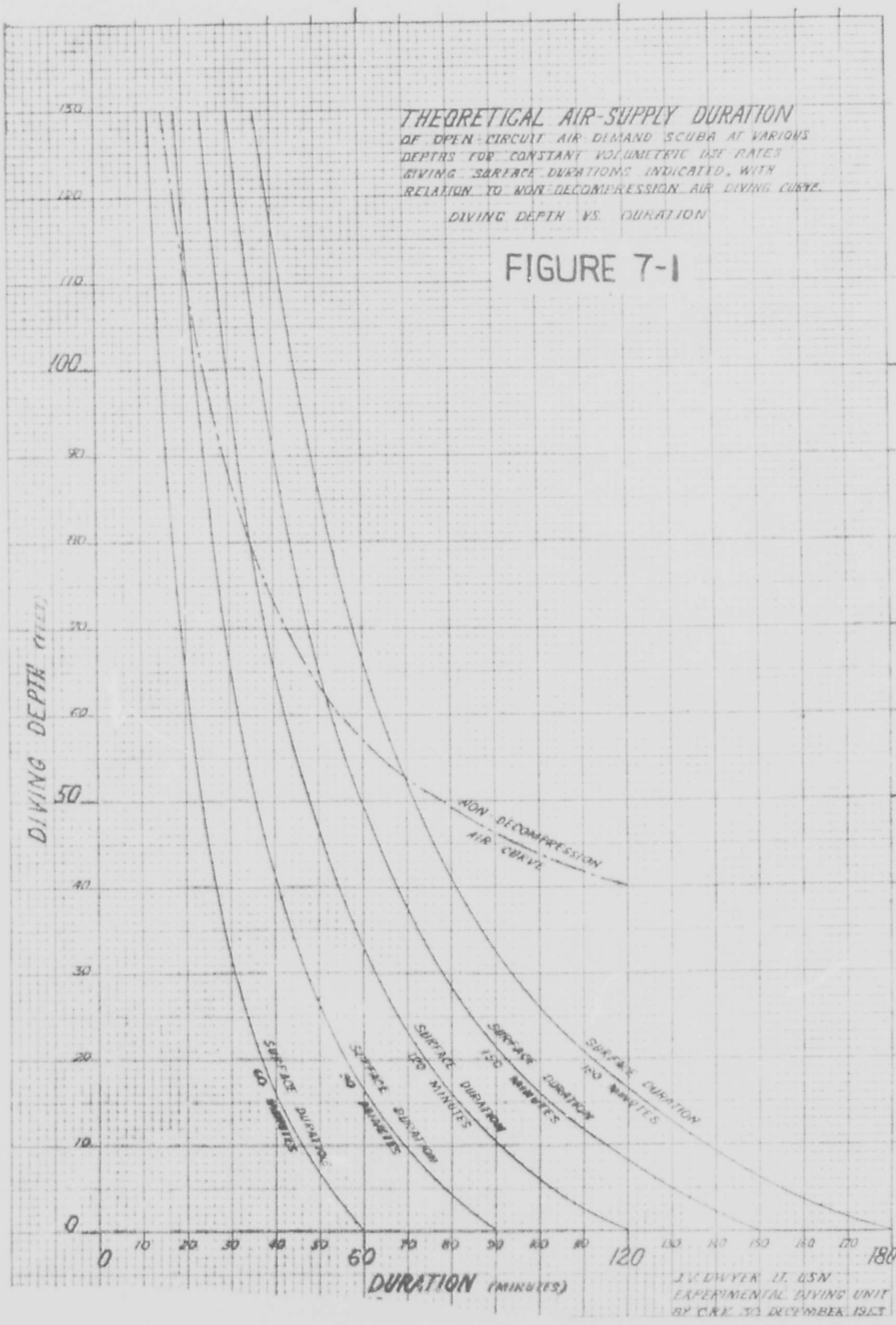
7.2.1 Decompression

The air-hose diver has an essentially limitless supply of air so long as the compressor is adequate for his depth. No matter how long he spends on the bottom, decompression is relatively simple, although it may be tedious. He has the following advantages:

1) His tender usually knows how deep he is to the nearest ten feet.
2) His tender can determine his bottom time to the exact second.
3) His tender can stop him off for adequate and proper decompression.
4) His air supply is limited.

Because his tenders are constantly in control of the dive, and are doing all of the thinking necessary for his safety from decompression sickness, the air-hose diver is free to devote all his attention to completion of his job on the bottom.

The air-SCUBA is not nearly so well off. His air supply restricts not only his bottom time in itself, but also the decompression time he can incur safely. Decompression itself may be tedious anc


THEORETICAL AIR-SUPPLY DURATION
OF OPEN-CIRCUIT AIR DEMAND SCUBA AT VARIOUS DEPTHS FOR CONSTANT VOLUMETRIC USE-RATES GIVING SURFACE DURATIONS INDICATED, WITH RELATION TO NON-DECOMPRESSION AIR DIVING CURVE.
DIVING DEPTH VS. DURATION
FIGURE 7-1
DIVING DEPTH (FEET)
DURATION (MINUTES)
NON-DECOMPRESSION AIR CURVE
SURFACE DURATION 60 MINUTES
SURFACE DURATION 90 MINUTES
SURFACE DURATION 120 MINUTES
SURFACE DURATION 150 MINUTES
SURFACE DURATION 180 MINUTES
J.V. DWYER LT. USN
EXPERIMENTAL DIVING UNIT
BY C.R.K. 30 DECEMBER 1953

7-1 THEORETICAL AIR-SUPPLY DURATION 7.2.2

The five duration curves shown the theoretical reduction in air-supply duration for open-circuit air-demand SCUBA at depth. Each solid line represents some constant volumetric demand rate of breathing which will give the apparatus the surface durations indicated. The broken line shows the zero-decompression limit and the relationship which it bears to the duration curves.

uncomfortable for the hose man, but it rarely presents a serious problem. With SCUBA, lack of preparations or a small error may make it impossible for the diver to get proper decompression at all.

The air-hose diver does not have to be concerned about decompression timekeeping or selection of the proper table. All of this is his tender's job, and the tender also sees that the diver stops at the proper depths for the right times on ascent. Except in very simple situations or when elaborate plans and arrangements have been made, the SCUBA diver may have to do much of this himself, and he is rarely in a position to do it well. In some situations he may find himself completely on his own with no idea how much decompression he requires.

7.2.2 Duration of air supply in air demand SCUBA

The available diving time with a given air supply depends on two factors: the quantity of air carried and the rate of consumption. The quantity is easily determined from the volume, number, and charging pressure of the cylinders. The rate of consumption depends upon the diver's respiratory minute volume (RMV) and upon the depth. The RMV is tremendously variable, being dependent upon a considerable number of factors (6.3.0). The depth itself may have some influence upon the RMV, but its major effect is to increase consumption in direct proportion to the absolute pressure. Figure 7-1 shows the theoretical effect of depth on air supply durations, computed according to Boyle's Law. For a given surface duration the figure shows the reduction of duration with depth. Assuming an air consumption rate of one cubic foot per minute, the surface durations shown correspond to prevalent types of air demand SCUBA approximately as follows:

60 minutes - single-cylinder model charged to 2000 psi.
120 minutes - double-cylinder model charged to 2000 psi.
180 minutes - triple-cylinder model charged to 3000 psi.

Figure 7-1 also shows the relation of these duration curves to the zero-decompression curve for air diving (7.5.1, 9.1.3). The most striking features of this relation are that the single-cylinder SCUBA does not allow diving into the decompression range until well beyond 110 feet, that the two-cylinder SCUBA allows diving into the decompression range beyond 80 feet, and that the three-cylinder SCUBA allows diving into the decompression range beyond about 50 feet. It can be seen that exhausting the air supply is no guarantee against requiring decompression. Even a single-cylinder unit can take the diver into the decompression range if he goes deep enough. Anything which causes the air supply to last longer than expected will increase the possibility of crossing the zero-decompression line. In practice the diver should have a good idea of his own average air-use rate. He must also keep accurate track of both depth and time on every dive which could conceivably run into the necessity for decompression. If he does not, he may easily place himself in need of prolonged stage decompression only to find that he has exhausted his air supply. Although the SCUBA diver can decompress adequately with special techniques, he may not have those techniques available. In any case, he runs a greater risk of decompression sickness than the air-hose diver because of the uncertainties of diving depth, bottom time, and stop depths.

7.3 AIR SCUBA DECOMPRESSION

The arrangements, techniques, and rules for SCUBA decompression are relatively simple if the practical difficulties are overcome.

7.3.1 Arrangements

A few simple provisions can increase the ease and safety of decompression in SCUBA diving very markedly.

1) Furnish a stage of some sort. Little more than a weighted line with a knot to mark the depth is actually required, but a simple "swing" upon which the diver can rest can be rigged even from a rubber boat. Since almost all decompression in SCUBA diving will take place at the 10-foot stop, a simple rest arrangement at that depth and a marker at 20 feet should suffice.

2) Always arrange an auxiliary air supply of some kind whenever even the possibility of decompression exists. This may be no more than a spare breathing unit, brought to the diver or secured at the stop, to which the man can switch when he exhausts his own supply. A mask or demand unit supplied by hose from the surface will often be more convenient. Either a small compressor or an adequate number of fairly large cylinders can supply the air in this case. The diver should never be obliged to surface to secure another SCUBA in the midst of his decompression, but he can do so in an emergency, keeping the surface interval to the barest minimum.

3) Set up routine procedures for various types of circumstances. Have surface personnel maintain primary control at all times. Provide some form of communication between the diver and the surface; a plastic slate on a line will suffice. Particularly provide the diver with a way to check with "topside" before he passes 20 feet during ascent, so that he can ascertain what decompression he requires, if any.

4) Surface decompression using oxygen (IA-3B2) can be an extremely valuable procedure for the SCUBA diver, and it should be used if the essential recompression chamber is available.

5) Keep rules for unusual circumstances in mind. For example: if a diver who requires decompression surfaces without making any stops, he should go at once to the first stop prescribed by the table and stay there for twice the specified time. If the first stop is deeper than 30 feet, an extremely unusual situation in this type of diving, he should double the 30-foot stop. If a diver surfaces in the midst of decompression (as to change SCUBAs), he should re-descend, complete the interrupted stop, repeat the same stop in its entirety with the remainder of decompression in a normal manner.

7.3.2 Techniques

There are four general methods of giving a SCUBA diver decompression. They are as follows:

1) An air hose supply from the surface can furnish air either for a mask or for a demand unit to which the diver may shift at the first decompression stop to take his entire decompression.

2) A second SCUBA, lowered to the proper depth, will allow the diver to shift without surfacing. If circumstances force him to surface for the second SCUBA, he should keep the surface interval to the barest minimum, returning to the proper depth as soon as possible.

3) Chamber decompression may subsitute for water decompression in part or in whole.

4) The original SCUBA must provide as much of the decompression as possible if no other method is available.

7.3.3 Rules

Circumstances may dictate any combination of the foregoing techniques. The following rules apply regardless of which method or combination is used.

1) Use the Standard Air Table for decompression while breathing air only (original SCUBA, second SCUBA, air hose supply from surface, or chamber without oxygen).

2) Use the Oxygen Surface Decompression Table if oxygen is available in a chamber.

3) If the diver surfaces before starting decompression on air, give him the standard decompression required and double his time at the first stop or at 30 feet, whichever is shallower.

4) If the diver surfaces after starting decompression on air, complete the interrupted stop, repeat that same stop, and complete the decompression on the standard table.

7.4 SPECIAL DECOMPRESSION PROBLEMS IN SCUBA DIVING

The foregoing discussion applies mainly to the type of self-contained diving which closely resembles conventional diving; descending to a given depth, staying a certain bottom time, and ascending to the surface or to the first decompression stop. When SCUBA diving diverges from this routine, decompression may present problems which are very difficult to solve with the present tables and rules, designed as they were for air-hose diving.

7.4.1 SCUBA decompression tables

The presence of large, irregular gaps between specified bottom times in the Standard Air Decompression Table works a severe hardship on the SCUBA diver. A large number or useful dives which are currently not feasible would become practical if interpolated values were available. At the present time a 15-minute dive to 130 feet is possible with most air-demand SCUBA because the total decompression time required is only about 5 minutes (ascent at 25 feet a minute). However, if the table is followed to the letter, a 16-minute dive to the same depth might be impossible because the diver would have to spend about 32 minutes in decompression. His air supply may very well be inadequate for this.

One way to relieve the situation is simply to compute and test a comparable table for 10-minute or shorter increments of time at the various depths. Necessity may ultimately produce such a table. For interim use, the rules and tables presented elsewhere (7.6.0) may help.

There is another promising approach: to present a table based on set increments of decompression time at the 10-foot stop. When the diver knows his probable depth in advance and knows his approximate air-use rate for that depth, such a table would permit him to determine his maximum permissable bottom time for a given increment of decompression. Spending four minutes at the 10-foot stop, for example, would permit a significant extension of bottom time at most depths. A table of this kind has been computed but has yet to be validated (9.1.3).

7.4.2 Repetitive dives

The Diving Manual states that a diver should not, except in emergencies, make more than one dive in 12 hours. Under normal circumstances, conventional diving practice does not permit more than one dive in 24 hours. When more than one dive must be made within 12 hours, the Manual specifies the following rules: To select the proper decompression schedule, take the depth of the latest dive and use the combined time on bottom (descent time plus actual bottom time) for all of the exposures. Under most conditions encountered in air-hose diving, this rule is safe and satisfactory. It cannot, of course, cover an indefinite series of such dives.

Many of the operations suitable for air-demand SCUBA call for repetitive dives separated by intervals ranging from minutes to hours. Under such conditions the rule will sometimes be prohibitively oversafe. However, especially when a relatively deep dive is followed shortly be a shallower one having much longer allowable time, the rule will not always be safe enough. To cover all brief-interval repetitive dives, safety demands use of the combined times and the depth of the deepest dive. Where significant depths are involved, repetitive dives will entail either unfortunate restrictions of time or a relatively high incidence of decompression sickness, or possibly both. Tables applicable to repetitive dives have been developed in France. These have greater flexibility than our present rule and, if proved safe, will represent a more practical approach to the problem (7a).

7.4.3 Multilevel dives

A multilevel dive can be defined as one in which the diver remains at different depths for varying times during the course of the dive. This is a very probable form of exposure for any dive involving free swimming, and it is even more likely to occur in the use of SCUBA than is the repetitive dive. At the present time there is no satisfactory method to determine exactly when a multilevel dive exceeds the zero-decompression limit, or just how much decompression it finally requires. The only safe rule available is to decompress for the entire time of exposure and for the greatest depth reached. This method of handling the problem will often be prohibitively restrictive - especially in cases where a deep descent occurs in the course of a predominantly shallow dive. Some modification such as counting only time spent deeper than 30 feet would help significantly but it would also greatly complicate the problems of timekeeping.

There is a concept that staying at a moderate depth during the latter part of a dive will automatically provide decompression for an earlier period at a greater depth. This concept can be seriously misleading, because the body may still be taking up nitrogen at the shallower depth instead of losing it.

The infinite number of combinations of depths and times possible in such dives renders the development of tables to cover them quite out of the question. A more hopeful possibility is an automatic device which can take the depth and duration of exposure into account and yield applicable decompression data. Munk and Groves (7b) have described the theoretical background of such a device and have presented plans for an analog computer which should function as a "decompression gauge". This has very interesting possibilities and may well represent the only means of solving the problem of decompression for multilevel dives. It would, of course, be useful in other connections.

7.5 CURRENT STATUS OF SCUBA DECOMPRESSION

The difficulties inherent in providing proper decompression for dives with self-contained equipment will not prevent the use of such equipment in situations requiring decompression. Offsetting these difficulties calls for dexterous application of present information and for rapid advancement of research efforts. Medical officers will be involved in both phases of the effort. In any event, once the need for decompression arises, the complexities and risks of SCUBA diving clearly increase many-fold - often to an extent scarcely justified by the work being pursued. Responsible personnel should insist that common sense demands staying within the zero-decompression range whenever possible.

7.5.1 Present diving limits

Normal air SCUBA diving limits are established in terms of zero-decompression time and of air-supply restrictions, as shown in Table 7-1 and Figure 7-1. The zero-decompression limit is primary, but the air supply duration will often prove more restrictive, especially at shallower depths. The most vital consideration is not to incur the need for decompression and then run out of air - unless ample provisions for this eventuality have been made.

7.5.2 Surface-to-surface diving time

Applying the zero-decompression time on a surface-to-surface basis (to make it include the ascent time at 25 feet a minute) will decrease the allowable bottom time slightly, but will provide a very desirable safety margin for the deeper dives. Because of the problem of accurate timekeeping under water, this procedure is particularly recommended where surface control is not used. In any case, the rate of ascent should never exceed 25 feet a minute, since the ascent itself constitutes decompression, and the rate is an essential part of the process.

7.5.3 Factors in very deep dives

Although zero-decompression times for depths greater than 130 feet can be specified, as they are in the table for surface decompression using oxygen (IA-3B2, DM), the amount of useful working time which remains after allowance for descent (and ideally for ascent as well) becomes very small. Furthermore, the extent to which these deeper zero-decompression times have been tested may leave something to be desired. Finally, many SCUBA divers will begin to show impairment from nitrogen narcosis beyond 130 feet.

7.5.4 Normal maximum depth limit

For normal air SCUBA diving, a maximum depth limit of 130 feet for a bottom time of 15 minutes is established at the present time.

While this is not an absolute limit, those who exceed it should be prepared to justify doing so in terms of the operational necessity, the skill of the diver concerned, and the appropriateness of the arrangements to handle both the certainty of decompression and the possibility of decompression sickness (5.9.0). Not only the greater depths but even the 130-foot limit presumes a high degree of skill and experience on the part of the diver. For the vast majority of SCUBA divers, a stringent limit of about 60 feet is much more appropriate.

7.6 THUMB RULES AND EMERGENCY LIMITS

A serious practical problem is presented by the possibility of running over the zero-decompression limits unintentionally or by the necessity of making a dive beyond those limits. It maybe exceedingly difficult to derive practical decompression data for such dives from the present table (7.4.1). Furthermore, for operations which are not controlled from the surface, it is highly desirable to provide a series of easily memorized rules to approximate the standard zero-decompression limits on the safe side.

The following thumb rules and limits embody straight-line approximations to the zero-decompression curve and to the single-stage decompression time curve for 15-minute dives beyond 130 feet (Figure 7-2).

7-2 SINGLE-STAGE DECOMPRESSION CURVES 7.6.0

These curves apply only to decompression for a 15-minute dive. The standard curve is extracted directly from the U.S. Navy Standard Air Table. The emergency curve is a straight-line approximation which is easy to recall and is well on the side of safety.

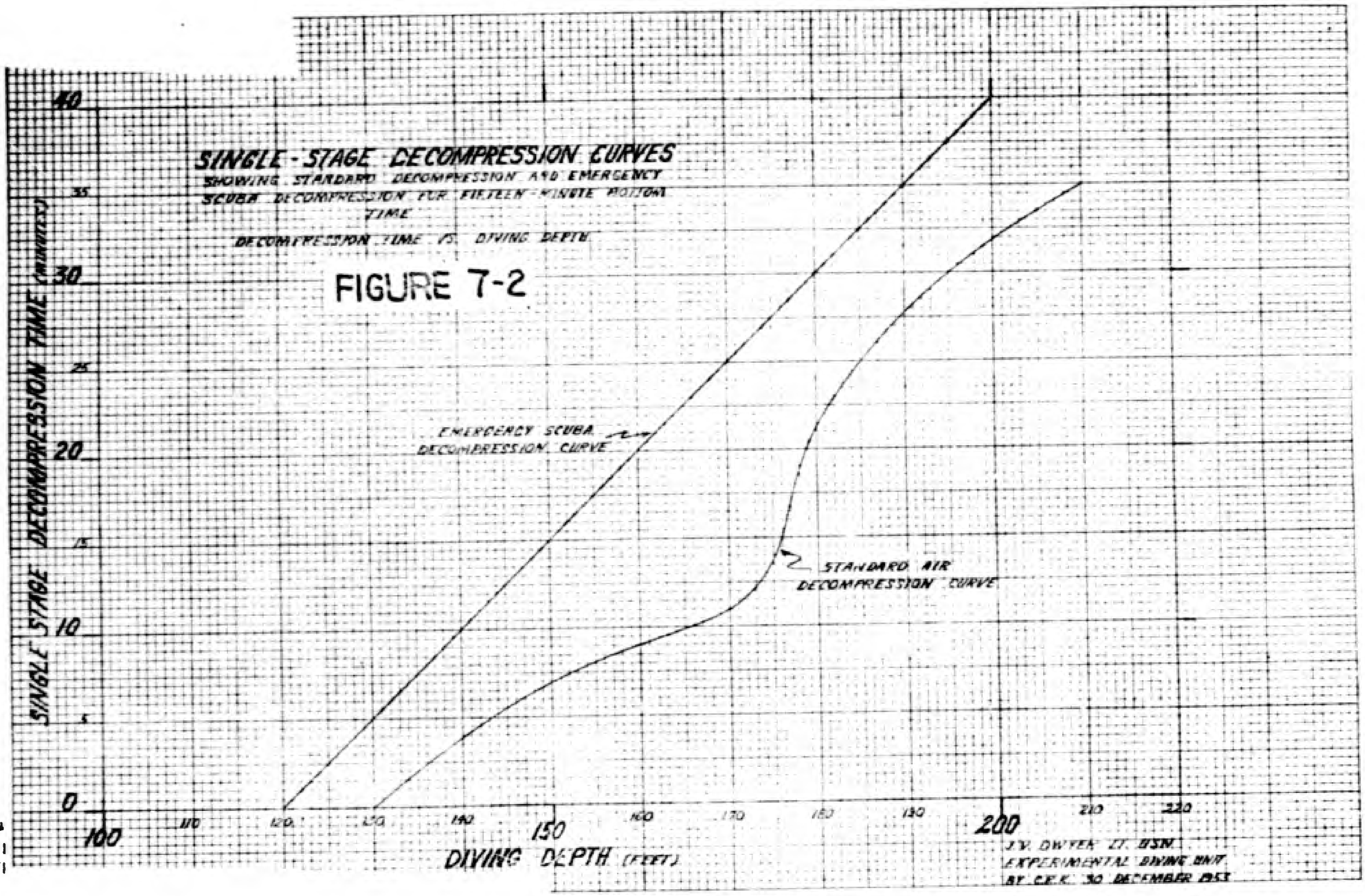

SINGLE - STAGE DECOMPRESSION CURVES
SHOWING STANDARD DECOMPRESSION AND EMERGENCY SCUBA DECOMPRESSION FOR FIFTEEN-MINUTE BOTTOM TIME
DECOMPRESSION TIME VS. DIVING DEPTH
EMERGENCY SCUBA DECOMPRESSION CURVE
STANDARD AIR DECOMPRESSION CURVE
SINGLE STAGE DECOMPRESSION TIME (MINUTES)
DIVING DEPTH (FEET)
0
5
10
15
20
25
30
35
40
100
110
120
130
140
150
160
170
180
190
200
210
220
J.V. DWYER LT. USN
EXPERIMENTAL DIVING UNIT
BY C.E.K. 30 DECEMBER 1953

FIGURE 7-2

7.6.1 Zero-decompression thumb rules

These rules yield the tabular values listed in Table 7-2. In general the values are only slightly inside the decompression curve down to 70 feet, and are right on the curve between 80 and 110 feet.

1) At depths less than 30 feet, diving time is unlimited

2) Allow 125 minutes zero decompression diving time at 30 feet, and subtract 25 minutes for every 10-foot increment to 60 feet inclusive.

3) Allow 40 minutes zero decompression diving time at 70 feet, and subtract 5 minutes for every 10-foot increment to 120 feet inclusive.

7.6.2 Emergency deep diving limits

A plot of decompression time against depth for 15-minute dives between 310 feet and 210 feet with standard air decompression gives the curve shown in Figure 7-2. The straight line drawn from zero decompression time at 120 feet to 40 minutes decompression time at 200 feet lies on the safe side of the standard curve at all times. This straight line forms the basis of Table 7-3, which applies to any air demand SCUBA giving at least 120 minutes duration at the surface for the same work conditions as at the depth. The table is meant for use when auxiliary decompression is not available and all decompression must be taken on the original SCUBA. The decreasing bottom times beyond 140 feet reflect the conservation of air supply necessary to complete the requiring decompression at the 10-foot stop.

When an auxiliary air supply is provided for decompression, the diver may simply terminate his dive when he reaches low air-supply warning, ascend at 25 feet a minute to his first decompression stop, and take decompression according to the standard table for whatever his depth and bottom time happened to be. In some cases, he may require stops deeper than 10 feet.

7.6.3 Emergency deep diving thumb rules

The emergency limits can be embodied in a set of thumb rules spelling out the entire dive.

1) Beyond 120 feet limit diving time to 15 minutes, and beyond 140 feet decrease by 2 minutes for each 10 feet if auxiliary decompression is not available.

2) At the end of this time, ascend at the rate of 25 feet a minute or less.

3) Stop at the 10-foot depth for decompression.

4) Spend 5 minutes there for every 10-foot increment of diving depth beyond 120 feet, to 200 feet inclusive.

Although this last rule provides somewhat more than "adequate" decompression, such a provision is unavoidable in a simple rule that is on the safe side at all points. The primary intent of all these rules is to provide handy memory aid for emergency use in the absence of more specific data.

7.7 PROSPECTS

Considerable progress in SCUBA decompression and related matters will undoubtedly occur in the next few years. A number of probabilities can be mentioned.

7.7.1 Air supply duration

There is a practical limit to the size of cylinders for SCUBA. Present two-cylinder commercial equipment uses cylinders having internal volumes ranging from 650 to 850 cubic inches. The latter size is very near the practical limit. However, the present upper limit of 2150-psi charging pressure is already being broken by stronger cylinders. Research and development are now aimed at 750 cubic-inch cylinders which can be charged to 3000 psi. The resultant increase in air supply duration will greatly improve operational capability both in and out of the decompression range.

7.7.2 SCUBA decompression tables

More readily-used forms of decompression data are necessary, and undoubtedly will be forthcoming. Computation and testing will cover zero-decompression times, exposure times for set increments of decompression, and various useful interpolations.

7.7.3 Special SCUBA decompression problems

More adequate methods of dealing with repetitive dives will probably be developed. A successful "decompression gauge" can greatly simplify both repetitive and multilevel diving. Finally, wider practical applications of mixed gas diving (9.0.0) may greatly modify the decompression problem itself.

7.7.4 Inadequate tables

A strong word of caution is in order concerning some possible developments. Many individuals will be tempted to make interpolations and adaptations of the decompression table, or similar efforts to produce decompression data for various purposes. In many cases, fallacious ideas about the over-safety of the table will influence the results. Some individuals will have no hesitancy in publishing such "aids" without having tested them thoroughly or at all. At the present time, it may be said almost categorically that no organization outside of the Navy is set up to perform appropriate tests of this sort. A few ill-controlled random dives can "prove" almost anything without furnishing any indication of actual safety. View decompression information from sources other than the Navy with a high index of suspicion unless it is clearly shown to be on the safe side of known data or to have received adequate tests.

TABLE 7-1

ZERO-DECOMPRESSION LIMITS

at various depths, showing allowable diving times which permit surfacing directly at 25 feet a minute with no decompression stops

DEPTH feet	TIME minutes	DEPTH feet	TIME minutes
40	120	90	30
50	78	100	25
60	55	110	20
70	43	120	18
80	35	130	15

TABLE 7-2

ZERO-DECOMPRESSION LIMIT APPROXIMATIONS

at various depths, showing thumb-rule diving times which permit surfacing directly at 25 feet a minute with no decompression stops (compare Table 7-1)

DEPTH feet	TIME minutes	DEPTH feet	TIME minutes
10	-	70	40
20	-	80	35
30	125	90	30
40	100	100	25
50	75	110	20
60	50	120	15

TABLE 7-3

EMERGENCY DEEP DIVING LIMITS

for nominal 15-minute dives, showing thumb-rule decompression required and corresponding maximum theoretical bottom time (including descent time) which will permit completing that decompression on the original SCUBA. Applicable to open-circuit air-demand SCUBA with surface duration of at least 120 minutes (see text)

DEPTH feet	BOTTOM TIME minutes	ASCENT TIME minutes	DECOMPRESSION minutes	TOTAL TIME minutes
120	15	5	0	20
130	15	6	5	26
140	15	6	10	31
150	13	6	15	34
160	11	7	20	38
170	9	7	25	41
180	7	8	30	45
190	5	8	35	48
200	3	8	40	51

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7a Tailliez, P., et al.: La Plonges en Scaphandre, Paris, Editions Elzevir, 1949

7b Groves, G., and Munk, W.: A decompression gauge for divers, Scripps Institution of Oceanography, La Jolla, Calif. Reference 53-64

CHAPTER 8

OXYGEN TOLERANCE

CONTENTS

CHAPTER 8

OXYGEN TOLERANCE

Oxygen poisoning (IA-6A11) is a serious possibility in the use of self-contained apparatus whenever a high partial pressure of oxygen may exist. Such partial pressures are encountered in many situations, and the risk of oxygen poisoning is by no means confined to the use of closed-circuit oxygen rebreathing apparatus. Oxygen limits are a major consideration in the use of mixed gas (9.1.4), including helium-mixtures (9.3.0), and oxygen poisoning is at least theoretically possible with air-demand apparatus at excessive depths.

DETERMINING FACTORS

The duration of exposure required to produce oxygen poisoning is basically a function of the partial pressure of oxygen. The higher the partial pressure, the less time is required to produce symptoms.

While the basic relationship of partial pressure and time holds for any specific situation, it is almost overshadowed by the importance of several variables which can greatly modify tolerance. Of these, physical exertion and excess carbon dioxide are the most importent. Environmental temperature, anxiety, and a number of physiological factors are also significant, but less strikingly so.

The situation is further complicated by the fact that individual variations are large and almost entirely unpredictable. Not only do individuals differ from each other, but their tolerance changes from day to day for reasons which are almost completely unknown.

8.2 EXPOSURE LIMITS

In order to make use of oxygen rebreathing equipment or of mixed-gas apparatus safe, it is clearly necessary to have accurate information about safe durations of exposure to various partial pressures of oxygen. Rules such as the 30-foot/30-minute limitation on the use of 100% oxygen in diving (IA-6A11) are not very useful even if perfectly valid. They give no information about the possibility of spending a shorter time at a deeper depth or a longer time at a shallower depth. The basic need is a limit-curve of partial pressure versus permissible exposure time, showing the limits which apply to specific diving conditions for the degree of safety desired.

8.2.1 Problems in establishing limits

Studies conducted in the past have established the significance of factors such as exertion but have not provided enough quantitative data to permit establishing such a limit curve without further investigation. In setting such a limit, all of the relevant conditions likely to be encountered deserve consideration. Individual variations in tolerance must be taken into account. The limit must be very safe because oxygen convulsions in SCUBA diving could easily end in death, but making it 100% safe for all individuals and all conditions may prove so restrictive as to be out of the question.

An ideal study of oxygen tolerance would include investigation of all significant variables, their degrees, and their combinations. A very large number of subjects would be employed to elucidate the question of individual variability, and all exposures would be carried to convulsion, which is the only unequivocal end-point of toxicity.

An ideal study should also include determination of oxygen tolerance using a variety of gas mixtures at appropriate depths, since the toxicity of oxygen may be modified by the presence of other gases. Recent studies (8a) indicate that increased nitrogen pressure can suppress the convulsive manifestations of oxygen toxicity in animals. However, later EDU studies indicate that the presence of nitrogen may decrease oxygen tolerance in man.

Change #1

8.2.2 Experimental Diving Unit Study of 1953

The Experimental Diving Unit faced the urgent necessity of establishing reasonable oxygen exposure limits, primarily for application to mixed-gas diving. Recognizing the practical impossibility of conducting an "ideal" study, the Unit attempted to plan the approach in such a way that deviations from the ideal would not introduce serious error. A detailed description of the method will not only explain what was done but will also show some of the problems which arise in conducting such studies.

1) General approach

Practical considerations such as morale eliminated unequivocal toxicity as the end-point for all exposures. Furthermore, the possibility of residual ONS damage from oxygen convulsion, while believed to be remote, could not be ignored. These facts precluded exposure at various partial pressures of oxygen until the appearance of conclusive symptoms, and subsequent derivation of limits from the actual tolerance times. It was necessary instead to establish partial-pressure time limits which would be reasonably safe and to test these limits as a working hypothesis.

2) The limit curve

Existing data provided little information about oxygen tolerance under conditions of exertion approaching those which can occur in SCUBA diving. Consequently, the proposed limit curve was a guess based to some extent upon field experience with previously established arbitrary limits. The solid line in Figure 8-1 shows the underwater working limit curve.

The limit curve, extended, reaches "zero time" at 55 feet. The proposed limit was, however, not extended beyond 45 feet-15 minutes. It was felt that accurate time-keeping would become too crucial beyond this depth and that a diver would be ill-advised to go to a depth at which he could not safely spend at least 15 minutes.

3) The test curve

Limitations of subjects and time impaired adequate consideration of the factor of individual variations. To offset this factor to some extent, the limit curve was over-tested by adding 25% to the specified times. The broken line in Figure 8-1 shows the resultant "125% test curve."

4) Physical exertion

Because time did not permit studying a range of work-rates, the work standard was set at a rate greater than a man would voluntarily sustain under diving conditions, although less than the maximum possible. Since duration of some of the runs would exceed a man's ability to continue a given type of work without excessive fatigue, three types of work - stationary swimming on the swim-ergometer (6.2.2), weight lifting, and underwater bicycling - in rotation, with brief rest periods between, allowed various sets of muscles to sustain a high overall exertion. To permit continued exertion in the presence of increasing fatigue, the rate of work also decreased somewhat with time.

5) Breathing arrangements

The subjects breathed cylinder oxygen (averaging about 99.5% purity) throughout the runs. The possibility of deriving protection from nitrogen was not studied. If that effect is a reality in man under these conditions, it will provide a safety factor of undetermined magnitude. The oxygen was administered by continuous flow through a facemask of the type used with the lightweight diving outfit, so the possibility of carbon dioxide accumulation through rebreathing or dead space was almost entirely eliminated. Since all studies were conducted underwater in the pressure tanks, there was no possibility of dilution of the oxygen by inward leakage of air. The depth-pressure determinations were referred, by the pneumofathometer principle (DM) to the subject's suprasternal notch, so the pressure could be maintained carefully at the specified level in spite of the subject's changes in position.

6) Conditions and precautions

The water temperature was maintained at a level which was comfortable for the subject, around 80° F.

The anxiety factor could not be controlled. Since convulsions did occur in the course of the study, there was considerable apprehension among the subjects. This was allayed only partially by the presence of two or three tenders, including one officer, in the water with the subject observing him carefully at all times. The subjects were at liberty to stop upon the development of any symptoms which they considered indicative of the onset of toxicity and were stopped by the tenders on appearance of any significant sign of toxicity.

All subjects and "baseline" electroencephalograms before the beginning of the study, and tracings were obtained within a few hours after convulsions when these occurred. Beyond this, no collateral studies were conducted.

7) Results

The results of the limit study are presented in Table 8-1 which shows the number or runs made at each depth and the symptoms which were encountered. A total of 51 runs were made by 19 subjects. It is impossible to assess with assurance symptoms other than convulsion or gross generalized twitching. The instances of nausea or nausea and vomiting occurred in runs made not long after eating rather heavy meals.

Neither of the two subjects who experienced convulsions had significant warning signs prior to onset.

Note that no unequivocal symptoms occurred within the area bounded by the proposed limit curve. The distribution of definite symptoms as related to depth suggests that the curve becomes considerably safer toward the surface and may be unnecessarily safe in the shallower range. However, the highest average work-rates were imposed in the shorter, deeper runs as a result of the rotation and gradual reduction of work. So the apparent increase in safety may be to some extent an artifact. Nevertheless, it is probable that there is a depth between the surface and 20 feet above which the central nervous system manifestations of oxygen poisoning do not occur regardless of duration of exposure.

8) Conclusions

Determination of the true shape of the tolerance curve must await a more ideal study. Lacking this, the proposed limit curve was accepted for tentative use in setting the parameters of nitrogen-oxygen diving. It is believed to be safe for the vast majority of individuals during vigorous exertion under conditions similar to those of the tests, but the influence of conditions not studied, such as various degrees of carbon dioxide excess, cannot be estimated.

Although the limit curve was investigated for application to mixed-gas diving, it should also be applicable to the use of closed-circuit oxygen apparatus. In this connection, however, strong words of caution are in order. The "depth in feet" scale presented in Figure 8-1 should not be taken literally for such use. In using 100% oxygen, a small error in depth measurement can make such a large difference in the safe time that it would be extremely foolish and dangerous to apply the limit literally. For diving on 100% oxygen, Table 8-2 gives the depth-time limits which should be followed. These limits are inside the limit curve of Figure 8-1 by a reasonable safety margin to account for depth errors.

8.3 IMPORTANCE OF CARBON DIOXIDE AND EXERTION

The fact that excesses of carbon dioxide will accelerate the onset of oxygen poisoning has been recognized for some time. As stated, no attempt was made to investigate the influence of carbon dioxide in the limit-curve study, and it must be assumed that a significant excess of carbon dioxide in the breathing system would render the limit curve unsafe. One cannot, furthermore, be at all sure that the presence of an excess of this gas will be detected by the diver (6.6.4).

The vagaries of respiratory responses to carbon dioxide in different individuals have been mentioned (6.6.2). The work of Lambertsen and his associates (8b) suggests that a man's oxygen tolerance, at least at rest, may be linked to his respiratory responsiveness to carbon dioxide. The effect in oxygen poisoning, have yet to receive thorough investigation. Some of the individual differences in oxygen tolerance can conceivably be explained on the basis of respiratory responses to carbon dioxide exposure and to exercise. If so, it might be possible to devise an oxygen tolerance test which would have greater applicability to the oxygen problems in SCUBA than does the present test. Tolerance at rest with no excess of carbon dioxide may not be a valid indication of normal oxygen tolerance while using self-contained gear. Some individuals may show unusual sensitivity only during exertion, for example.

8.4 AVOIDANCE OF OXYGEN POISONING

At the present, no sure method of forestalling oxygen poisoning can be suggested beyond avoiding excessive exposure to high partial pressures of oxygen.

The observation that brief intermittent periods of air breathing definitely prolongs tolerance time is currently receiving increased attention and may have considerable significance.

The hope of discovering an "antidote", such as a drug which would increase oxygen tolerance, should not be abandoned. Substances studies to date have not been very promising: most of those which provided definite protection also had prohibitive side actions such as general depression. However, even in the field of anti-epileptic drugs - which may or may not be the right place to look - there are many new compounds which have never been studied against oxygen. Even a small degree of reliable protection without undesirable side-effects might permit shifting the limit curve, thereby increasing the benefits gained from the use of gas mixtures as well as increasing the range of usefulness of closed-circuit oxygen gear. Finding effective means of protection may have to await elucidation of the basic mechanism of oxygen poisoning.

An individual who experiences one of the minor symptoms of oxygen poisoning (IA-6A6) may be able to take steps to lower the oxygen partial pressure in time to prevent convulsion. However, no individual should depend upon the occurrence of such symptoms for a warning of excessive exposure, because many victims go into convulsion with no prior symptoms. A drug which did no more than promote the occurrence of warning signs would have definite value.

Schaefer (8c) has reported that underwater swimmers breathing oxygen show a progressive bradycardia and that the great majority of the men who developed symptoms of oxygen poisoning showed a fixation of pulse rate - a failure of the pulse rate to change with shifts from exertion to rest - prior to onset of symptoms. The possibility of devising an oxygen toxicity warning device making use of this phenomena has been suggested. Such an instrument might be used in conjunction with "intermissions" of air-breathing mentioned above.

8.5 CONCLUSIONS

Any contribution toward increasing the allowable exposure time for high oxygen partial pressures will aid progress. This is true whether the contribution actually provides a reduction in oxygen toxicity or whether it merely provides a better delineation of the safe exposure limits.

Reduction of the inert gas partial pressure seems to be the only basic way to minimize the problem of decompression, and such a reduction invariably necessitates an increase of the oxygen partial pressure. These considerations confine the possibilities of progress to extension of exposure times for high oxygen partial pressures. The present limits may represent the ultimate: more probably they do not.

Basic and "applied" research in this field should proceed simultaneously.

TABLE 8-1

Results of Experimental Diving Unit Oxygen Tolerance Study of 1953

Depth (ft.) breathing "100%" O2	Time (min.) Limit curve	Test curve	Number of Runs	Symptoms (with time of onset) Convulsion	Prodromal or dubious
15	120	*	- -	- -	- -
20	90	113	10	0	0
25	65	81	5	0	0
30	45	57	11	0	0
35	34	43	5	1 (42 min.)	1--nausea, 28 min.#
40	25	30	13	1 (31 min.)	2--mild nausea, 17 min.# --nausea and vomitting, 18 min.#
45	15	19	5	0	2--mild tinnitus, 9 min.# --"rotating ears" 17 min.##
50	**	15	2	0	(see note)

* Not studied

** Beyond proposed depth-limit

\# Run discontinued at onset of symptoms

\## Run continued uneventfully

NOTE:

Same subject made 2 runs at 50 feet:

1) Light work -- no symptoms

2) Heavy work -- generalized muscular spasms without loss of consciousness, 14 min. 45 sec.

TABLE 8-2

DEPTH-TIME LIMITS
for diving on 100% oxygen

DEPTH feet	TIME minutes
40	15
35	20
30	30
25	45
20	65
15	90
10	120

CHAPTER 8

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4. Comroe, J.H.,Jr. and Dripps, R.D.: The physiological basis for oxygen therapy, Springfield, Ill., Charles C. Thomas Publisher, 1950.

Oxygen Limit Curve

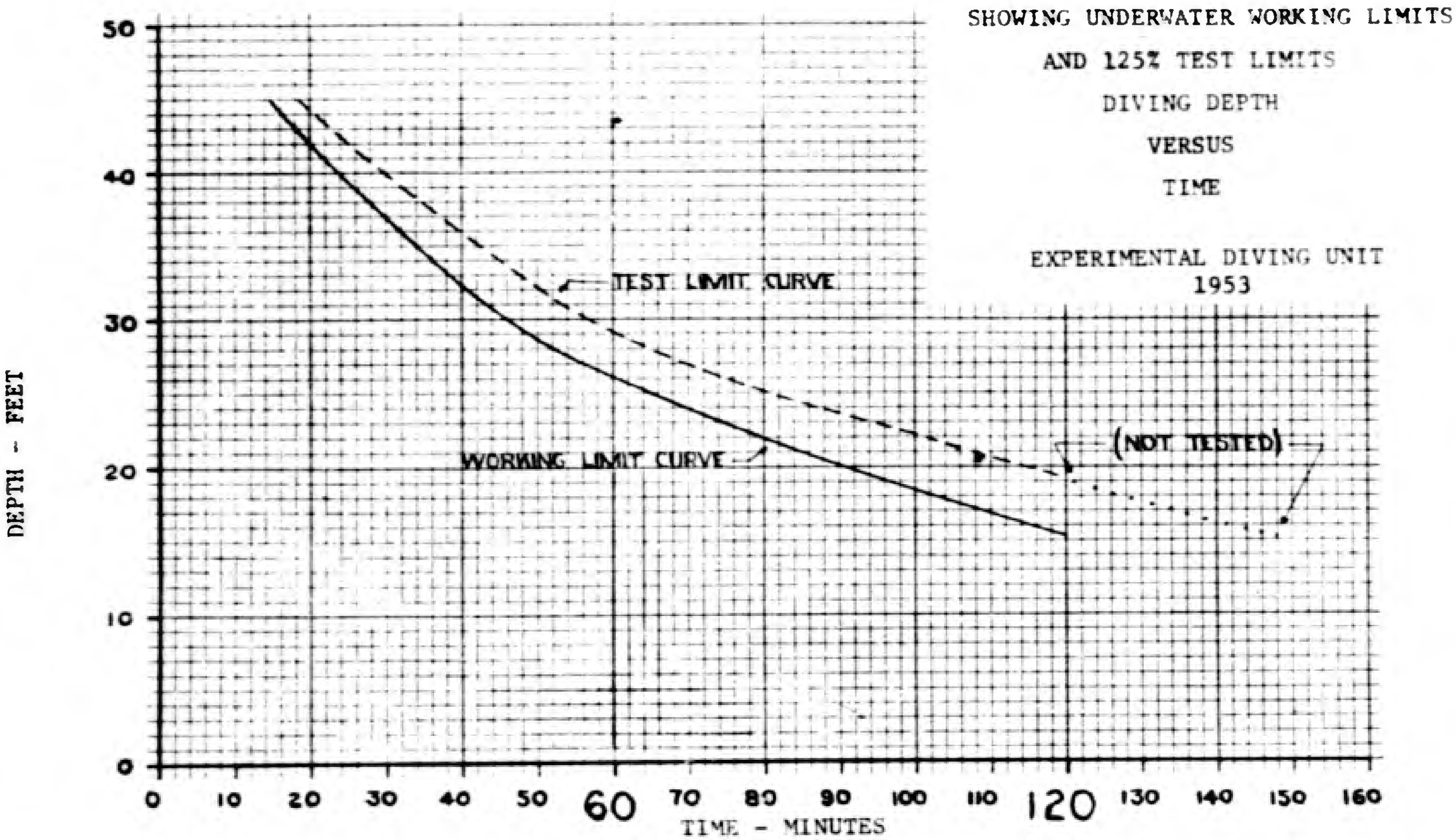


FIGURE 8-1

OXYGEN LIMIT CURVE 8.2.2

The graph shows the time-limit curve (solid line) for exposure to oxygen in working dives. The broken line shows the longer times of exposure used in testing oxygen tolerance under working conditions. Test dives were made in 5-foot increments from 20 to 45 feet. Depths shallower than 20 feet were not tested. The Experimental Diving Unit made the study in 1953.

CHAPTER 9

GAS MIXTURES IN SELF-CONTAINED DIVING

CONTENTS

SPECIAL REPORT 9-54

NOTE:

The following discussion was included in order to familiarize the reader with the theoretical background of the use of nitrogen-oxygen mixtures in diving. Experimental verification of the principles discussed has not been completed.

Operational application of these principles must be withheld until tests have been completed and appropriate tables have been promulgated through official channels.

CHAPTER 9

GAS MIXTURES IN SELF-CONTAINED DIVING

The necessity for stage decompression after exposures of substantial depth or duration is a factor which seriously limits any type of diving, but it particularly limits self-contained diving, because circumstances are frequently unfavorable for proper decompression with SCUBA. Unless special provisions are made, the limited gas supply must serve for decompression as well as for the dive itself (7.2.2).

Since the need for decompression arises from exposure to increased partial pressures of nitrogen, the necessity can be reduced by using breathing media which contain less nitrogen and more oxygen than air. This approach to the problem works well up to the point at which the partial pressure of oxygen in the mixture reaches toxic levels. However, the characteristics of available breathing apparatus and the work of mixing the gas may limit the practicability of using oxygen-rich mixtures.

While the use of gas mixtures is necessary to attain the full potentialities of SCUBA, the advantages of mixed gas cannot be realized without special types of SCUBA. Consequently, the subject of "gas mixtures in self-contained diving" has two primary aspects: 1) the principles of diving with mixed gas, and 2) the apparatus required for its use.

The following discussion is confined to nitrogen-oxygen mixtures. The use of helium-oxygen mixtures is possible, but it is less immediate significance and presents special problems. Possible applications of helium will be discussed elsewhere (9.3.0).

9.1 NITROGEN-OXYGEN MIXTURES

9.1.1 Definitions

To clarify the following discussion, it is necessary to define the special terminology used. Three different designations can be applied to a given mixture, depending upon the effects being considered. The general designation for a nitrogen-oxygen mixture is created by specifying the ratio of nitrogen percentage to oxygen percentage. It has become customary in this country to state the percentage of nitrogen first. Consequently, a mixture containing 40% nitrogen and 60% oxygen is called a 40/60 nitrogen-oxygen mixture. In practice, the explanatory term "nitrogen-oxygen" is frequently dropped when doing so will not lead to confusion. In these terms, air is a "79/21 mixture".

If the nitrogen in a mixture is the controlling factor, as in mixed-gas decompression, the mixture may be identified by its nitrogen percentage. For example, a 40/60 mixture is called a 40% nitrogen mixture. Here, the explanatory term "nitrogen" must not be dropped. Air is a "79% nitrogen mixture."

Where the oxygen in a mixture is the controlling factor, as in considering oxygen tolerance in mixed-gas diving or in dealing with oxygen consumption effects, the mixture may be identified by its oxygen percentage. A 40/60 mixture would be called a 60% oxygen mixture, and the explanatory term "oxygen" must be retained. Air is a "21% oxygen mixture."

A sharp distinction must be made between the supply mixture and the mixture which the diver is actually breathing. The two are identical only in an open-circuit SCUBA. In a rebreathing apparatus, the man's oxygen consumption reduces the oxygen level of the breathing mixture below the supply mixture oxygen percentage. In some breathing systems, the disparity may be as great as 30%. Throughout this section, the word "mixture" refers specifially to the breathing mixture except where it is qualified by the word "supply".

9.1.2 Basic principles

Consideration of nitrogen-oxygen mixtures for diving requires a careful analysis of the two main physiological effects involved. The effect of high nitrogen partial pressures must be isolated in order to correlate the decompression advantages offered by various mixtures, and the effect of high oxygen partial pressures must be isolated in order to define the limits it imposes on the use of these mixtures. For convenience, partial pressures are expressed in "feet of sea water" to permit consideration of depth and partial pressure in the same units without conversion.

9.1.3 Nitrogen effects

The U.S. Navy Standard Air Decompression Table provides a substantial body of data from which the necessary information about the decompression aspects of mixed-gas diving may be derived. In particular, at depths between 40 and 130 feet the table specifies the durations of exposure which are permissible without decompression stops on ascent, provided that the rate of ascent does not exceed 25 feet a minute. When plotted graphically, these depths and times form a "zero-decompression curve" representing the depth-time relationships for dives which do not require stage decompression. This curve, shown in Figure 9-1, represents the zero-decompression limits for the most common of all mixed gases air. Decompression requirements are assumed to be dependent only upon the duration of exposure and the partial pressure of the inert gas involved. Therefore, the zero-decompression diving time for any depth on air is also the zero-decompression exposure time for the corresponding nitrogen partial pressure. This nitrogen partial pressure for a given mixture at any specified depth can be determined by a simple mathematical transformation. This involves only conversion of the diving depth to "absolute depth" and multiplication of this value by the nitrogen percentage decimal for the mixture, as shown in the following formula:

$$N = n\ (D + 33) \qquad (9\text{-}1)$$

Where N = partial pressure of nitrogen, feet of sea water
n = decimal percentage of nitrogen in the breathing mixture (0.79 for air)
D = diving depth, feet of sea water
(33= one atmosphere, in feet of sea water)

A curve of zero-decompression diving times in terms of partial pressures of nitrogen can be obtained simply by converting the various depths of the zero-decompression curve for air into the corresponding partial pressures of nitrogen. Using 0.79 for "n" in Formula 9-1 gives the curve shown in Figure 9-2. This curve can give the zero-decompression diving time for any nitrogen-oxygen mixture, when the mixture nitrogen percentage and the depth are known. Formula 9-1 yields the value of the nitrogen partial pressure in the mixture, and the graph gives the diving time for that value.

For given mixtures, it is simpler to use depth-time curves which can be entered directly with the diving depth. A restatement of Formula 9-1 allows translation of the zero-decompression nitrogen partial pressure curve into a depth-time curve for any specific mixture.

$$D = \left(\frac{N}{n}\right) - 33 \qquad (9\text{-}2)$$

Figure 9-3 shows such curves for various nitrogen mixtures from 70% to 40%, and illustrates dramatically the decompression advantage available from the lower nitrogen mixtures.

From the standpoint of SCUBA diving, either with air or with nitrogen-oxygen mixtures, one of the most useful approaches to exposures which require decompression would be to have corresponding curves for stated decompression times - as for 4-, 8-, or 12-minute stops at the 10-foot stage. With such curves, a diver who could not expect to complete his work within the zero-decompression time could readily determine how much additional time he could gain by planning, for example, a 4-minute decompression stop (at 10 feet) on ascent. In their present form, the tables have large gaps between various "bottom times", and a man who overstays zero-decompression time even by a minute often has no safe alternative but to take prolonged decompression.

Such curves for specific amounts of decompression are not derived from the standard air table so readily as the curve for zero-decompression, because the table does not present uniform increments of bottom time or of decompression time. The derivation of diving-time curves for various increments of decompression involves construction of cross-curves of decompression time against diving time for the various stated depths. These curves must then be interpolated to yield curves of time against depth (comparable to the zero-decompression curve) for various stated decompression times. This process yields curves for air, but converting these to curves for partial pressure of nitrogen is simply a matter of computation using Formula 9-1. Further conversion to depth-time curves (similar to Figure 9-3) is accomplished by use of Formula 9-2.

The derivation of curves for 4-, 8-, and 12-minute decompression stops at the 10-foot stage has been carried out. However, the many large gaps in the standard table necessitated considerable interpolation. The interpolations were always kept on the safe side, but the entire process was liable to some margin of error. Experimental proof of these curves has not been completed at this writing, and they will not be mentioned further in this chapter. Tables derived from them will be promulagted through appropriate channels when they are ready for use.

Although the "zero decompression" curve has been presented here as a proved and accepted entity, its application must still be approached with caution (7.5.0).

9.1.4 Oxygen limits

A decrease in the nitrogen percentage means an increase in the oxygen percentage and in the corresponding oxygen partial pressure at a given depth. Since the body's reaction to increased oxygen tensions is a function of both partial pressure and time, it is vitally necessary to establish definite time limits for exposure to various partial pressures of oxygen under diving conditions. The limits must then be imposed as absolute boundaries for the depth and time of dives with the various mixtures.

Chapter 8 covers the current state of knowledge about exposure to oxygen. Figure 9-2 shows the proposed limit curve for partial pressure and time, and its relation to the nitrogen partial pressure exposure limits for zero decompression.

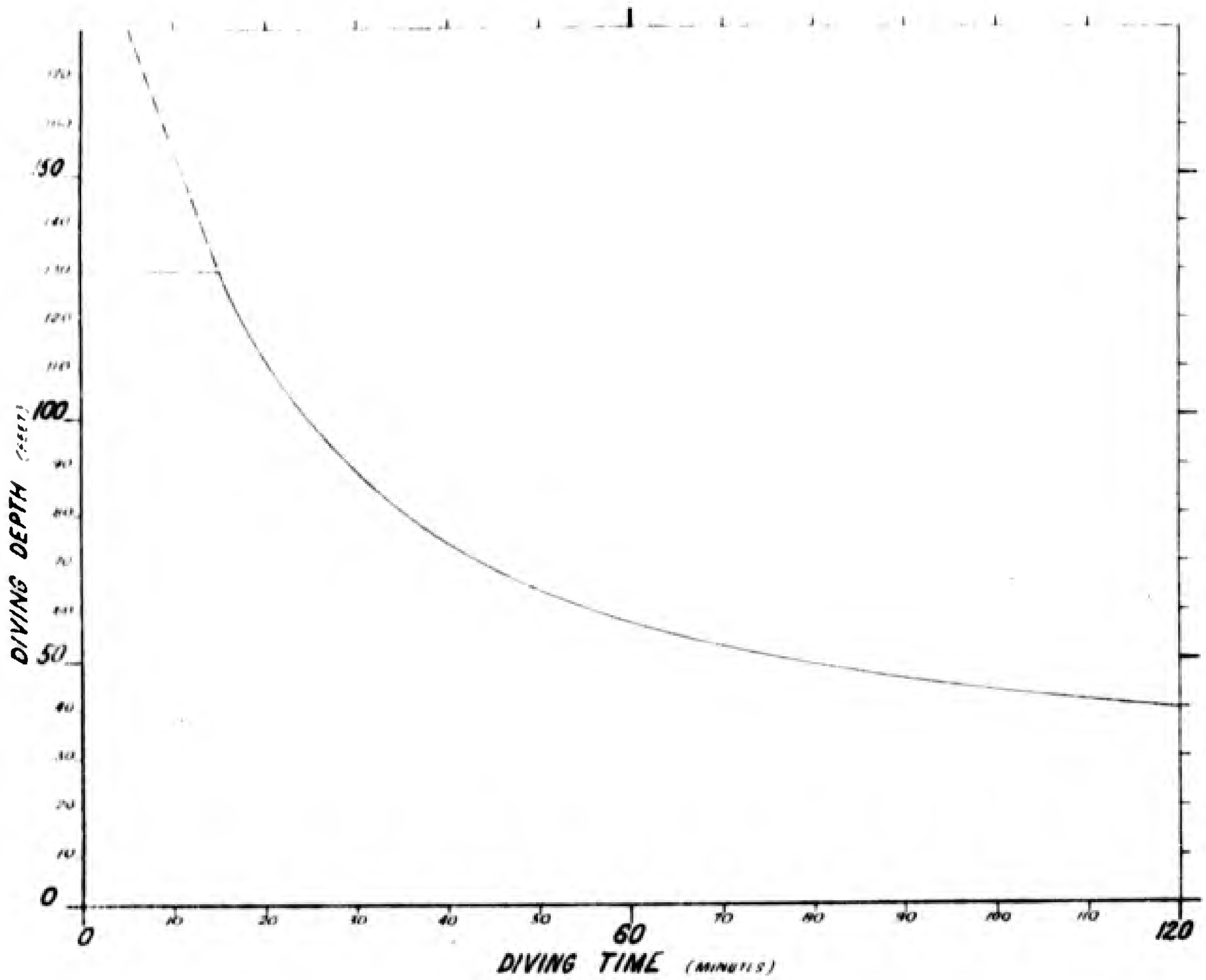


FIGURE 9-1

ZERO-DECOMPRESSION CURVE FOR AIR 9.1.3
diving depth versus diving time

The solid line shows the depth and time limits for dives which require no decompression except ascent at 25 feet a minute. The curve is derived from the U.S. Navy Standard Air Decompression Table, which cuts off at 130 feet. The broken line is an extrapolation based on the U.S. Navy Surface Decompression Table Using Oxygen. However, attempts to dive beyond 120 feet are not recommended for normal SCUBA practice, and emergency dives beyond 120 feet should always include decompression for at least 15 minutes bottom time.

9-2 PARTIAL PRESSURE EXPOSURE LIMITS 9.1.4

partial pressure versus exposure time

These curves show the time limits for exposures to various partial pressures of oxygen and nitrogen. The oxygen curve indicates the time limit for oxygen tolerance. The nitrogen curve indicates the time limit for zero decompression which corresponds to figure 9-1.

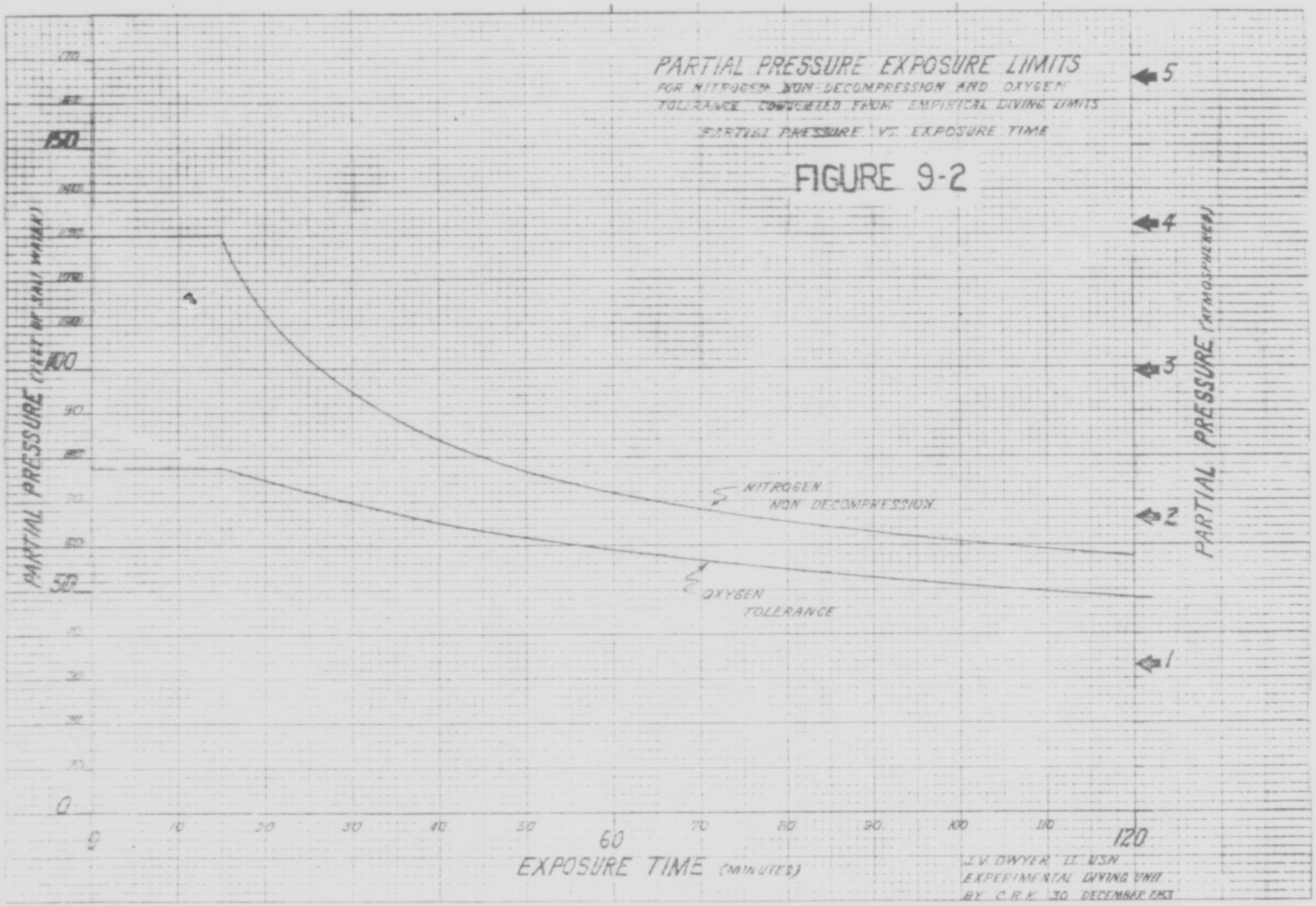

PARTIAL PRESSURE EXPOSURE LIMITS
FOR NITROGEN NON-DECOMPRESSION AND OXYGEN
TOLERANCE CONVERTED FROM EMPIRICAL DIVING LIMITS
PARTIAL PRESSURE VS. EXPOSURE TIME
PARTIAL PRESSURE (FEET OF SALT WATER)
150
100
90
60
50
0
PARTIAL PRESSURE (ATMOSPHERES)
5
4
3
2
1
NITROGEN
NON DECOMPRESSION
OXYGEN
TOLERANCE
0
10
20
30
40
50
60
70
80
90
100
110
120
EXPOSURE TIME (MINUTES)
J.V. DWYER LT. USN
EXPERIMENTAL DIVING UNIT
BY C.R.K. 30 DECEMBER

FIGURE 9-2

As in the case of decompression, oxygen tolerance time is assumed to be dependent only upon the partial pressure of the gas involved.

Translation of the partial pressure curve for oxygen into depth-time curves follows a formula similar to that for nitrogen partial pressure translation,

$$D = \frac{X}{X} - 33 \qquad (9\text{-}3)$$

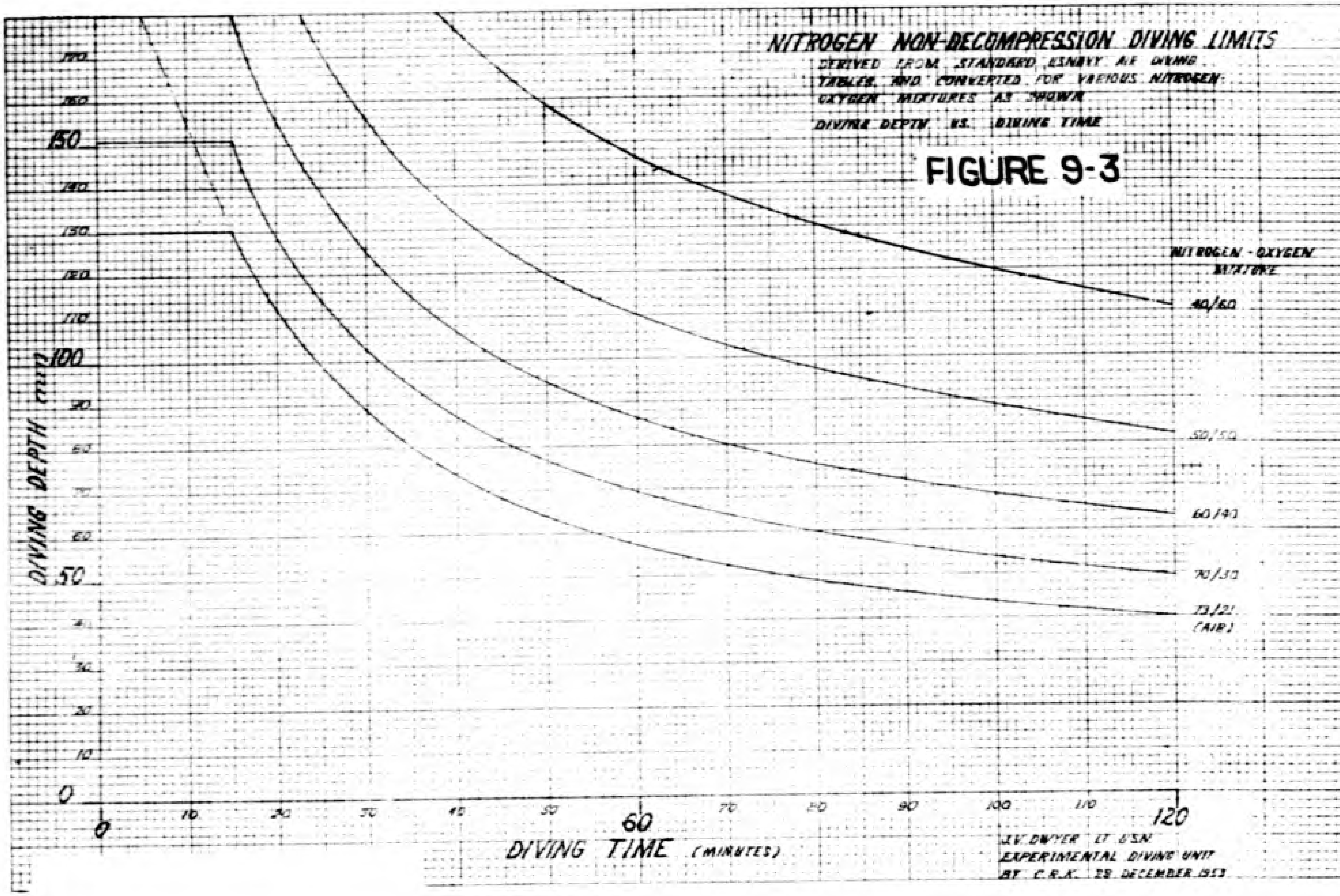
Where D = diving depth on the mixture, feet of sea water.
X = oxygen partial pressure, feet of sea water.
x = oxygen percentage decimal in the breathing mixture.

(33 = one atmosphere, in feet of sea water)

Figure 9-4 shows a family of diving-time limit curves for various oxygen mixtures.

9-3 **NITROGEN NON-DECOMPRESSION DIVING LIMITS** 9.1.3
diving depth versus diving time

These curves all derive from the zero-decompression curve for air (figure 9-1). They show the extension of diving depth-time limits available by breathing **a** mixture having **less nitrogen and more oxygen than air.** They must be used in conjunction with the oxygen tolerance diving limits of figure 9-4.


NITROGEN NON-DECOMPRESSION DIVING LIMITS
DERIVED FROM STANDARD U.S.NAVY AIR DIVING TABLES AND CONVERTED FOR VARIOUS NITROGEN-OXYGEN MIXTURES AS SHOWN
DIVING DEPTH VS. DIVING TIME
FIGURE 9-3
NITROGEN - OXYGEN MIXTURE
40/60
50/50
60/40
70/30
79/21 (AIR)
DIVING DEPTH
150
100
50
0
60
120
DIVING TIME (MINUTES)
J.V. DWYER LT USN
EXPERIMENTAL DIVING UNIT
BY C.R.K. 29 DECEMBER 1953

9-4 **OXYGEN TOLERANCE DIVING LIMITS** 9.1.4
diving depth versus diving time

These curves all derive from the empirical 100% oxygen tolerance curve established by Experimental Diving Unit study of 1953. They show the marked decrease of depth-time limits caused by enriching breathing mixtures with oxygen.

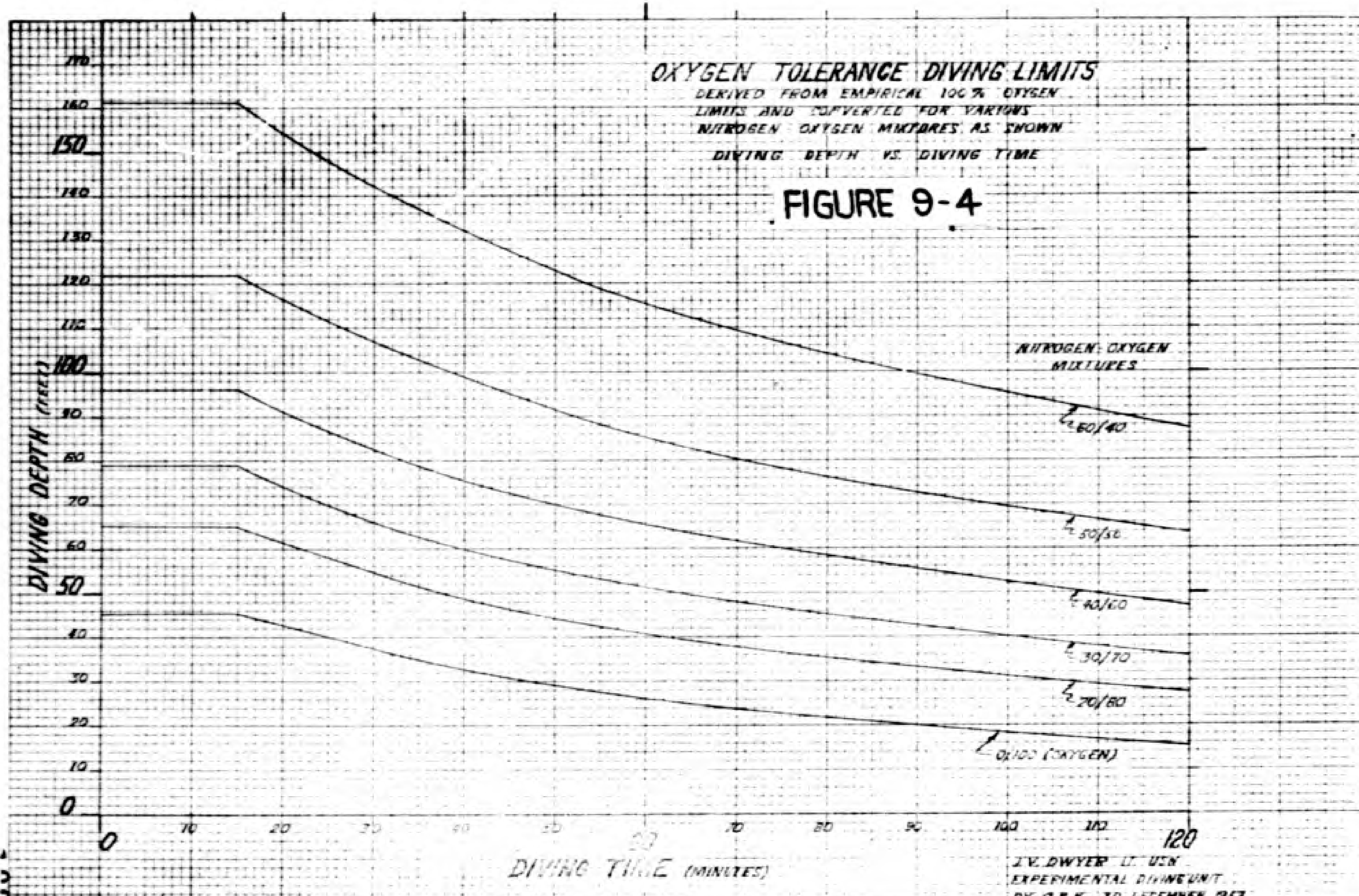
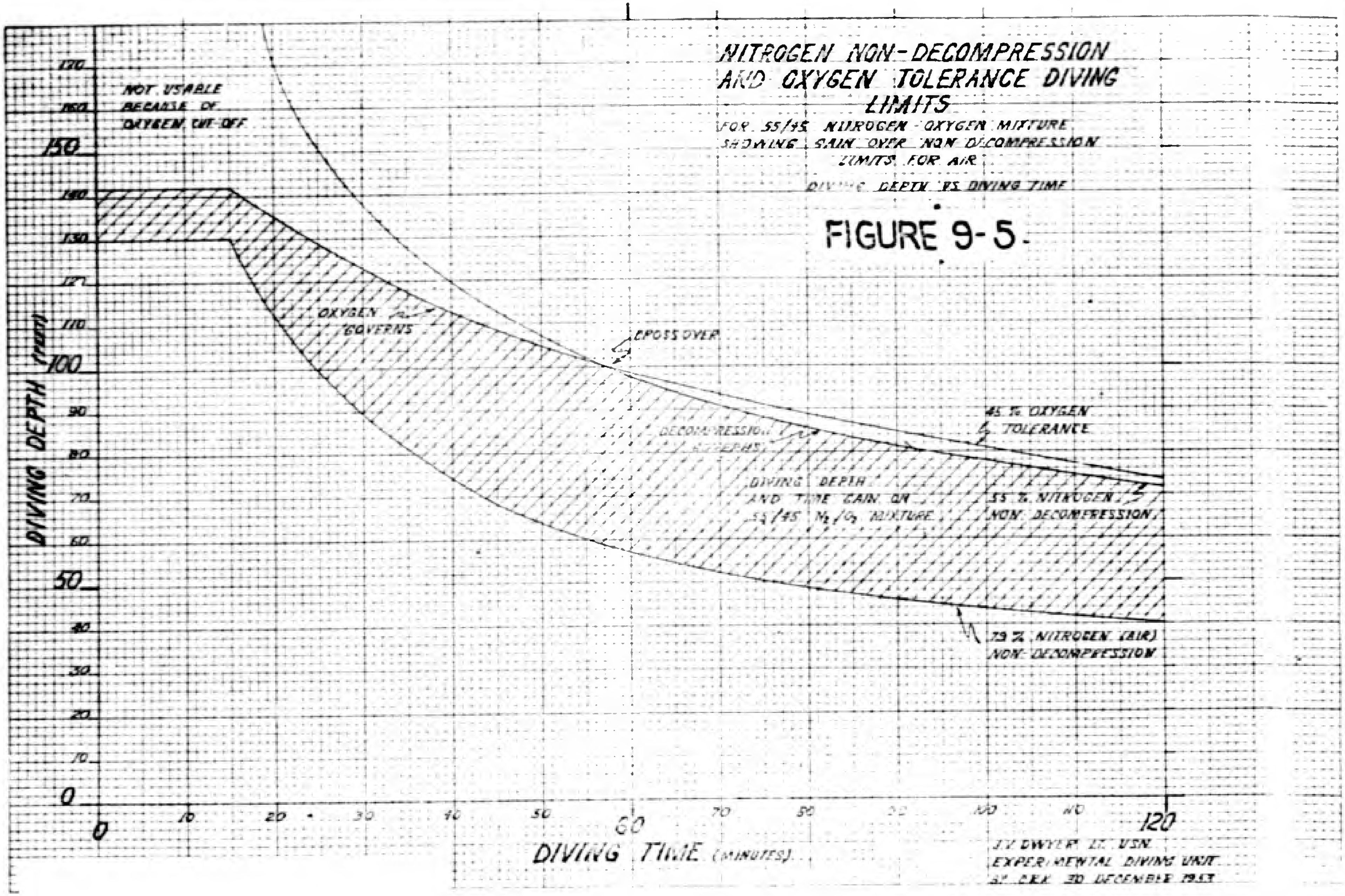

OXYGEN TOLERANCE DIVING LIMITS
DERIVED FROM EMPIRICAL 100% OXYGEN LIMITS AND CONVERTED FOR VARIOUS NITROGEN OXYGEN MIXTURES AS SHOWN
DIVING DEPTH VS. DIVING TIME
NITROGEN: OXYGEN MIXTURES
60/40
50/50
40/60
30/70
20/80
0/100 (OXYGEN)
DIVING DEPTH (FEET)
DIVING TIME (MINUTES)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
J.V. DWYER LT USN
EXPERIMENTAL DIVING UNIT
BY C.R.K. 30 DECEMBER 1953

FIGURE 9-4

9-5 **NITROGEN NON-DECOMPRESSION AND OXYGEN TOLERANCE DIVING LIMITS** 9.1.5

for 55/45 nitrogen-oxygen mixture
diving depth versus diving time

This figure shows the non-decompression limit for 55% nitrogen, the tolerance limit for 45% oxygen, and the non-decompression limit for air. The area between the mixture and the air curves covers the increase in depth-time limits available from using a 55% nitrogen mixture instead of a 79% nitrogen mixture (air). Being flatter, the oxygen tolerance curve controls the time gain for dives up to one hour.


NITROGEN NON-DECOMPRESSION
AND OXYGEN TOLERANCE DIVING
LIMITS
FOR 55/45 NITROGEN - OXYGEN MIXTURE
SHOWING GAIN OVER NON DECOMPRESSION
LIMITS FOR AIR
DIVING DEPTH VS DIVING TIME
NOT USABLE
BECAUSE OF
OXYGEN CUT-OFF
OXYGEN GOVERNS
CROSS OVER
DECOMPRESSION GOVERNS
DIVING DEPTH
AND TIME GAIN ON
55/45 N2/O2 MIXTURE
45 % OXYGEN
TOLERANCE
55 % NITROGEN
NON DECOMPRESSION
79 % NITROGEN (AIR)
NON DECOMPRESSION
DIVING DEPTH (FEET)
DIVING TIME (MINUTES)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
J.V. DWYER LT. USN
EXPERIMENTAL DIVING UNIT
30 DECEMBER 1953
FIGURE 9-5.

9.1.5 Mixed gas diving limits

The physiological effects of nitrogen and oxygen generate a dual set of curves for each nitrogen-oxygen mixture. One curve establishes the depth-time limit for zero-decompression (or for a given amount of decompression). The other establishes the concurrent oxygen tolerance limits. In general, the decompression curve is steeper than the oxygen tolerance curve for the shorter diving times. Consequently, there is usually a crossover of time control from oxygen tolerance to decompression. This is easily seen in Figure 9-5, which shows the zero-decompression and oxygen curves for the 55/45 nitrogen-oxygen mixtures. The greater zero-decompression diving depths allowable from the 55% nitrogen curve are cut off by the shallower 45% oxygen tolerance curve for about the first 60 minutes of diving time. Beyond the crossover point, the nitrogen curve dips slightly below the oxygen curve and governs allowable diving time. If greater depths or longer times short of the crossover point are required, a mixture containing less oxygen is necessary. This, in turn, would increase the restrictions imposed by decompression.

Figure 9-5 indicates that the 55/45 mixture is the optimum breathing medium with which to gain maximum zero-decompression depth-time limits. A higher nitrogen percentage brings the zero-decompression limit inside the 55% nitrogen curve; a lower nitrogen percentage brings the oxygen tolerance limit inside the 45% oxygen curve. In the case of a 60/40 mixture, decompression governs almost exclusively. In the case of a 50/50 mixture, oxygen tolerance governs almost exclusively.

Upon completion of the long-range study of mixed-gas decompression and oxygen limits, the complete interrelated curves will be published in tabular form for ready use. It cannot be emphasized too strongly that tests of these limits have not been completed and that attempts to apply the above information in the field must be withheld pending official promulgation of appropriate tables. Change #1

9.1.6 Variations in mixture composition

The foregoing discussion assumes that the composition of the breathing mixture is known and that it remains constant. If this is not the case, some or all of the advantage of using mixtures will be lost. For example, if the intended mixture is 55/45, but a variation of plus or minus 10 per cent may occur, it is necessary to apply the decompression limits for a 65% nitrogen mixture and the oxygen limits for a 55% oxygen mixture. The allowable exposure time at a given depth is then decidedly less than the allowable exposure time with a stable 55/45 mixture. While it might be possible to compromise on the basis of the expected mean composition, enough information on the degree and time-factors of expected variation is rarely available to permit doing this safely.

If the composition of the breathing mixture does not remain relatively stable, and if its range of variation cannot be predicted with reasonably accuracy, the use of gas mixtures may lose all of its advantages and in some cases may become hazardous. These considerations directly influence the problem of suitable breathing apparatus.

9.2 BREATHING APPARATUS

Two primary considerations generally determine the suitability of breathing apparatus for use with gas mixtures. First of all, the apparatus must supply a breathing mixture of reasonably stable composition. The minimum requirement for stability is elimination of the extremes of varition - anoxic levels on one hand and toxic levels on the other. In order to derive full advantage from the use of mixed gas, the maximum requirement is complete stability of composition (9.1.6).

The second consideration is the usable duration of the apparatus. It is not worth while to extend the depth-time limits by using mixed gas if the apparatus exhausts its gas supply far short of the extended time.

The various types of apparatus which can be used for mixed-gas diving fall into familiar categories.

9.2.1 Open-circuit systems

Open-circuit SCUBA, represented by any demand apparatus (2.1.2) charged with the desired gas mixture, provides complete predictability and stability of the breathing medium. The diver breathes exactly what is in the cylinders.

However, open-circuit systems do not generally meet the criterion of duration (7.2.2). The increased use of gas at the greater depths greatly shortens the duration of the supply. This curtailment of diving time obliterates the benefits of mixed gas to such an extent that it is hard to justify the work of mixing, analyzing and transporting the vast amounts of gas required. Although increases of cylinder size and charging pressure can extend duration considerably, it is doubtful that any extension can be great enough to override the basic objections to open-circuit equipment. In addition, the bubbling of exhaled gas and the noise of a demand system disqualify it for any application requiring stealth or quiet.

9.2.2 Closed-circuit systems

From all standpoints, optimum utilization of gas mixtures requires a closed-circuit rebreathing apparatus (2.2.0). By conserving gas, a rebreathing apparatus augments duration and minimizes the logistics problem. It also reduces noise and bubbling. Unfortunately, the process of rebreathing a mixture involves serious complications.

The body consumes oxygen continuously, at a rate which varies widely with the degree of exertion (6.2.1). The variations may occur abruptly and produce oxygen consumption rates much higher or lower than "average" for prolonged periods during a normal dive.

When oxygen is rebreathed in a properly purged closed-circuit apparatus (2.2.5), these variations produce only volume changes in the system. The composition of the breathing medium is hardly altered. Complete deflation of the breathing bag upon inspiration reliably signals the diver that he needs to add more oxygen, and he can readily make the replacement on a volume basis.

However, if the same system were filled with a nitrogen-oxygen mixture, the oxygen percentage in the rebreathed gas would decrease progressively. Under working conditions, the depletion could occur with extreme rapidity. Although the total volume of the system would decrease simultaneously, the volume decrement would not be a reliable indication of the need to add oxygen. The oxygen percentage might reach anoxic levels while the total volume remained sufficient to permit normal breathing.

Introduction of pure oxygen is the only way to accomplish oxygen replenishment in a closed-circuit mixed-gas system, because addition of more mixture results in an accumulation of nitrogen and a reduction of the oxygen percentage. However, in using oxygen alone to restore lost volume, there is no assurance that the oxygen level will not become excessively high. Loss of nitrogen through leakage, or compression of the gas by further descent, can greatly decrease the volume of the system without providing any criterion at all for oxygen replacement. In such a situation neither the breathing apparatus nor the body can be expected to give adequate warning of impending anoxia or of imminent oxygen poisoning.

Since the diver's oxygen consumption can vary so widely and rapidly, replacement must match consumption almost on a moment-to-moment basis in order to maintain safe oxygen levels over a reasonable range of work rates. No closed-circuit mixed-gas system using volumetric replacement of oxygen can assure safe levels, much less provide the desired degree of mixture stability. Knowing the basic difficulties of oxygen replacement simplifies any critique of the various methods of using mixed gas in a rebreathing system.

9.2.3 Closed-circuit apparatus with oxygen replacement

A completely closed rebreathing circuit offers the advantages of maximum utilization of the gas supply, absence of bubbles except during ascent, and minimum noise. The many attempts which have been made to adapt closed-circuit systems to the use of gas mixtures are not suprising. The great difficulty of making reliable adaptations can be appreciated from the foregoing discussion, and the fallacy of most proposals along these lines is apparent. However, some of these suggestions arise frequently enough to warrant discussion. They may generally be classified into three groups.

T

(1) Refinements of the volume-replacement principle. Logically, periodic restoration of the total volume of the system to a definite value by addition of oxygen can keep the composition of the mixture relatively constant. For example, the diver's vital capacity can serve as a measure of the volume in a system. After such a system was filled initially with a volume of mixture equal to the diver's vital capacity, a demand valve on an oxygen supply would restore the system to its original volume every time the diver inspired maximally. In theory the oxygen percentage would then return to its initial value. The fault of the idea, even assuming that the diver would remember to fill his lungs frequently, is that the gas volume in the system could decrease not only because of the diver's oxygen consumption but also for such reasons as leakage or increased depth. No satisfactory method of taking such changes into account, except compensation for the initial descent, has been suggested.

(2) Continuous injection of oxygen. Presumably, admission of oxygen to the system at a rate equal to the diver's average oxygen consumption would keep the oxygen content of the breathing mixture relatively constant. Especially at depth, the "buffering" action of the total gas volume would considerably slow the change in oxygen level caused by deviations from the average oxygen consumption. The actual consumption rate might well return to average or deviate in the opposite direction before the bag oxygen level became anoxic or hyperoxic. Although the value of his average oxygen consumption for an entire dive may coincide exactly with the constant oxygen injection rate, a diver can easily sustain oxygen consumptions of half or twice that value for prolonged periods. With the lower oxygen consumption, the constant oxygen injection would first fill the system and then spill some of the gas, depleting the nitrogen in the system. With the higher consumption, the constant injection would not meet the diver's requirements, and the oxygen percentage in the system would fall steadily toward anoxic levels. In either case the only evidence of unbalance would be the changes in the total volume of the system, and this indication would be highly unreliable.

Such a system could compensate reasonably well for descent by adding mixed gas upon volumetric demand, but it would have no reliable means to compensate for leaks.

(3) Oxygen replacement linked to respiration. Oxygen consumption and ventilation are closely related entities (6.2.1, 6.3.0), so that providing oxygen replacement in a fixed mass ratio to the diver's respiratory minute volume would apparently achieve a stable mixture. Unfortunately the relationship is neither precise nor completely predictable, and several factors can influence it; consequently the actual ratio can deviate considerably from the assumed ratio. Calculations show that even a small deviation, well within the normal range of variation, can produce unsafe oxygen levels in a very short time under working conditions.

(4) Summary. This discussion by no means covers the range of possibilities, but it includes the elements of the more plausible suggestions. The basic fault of all of these systems is that they can easily produce unsafe oxygen levels without ever warning the diver of impending trouble. It seems unlikely that any simple method of using mixed gas safely in a true closed circuit will be discovered. A system which provides complete utilization of the gas supply and reasonable freedom from bubbling will probably have to await the development of "senser" apparatus (9.2.5).

9-6 BAG OXYGEN PERCENTAGE 9.2.4

oxygen percentage versus oxygen consumption

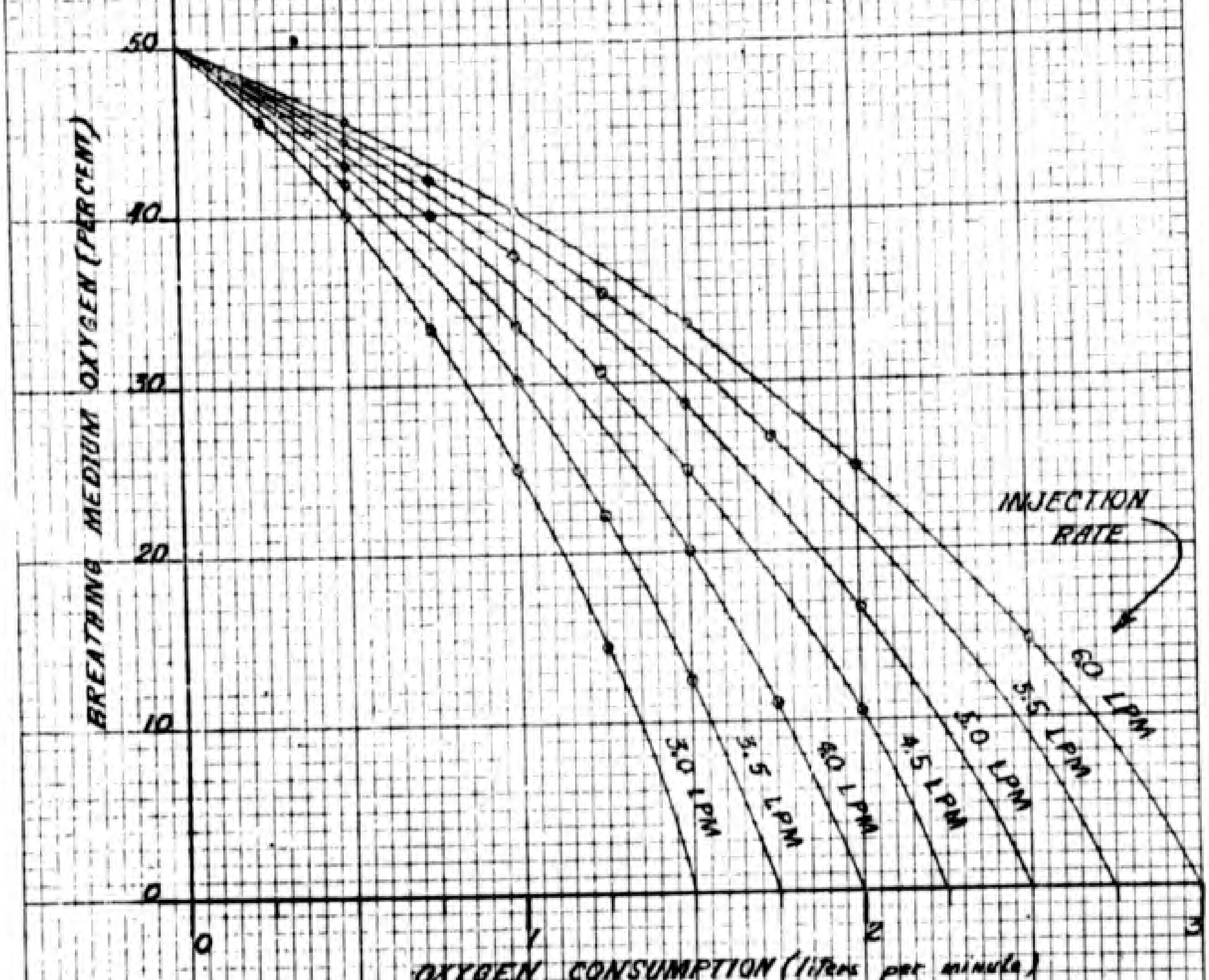
These curves show the drop of oxygen percentage with a rise of oxygen consumption in a semi-closed-circuit mixed-gas system using a 50/50 nitrogen-oxygen mixture injected at various rates as shown. All flow rates are for standard surface conditions.

UNCLASSIFIED

BAG OXYGEN FERCENTAGE
IN MIXED GAS SCUBA WITH POPOFF
FOR 50/50 NITROGEN-OXYGEN MIX
INJECTED AT VARIOUS CONSTANT
RATES AS SHOWN.

OXYGEN PERCENTAGE VS. OXYGEN CONSUMPTION

FIGURE 9-6



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EXPERIMENTAL DIVING UNIT

9.2.4 Semi-closed circuit systems

Frequent flushing with mixed gas of the desired composition can enhance the reliability of "approximate" methods of oxygen replacement and make them practical, although the systems are then no longer "closed". Many of the requirements for mixed gas in self-contained diving can be satisfied by apparatus falling short of complete utilization of the available gas supply. Bubbling is not always objectionable, and some variation in mixture composition is often allowable. On this less demanding level several adequate solutions are available.

(1) Mixed-gas injection with pop-off. The simplest method of accomplishing oxygen replacement and "washout" combines the two functions. An injector supplies the appropriate nitrogen-oxygen mixture to the system at a set rate. The injection rate must provide sufficient oxygen to exceed the diver's oxygen consumption at all times, and must also be high enough to keep the breathing medium within the desired limits of variation throughout a wide range of physical activity.

In this system the bag oxygen level cannot exceed the supply oxygen level; so the upper limit of breathing medium oxygen can be firmly fixed. Since the diver continuously consumes oxygen from the system, the bag oxygen level will always be lower than the supply oxygen level. An adequate injection rate prevents the bag level from falling too low. All of the nitrogen in the injection, together with the excess oxygen, washes through the system to the overflow of "pop-off valve", so that a portion of the breathing mixture is continuously lost.

(a) Bag oxygen level. In a properly designed injection apparatus the bag oxygen level is a function of three variables: the oxygen percentage in the supply mixture; the mixed-gas injection rate; and the oxygen consumption. Setting these variables allows precise analysis of the breathing medium oxygen percentage.

Two of the variables can be set readily. First, charging the cylinders from a pre-mixed source fixes the supply oxygen percentage. Second, proper design of the injector fixes the injection rate at the desired constant mass flow. (Constant mass flow is injection of a fixed number of molecules per unit time. It is usually expressed in terms of constant volumetric flow at the surface, such as "surface liters per minute". A constant mass flow is most economical of the gas supply because the body consumes oxygen on a mass basis; any increase of mass injection over design conditions needlessly wastes the gas supply. Since mass flow is independent of depth, the corresponding volumetric flow actually decreases with depth.)

If the supply percentage and mass injection are fixed, only the oxygen consumption affects the breathing medium oxygen level. The steady state equation is:

$$B = \frac{mS - c}{m - c} \qquad (9\text{-}4)$$

where B = breathing medium oxygen percentage decimal
S = supply oxygen percentage decimal
m = mixed gas injection rate, liters per minute
c = oxygen consumption, liters per minute

Or, in terms of the oxygen injected: $x = mS$

and

$$B = \frac{x - c}{m - c} \qquad (9\text{-}5)$$

where x = oxygen injection rate, liters per minute

Figure 9-6 shows the family of curves for the variation of bag oxygen level with oxygen consumption, at various injection rates of a 50/50 supply mixture.

(b) Analysis. Applying reasonable values for high and low oxygen consumption limits to analytical aids such as Formula 9-5 and Figure 9-6 will define the probable range of mixture variation in a given apparatus. For example, the design conditions in one apparatus provide an injection rate of six lpm of a 50/50 nitrogen-oxygen mixture, so that the injected oxygen is three lpm. Formula 9-5 shows that if the diver consumes one lpm of oxygen during work, his breathing medium will stabilize at 40% oxygen. If his consumption drops to one-half lpm during rest, the bag level will rise to just over 45% oxygen. If his consumption reaches three lpm during very heavy work, the bag oxygen percentage will stabilize at zero. The last conditions is hypothetical, because the diver will become anoxic, automatically reducing his work rate and the corresponding consumption, the following simple tabulation summarizes this analysis:

m = 6.0 lpm and x = 3.0 lpm

CONDITION		c	x - c	m - c	B
Rest		0.5	2.5	5.5	0.45
Light work		1.0	2.0	5.0	0.40
Comfortable swimming	(0.8 k)	1.5	1.5	4.5	0.33
Fast swimming	(1.0 k)	2.0	1.0	4.0	0.25
Vert fast swimming	(1.2 k)	2.5	0.5	3.5	0.14
Spurt swimming	(1.5 k)	3.0	0.0	3.0	0.00

Formulas 9-4 and 9-5 are steady-state equations, and apply only to the bag level ultimately reached with a given oxygen consumption. The transient bag level following a change in oxygen consumption is a function of two more variables: the total volume of the system: and the depth. It is not necessary to formulate the transient equation here, but it is evident in the example given that if the diver maintains an oxygen consumption of 3 lpm or more for a sufficient time, a 6 lpm injection of the 50/50 mixture will be unsafe. In actual practice such a high consumption is very unusual and can rarely be sustained long enough to cause serious trouble.

A restatement of Formula 9-4 solves for the supply oxygen percentage required for a set injection to maintain a certain bag level with a given oxygen consumption:

$$S = \frac{mB = c(1 - B)}{1} \qquad (9\text{-}6)$$

Another restatement of Formula 9-4 solves for the injection required for a known supply oxygen percentage to maintain a certain bag level with a given oxygen consumption:

$$m = \frac{c\ (1 - B)}{S - B} \qquad (9\text{-}7)$$

(c) Discussion. In the foregoing analysis the bag oxygen level falls to 25% with a 2 lpm oxygen consumption, which a diver might easily sustain for a prolonged period. Under these conditions he gains little reliable decompression advantage from the use of the mixture. However, if the injection is increased to 12 lpm the bag oxygen level will stabilize at 40% with a 2 lpm oxygen consumption. Although the resting level may approach 48% with a 1/2 lpm oxygen consumption, the total range of variation has been cut in half. Maintaining a 12 lpm flow for a long dive requires a considerable supply of gas, but the amount is only about one-tenth of the supply required by open-circuit equipment for a similar dive to 100 feet.

(d) History. Injection apparatus antedates open-circuit air-demand SCUBA, and for some time it provided the only means of making deep dives with a self-contained gas supply. The original objective seems to have been to permit self-contained diving "on-air" without the prohibitive waste involved in adapting a self-contained air supply to a standard deep-sea dress. Most of the earlier types of injection equipment supplied gas to a conventional suit and helmet equipped with a lightweight combination lifeline and telephone cable. They were not SCUBA in the present sense, but this type of apparatus is still very much in use. When the equipment did not have a breathing circuit within the helmet, a venturi on the injector provided for recirculating the gas breathing medium through a carbon-dioxide absorbent. In either case the suit itself served as a breathing bag. Since "constant mass flow" is a recent principle in diving apparatus, the injection in older systems tended to follow a rising mass flow pattern, causing considerable waste. The present helium-oxygen rig embodies most of the features of early injector apparatus (DM 882, 883).

(e) Disadvantages. From the standpoint of safety there are a number of objections to the injection principle. Heavy exertion may produce anoxia. Canister failure may produce carbon-dioxide accumulation. Oxygen poisoning is possible, although it is unlikely if the supply mixture is appropriate for the depth and duration of the dive. Exhaustion of the gas supply or failure of the injection system can be extremely hazardous, because anoxia will develop rapidly if the flow drops any significant amount. Reduction of injector noise and pop-off flow may warn the diver if he happens to notice the change, but it is not probable that he will. The various methods which have been proposed to provide adequate warning of failure and to make the apparatus "fail safe" deserve further study.

(2) Possible improvements. One of the most serious objections to the injection principle is the large flow necessary to compensate for the possible extremes of oxygen consumption - and the consequent waste, noise, and bubbling. During low or average exertion, most of the injected gas serves no useful purpose.

It has often been suggested that the performance of injection systems would be greatly improved if the flow could be adjusted in proportion to the diver's oxygen consumption. A proportional flow would provide better stability of the breathing medium, and it would effect a considerable economy of gas if the proportioning were compensated for depth.

The suggestion of admitting pure oxygen to a closed circuit in proportion to the diver's respiratory minute volume has already been mentioned and dismissed (9.2.3 (3)). However, admitting a gas mixture to a semi-closed system on a similar basis is by no means impractical. The flushing aspects of such an arrangement would compensate for the inevitable variations in the ratio of oxygen consumption to ventilation. There are a number of ways to accomplish the proprotioning required by this principle. Compensation for depth is somewhat more difficult than in the constant mass flow system, but the prospects for over-all reliability appear better.

It is not impossible that oxygen and air could be admitted simultaneously through separate proportioning systems with an adjustable relationship to each other. If this could be accomplished reliably, the system would mix its own gas - an attractive possibility from the logistic standpoint.

9.2.5 Automatic mixture control

The ultimate type of mixed-gas breathing apparatus will have an automatic mechanism to analyze the breathing medium and to add oxygen in exactly the amount required to maintain the desired composition. Devices which perform similar operations are now commonplace in many fields, and oxygen has physical properties which permit analysis by a variety of methods. Consequently, the possibility of successful development of a breathing apparatus embodying automatic mixture control is not too remote to consider.

The problems of making such a unit sufficiently reliable to be entrusted with human life and rugged enough for use in the field are considerable, but they are not insuperable. However, reliable its operation might be, such an apparatus would have to be designed to "fail safe" and to warn the diver of the failure. This requirement, though, applies to any type of SCUBA.

A reliable senser system would permit literal application of the mixed-gas diving tables. The attendant advantages would be considerable.

Another possibility lies in the use of an analyzer which determines oxygen partial pressure rather than oxygen percentage. Maintaining a constant oxygen partial pressure, or perhaps decreasing the partial pressure with time, would reduce the necessity for decompression to its lowest possible value. This system would necessitate a more complex approach to mixed-gas diving which would differ considerably from the present approach (9.1.0), but the ultimate in future development may lie in this direction.

9.2.6 Variable mixture composition

Most of the preceding discussion has implied that a mixed-gas breathing apparatus permits the greatest gain in decompression advantage if it maintains a constant level of oxygen percentage in the mixture. With present knowledge this is true, but it is not necessarily the final answer. The possibility that a stable partial pressure of oxygen might be more desirable has been mentioned briefly. In addition to this, two other concepts deserve mention.

(1) Decrease of oxygen level with increase of exertion. It has been pointed out that the continuous injection systems have a characteristically varying oxygen level which falls with increased oxygen consumption during exertion. This characteristic has generally been viewed as a rather serious disadvantage. However,

since it is accepted that the greatest danger of oxygen poisoning arises during the greater degrees of exertion, a drop in oxygen level coincident with increased exertion should be a distinct advantage. The body can tolerate higher oxygen levels during periods of milder exertion and might gain a worthwhile decompression advantage from exposure to reduced nitrogen partial pressures. Unfortunately, the increase in nitrogen level during exertion would favor saturation of the tissues with that gas. The difficulties of quantitating all of the factors involved in applying this principle and of making accurate predictions are formidable. Too little is known at the present time about these factors and their interrelationships.

(2) Intermittent exposure. The fact that the danger of oxygen poisoning imposes severe limitations upon the mixed-gas principle has been stressed (9.1.4). If this danger could be eliminated or materially reduced by some means other than imposing partial pressure limits, the decompression problem would virtually cease to exist. The possibility of forestalling oxygen poisoning by such means as the use of drugs merits further investigation, but it does not seem particularly promising. A much more immediate possibility is presented by an observation which has already been confirmed roughly in man and quantitated in small animals: Relatively brief intermissions on low partial pressures of oxygen restore the greater part of the tolerance time for exposure to high partial pressures of oxygen. These interruptions of exposure in effect greatly increase the allowable duration of exposure to a given partial pressure of oxygen. The implications for mixed-gas diving may be impressive, but again both the "oxygen" and "nitrogen" aspects of such a procedure require extensive study.

Although these comments may be very premature, it is well to recognize that the frontiers of mixed-gas diving are still far from their ultimate limits. In general, the practical applications are lagging far behind the theoretical possibilities, primarily because of the great number of uncertainties which the theories do not quantitate, but also because of a lack of concerted effort in the field of apparatus construction. Undoubtedly, many of the present theoretical considerations wuld be given safe, usable form and substance with very little effort is some agency could concentrate exclusively on the problem of translating theories into equipment.

9.3 HELIUM-OXYGEM MIXTURES

Suggestions on the use of helium mixtures in self-contained underwater breathing apparatus arise frequently. In the consideration of these suggestions, the main factors are the probable advantages and possible complications.

9.3.1 Feasibility

The technique of helium-oxygen diving is already well established. It can be applied to self-contained diving without great difficulty provided that appropriate breathing apparatus is available. The basic design considerations (9.2.0) apply equally to helium or nitrogen mixtures, although differences in physical properties of the two gases will influence details. Furthermore, for use with present helium-oxygen decompression tables, the apparatus must have integral or auxiliary provisions for shifting to oxygen during decompression.

One modification of the helium-oxygen technique is strongly suggested. The oxygen tolerance study (8.2.2) indicates that the 2.3 atmosphere oxygen limit (DM 924), equivalent to breathing 100% oxygen at 43 feet, is not sufficiently safe for hard-working dives longer than about 20 minutes. It would be considerably safer to apply the oxygen limit curve, which takes duration of exposure into account, rather than the 2.3 atmosphere rule. This suggestion applies equally to helium-oxygen diving with surface connections, but it is particularly vital in SCUBA.

It should be emphasized that approaches to the use of helium in SCUBA other than application of the regular helium-oyxgen technique would require specific research and development to that end.

9.3.2 Advantages of using helium

Assuming the availability of appropriate equipment, using helium mixtures in SCUBA might, in fact, be simpler in some ways that using the standard helium rig. However, the complications are sufficient to require justification in the form of concrete advantages. Several advantages are possible:

1) Elimination of nitrogen narcosis in deep dives is desirable in SCUBA because loss of mental clarity can have very serious consequences. From this standpoint, the use of helium in SCUBA diving would be highly desirable in dives deeper than 150 feet and almost mandatory beyond 250 feet. It is this range, however, that SCUBA diving itself can be most seriously questioned except as an emergency measure. Especially when short-duration gear is involved, the use of helium will scarcely alter the general undesirability of SCUBA for such dives.

2) The reduction of breathing resistance in SCUBA may be an important consideration in working dives. The increased density of respired gas at depth affects the resistance of most breathing systems very adversely and has similar effects in the diver's own respiratory tract (6.7.0). The lesser density of helium may prove to be a crucial advantage in situations where a SCUBA diver must engage in heavy exertion at greater depths.

3) Advantages related to decompression are often cited in favor of the use of helium. In this connection, the early view of helium as a panacea for decompression problems has apparently received wider acceptance than the sobering facts subsequently revealed by careful investigation. The use of helium does provide shorter decompression times in longer, deeper dives. However, it has also been shown conclusively that a man can go deeper in brief dives without requiring decompression when breathing air than he can when breathing an equivalent helium mixture.

Although no controlled studies have been undertaken specifically to define the relative decompression advantages of helium and nitrogen in the area between "bounce" dives and long, deep exposures, some information can be derived from comparisons of the existing decompression tables for air and helium-oxygen.

Figure 9-7 shows the results of such a comparison. Area (A) represents the depth-times for which breathing air and using standard air decompression yields shorter total decompression times than does the use of 79/21 helium-oxygen and the appropriate partial pressure decompression table for helium. Stated in another way, the solid line represents the depths and times for which air diving and 79/21 helium diving will yield the same decompression time. In this comparison, helium derives spurious superiority from the routine use of oxygen during decompression. Comparable tables for the use of oxygen during decompression from air dives do not exist; so a valid comparison on this basis cannot be made. The closest approach is found in the (Air) Table for Surface Decompression Using Oxygen (IA 3B2), and approximate figures for oxygen decompression from air dives were derived from this table by extrapolation. The added advantage offered by decompression using oxygen is shown roughly by area (B). (No valid extrapolation was possible beyond 170 feet).

On the basis of available information, area (C) represents the approximate depth-time area in which helium has intrinsic decompression advantages as compared with nitrogen. The broken line represents the depths and times where nitrogen and helium, employed in the same way, will require the same decompression. (Conversion of the depth scale to partial pressure of inert gas would permit comparison of any equivalent nitrogen-oxygen and helium-oxygen mixtures). The decompression advantages of helium

9-7 ISOCHRONIC CURVES
diving depth versus bottom time

The solid line joins those depth-time points for which total decompression time is the same whether the diver breathes air or an air-equivalent (79/21) helium-oxygen mixture. Within area A, total decompression will be less for an air dive. In areas B and C, total decompression time will be less for the helium mixture than for air. The dotted line shows approximately the depth-time points for which total decompression time on air and oxygen (using helium-oxygen techniques) is the same as the total decompression time for a 79/21 helium-oxygen mixture. Any depth and time within area A shows a decompression time advantage for air over an air-equivalent helium mixture. Since these depth-time points cover the practicability of SCUBA, use of helium-oxygen mixtures in SCUBA is generally disadvantageous from a decompression point of view.

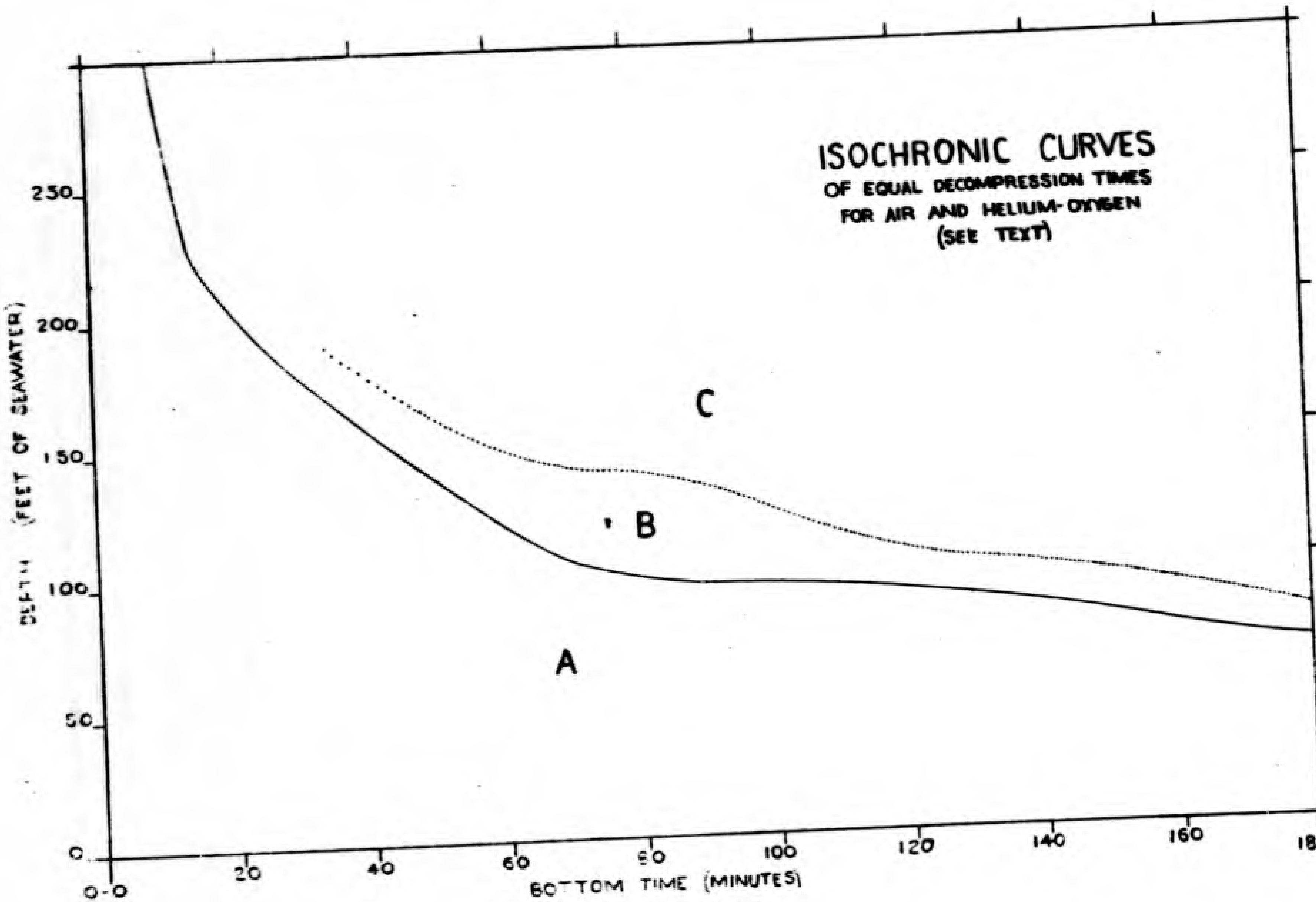
ISOCHRONIC CURVES
OF EQUAL DECOMPRESSION TIMES
FOR AIR AND HELIUM-OXYGEN
(SEE TEXT)
C
B
A
250
200
150
100
50
0
DEPTH (FEET OF SEAWATER)
0-0
20
40
60
80
100
120
140
160
180
BOTTOM TIME (MINUTES)

FIGURE 9-7

do not become evident until higher partial pressures of inert gas and relatively long exposures are reached. The total decompression times required, even with oxygen decompression, are close to or in excess of one hour throughout the depth-time dividing line. It appears unlikely that the decompresison advantages of helium would often be accessible in SCUBA diving. In short-duration dives, the use of helium to avoid nitrogen narcosis would frequently necessitate longer decompression.

9.3.3 The use of mixtures containing both helium and nitrogen

Several considerations make the possibility of using two (or more) inert gases in a given dive worthy of mention.

1) If helium must be used to combat nitrogen narcosis at a depth and time where helium requires longer decompression than air, it might be possible to offset this effect in part by using a certain amount of nitrogen in the mixture. It might be assumed, for example, that a mixture whose inert gas component was half helium and half nitrogen would have decompression characteristics midway between those of equivalent helium-oxygen and nitrogen-oxygen mixtures. It is not possible to say whether such an assumption is valid or not. Nor is it possible to be sure how valuable the application of this principle might be. Application would, in any event, necessitate the construction and proof of new tables.

The possibility that the "undesirable" properties of the two inert gases might prove to be synergistic in combination, rather than neutral or subtractive, must be considered.

2) The concept of separate solubility represents a recurrent hope in the use of more than one inert gas.

Gas going into solution in the body has often been compared to salts going into solution in water; and the formation of bubbles on decompression has been compared to the precipitation of crystals from solution. In general, the solubility of a given salt is independent of the presence of other salts in the same solution. A large total mass of solute can thus be kept in solution if it is composed of a number of different compounds.

That gases in solution in the body might behave in the same way has often been suggested. It is much more probable that the total number of molecules of inert gas present in solution, regardless of their identity, is the crucial factor in determining the formation and growth of bubbles.

3) What might be called sequential exposure to different inert gases in another suggested method of reducing decompression time. If a diver breathes a nitrogen mixture during the first half of a dive

and a helium mixture during the last half, the switch to helium will produce a high outward gradient for nitrogen. As a result, nitrogen will come out of the tissues very rapidly, especially at first while the gradient remains high. This seems an obvious advantage. Simultaneously, however, an even higher inward gradient for helium will have been established, so helium uptake will be at least as rapid as nitrogen loss. The uptake of helium will then compensate for the loss of nitrogen, and the partial pressure of total inert gas in the body will probably increase at least as rapidly as it would if nitrogen were used throughout the dive. Although some such manipulation of gases might be beneficial, the benefits are not likely to be very great.

4) The present state of knowledge concerning the gas solubilities in various tissues, tolerable saturation ratios, rates of uptake and elimination, and other properties of inert gases either singly or collectively is not impressive. It does not permit either reasonable predictions or valid conclusions in these complex matters. The very small amount of experimental evidence currently available, derived mainly from experiments on use of air for decompression from helium dives, does little more than indicate the following probabilities:

a) Attempts to apply present methods of computation when more than one inert gas is present are fruitless. Much more information is required to make this worthwhile.

b) The idea of "separate solubility" is a delusion.

c) "Sequential exposure" is greatly complicated by the uptake of the second inert gas.

A large number of extremely well-designed studies would apparently be required to derive the basis for constructive consideration in this field.

In the absence of controlled investigation, the results of random experiments in these matters should be viewed with considerable skepticism. The many variables affecting decompression, and the possibility of results like those which led to the unwarranted early optimism about helium, should be kept in mind.

CHAPTER 10

PROTECTIVE CLOTHING AND OTHER ACCESSORIES

CONTENTS

CHAPTER 10

PROTECTIVE CLOTHING AND OTHER ACCESSORIES

An effective free diver requires considerably more than a breathing unit to be equipped for useful underwater work. Much of his accessory gear has been mentioned in passing in other chapters, although relatively little of it is of specific medical interest. There are, however, some items of a diver's non-respiratory equipment which merit the medical officer's attention.

10.1 PROTECTIVE CLOTHING - BACKGROUND

The self-contained diver generally prefers to operate without the encumbrance of any clothing except swim trunks, but he is frequently obliged to protect himself from abrasion, grossly contaminated water, or cold. Of these, cold is by far the most important. Cold water may limit the diver's ability to remain submerged and to do useful work more severely than almost any other factor, and the difficulties of protecting him adequately from cold are considerable. Excessively warm water, fortunately less often encountered, may present even more formidable problems.

10.1.1 Water temperatures

The range of temperatures in which a diver may operate without protection of some kind is very limited. Table 10-1 presents some approximate relationships. The figures given are approximate because individuals vary considerably in their tolerance and because the work rate has substantial influence.

TABLE 10-1 EFFECTS OF WATER TEMPERATURE IN SCUBA DIVING

Temperature		Effect
F	C	
96	35	Resting diver will overheat
86	30	Working diver will overheat
78	25	Resting diver will chill in 1 - 2 hours
65-70	18-21	Unprotected diver exhausted in 150 - 210 minutes at work
60-65	15-18	Unprotected diver exhausted in 45 - 90 minutes at work
55-60	13-15	Unprotected diver exhausted in 30 - 45 minutes at work
50-55	10-13	Unprotected diver exhausted in 15 - 30 minutes at work
70	21	Protection is generally required below this temperature
60-70	15-21	Diver's wool underwear generally suffices
60	15	Special protective clothing is required below this temperature
28	-2	Protection for this temperature is required in arctic work

10.1.2 Body temperatures

The mean skin temperature is generally a good index of comfort. When the skin temperature is at the "shivering" level (about 30 C) the deep body temperature will usually be about 0.6 C below normal. Table 10-2 shows the principal relationships for the skin and for the hands.

TABLE 10-2 COMFORT AND SKIN TEMPERATURE adapted from Winslow, et al. (10a)

Sensation	Skin Temperature	Mean C	Mean F	Hands* C	Hands* F
Unpleasantly warm	above	35	95	-	-
Comfortable	at	34	93	-	-
Uncomfortably cold	below	31	88	20	68
Shivering	at	30	86	-	-
Extremely cold	at	29	84	15	59
Intolerable pain	below	-	-	15	59
Numbness	at	-	-	10	50

*Corresponding temperatures for the feet are 3 degrees centigrade (5 F) higher.

The temperature of the extremities is important not only in relation to a man's comfort but also in relation to his efficiency. If the mean skin temperature falls below 30 C, a sharp drop in the temperature of the extremities will usually occur. On the other hand, maintenance of mean skin temperature well within the comfortable range (33 - 35 C, 91 - 95 F) will tend to prevent peripheral vasoconstriction and may keep the temperature of the extremities up even under rather cold conditions.

10.1.3 Heat production

The amount of heat produced by the body depends primarily upon the amount of physical exertion. Heat production is, in fact, the most basic measure of metabolism, although not the most readily determined (6.1.0). The amount of heat produced can be estimated if the oxygen consumption and respiratory quotient (RQ) are known. For most purposes, it is satisfactory to assume that the RQ is about 0.85. At an RQ of 0.85, the amount of heat produced is approximately 4.85 kilogram-calories per liter of oxygen consumed.

In conjunction with oxygen consumption determinations (6.2.2) this conversion factor gives useful approximations for an average underwater swimmer's heat production under different conditions. The units generally employed in considering metabolic heat are kilogram-calories per square meter of body surface per hour. The average man has a body surface area of roughly 1.8 square meters. The following formula gives the conversion from oxygen consumption to metabolic heat production.

$$H = (4.85)(60)(C) = 161.7C \qquad (10\text{-}1)$$

where H - metabolic heat production (kg-cal/m^2/hr)
C - oxygen consumption (liters/min)

An average swimmer is not likely to consume less than 0.4 lpm (liters per minute) of oxygen for any length of time, and at this rate he will produce heat at about 65 metabolic units (kilogram-calories per square meter of body surface per hour). At a comfortable swimming rate (0.8 to 0.9 knot), he will use about 1.4 lpm and produce heat at approximately 225 units. At 1.2 k, which he is not likely to exceed for more than a few minutes, the swimmer will use 2.5 lpm of oxygen and produce heat at about 400 units. Table 10-3 summarized these values.

TABLE 10-3 MATABOLIC HEAT PRODUCTION IN UNDERWATER SWIMMING
(values for an average competent swimmer)

Probable minimum (rest))	- 65 kg-cal/m^2/hr
Average (0.8 to 0.9 knot)	- 225 kg-cal/m^2/hr
Probable maximum (1.2 knot)	- 400 kg-cal/m^2/hr

10.1.4 Heat loss

The body maintains optimum temperature by varying its heat loss to balance its heat production. In air, most of the heat is lost from the skin surface by radiation and convection, and by the evaporation of perspiration. When the body is submerged, conduction becomes important while convection and evaporation drop out of the picture.

With evaporation no longer a factor, the rate of heat loss depends almost entirely upon the thermal gradient between skin temperature and water temperature. Since a drop in skin temperature will decrease the gradient, the body can exercise a degree of control over heat loss by varying the skin temperature by vasomotor control. Actually much of this regulation occurs without vasomotor changes: if the peripheral circulation remains constant, an increase in heat loss will naturally lower the temperature of the skin.

The rate of heat loss is generally expressed in thermal units of kilogram-calories lost per squaremmeter of body surface per hour per degree centigrade of thermal gradient. Whether the gradient is measured from the skin temperature (skin-to-ambient gradient) or from the deep body temperature (body-to-ambient gradient) must be specified.

In terms of the body-to-ambient gradient, the rate of heat loss can vary from about 9 thermal units to as much as 50. This range is mainly a reflection of variations in skin temperature. Conservation of heat through lowered skin temperature can be accomplished only to a limited extent without involving considerable discomfort. The mean skin temperature cannot fall much more than 3 degrees centigrade without producing an extremely unpleasant sensation of cold, together with shivering. Shivering will tend to increase the rate of heat loss.

If heat production is exceeded by heat loss, the body temperature will naturally fall. It will do so gradually since the body represents a considerable thermal reservoir. The average man who is comfortably warm can lose approximately 45 kg-cal/m^2 before becoming uncomfortably cold. Therefore a moderate rate of heat loss may be accepted if exposure is not too prolonged. If the rate of heat loss under given conditions is known, the comfortable duration of exposure can be estimated.

10.1.5 Insulation

In air, the body derives some protection from cold from the fact that the layer of air next to the skin tends to become warm, substantially reducing the thermal gradient. For air, this warming does not require a great amount of heat. When the body is surrounded by water which is not in motion, a somewhat similar effect takes place. For water, however, this warning requires about 3000 times as much heat as for air to give t e same temperature rise in equal volumes, and the loss by conduction is therefore much greater in water. If the water is in motion, no measurable reduction in gradient will occur.

Production by the use of some form of insulation is necessary except under almost ideal conditions. An index for comparing the insulating value of various materials is thermal conductivity, expressed in the number of kilogram-calories which will be conducted through one square meter of a one-centimeter thickness of the material in one hour per degree centigrade of thermal gradient. Table 10-4 lists the thermal conductivities of several materials.

TABLE 10-4 THERMAL CONDUCTIVITY OF VARIOUS SUBSTANCES (*)

Substance	Thermal conductivity (**)
Water	53
Still air	2.3
Wool clothing (normal)	8
Wool clothing (maximum)	3.4
Foamed neoprene	4.6
Solid neoprene or rubber	16
Rubber impregnated cloth	16

*From Report of the cooperative underwater swimmers project (10b)
**Kg cal/m^2/hr/deg C/1 cm. thickness.

The figure for water, representing water not in motion, is very high in comparison with most of the others. Note, however, that the conductivity of flowing water is in effect almost infinite. The figures for wool clothing represent dry wool. The corresponding values for wet wool , as for divers underwear worn under water without a rubber suit, would be essentially that for still water, but in spite of high conductivity, this is a considerable improvement over no protection at all. The conductivity of plain rubber suit material or rubberized fabric of usual thickness is very high. Such materials, used alone, will be of little value. Insulation of wool underwear worn beneath a suit is chiefly derived from air trapped in the interstices: so most of the value is lost if the underwear becomes wet. However, the swimmer is still considerably better off than he would be with no suit.

The conductivity figures for foamed neoprene, comparable for other types of unicellular plastic materials, are noteworthy. Materials of this type also derive most of their insulating value from entrapped gas, but since their air cells do not communicate with each other or with the outside, the insulating properties are not lost when the materials become wet.

10.1.6 Calculations

The thermal conductivities and other values discussed above permit calculation of such factors as the amount of insulation required under various conditions and the tolerable duration of exposure with a given suit in water of a given temperature. Unfortunately, the calculations involved are not entirely simple; and a number of special problems, such as those involving the extremities and any exposed areas, must be taken into account for optimal predictive value. An example of calculations related to suits is presented in the CUSP report (10b).

10.1.7 Consideration other than warmth

Providing warmth is almost always the prime function of suits for SCUBA divers, but efficiency in this respect does not necessarily guarantee that the suit will be satisfactory.

The suit should be comfortable in every way, and it should not interfere significantly with the man's freedom of movement or cause trouble from the standpoints of buoyancy or balance.

Ease of getting in and out of the suit is very important, as is the efficiency with which the openings seal against leakage in the "dry" type of suit.

The suit should be durable: not easily torn or otherwise damaged, not prone to deteriorate rapidly with age, and easy to repair.

The list of "desirable qualities" could be extended considerably, but the foregoing are the most important.

10.2 TYPES OF COLD-WATER SWIM SUIT

The number and variety of suits which are available or which have been tried out for protecting swimmers from cold reflect two things: It is necessary to use different types of suit for different degrees of protection and for different purposes; and it is difficult to find any suit which is wholly satisfactory even for a limited range of uses.

Protection from water temperatures not lower than 60 F is not extremely difficult. Wool underwear alone is often sufficient. Additional protection can be achieved by wearing a rubber shirt over underwear, making no attempt to keep it dry inside. This measure is effective only because it cuts down in the circulation of water - not because the shirt itself has any particular insulating value. Several types of partial-cover suits are used for different purposes in waters which are not too cold.

Water temperatures below 50 F present more serious problems and are of primary concern here. Means of protecting SCUBA divers in water temperatures down to the freezing point of sea water (about 28 F. -2C) are, in fact, needed. Protection in this range necessitates covering the body almost completely, and requires a considerable amount of insulation. Suits for such purposes fall into two broad classifications: "dry" and "wet".

In a "dry" suit, an attempt is made to prevent entry of water. Dryness is essential if the air spaces of wool underwear, for example, are depended upon for insulation. A suit of this type does not necessarily cover the body completely. Models are available which protect little more than the trunk or which leave the head, hands, or both, uncovered. In most models the face is left exposed. Dry suits can be subdivided into two types: those which have special arrangements for equalization of pressure and those which do not. ("Wet" suits are discussed in section 10.5).

10.3 NON-EQUALIZING DRY SUITS

The most prevalent type of dry swim suit is one which is simply worn over wool underwear and which terminates either at the neck or about the face. There is no intentional connection between the suit and the breathing circuit.

10.3.1 Materials

Suits of this kind may be constructed of several types of material ranging from thin gum rubber (made from sheet rubber or "dipped" as a whole) to coated, impregnated, or laminated fabric-rubber materials. Gum rubber suits which are not reinforced with fabric have the advantages of great elasticity and pliability, but they tend to tear readily. Although some of the reinforced types are much too stiff and inelastic, those made on a knit fabric base which stretches well in at least one direction may be quite comfortable, as well as resistant to damage. The sealing areas (cuffs, face or neck seal, and entry) of such a suit will generally have to be made separately of gum rubber and cemented on. Some types of non-rubberized waterproof fabric are said to deserve investigation as suit materials. One solution to the rip problem is use of a simple gum-rubber suit with a separate plain fabric "overall" to provide protection.

10.3.2 Methods of entry

The problem of getting in and out of a dry suit with reasonable ease and without large probability of leaks is a difficult one. Many solutions have been tried.

One of the earliest methods of entry, often referred to as "bunch back", provides a "tunnel" through which the diver climbs into the suit. This tunnel is then folded together in a specific manner and is either clamped or tied. The tunnel may be of the same material as the suit or of a much lighter rubber. In the latter case, the fabric of the suit generally folds over the entry area, providing a zipped or laced enclosure to protect the tunnel. The use of thin rubber for a tunnel greatly reduces the problem of bulk, which is extreme when a large amount of heavy suit material is folded together under a heavy clamp. The closure may be so bulky as to preclude wearing breathing apparatus over it. In any case, most bunch-back suits cannot be donned and sealed without assistance.

The "waterproof zipper" was tried as a substitute for a bunch-back. The diver can generally don and close a zipper suit without assistance, and there is no excessive bulk. Unfortunately, such closures are frequently not waterproof, or soon cease to be, and the zippers themselves not infrequently fail. A single grain of sand can cause considerable trouble.

A reasonably satisfactory form of closure is achieved in two-piece suits which have a waist seal. Closure is accomplished by rolling together the gum rubber "skirts" attached to the shirt and trousers of the suit, or by folding or clamping them over a waist ring. A diver can usually don such a suit without assistance, but if he does not roll or fold the skirts with decided skill, the suit will leak.

Suits with a neck ring closure have an extremely elastic type of rubber at the neck. Assistants stretch the neck opening while the diver climbs through. Next they slip a ring over his head and stretch the neck opening over the ring. The diver then dons a hood which also seals over the ring. In at least one suit using this principle, the opening and ring are large enough to require little stretching. The main disadvantage of this particular suit is the resulting bulk of the closure; the usual neck entry has virtually no bulk at all. The main advantage of any neck ring closure is that it is almost always reliable and tight. Several ingenious methods of providing an ample opening without bulk have been tried or suggested, in order to attain a suit which a man can don without assistance.

10.3.3 Inherent problems

Leakage is one of the most serious difficulties with all suits that must be completely dry inside to have effective insulation. Leaks may occur not only at the entry but about the face seal, at the cuffs if integral gloves are not used, and at any rip, puncture, or serious abrasion of the material.

Buoyancy, balance, and maneuverability are problems, since the insulative value depends on the air trapped in the wool underwear or whatever is worn. Excess air is usually vented as completely as possible on submergence, but some may remain. Any excess air may shift the balance of the diver as he changes position. The diver must use weights to offset the additional buoyancy, but compression of the air space makes him heavier as soon as he descends. With considerable insulation, the buoyancy change may be very serious; and in the presence of a bad leak, the diver may become not only cold but effectively water-logged.

The phenomenon of "suit squeeze" or "pinch", with its skin and ear manifestations, usually accompanies compression of the trapped air (5.3.0). The squeezing, pinching sensation is not only unpleasant but involves limitation of movement. The ear phenomenon has serious potentialities.

Loss of insulation. Compression of the air in the suit also reduces the insulating value along with the volume.

Over-heating. During a dive there is no way to change the amount of warmth provided in a closed suit. A diver with enough protection for light work will become too warm during heavy work. As he over-heats he may sweat considerably, greatly reducing the insulative value of his clothing. Then, when he returns to a low work-rate, he will probably chill.

10.4 DRY SUITS WITH EQUALIZATION

10.4.1 Principles and operation

In conventional deep-sea dress a continual decrease in buoyancy does not occur with increasing depth, because the whole suit communicates freely with the air in the helmet and equalizes automatically as the diver regulates the air supply. Consequently, the only squeeze felt by the diver results from the hydrostatic differential between his head and his feet.

In suits for self-contained diving a simple connection between the suit and the breathing circuit can provide similar equalization to offset the compression effect. Cousteau's constant-volume suit uses such a connection. The suit completely covers the body, including the head, and has a neck-ring entry (10.3.2). The hood, which covers the entire head, has an integral rubber face mask over the eyes and nose. The faceplate opens readily and seals effectively. The mouthpiece of the breathing apparatus enters the hood through a seal below the faceplate.

In this suit, descent will squeeze the diver much as it will in any dry suit. However, a slight exhalation through his nose will force air into the mask, from which it will escape into the suit, equalizing the pressure and relieving the squeeze. Since this procedure keeps the volume of the suit constant, the buoyancy does not change either.

Although the diver can readily control the amount he "snorts" into the mask, he can still force too much air into the suit unintentionally. A valve on top of the hood relieves any excess, and also exhausts expanding air during ascent. This valve will exhaust excess air only when the diver is upright. In the horizontal head-down position excess air may accumulate in the legs of a dry suit, inverting the diver and causing him to blow up, just as may happen in a deep-sea dress. Instead of lacings and heavy shoes, however, the constant-volume suit uses an exhaust valve at each ankle to solve the problem.

Several methods of equalization on the constant-volume principle can be devised. A channel from the face mask to the hood, or a simple tube from the breathing circuit to the suit, can provide constant volume in almost any full suit. However, connections of this sort must have a positive control. Otherwise, in the inverted position, the hydrostatic differential between the feet and the breathing circuit will cause the legs of the suit to inflate rapidly if the connection remains open. Suitable exhaust valves at the ankles are also mandatory.

10.4.2 Advantages and disadvantages

A suit which maintains the same buoyancy regardless of depth and which does not squeeze has obvious advantages. The diver can wear as much underwear as he needs and ballast himself to make up for its buoyancy without fear of being too heavy at depth. Leaks are less likely with equalization because there is minimal "suction" in the suit tending to pull water in.

Total enclosure may be a disadvantage if the diver wishes to breathe ambient air at the surface. Although he can open his faceplate in the Cousteau suit and breathe through his nose, he runs a risk of shipping water through the opening. Flooding the suit may destroy his buoyancy and drag him under. This accident is not probable but the possibility must be considered.

10.4.3 Possible improvements

A very good dry suit would probably have a neck entry or a reliable two-piece waist seal. The head would have an integral full facemask with a faceplate which the diver could open readily. The mask design should forestall flooding the suit through an open faceplate. An easily operated, positive closure between the mask and suit would permit equalization. An exhaust valve in the hood and at each ankle would complete the suit.

The suit should come in a reasonable range of sizes. A waist closure can itself provide a considerable amount of adjustment for height. Various provisions would be necessary for good fit in other areas, such as the arms and legs.

An excellent material for such a suit is a knitted fabric with maximum elasticity, rubberized on the outside. Tear-resistant foam material with a tough outer surface would also be satisfactory. Underwear of wool, non-unicellular foam-rubber or expanded plastic could provide any additional insulation necessary. Joint areas should be designed to eliminate bunching but permit free movement.

The breathing circuit should have a positive shut-off, with provision for shifting to a reliable surface breather or an optional snorkel attachment. The design must provide for clearing water from the mask as well as from the breathing circuit.

10.5 WET SUITS

10.5.1 Background

Cousteau's group investigated various protective measures for diving in chilly water which was not cold enough to warrant a full suit. They discovered that a torso covering made of unicellular foam material would provide a remarkable amount of protection even though it did not keep the diver dry. Other investigators later extended this idea to full body protection in theory and in actual trial, especially Bradner and associates. Their work formed part of the CUSP Project (10b), and it established the practicability of the "wet" principle for protection in water at least as cold at 50F (10 C), and probably colder.

10.5.2 Principles

A unicellular material has air cells which do not communicate with each other or with the outside. Its insulating value does not depend upon keeping the material dry. In theory, a sufficient layer of this material worn as a suit would provide insulation even if water remained between the body and the foam material. A snugly fitting suit could keep the water to minimum volume, impede its circulation, and prevent free exchange with the water outside. The thin layer of water would warm rapidly, and its presence should scarcely impair the protection.

This concept appears to be well established as a fact. The principal problem is keeping the flow of water through the suit to a minimum - 50 cubic centimeters a minute or less, according to calculations. Solving this problem is not extremely difficult, and does not require elaborate closure seals. Snug fit is the main necessity, because any area which does not fit snugly at all times may have a pumping action with respiration or body movements.

10.5.3 Advantages

a) Entry and closure can be greatly simplified because positive sealing is not required. Standard zippers, snaps, or lacing suffice it the material is overlapped at points of closure. The diver can easily dress without assistance.

b) Wet suits are usually quite comfortable. The material is soft and elastic, and the layer of water between the material and the skin tends to inhibit chafing.

c) Since there is no entrapped air, there is no "squeeze" or"i"pinch" at greather depths and no method of equalization has to be provided.

d) The absence of entrapped air also means that there are no shifts in balance due to movement of air within the suit.

e) The change of buoyancy with descent is somewhat less marked than in a non-equalizing dry suit since the internal structure of the foam material tends to resist compression of the air cells.

f) Rips and tears may reduce the insulating qualities by exposing skin to the water; but there is no profound loss of insulation and buoyancy as in a damaged dry suit.

g) The diver can perspire freely without spoiling the insulating properties of his suit.

h) Portions of the wet suit may be deliberately left open to reduce the degree of insulation either at the surface or when submerged, The diver does not have to overheat during work in order to be comfortable at rest.

i) Provision of a fly opening permits urination without removal of the suit. The ability to urinate without surfacing is a considerable advantage in prolonged jobs.

10.5.4 Disadvantages

a) The buoyancy of a wet foam suit, and the buoyancy change with depth may prove to be a limiting factor especially when a considerable. The change is buoyancy will not be as great as with a non-equalizing dry suit of comparable warmth, but it will be considerable compared to that of a constant volume suit. It might, of course, be possible to devise a variable ballast arrangement which would permit compensation for these changes.

Two points should be mentioned in this connection. One is that unicellular foam cannot be made to retain its original volume even if it is used within an equalizing suit. The other is that compression will detract from the insulating value of foam.

b) Some doubts have been expressed as to the ultimate degree of protection that a diver can derive from the wet principle. No one has explored the full range of its ability to protect the diver. Prolonged dives in freezing water will be difficult to attain with any type of suit, and the relative merits of wet and dry suits have not been studied sufficiently to permit positive statements. In particular, the wet suit may not provide enough protection for a man who must emerge into a cold environment following a dive.

c) A wet suit will not offer protection against contaminated water. This may or may not be a disadvantage depending entirely upon the circumstances. When necessary, one of the lighter types of dry suit might be worn under the foam suit.

d) Most of the current wet suits are rather friable, but various means of reinforcement and edge-binding probably can remedy this defect.

10.6 POSSIBLE DEVELOPMENTS IN SUITS

The question of appropriate protective suits for underwater swimmers has received much less concentrated study and developmental work than it deserves, and the present status reflects this relative neglect. The near future is obliged to show considerable progress.

10.6.1 Warmth, bulk, and buoyancy

a) General.

It does not appear probable that any of the suit types described can be perfectly satisfactory for prolonged submergence in very cold water. Because the insulation depends upon air space of some kind, the amount required will be bulky and over-buoyant regardless of its type. Even with equalization, satisfactory insulation will cause more restriction of movement and loss of maneuverability than can ultimately be accepted.

b) Regulation of protection.

In addition, there seems to be no ready solution to the problem of adjusting the amount of protection: to keep a man warm enough during the less active part of a job without causing overheating when more exertion is called for. (Controlling the flow of water through a wet suit provides a partial solution to this problem).

c) The hands.

The problem of protecting the hands from cold without greatly limiting their dexterity is also a serious one. Any insulating material which will protect them sufficiently in freezing water will necessarily be bulky and cumbersome, limiting both tactile sense and dexterity. One method of circumventing this difficulty in part is to provide attached gloves which are of the maximum warmth compatible with required dexterity and touch but in addition to have very warm gloves or pockets available in which the hands can be warmed.

10.6.2 Positive heating

a) Advantages

Providing satisfactory protection solely through insulation may be close to hopeless for very low temperatures, long times, and great depths. Besides insulation, the only apparent way to provide protection against cold is to supply heat.

Relatively small additions to "heat production" would make a considerable difference in the amount of insulation required (10.1.0). Furnishing heat directly to the hands and feet would greatly simplify the problem of keeping them warm. The greatest advantage of positive heating would be the ability to regulate heat in accordance with the need.

b) Sources of heat

Finding a satisfactory heat source for a self-contained diving suit will undoubtedly present difficulties.

The use of electrical heating in diving has a good precedent, it not a wholly successful one, in helium-oxygen work (DM 886). Investigations conducted some time ago indicated that the power requirements would exceed the feasible range of batteries to be carried by a free diver. However, recent developments such as silver cells and cells activated by sea water may have brought "self-contained electrical heating" within the realm of possibility.

Almost any type of submersible craft or propulsion unit could carry enough batteries for the purpose. The main advantage of an electrical system would be that the heat could be placed exactly where needed. The possibility of wetting the coils through leakage or sweating would necessitate specialized arrangements. Distribution of heat from a central point by means of circulated water might be more desirable and it not impossible.

Other sources of heat might prove more practical than electricity, but most of them would require a central heating unit and distribution system. Various chemical reactions, including catalytic oxidation of certain materials, might provide an efficient and manageable source of heat. Some substance which goes from a liquid to a solid state at approximately body temperature might prove very satisfactory if it had a fairly high latent heat of fusion. The old technique of heating a solid material to a high temperature and utilizing its heat over a long period of time might be adapeted in some way.

Since a number of methods of providing heat to a swimmer are possible, investigation appears to be in order.

10.7 MISCELLANEOUS ACCESSORY EQUIPMENT

10.7.1 Swim fins

Rubber "flippers" worn on the feet are one of the SCUBA diver's most vital accessories. Unless he wears weights and walks on the bottom, he can scarcely propel himself without fins. While underwater swimming, even with fins, is an extremely inefficient means of propulsion (6.2.2), it is unlikely that any form of propulsive device (10.7.2) can completely replace swimming. Consequently, efforts to select the best available type of fin and to develop better varieties are warranted. To date, a work by Frassetto (10c) represents almostthe only study devoted to fin characteristics. The two main considerations in swim fins are efficiency and comfort.

Since the object of using fins is to increase the amount of propulsive force transmitted from the legs to the water, it follows that fins should have a large surface area and considerable rigidity. The practical limits of size and stiffness are, however, set by the amount of force available. When the size and rigidity are out of proportion to the strength of the legs, the back pressure on the moving fins is too great for efficient sustained exertion, and fatigue quickly results. Although no form of fin is likely to yield impressive efficiency of propulsion, the differences between available varieties are nonetheless considerable. The situation is further confused by the close interrelation between the swimmer's technique and the type of fin he prefers. A swimmer who becomes accustomed to using one type of fin and then shifts to another may find that the second type is satisfactory only with a considerable change in swimming style. Technique itself is a highly controversial subject - another area in which a study by Frassetto stands almost alone (10c). Much remains to be done in respect to quantitative study on the efficiency both of fins and of techniques. A number of possibilities such as hinging the fin to reduce drag on the return stroke also deserve investigation.

Comfort is important. Fins which are poorly designed, too tight, or too loose can chafe and blister the feet in short order, putting a man out of action for several days. Assuming proper configuration and fit, pliability of the rubber surrounding the foot is the main factor affecting comfort. Unfortunately, rubber soft enough for comfort may be too pliable for efficient fins. The possibility of constructing the fin from two kinds of rubber or of reinforcing the web has been suggested.

There are various methods of adjusting fins to improve fit, including adjustable heel straps and lacings for the portion covering the foot itself. One of the problems related to fit is the need to use fins both with and without a suit. The best solution is generally to have two pairs - one for use on the bare foot and another with sufficient space to accommodate the bulk of suit material and wool socks. Some fins have a large cutaway at the heel which permits wearing them inverted. A few fins enclose the heel, but most do not; means of protection should be provided when injury is possible. Fins should have approximately neutral buoyancy. Slight positive buoyancy is preferable to excessive heaviness.

Webbed gloves have been used as an adjunct to fins for increasing the efficiency of swimming. However, the SCUBA diver generally needs his hands free for other purposes. Furthermore, the lower efficiency of arm work as compared to leg work argues against using the arms for propulsion.

10.7.2 Propulsion devices

Because of the inefficiency of the unaided swimmer, devices to assist in propulsion are essential for anything beyond local operations under favorable current conditions. There is much to be gained by improving the way in which muscular work of the swimmer is applied to the water and by eliminating excessive drag and other sources of inefficiency. Correctly designed propellers driven from bicycle pedals, especially when coupled with a properly stream-lined housing to contain the whole swimmer, can produce a marked increase in efficiency, making speeds fof several knots practical without exceptional work.

Possible motor-driven propulsion units might range from an "outboard motor", which the swimmer would virtually wear, to a variety of craft resembling sleds or torpedoes - with and without cockpits, "windshields," and the like. Early devices of this kind, where the swimmer is exposed to water and to pressure, included the "chariots" (10d) used by the Italians and by British frogmen, in World War II.

10.7.3 Flotation gear

Mentioned under safety considerationss (4.6.2) and elsewhere was the desirability of including arrangements among the swimmer's personal equipment. As stated, there are several situations in which such equipment could be of life-saving importance.

One well though-out SCUBA unit has integral flotation arrangements which can be inflated by carbon-dioxide cartridges or by mouth. The flotation elements are designed to keep a swimmer in the proper position on the surface with no effort on his part. Non-integral flotation devices should be able to provide similar advantages.

Flotation gear can have a definite role in the process of ascent after breathing apparatus failure (4.8.7).

10.7.4 Communication equipment

Communication - particularly by telephone - increases not only the efficiency of an operation but also the safety of the participants. Where telephone communication is possible, masks must be designed to accept microphones, and suit hoods must have appropriate headphone housings. Such matters as fitting phones of the hearing-aid type may concern the medical officer. If phones of the plug or ear-mold type are used, care must be taken to vent the closed portion of the external ear to prevent external ear squeeze.

10.7.5 Small personal accessories

Items of equipment such as the knife, watch, and depth gauge are of medical interest only as they relate to general safety. Matters such as oxygen tolerance limits and the depth and time factors in decompression make the watch and gauge very important accessories. The value of the knife lies mainly in the possibility of becoming fouled, but it may find use against certain forms of marine life.

CHAPTER 10

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CHAPTER 11

DIVING WITHOUT BREATHING APPARATUS

CONTENTS

CHAPTER 11

DIVING WITHOUT BREATHING APPARATUS

Concern with the use of self-contained underwater breathing apparatus ought not to obscure the importance of diving without respiratory equipment. Man has probably been diving by holding his breath since before the dawn of recorded history, and the exploits of pearl and sponge divers in various parts of the world are well known.

During World War II, almost all of the underwater work of the U.S. Navy Underwater Demolition Teams was accomplished by "skin diving"; and even at the present time, a large share of the work of the teams is performed in this way.

O· the civilian side, the recent development of activity in underwater pursuits such as spearfishing has been largely a matter of diving without breathing equipment. The present popularity of SCUBA in an outgrowth of skin diving enthusiasm rather than its precursor. Of the estimated million or more American skin divers and their scores of clubs only a small proprotion is exclusively concerned with SCUBA. Anyone who has access to a body of water larger than a bathtub and who can afford a mask and swim-fins is a potential skin diver and is increasingly likely to become one. The necessary equipment will probably be found at the corner drug store along with the beach-balls and water wings of yesteryear. An activity as wide-spread as this could not escape being of some medical interest even if it were completely benign, which it is not. The number of accidents is admittedly small in the total picture of the activity, but the casualties which occur are not confined to those enthusiasts who deliberately court danger. Many pools and beaches have prohibited the use of masks as a result of casualties. And as in SCUBA diving, the statistics are misleading. The word "drowning" on a death certificate may leave much untold.

11.1 GENERAL MEDICAL ASPECTS

Diving without breathing equipment has four main aspects from the medical standpoint: submergence, exposure to pressure, breath-holding, and exertion. Each of these has importance for its own sake and because of interrelated implications.

11.1.1 Fitness and training

One thing which all of these aspects have in common is that in one way or another they can put a definite strain upon the body. This strain will not amount to much if skin diving is no more than a mild adjunct to casual swimming, but it may become significant in anything beyond this.

Skin diving for sport does not necessarily require an athlete in the peak of condition, but in no degree is it suitable for the lad with a dubious rheumatic history or for the businessman with aging coronaries. More vigorous phases, like spear fishing, are equivalent to military applications in their demands.

The aspirant skin diver should not neglect the necessity for being a decent swimmer and very much at home in the water. The mask and fins are a great help in giving confidence to those who are poor swimmers. In this sense, they may be a real aid in the process of learning. But the person whose confidence in the water is dependent on the water-tight integrity of his mask is not ready to become a skin diver. He will be led into situations with which he is unable to cope.

11.1.2 Physical qualifications

The qualifications for skin diving, as applied to UDT personnel, are identical to those for diving duty (IAI/I, 3.1.2). This is as it should be. Serious pursuit of skin diving is in no way less demanding than the use of conventional diving gear or SCUBA and in some ways it is more demanding.

The skin diver is exposed to pressure. He must be able to equalize pressure readily. He should thus have no disease of the ear, nose, or throat and he must be able to pass the pressure test.

The combination of exertion and breath-holding can place more strain on the cardiovascular-respiratory system than almost any other type of activity. In military applications of skin diving, the diving and swimming involved require a very high degree of fitness. It might be desirable to apply more than the usual measures of pulmonary and cardiovascular integrity (11a) if useful standards for such tests could be derived. It would be desirable to bar those with tendencies toward neurocirculatory asthenia as well as those with hypertensive manifestations. Older men who cannot be deterred on general principles should be required to have elctrocardiograms.

Especially in military applications of skin diving, the psychological and psychiatric aspects of qualification are no less important than they are in SCUBA diving (3.1.4).

11.2 SUBMERGENCE AND PRESSURE

11.2.1 Barotrauma and squeeze

The skin diver is as prone to barotrauma of the ears and sinuses as any other diver. He is generally vulnerable to the same forms of squeeze as the SCUBA diver (5.3.0).

11.2.2 Thoracic Squeeze

The skin diver must be especially concerned about the possibility of thoracic squeeze since this may readily occur if he goes too deep (5.3.2).

The theoretical limit of a skin diver's descent is that depth at which the total volume of gas present in his lungs will be compressed into his residual volume. Since total lung capacity and residual volume are both highly individual matters, it is not prudent to give approximate maximum depths. The range could be from less than 100 to more than 200 feet. It should be noted that "residual volume" in this sense includes not only the lungs but also the respiratory passages and the volume of any mask or similar accessory which is connected to the respiratory tract.

Few divers know their vital capacity and residual volume, and even knowing these values does not always permit reliable calculation of maximum depth. Failure to take in a full breath, or loss of gas in the process of trying to equalize, are capable of limiting descent for obvious reasons. The warning sensations of thoracic squeeze are not always very clear: more than one diver has been surprised to find himself with thoracic pain and hemoptysis after diving to a depth which he has usually reached without trouble.

It is at least of theoretical interest to note that the mass of gas present in a man's lungs actually decreases during dives of this type (11.3.2).

The treatment of symptomatic thoracic squeeze is conservative (5.3.7). Cases encountered in the course of skin diving are not likely to be severe in comparison with serious accidents of this type in air-hose diving. Nevertheless, thoracic squeeze represents a potentially serious form of injury in skin diving.

11.2.3 Decompression Sickness

Decompression sickness is virtually impossible for the skin diver because he cannot submerge deep enough or remain long enough to take up a troublesome amount of nitrogen -- unless he has access to a supply of air at depth. Skin divers who work out of a submerged bell must consider the possible necessity of decompression very seriously.

11.2.4 Air Embolism

If the skin diver simply takes in a breath at the surface, submerges, and returns, he is not subject to air embolism in the usual sense. The air cannot expand to more than its original volume. The only ways in which he might conceivably develop air embolism are through voluntarily producing excessive expiratory pressure -- an unlikely mechanism -- or through an imporbable situation involving

11.3 BREATH-HOLDING

Much has been written on various aspects of voluntary apnea. However, very little in the vast literature on breath-holding deals with the exact form encountered in skin diving where, in the midst of apnea, a significant temporary increase in ambient pressure occurs as a result of the diver's descent.

11.3.1 Peculiarities of breath-holding in skin diving

Studies at the Submarine Escape Training Tank in New London have established that voluntary apnea under pressure, and with changes in ambient pressure, has some very unusual and interesting aspects. For example, it was clearly established that the break-point is significantly delayed when breath-holding is done under pressure (11b). Tank instructors as a group were found to have unusual breath-holding ability, a low respiratory sensitivity to carbon dioxide, and certain unusual features of their normal respiration (11c, 11f). The alveolar gas concentration after deep "skin dives" are quite unlike those after breath-holding of similar duration at the surface (11f).

11.3.2 Oxygen and pressure effects

The fact that hyperventilation "to blow off carbon dioxide" will increase breath-holding time is well known. Not so widely appreciated is the fact that inhalation of oxygen for a few minutes without hyperventilation will increase the breath-holding time of most individuals to a considerably greater degree then does hyperventilation. In view of the above, it seems probable that the elevation of oxygen tension under pressure is the principal explanation for the longer breath-holding times demonstrated at depth. When apnea is begun at depth, neither the rate of increase nor the absolute values of carbon dioxide partial pressure should differ significantly from those during apnea at the surface.

It is interesting to consider what may happen during the apnea associated with a skin dive. During descent, the alveolar carbon dioxide tension would rise to the point that a reverse gradient for carbon dioxide would exist. The gas should pass back into the blood under these circumstances, and it appears to do so (11f).

Individuals being weighed while submerged during apnea, especially after breathing oxygen, have been shown to become heavier with the passage of time. The apparent increase in weight is greater than could be explained on the basis of the respiratory quotient (6.4.1). During apnea, there will always be an alveoli-to-blood gradient for oxygen since oxygen is being consumed continuously by the body. The unrelieved increase in alveolar tension would meanwhile almost abolish the blood-to-alveoli gradient for carbon dioxide. The continued absorption of oxygen would decrease the volume of lung-gas and thus decrease the subject's buoyancy and increase his apparent weight. The volume-decrement would not be offset by a corresponding transfer of carbon dioxide. Instead, the carbon dioxide percentage in the alveoli would be further increased by the decrease in volume, and the gas would be retained in the body.

Changes similar to this could be expected during skin dives after breathing air. The increased oxygen tension at depth would continue to promote absorption of oxygen from lung-gas for some time, and the carbon dioxide would not take its place. Here, however, the volume change would be less important than the change in oxygen percentage. The oxygen level might become extremely low during prolonged apnea at greater depths. When the diver ascended, the oxygen tension might fall low enough to cause frank anoxia. In fact, a reversed gradient could exist with oxygen passing from the blood to the lungs. Temporary loss of consciousness due to anoxia during ascent thus appears to be possible under certain conditions.

11.3.3 Methods of prolonging breath-holding

Skin divers habitually use hyperventilation to prolong breath-holding; and within limits, this is probably not hazardous. The demonstrated ability of oxygen-breathing to prolong voluntary apnea may suggest tempting possibilities to the skin diver. He should scrupulously avoid such measures. There are said to have been cases in which exertion during apnea following hyperventilation on oxygen has caused unconsciousness and death. The mechanism is not entirely clear, but the implied warning is evident enough.

A method occasionally suggested for prolonging the duration of a skin dive is to provide a small rebreathing bag. The object here is to permit flushing the relatively fresh air in the mask and respiratory dead space into the lungs. A brief postponement of break-point could be expected from this maneuver. It has been found, however, that permitting a man who is holding his breath to breathe almost any gas -- however low in oxygen and high in carbon dioxide -- will dull the drive to breathe to an extent well beyond that which can be explained on the basis of gas exchange. This phenomenon has recently been discussed by Fowler (11d). Such rebreathing could encourage the diver to remain submerged long enough to be in real danger from anoxia and carbon dioxide excess.

11.3.4 Black-out during skin diving

In a number of cases, men have lost consciousness during skin dives which involved neither marked depths nor large changes in depth. Since voluntary apnea and exertion were evidently the prime factors involved, it may be supposed that the explanation lies therein. Some of the cases have occurred when men were trying to swim unusual distances underwater and who therefore probably experienced and strongly repressed the break-point impulses. It is conceivable that under some such circumstances the drive to resume respiration fails to become overwhelming before the man loses consciousness. If such a phenomenon exists, it may be related to shallow water blackout (5.6.2). The potential danger is obvious.

11.3.5 Cardiac abnormalities

Cardiac arrythmias have been reported as a consequence of exertion during unusually prolonged breath-holding. They have also been described in exposures to great excesses of carbon dioxide (11e). The exact relationships and ramifications are not clear. In the absence of adequate information, the development of ventricular fibrillation under such circumstances could not be considered impossible.

11.3.6 Summary

The phenomena associated with breath-holding in skin diving offer a considerable field for further study. At the present time, no arbitrary time limits or other safety precautions can be provided, but the employment of great moderation and common sense is clearly necessary.

11.4 DROWNING (5.1.0)

Drowning is a probable end-result for almost any accident in skin diving. In addition to loss of consciousness for reasons such as those mentioned above, causes range from being trapped underwater to becoming panicky after an accident like breaking a face-plate or losing a mask.

11.5 MISCELLANEOUS ACCIDENTS

The variety of mishaps which may occur in skin diving is probably endless, and many of them will never be fully explained. A list of all of the varieties of accidents which have been reported, with relevant comments, could occupy a volume of itself.

11.6 THE USE OF A "SNORKEL"

An interesting modification of skin diving involves the use of a breathing tube to the surface. The degree of submersion possible with such an arrangement is extremely limited because of the hydrostatic imbalance produced (6.7.1), but even being able to breathe with the face submerged is an advantage.

11.6.1 Applications

A snorkel enables a man to swim comfortably at the surface without having to raise his head to breathe, and it makes surface swimming feasible in surprisingly choppy water. A snorkel not only is valuable for the skin diver but it can be a useful adjunct to SCUBA -- permitting safe conservation of respiratory gas whenever the user is at the surface. Without a snorkel attachment, the surface-breathing port provided on most SCUBA is not far enough out of water to be fully useful or safe in rough water.

The snorkel can be a valuable adjunct to SCUBA training in that it permits the novice to get the approximate "feel" of breathing apparatus and to practice swimming technique under conditions resembling the actual underwater situation. Many SCUBA divers employ snorkels for swimming "to keep in shape" -- when the trouble of charging or transporting breathing apparatus cannot be justified.

11.6.2 Advantages and possible hazards

It is probable that the use of a snorkel increase the overall safety of skin diving, especially in rough water. It may, of course, encourage a swimmer to be excessively bold -- to swim too far from assistance or to expose himself to unduly unfavorable conditions. Unexpectedly inhaling water through the snorkel can be unnerving, especially if it occurs in the midst of heavy exertion and air-hunger.

Few if any, available snorkels are valved for one way flow, and in some of them, dead space may be considerable. This is not likely to be a serious problem but the dead space of the mask-type especially may be well above desirable limits (6.5.0).

CHAPTER 11

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