DEEP DIVING AND SUBMARINE OPERATIONS

ROBERT H. DAVIS

Kt., D.Sc., F.R.S.A.

NINTH EDITION
Part 1

# DEEP DIVING
## AND
## SUBMARINE OPERATIONS

A MANUAL FOR DEEP-SEA DIVERS
AND COMPRESSED AIR WORKERS

**PART 1**

ONE HUNDRED & SEVENTY FIFTH
SIEBEGORMAN
ANNIVERSARY

By
ROBERT H. DAVIS
**Kt., Hon. D.Sc. Birmingham University, F.R.S.A.**
formerly Principal and Managing Director of
Siebe, Gorman & Company Ltd.

ONE HUNDRED & SEVENTY FIFTH

SIEBE GORMAN

ANNIVERSARY



A

Limited Edition

No. 1383 of 1500

***The Standard Diver*** *circa 1840*

*'A man, who is employed for subaqueous operations; for which purpose he is fitted with a waterproof dress, the head piece of which has a tube connected with an air pump at the surface, to keep up a continuous supply of fresh air to the diver while below. Apertures in the helmet are glazed permitting him to see the objects under water, on which he is required to work.'*

The diver's dress in those days weighed nearly 200lb out of the water. Each boot weighed 18lb. He had lead weights, each of 40lb, on his chest and on his back. His helmet weighed another 30lb and the dress itself, over 20lb. This weight was of course counteracted under water by the buoyancy of the air trapped within the diving suit.

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NINTH EDITION 1995

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AND

# SUBMARINE OPERATIONS

## A MANUAL FOR DEEP SEA DIVERS AND COMPRESSED AIR WORKERS

By

SIR ROBERT H. DAVIS

Kt., Hon. D.Sc. Birmingham University, F.R.S.A. (Thomas Gray Lectures)

formerly Principal and Managing Director of

Siebe, Gorman & Company Ltd

PARTS I & II

AUGUSTUS SIEBE, 1788-1872

SIEBE, GORMAN & COMPANY LTD

CWMBRAN, GWENT

*By the same author:*

"Breathing in Irrespirable Atmospheres", 385 pp., fully illustrated.

Royal Society of Arts (Thomas Gray Lectures, 1934) ("*Deep Diving and Underwater Rescue*").

"Encyclopædia Britannica" (13th and 14th editions) ("*Divers and Diving Apparatus*").

Royal Society of Arts, 1955 ("*Recent Developments in Deep Sea Diving*").

"A Brief Personal Record of the firm of Siebe, Gorman & Co. Ltd. 1819–1957" (240 pp.).

"A Few Recollections of an old Lambeth Factory and its Vicinity, including some Odd Notes" (148 pp.).

"The Highest and the Deepest", with drawings and key thereto (18 pp.).



PRINTED IN GREAT BRITAIN

*[Imperial War Museum photograph]*

H. M. The late King George VI inspecting crews of "Human Torpedoes"

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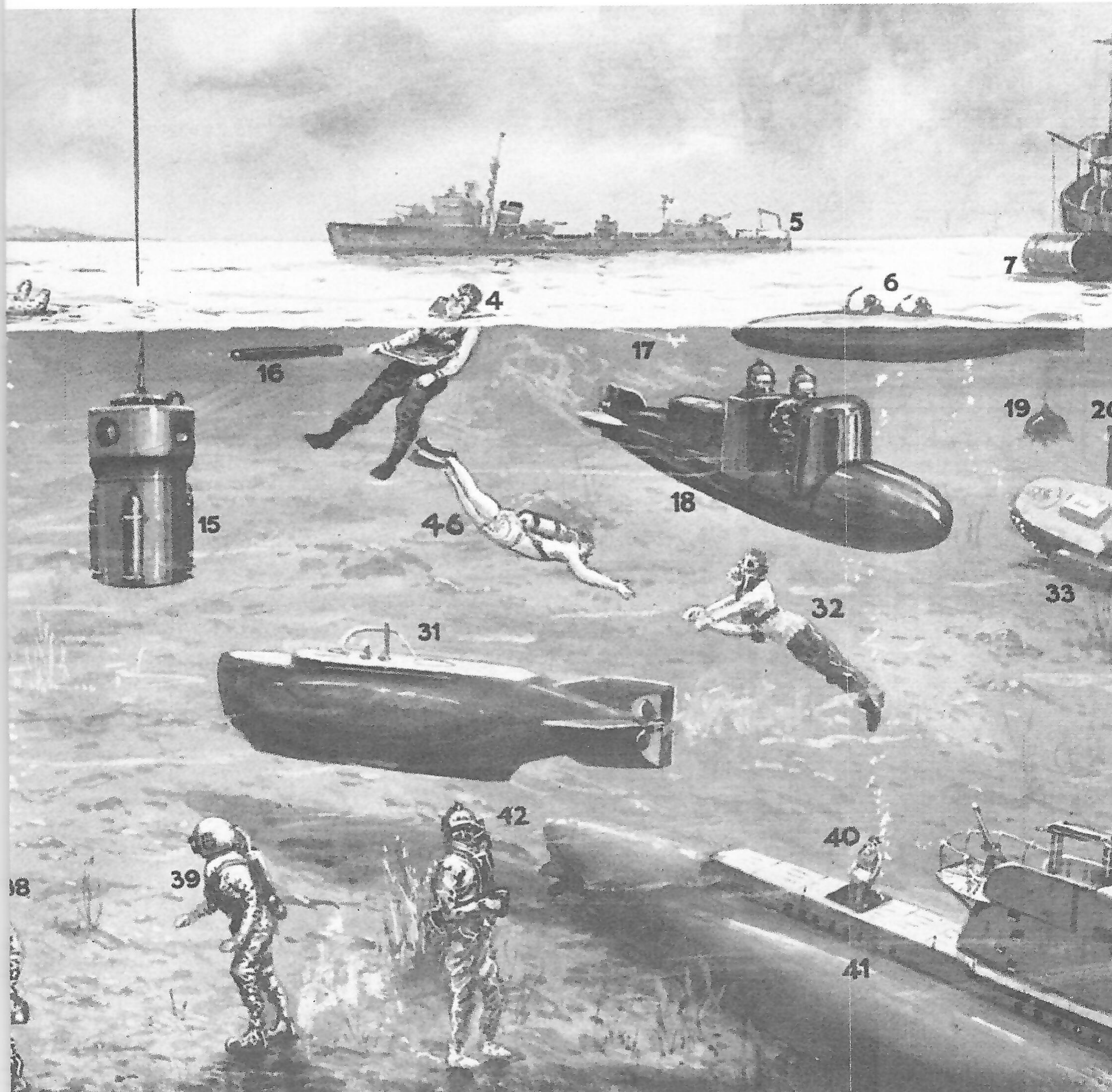


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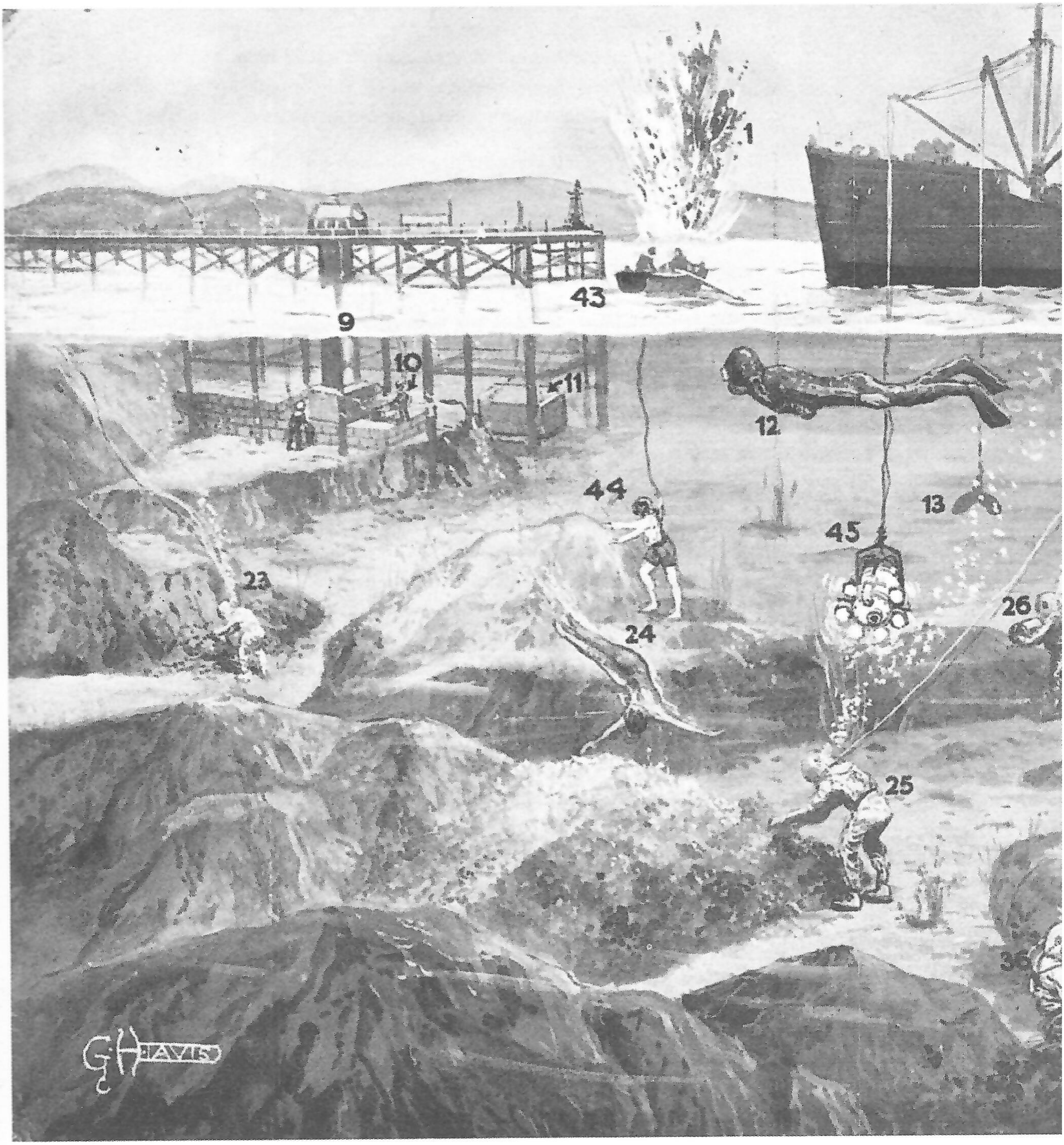


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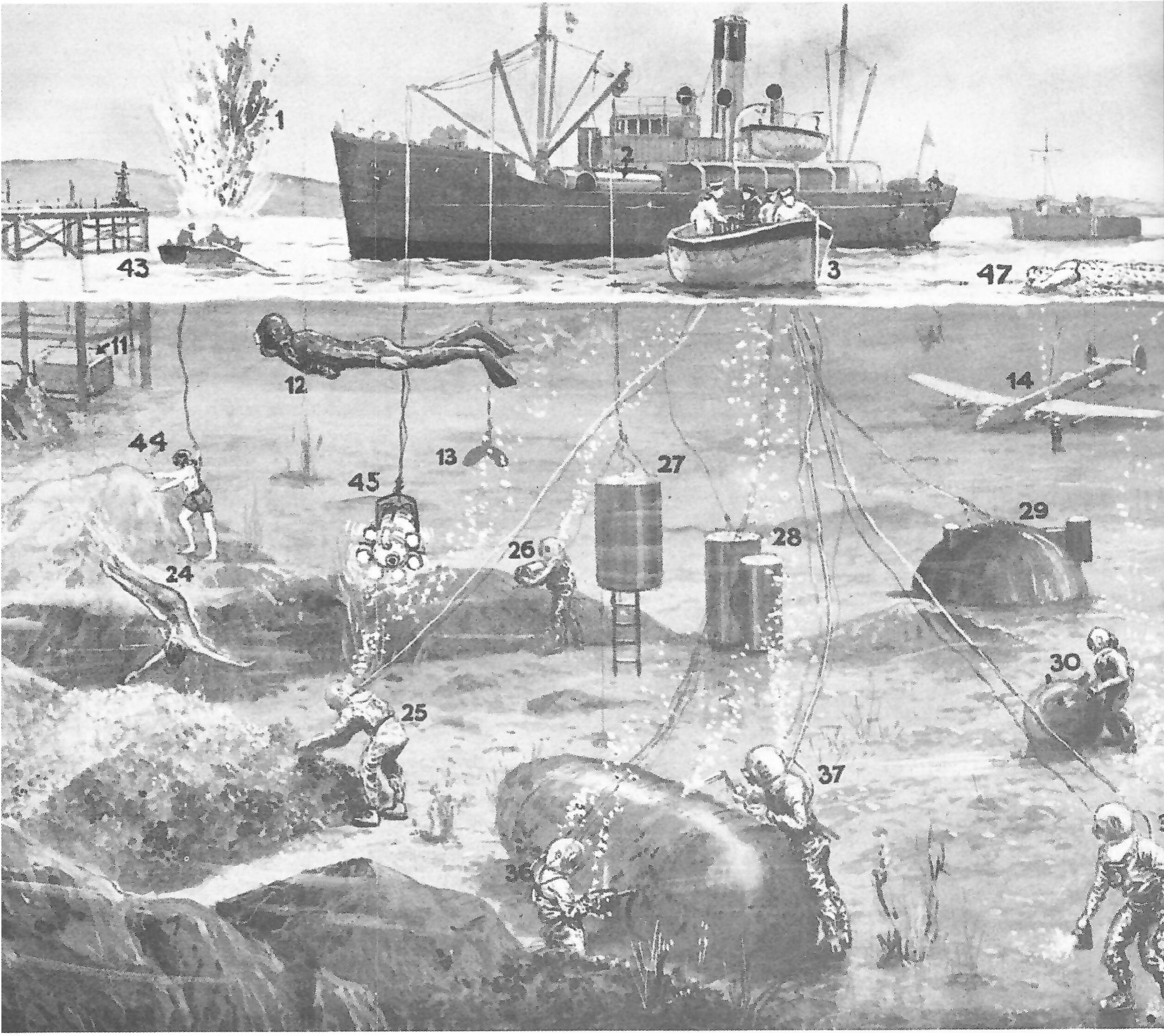


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# *Introduction to Ninth Edition*

THIS ninth edition of 'Deep Diving and Submarine Operations' has been produced by Siebe Gorman & Co Ltd in response to a steady demand from historical diving enthusiasts for a further reprint of Sir Robert Davis' classic work.

That such a demand should still exist, some thirty years since the last revision, is indicative of an immense and growing interest in the history of diving and underwater exploration.

Sir Robert Davis first wrote a book on diving and underwater engineering in 1909, entitled 'Diving Scientifically and Practically Considered, being a Diving Manual and Handbook of Submarine Appliances'. This work was reprinted and revised under a number of titles until, in 1935, when the first 'Deep Diving & Submarine Operations' appeared as the fourth edition of the manual. The book had grown from a simple description of Siebe Gorman's submarine products and how to use them, to a cornucopia of diving facts, figures, anecdotes, and history.

Throughout Sir Robert Davis' eighty-two years with Siebe Gorman, forty as principle executive, the firm provided much of the worlds diving aparatus and expertise. In peace and war Siebe Gorman equipment and training proved vital to subsea engineering, salvage, and combat, in every corner of the globe. In addition Sir Robert invested, heavily and indulgently, in research and development, working closely with the Royal Navy to pioneer very deep diving. During a vital series of experiments in the early 1930's they laid the foundation for the 'saturation' systems in use today.

Sir Robert diligently recorded all these activities and achievements in successive editions of 'Deep Diving'. The illustrator G.H. Davis, whose submarine drawings for the London Illustrated News Sir Robert so greatly admired, was commissioned to produce dozens of new drawings which compensated handsomely for the inevitable lack of underwater photographs. The seventh edition and last revision published in 1962, of which this ninth edition is a facsimile, provides an almost complete record of Siebe Gorman's submarine achievements to that date, together with the collected thoughts, musing and 'yarns' of generations of divers. Yet it also retains its original function as a manual from which those many divers whose underwater work included use of the famous 'Siebe Gorman Standard Dress' could learn.

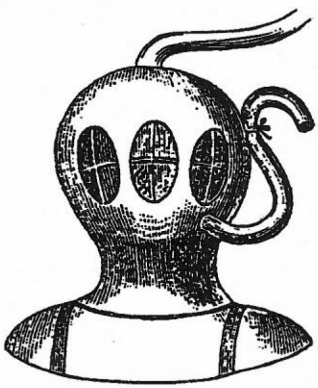
Inevitably the past thirty years have seen great changes in subsea activity, not least an explosion of underwater exploration and exploitation made possible by the aqualung, which has not only revolutionised commercial and military underwater work, but enabled millions of individuals to experience first hand the 'wonders of the deep'. Out of this immense expansion of underwater engineering, science, and sport, has emerged a keen interest in the history of diving. Deep Diving and Submarine Operations stands firmly at the centre of this history. No one with even a passing interest in the subject can ignore it

Although serious students should be warned not to take everything Sir Robert writes too literally, the fact remains that 'Deep Diving' provides not just the bones of Diving history but it's very spine. Indeed it is easy to forgive the odd historical omission or misinterpretation, overshadowed as it is by the rich, varied, and immensely enjoyable general content, interwoven throughout with Sir Robert's impish good humour and delight in the novelty, and wonder, of the underwater world.

As founder of the Historical Diving Society I have been privileged to take part in the establishment of a formal infrastructure for the study and appreciation of the history of diving and underwater technology. This ninth edition of Deep Diving & Submarine Operations will, I am certain, contribute greatly to furthering the Society's aim of ensuring that diving is at last recognised as one of the greatest technologies of our age, with a history as noble, as fascinating, and worthy of serious study, as railways, flight, or automotive travel.

NICK BAKER

Secretary of The Historical Diving Society.
Stourbridge, West Midlands. 1995.



During a 1993 visit to Siebe Gorman I was introduced to the two executives in charge of the Company's famed diving museum. In the course of our conversation we discussed publishing a 9th edition of Sir Robert H. Davis' pioneering work, *Deep Diving and Submarine Operations,* as the book was unavailable to the current generation of divers, and international interest in the history of diving was rapidly increasing. The publishing of "The 9th" became a regular topic of our transatlantic telephone conversations for the next two years, and I am deeply honored by their invitation to contribute to this edition, which is published in two volumes as originally conceived by Sir Robert.

During the course of the 20th century, *Deep Diving and Submarine Operations* has become not only the cornerstone, but the very foundation of many diving libraries. Updated through various revisions it has, for almost ninety years, instructed and captivated readers of all ages. The book's rich technical detail, chronology of diving history and graphic description of the divers adventurous world, make it not only indispensable to the scholar, but irresistible to even the casual reader. A frequently cited source in underwater bibliographies, its historical significance is further enhanced by its enduring value as a practical divers reference book.

Contained in the text are seeds that later blossomed into new underwater technologies, and which continue to bear fruit today, growing far beyond the scope of Sir Robert's original ideas.

This new technology has led to many advancements during the brief thirty-three years since the final revision of the book, transforming many established diving disciplines and creating the fertile environment necessary for the growth of others. A complete accounting of this progress would require a third volume to be added, but since this is not possible a select general overview must suffice.

The modern diver's world has become a much safer place, due in part to the advances made in the fields of diving medicine and physiology. The results of continuing research by military and commercial agencies into mixed gas decompression, covered in chapters seven and eight, have now found an additional eager audience among the growing group of recreational technical divers, whose equipment origins can also be found in the text relating to Henry Fleuss. Sir Robert's proposed divers "home from home" concept has flourished with the work of SEA LAB, CONSHELF, MAN IN THE SEA and other similar international underwater habitat and saturation projects.

The field of one atmosphere diving systems has continued to compete with that of the ambient pressure diver. Referred to by Sir Robert as "metal armour", suits in varying forms, such as the JIM suit, WASP and NEWTSUIT have established themselves in both military and commercial fields.

Public access to information on diving has expanded significantly with an abundance of periodicals, books, videos, computer programs and cable television shows. Those wishing to experience the thrill of diving can enroll in a sports diving program offered by one of several international instructional organizations, or pursue a diving career through the numerous commercial schools that have been established.

The proliferation of self-contained underwater breathing apparatus (SCUBA) during the latter part of this century has fuelled the recreational invasion of our undersea world, transforming what was a fledgling sport at the time of the last revision, into a global industry. Yet its contribution was not solely limited to that field. Scuba was the tool that powered underwater archaeology , leading to some of the eras most significant discoveries, including the spectacular recovery of the *Mary Rose.* The detailed research that led to the salvage of that vessel, in turn, revealed information which clarified the roles of some of the early contributors to the development of helmet diving. Scuba has also provided the world's ocean environmental groups with a vehicle to investigate and report on the decline of our seas, a topic of little concern during Sir Robert's lifetime.

Much of the recorded diving history contained in the book naturally centers around the profession of helmet diving, and this area has witnessed perhaps the most radical change. Sir Robert passed away in 1965 at a time when the occupation of "standard" or "heavy gear" diving was being revolutionized by the equipment innovations developed in Santa Barbara, the Gulf of Mexico and elsewhere. The availability of "off the shelf" recirculating mixed gas helmets and lightweight swim gear increased diver operational depths by hundreds of feet. Combined with other developments in the search for off-shore oil, this equipment propelled commercial diving from a small regionalized trade to a vital international industry.

However, as significant as these advances have been, the challenge of the depths continues to beckon. Man has left his footprint 240,000 miles away on the moon, but not 7 miles down in the Mariana Trench.

Deep Diving and Submarine Operations continues to endure as a functional educational tool in the diver's changing world. It has provided an indispensable reference to this century's diving pioneers, and yet again stands ready to motivate and inspire a new generation of divers as they prepare to take us forward into the adventures of the 21st century..... and beyond.

Leslie Leaney
President
The Historical Diving Society U.S.A.
Santa Barbara, California, U.S.A.
July 1995

# *Introduction to the Sixth (and Seventh) Editions*

THIS edition of "Deep Diving and Submarine Operations", has been revised in the light of developments which have taken place in a number of underwater appliances since the fifth edition was published. It contains, among other new matter, descriptions and illustrations of:

(*a*) The MARCONI-SIEBE, GORMAN UNDERWATER TELEVISION APPARATUS, and an account of the original successful use of this remarkable instrument in the SEARCH FOR, AND THE FINDING OF THE ILL-FATED SUBMARINE *AFFRAY*, sunk at a depth of 276 feet off the Hurd Deep, in April 1951.

(*b*) The recovery, with the aid of an improved Marconi-Siebe, Gorman Television and Illuminating Apparatus, from a depth of 360 feet, of the ENGINES AND OTHER VITAL PARTS OF THE COMET AIR LINER *YOKE PETER*, which crashed into the sea off the Isle of Elba, in January 1954. Both DRESS-DIVERS AND MEN IN SUBMARINE OBSERVATION CHAMBERS were engaged in these important operations.

(*c*) The FREE BREATHING METHOD OF ESCAPE FROM WRECKED SUBMARINES, as originally adopted a few years ago by the United States Navy.

(*d*) The ONE-MAN ESCAPE CHAMBER on the principle designed by the Author in 1914, patented by him in 1915, and adopted in Midget and larger submarines for escape by men wearing D.S.E.A. (Davis Submerged Escape Apparatus) or without breathing apparatus.

(*e*) Accounts of a few of the successful ESCAPES FROM WRECKED SUBMARINES by men equipped with the D.S.E.A.

(*f*) The "ESSGEE" AQUALUNG SELF-CONTAINED DIVING APPARATUS, carrying its own high pressure compressed air supply, and automatic lung-governed breathing devices – an apparatus which is becoming increasingly popular for under water swimming, for observation of marine life, as well as for utilitarian purposes. Many of the scenes below are very beautiful, especially in the warmer waters of the world. Apart from the exercise the Aqualung affords, good sport can also be had with submarine gun and spear against the larger and more combative inhabitants of the silent deep.

ROBERT H. DAVIS

Tolworth, Surbiton, Surrey, 1955 (and 1962)

# *Introduction to Fifth Edition*

THIS revised edition of "Deep Diving and Submarine Operations" contains, in addition to other new matter, descriptions and illustrations of the developments in diving appliances during the 1939-45 War period and since.

In those twelve years, there has been a considerable increase in the employment of the self-contained types of apparatus on the regenerative system using oxygen and $CO_2$ absorbent, and it is particularly gratifying to my company and myself that the first practicable apparatus on this system, both in its application to diving and to work in irrespirable atmospheres, was originally designed and produced by the late H. A. Fleuss in collaboration with Siebe, Gorman & Co., over seventy years ago (see pages 570-573). Like so many devices which at the time of their invention were considered too revolutionary, there was but little demand for diving apparatus of this type for many years. Although my Company had long been making large numbers of breathing apparatus on this principle for work in poisonous atmospheres, in mines, fire brigades, chemical works, gas works, etc., the demand for its application to the diving dress was comparatively small until the exigencies of war brought it into use and proved its value. The same remarks apply to the Davis Escape Chamber in midget submarines, the diver being equipped with self-contained diving apparatus enabling him to leave the chamber, to do the work assigned to him, and then to return to the chamber and the dry interior of the vessel, or to the surface.

When the Admiralty decided to adopt apparatus on the self-contained principle, we were in the happy position of being able to place our research and experimental department and special knowledge of this type of apparatus at their disposal. The Admiralty Experimental Diving Unit was formed with Lieutenant-Commander (later Captain) W. O. Shelford, R.N., in charge, and for over three years, in association with my Company, it carried out the work of adapting and testing various underwater equipments, and training recruits in their use in the Company's special diving and pressure chambers. These men became the "frogmen", "human torpedoes", midget submarine divers and "M.R.S." (Mine Recovery divers) of the last war.

At the invitation of the author, Captain Shelford has contributed in Chapter 15 an account of the Unit's work in our establishment. Surgeon Lieutenant-Commander K. W. Donald, D.S.C., R.N. (retd.), chief Medical Officer of the Unit, has also contributed physiological facts.

Professor J. B. S. Haldane, F.R.S. (son of the late Professor J. S. Haldane, C.H., F.R.S.), his colleague Martin Case, PH.D., and Surgeon Lieutenant-Commander (now Commander) W. M. Davidson, R.N., also did very important work with the Unit.

A device which has proved itself increasingly valuable for deep sea salvage operations, as will be seen in the following pages, is the Submersible Observation Chamber.

For many years inventors have worked on designs of metal diving armour of the articulated type, with varying degrees of success; the latest, which is also described and illustrated in this book, may prove to be the most successful.

It appears that in recent years there has been some misapprehension as to the responsibility for the calculation of the Deep Diving Decompression Tables (Air and Oxygen) on pages 160-179, which, in 1931-33, enabled the safe maximum depth for diving in the flexible dress to be increased from 204 feet to 320 feet. I have, therefore, thought it advisable to record the facts more precisely on pages 6, 7, 8 and 9.

The Ocean's depths, their inhabitants (how marvellously has Nature adapted the organisms of her creatures to their environment), their flora and geological formations, their mountains and valleys (when one thinks geologically, how insignificant are a few hundred thousand years in the Universal scheme), and the mysteries which they still hold, all make a fascinating study. Some readers of this book may wish to learn more about the subject, and they may, in contemplative mood, raise the curtain of the imagination and, with the mind's eye, visualize some of the wonders of the deep.

ROBERT H. DAVIS

Tolworth, Surbiton, Surrey, 1951

# *Introduction to Fourth Edition*

IN this, the fourth edition of my "Diving Manual", I have aimed at as complete an exposition of the art of deep diving as is possible within the compass of 500 pages. I hope it may prove instructive and helpful, not only to divers and other workers in compressed air, but also to their employers. The less technical parts, giving examples of successful work accomplished by divers, may be interesting to the general reader also.

The book includes the results of the research and practical experimental work carried out during the past three years by the British Admiralty Deep-Diving Committee in collaboration with my Company. This work has made it possible to extend the safe limit of depth, for divers wearing the Siebe flexible dress, to 300 feet, which is now the official limit adopted in the British Navy. Further, by the new system evolved, which is based on, and is an extension of, the stage decompression principle devised by Professor J. S. Haldane, C.H., F.R.S., the decompression times for the deeper dives have been considerably reduced. New decompression tables* have been calculated, and these appear in their proper place in the book.

The chapters on "The Physics and Physiology of Diving", "Diving Appliances, etc.", "Instructions and Hints to Divers", "Decompression, First-Aid and Recompression" have been revised and brought up to date.

The chapter on "Escape from Disabled Submarines" gives descriptions of the apparatus, escape-locks and methods employed.

The sections dealing with "Salvage of Ships"† and "Recovery of Sunken Treasure"† include some recent successful cases as well as a few of the more interesting of the past. Those of the last hundred years may be taken also as a record of some of the work of Siebe, Gorman & Co. Ltd., for there have been few such operations during that period in which my firm's submarine appliances have not played a part.

The present volume gives a more complete "History of Diving and Diving Appliances"† than appeared in the earlier editions, and in deference to the wishes of a number of friends, further stories of divers' adventures, which I have called "Divers' Yarns",† have been included.

For permission to quote extracts, or to reproduce illustrations from their copyright works I have to thank Messrs. Chatto & Windus, Allen & Unwin, C. A. Pearson Ltd.,

* Which are the copyright of Siebe, Gorman & Co. Ltd., London

† Contained only in Part II of the complete edition

Putnam Sons, *Journal of Hygiene*, Dr. William Beebe, Commander Ellsberg, *The Times*, Royal United Services Institution, Committee of Lloyd's, and the Oxford University Press.

My best thanks are due also to the following friends: Captain G. C. C. Damant, C.B.E., R.N. (retd.), for his assistance in revising some of the chapters in the light of the latest deep-diving practice; Lieut.-Cdr. R. T. Gould, R.N. (retd.), for help in connection with the records of early diving appliances; Major Desmond Young, M.C., for matter relating to the work of his father, the late Sir Frederick W. Young, K.B.E.; also to my sons, R. W. Gorman, W. Eric and R. J. Peter Davis, for reading and correcting the proofs of this book.

ROBERT H. DAVIS

London, 1935

# I

# *A Summary of the Present State of the Art of Deep Diving*

*The Moon and its secrets are the goal of the Airman; the abysmal depths of the Ocean and its mysteries the goal of the Submarine Explorer.* R.H.D.

The purpose of this opening chapter is to summarize the various types of diving and other submarine apparatus and ancillary appliances in use today, and briefly to explain the principles underlying the art of deep diving.

The practical day to day diving carried on all over the world takes place in comparatively shallow water—in harbours, docks, rivers, canals, bridge and pier works, pearl and sponge fisheries, ship-raising operations in coastal waters, etc. Certain naval and salvage and treasure recovery operations demand special appliances and technique to enable divers to reach much greater depths. The present volume gives some account of the problems that have had—and have still—to be overcome in dealing with these greater depths, and it also records the salient facts of the many years of research and experimental work that have made present achievement possible.

**Pressure.** For all practical purposes we may say that the atmosphere which surrounds us to a height of about 300 miles weighs upon everything at sea level with a pressure of 14·7 lbs. per square inch, or one atmosphere. A depth of 33 feet of sea water also weighs 14·7 lbs. per square inch, so that at that depth a diver has two atmospheres absolute of pressure upon him, at 66 feet three atmospheres, at 99 feet four atmospheres, and so on. A table of depths down to 1,020 feet, with corresponding pressures, is given in chapter 16.

To make diving possible, the diver must be supplied with an adequate amount of pure air at a pressure equal to the depth at which he is working. This countervailing pressure is transmitted equally throughout the diver's body, and is no more felt than is the ambient air which we breathe normally. *If a diver breathing air at a certain pressure were suddenly, by some mischance, to be subjected to a greatly increased water pressure he would be forced up into his helmet with very serious consequences.

**Nitrogen** (N). Our bodies consist mainly of liquids, and all gases dissolve in liquids in quantity proportional to the pressure. At, say, seven atmospheres, equal to a depth of about 200 feet, there is seven times as much nitrogen in solution in the diver's body as normally. Fat men saturate more slowly than thin men, and take longer to desaturate. Organs well supplied with blood—the liver, brain, etc.—absorb nitrogen quicker than those with a poor supply, e.g. the joints, fat, etc. While the oxygen content of the air supplied to the diver is used up by the tissues and is exhaled in the form of carbon dioxide, the excess of nitrogen remains. It is essential, therefore, in order to avoid compressed air troubles (variously described as the "bends", "caisson disease" and diver's paralysis) that this excess of nitrogen be released gradually as the diver returns to normal pressure at the surface; this is done in stages of reducing pressure in accordance with the decompression tables in Chapters 4 and 7.

**Helium** (He). Research and practical experiment discovered that nitrogen breathed at pressures above that found at about 240 feet, has a narcotic or mildly intoxicating effect. This narcosis, as it is called, led United States experts to adopt, instead of atmospheric air (nitrogen and oxygen), helium and oxygen in the same proportions, with the result that this disability was eliminated. It is unfortunate that helium in

* It is of interest to note that pressure of water over 400 atmospheres kills all surface animals by stiffening the living substance. To this, deep-sea fish must be immune if living at depths greater than that corresponding to such pressure.

sufficient quantity can only be obtained from America at considerable cost. Hydrogen and oxygen make an equally effective deep diving mixture, but the risk of explosion in inexperienced hands make one extremely cautious in using it.

**Carbon Dioxide** ($CO_2$). Since the bad effects on the diver of any $CO_2$ in his helmet increase as the depth (for example, 1 per cent of $CO_2$ at ten atmospheres, or 300 feet depth, would have the same effect as 10 per cent $CO_2$ at atmospheric pressure) it is imperative that his helmet be supplied with air in adequate quantity to keep the percentage of $CO_2$ down to the lowest possible point. In deep diving and self-contained types of apparatus, the efficiency of the $CO_2$ absorbent used is highly important.

**Oxygen** ($O_2$). Oxygen poisoning is another risk to be most carefully guarded against. The breathing of *pure* oxygen above two atmospheres pressure=33 feet of water, may give rise to nervous symptoms leading to convulsions and blackouts. Its effects are variable, not only in the same individual, but also in different subjects. Warning symptoms are usually stiffening and twitching of the face muscles, but some subjects have no warning and suddenly lapse into unconsciousness. Pure oxygen must, therefore, be avoided for depths beyond, say, 30 feet; for deeper work the oxygen must be diluted in proportions varying with the depth (see pages 10–16).

## SELF-CONTAINED DIVING APPARATUS

**Principle of the Self-contained Closed-circuit Regenerative Type.** The air in which we live contains, approximately, nitrogen (N) 79 per cent, oxygen ($O_2$) 21 per cent and carbon dioxide ($CO_2$) ·03 per cent. After inhaling this atmosphere, we exhale, under normal working conditions, nitrogen 80 per cent, oxygen 16 per cent, carbon dioxide 4 per cent. It will be seen, therefore, that to bring the exhaled air back to normal, it is necessary to replace the 5 per cent of oxygen lost, and to absorb the 4 per cent of carbon dioxide. The closed-circuit breathing apparatus carries out these requirements automatically.

Since the last edition of this book, the Second World War has brought into greater prominence underwater breathing apparatus on the self-contained principle, as originally designed by H. A. Fleuss in collaboration with Siebe, Gorman & Co. (who have made it in various forms ever since) over 70 years ago. As its description implies, this type of apparatus dispenses with tube connected to an air pump at the surface, the diver being equipped instead with cylinders of compressed air or oxygen or special mixtures of oxygen and nitrogen in proportions varying with the depth of submersion. Since these breathing mixtures contain more oxygen than does atmospheric air, they have the advantage of accelerating the rate of decompression.

The types of self-contained apparatus, variously described as "Salvus A.N.S.", "Human Torpedo", "Frogman", "Mine Recovery Suit", are all based on the system originally designed by Fleuss—Siebe, Gorman & Co. The author, who entered the works of that firm 73 years ago, is aware of all the developments that have taken place in those seven decades in all parts of the world, and has himself been responsible for many of them. For many years before the war he was using mixtures of oxygen and nitrogen in diving apparatus, and over 20 years ago he submitted to the Admiralty for trial, with very satisfactory results, apparatus using such mixtures.

On the physiological side of his experimental work he has had the friendship, advice and assistance of the eminent physiologist, the late Sir Leonard Hill, F.R.S., LL.D., M.B., whom he invited to join his company's consulting staff 50 years ago. To the late Professor J. S. Haldane, C.H., F.R.S., M.D., (1860-1936), of Oxford University, he also owed grateful thanks for friendship and advice on physiological problems for many years.

**Self-Contained (Open-circuit) Non-regenerative Apparatus.** Another design of self-contained diving apparatus is the compressed air open-circuit type, i.e. instead of being rebreathed after having its $CO_2$ absorbed and the compressed oxygen replaced, as in the closed-circuit apparatus, the exhaled air is vented from the dress into the water, the diver being entirely dependent on the supply of compressed air which he carries. It will be seen, therefore, that cylinders of greater capacity are necessary for a given depth comparable with the regenerative type of apparatus using oxygen and $CO_2$ absorbent.

The other forms of diving and ancillary appliances described and illustrated in the present volume are:

**The Diving Bell.** This is a steel chamber, open at the bottom, which, when lowered under water, is supplied with air from the surface at a pressure slightly in excess of that at its depth, thus preventing the water from entering. The occupants do not require any diving or breathing apparatus. The use of the diving bell is mainly limited to dock and harbour construction and repairs (see Chapters 2 and 9).

**The Standard Flexible Closed Diving Dress.** As originally invented by Augustus Siebe, in which the divers breathe air—supplied from the surface by pump, compressor, or highly charged air cylinders—at a pressure corresponding to that at the depth at which they are submerged. The Siebe principle is still in universal use today.

**Decompression and Recompression Chambers.** In order to prevent compressed air illness, a diver who comes up too quickly must, without delay, either be sent down again to the depth from which he came, and brought up in accordance with the Decompression Tables, or he must be put into a recompression chamber, if one is available, and recompressed and decompressed (see Chapters 4 and 6).

**The Davis Submerged Decompression Chamber** (see Chap. 7). The Royal Navy uses this chamber for very deep dives. It is normally lowered to 60 feet, air being supplied to it at a pressure equivalent to the depth of submergence. After carrying out deeper air stoppages, the diver enters it by the lower hatch which is then closed; the chamber is lifted on board. At a pressure equal to a depth of 60 feet, the diver begins to breathe oxygen which expels the excess of nitrogen more quickly, and enables him to be decompressed in much less time than if he breathed ordinary air (see Chapter 7).

**The Davis Three-compartment Static Decompression Chamber.** In 1931 the author designed the original chamber of this type (Fig. 137), for use primarily in conjunction with his submerged decompression chamber, whereby the diver could be transferred from the latter, without change of pressure, and the submerged chamber thus freed for use with successive divers.

The three-compartment chamber is also made without the transfer attachment and is employed for decompressing divers who are brought to the surface without the usual decompression formulae, and are put without delay into the chamber through one of the end doors. The Royal Navy is using a three-compartment chamber in this way in its latest deep diving vessel, H.M.S. *Reclaim.*

**Metal Articulated Armour.** In this the diver is protected from water pressure and so breathes air at normal atmospheric pressure. Oxygen and $CO_2$ absorbent are used to recondition the diver's exhaled air. The shortcomings of this apparatus are pointed out later; one of these arises from the fact that, while the metal arms and legs are fairly flexible in shallow water, they become increasingly less flexible the deeper the diver goes because of the greater pressure on every square inch of the joints. The diver in deep water loses mobility almost entirely, with the result that the armour becomes of no greater practical value than the less expensive observation chamber.

**The Davis Vertical Cylindrical Observation Chamber** in which the diver is also protected from water pressure, and in which is installed an air-regenerating apparatus. Fitted with windows, the chamber is used for observation and directional purposes, the diver, aided by submarine lamps, directing salvage operations by telephone to the surface from which explosives and grabs are lowered where required.

**The Spherical Bathysphere,** as used by Dr. Beebe, the American naturalist, who has descended to over 3,000 feet (see Chapter 11).*

When the technical difficulties of diving in shallow water had been overcome, and the pioneers were tempted to go to greater depths, it was found that the more

* Since exceeded by Professor Piccard and two French Naval Officers. See page 688.

venturesome were liable to be struck down by a mysterious illness, then called "Divers' Palsy" but now known as "Compressed Air Illness". Until its nature was understood and means for avoiding it were discovered, progress was impossible. The subject is discussed in Chapter 2 (pages 38 to 40), but it may here be remarked that the illness only appears after the diver has returned to the surface. As greater depths were attained and further experiment carried out, other problems revealed themselves. Two of these, nitrogen narcosis and oxygen poisoning, are discussed later.

**Diver Under Pressure Analogous to a Bottle of Soda Water.** Professor Leroy de Mericourt* was the first to liken the blood of the worker in high air pressure to a bottle of soda water. He said: "The greater the depth, and the longer the stay at the bottom, the more will the blood be charged with an excess of gas in solution. The diver is really, from a physical point of view, like a bottle charged with carbonic acid".

## EARLY RESEARCH WORK

To **Paul Bert** (1833-1886), the great French physiologist, is due the foundation of our knowledge of respiration at high and low pressures, and at low and high tensions of oxygen. His research and practical experimental work proved the dangers of breathing pure oxygen above a certain pressure; showed the importance of using mixtures of oxygen and nitrogen or oxygen and hydrogen for deep diving; how essential it is for the diver and the caisson worker to decompress slowly—"For they must not only allow time for the nitrogen of the blood to escape, but also to allow the nitrogen of the tissues time to pass into the blood"—; and suggested stopping of the diver halfway to the surface during decompression after deep dives.

Bert's work is summarized in his book *Barometric Pressure—Researches in Experimental Physiology*† a classic of the highest scientific distinction, published in Paris in 1878. But only since the development of deep diving and aviation have his genius and work been fully recognized and appreciated. He delved deeply into the subject and left us a legacy of great worth. All later physiologists who have worked in this field of research, designers of breathing and diving appliances and men who fly at great altitudes or go deep under the sea, are his debtors.

That Bert knew of Siebe's original work is shown by what he wrote in 1877—"It is only during the last fifty years that Siebe, of London, was the first to have made a practical diving apparatus; then M. Cabirol; finally MM. Rouquayrol and Denayrouze".

Bert's experiments showed clearly that the illness was due to liberation in the blood and tissues of bubbles of gas consisting almost entirely of nitrogen. He showed, too, that the dangers to which workers in compressed air are exposed are due to the increased partial pressure of the gases in the air breathed.

He recommended slow and gradual decompression (later known as the "uniform" decompression method) as a preventive of compressed air illness, the diver starting from the bottom and ascending at a constant rate all the way to the surface. But this method, though a great advance on the old method of diving, was not always successful. From Bert's experiments, however, workers in compressed air who were affected soon discovered that "bends"‡ could be relieved by returning into the compressed air of the tunnel or caisson, and this fact led to the introduction of the steel Recompression Chamber (see Chapter 6) for preventing (if used in time) the onset of compressed air illness, or for alleviating symptoms which appeared when the preventive rules were not followed.

It is recorded that this method of treatment was suggested in a report made over sixty years ago to the Brooklyn Bridge directors by Dr. Andrew H. Smith, M.D., who was then on the staff of St. Luke's Hospital, New York, and had previously been on the medical staff of the Bridge Works. It is agreed, however, that the first actually to provide a recompression chamber on public works was the late Sir Ernest Moir, Bart., M.INST.C.E., who installed a chamber when he was engaged on the Hudson River Tunnel operations which were carried out by the London firm of Pearson, in 1893.

* Ann. d'Hygiene Publique et de Medicine Legale, 1860. 2e Serie XXXI.

† An excellent translation into English by Professor Mary Alice Hitchcock, M.A., and Frederick Hitchcock, PH.D., Professor of Physiology, Ohio State University, is published by the College Book Co., Columbus, Ohio, U.S.A.

‡ "Bends" – so called by workers in compressed air – are one of the commonest symptoms of compressed air trouble, and are characterized by attacks of pain, most frequently in the limbs. The trouble usually disappears quickly on recompression.

By its use he was able almost completely to abolish fatalities which had been numerous up to the time his firm took over the contract. Moir, however, knew nothing of Bert's work or of the true cause of "bends". He thought the blood was forced by the air pressure into the central nervous system.

Bert also tried another method of treatment, viz. the administration of pure oxygen for the purpose of washing out the excess nitrogen from the body. Here we have the genesis of the idea of using pure oxygen to hasten the decompression process in connection with the latest aid to deep diving—the Davis submersible decompression chamber, which will be described later.

Bert's method of a slow, even rate of decompression was in general use until 1907, but, as we have already stated, it was not always successful; there were still many victims of compressed air illness.

In the meantime, however, after Paul Bert's death, a number of eminent physiologists and specialists had been working at the subject, the late J. S. Haldane (1860-

Fig. 1. Diving tank as erected in H.M.S. *Excellent*, Portsmouth, in which recruit divers received initial training. Presented by Siebe, Gorman & Co. to the Royal Navy about fifty years ago and now re-erected in H.M.S. *Vernon* for underwater cutting and welding instruction

1936),* H. von Schrotter,† Leonard Hill,‡ Greenwood, McLeod, Lorrain-Smith, Boycott, G. C. C. Damant, R. H. and R. W. G. Davis of Siebe, Gorman & Co., etc. Hill and his colleagues, Greenwood and McLeod, using Siebe, Gorman & Co.'s experimental plant, confirmed Paul Bert's original work, which showed that an excess of nitrogen is dissolved in the blood at high atmospheric pressure. They also discovered that there is the same excess in the urine, and Hill observed directly the sudden appearance of gas bubbles in the capillaries of the frog's web when the animal was decompressed from a high pressure and their disappearance on recompression.

## FIRST ADMIRALTY DEEP DIVING COMMITTEE AND PROFESSOR J. S. HALDANE'S SYSTEM OF STAGE DECOMPRESSION

In 1905, the Admiralty appointed a Committee, under the chairmanship of Captain F. T. Hamilton, M.V.O., R.N., to consider proposals which had been made by Professor John Scott Haldane, F.R.S., to enable men to dive in 30 fathoms of water and do a normal amount of work, without suffering the respiratory distress, occasional loss of consciousness, and danger from compressed air illness, which had hitherto, except in the cases of a few men of exceptional skill and endurance, prevented divers doing useful work at more than 15 or 20 fathoms. Haldane had recently discovered the effect of carbon dioxide when breathed at high pressures and, becoming the scientific member of the Committee, arranged a series of experimental dives at Portsmouth in which, for the first time, samples of air were collected from divers' helmets during the performance of measured work at various depths. Analysis of these samples showed that the respiratory distress experienced on the bottom was entirely due to the pressure of $CO_2$ in the helmet air, and could be obviated by increasing the supply of air in direct proportion to its increase in absolute pressure. The important rule was established that, for efficiency, a diver needs an air supply of at least one and a half cubic feet, *measured at the existing pressure*, per minute. When this minimum ventilation had been assured by new methods of testing the air pumps, and by coupling up additional pumps when necessary, it was found that divers no longer suffered from the physical distress which had formerly been vaguely attributed to "pressure", but were able to work in comfort for long periods at the greater depths. The problem of how to bring them safely to the surface remained, and it is interesting to read the highly original reasoning by which Haldane solved it, and on which he based his system of "stage" decompression which has since been adopted by all Navies and employers of deep divers throughout the world, to say nothing of caisson and tunnel workers in compressed air.

Haldane wrote: "The formation of bubbles depends, evidently, on the existence of a state of supersaturation of the body fluids with nitrogen. Nevertheless there was abundant evidence that, when the excess of atmospheric pressure does not exceed about one-and-a-quarter atmospheres, there is complete immunity from symptons due to bubbles, however long the exposure to the compressed air may have been, and however rapid the decompression. Thus, bubbles of nitrogen are not liberated within the body unless the supersaturation corresponds to more than a decompression from a total pressure of two-and-a-quarter atmospheres to a total pressure of one atmosphere (i.e. that normally existing on the surface of the earth). Now the volume of nitrogen which would tend to be liberated is the same when the total pressure is halved, whether the pressure be high or low. Hence it seemed to me probable that it would be just as safe to diminish the pressure rapidly from four atmospheres to two, or from six atmospheres to three, as from two atmospheres to one. If this were the case, a system of stage decompression would be possible and would enable the diver to get rid of the excess of nitrogen through the lungs far more rapidly than if he came up at an even rate. The duration of exposure to high pressure could also be shortened very considerably without shortening the period available for work on the bottom."

Haldane's theory was tested in a long series of experiments on goats, conducted by Professor A. E. Boycott, F.R.S., and Lieutenant G. C. C. Damant, R.N.,§ in a pressure chamber at the Lister Institute. Having been found to be true within the limits of

* "Respiration", J. S. Haldane and J. G. Priestley, Oxford University Press.

† "Luftdruck Erkrankungen", Vienna, 1900.

‡ "Caisson Sickness."

§ Later Captain, C.B.E.

pressure available (about 80 lbs. per square inch) it was embodied in a set of decompression tables calculated by Professor Haldane for the use of human divers, and all was ready for real diving under the new conditions. Working from H.M.S. *Spanker* in Scottish waters, the Committee's experimental officers, Mr. A. Y. Catto, Commissioned Gunner, R.N., and Lieutenant G. C. C. Damant, R.N., dived at depths which were progressively increased to 35 fathoms without oppression or ill-effects of any kind, and with full power of moving freely on the bottom and doing work. So far as is known, this was the first time that such a depth had been attained. Nothing deeper was attempted because the limit of what could be done on hand pumps had been reached. Three pumps were coupled up to each diver, each pump being manned by six men who had to be relieved at five-minute intervals in order to keep up 25 revolutions per minute against 92 lbs. pressure. These pumps and all the equipment were supplied by Siebe, Gorman & Co.

Following the report of the Committee, the Admiralty adopted all its recommendations and authorized diving to the new limit of 34 fathoms on hand pumps. Only those who have dived deeply under the old conditions can realize the change brought about by this Committee's work, or properly appreciate the resolution and endurance displayed by such famous old-time divers as Lambert and Erostarbe (see pages 354 and 355). It was decided to publish the Committee's report in the form of a blue book available to the public at large. The Committee's conclusions were universally accepted and it became the foundation of all later improvements in diving, both at home and abroad.

Haldane's diving tables, somewhat amplified and re-arranged, will be found on pages 100-108, with an explanation on page 94. At the time they were issued, divers could only be decompressed "on the shot-rope", and, as this is a tiring process, dives which would entail more than half-an-hour's decompression were not permitted. Since, however, accident or emergency might compel such dives to be made, the tables provided decompressions for them "below the black line". These decompressions were deliberately shortened below the theoretical standard so that exhaustion might be avoided at the cost of some liability to the less serious symptoms of compressed air illness.

## SECOND DEEP DIVING COMMITTEE APPOINTED BY THE ADMIRALTY

After some years of successful diving under the new conditions, it was appreciated that still greater depths could be reached, and longer dives made, if the fatigue and exposure of the consequent long decompressions on the shot-rope could be got rid of. In 1928, the author designed and built a Submersible Decompression Chamber (see Chapter 7, page 136) which not only allowed of the diver being decompressed in comparative comfort, but enabled him to breathe oxygen in such a way as to shorten the process by nearly 50 per cent. The author had also invented the injector type helmet (page 146) which seemed particularly suitable for keeping down the partial pressure of $CO_2$ in the helmet at great depths, without an inconveniently large current of ventilating air. It was probably the appearance of these new appliances which led the Admiralty in 1930 to appoint a committee to recommend in detail what equipment was necessary to enable useful work to be carried out by divers at depths of at least 50 fathoms. The successive Chairmen were Captain F. A. Buckley, R.N., Captain (now Admiral Sir Francis) Pridham, K.B.E., R.N., and the late Captain G. W. T. Robertson, R.N. Included among the members were Sir Leonard Hill, F.R.S., LL.D., and Mr. (now Sir) Robert H. Davis.

In experimental diving from H.M.S. *Tedworth*, it was soon found that, using the Davis inventions, divers could descend to 50 fathoms without much difficulty, and that oxygen could be safely breathed during the greater part of the decompression and would shorten it. But unfortunately, in the earlier experimental dives, the Committee discarded the Haldane system of decompression and tried another which failed to protect the diver. At this point, the author, in view of the proved success of the Haldane tables up to 34 fathoms depth, urged that their principle should be retained as the basis for calculating extended tables to cover the greater depth of 50 fathoms now aimed at. To this end, in his capacity as head of Siebe, Gorman & Co. Ltd., and on his own initiative and at his own cost, he engaged Captain G. C. C. Damant, C.B.E., R.N. (retired), to tackle the problem. The author, having helped with the work of the first Committee, knew that Damant had worked in close collaboration with Haldane, and was fully conversant with the reasoning and calculations which had produced his original decompression tables.

Haldane had found that, within the range of his tables, it was safe to reduce the external absolute air pressure to one half of that at which the diver's body was saturated, and that, as his saturation fell under the pressure difference, the external pressure could safely be reduced at such a rate as to maintain this proportional difference and so continue the process of desaturation. Since some parts of the body absorb gases more quickly than others which have a slower circulation, certain assumptions have to be made in estimating the degree of saturation of a diver on leaving the bottom and during the successive stages of decompression and the calculation of tables is rather complicated.*

From the first, Haldane had realized that halving the absolute pressure might not be safe at greater depths than had yet been explored, and in 1908 wrote: "Whether the law holds good for pressures much exceeding six atmospheres is still doubtful, as no experimental data exist."†

In spite of this characteristic caution, later writers have mistakenly credited him with asserting that rapid decompression from *any* pressure "2n" to pressure "n" is safe.‡

## EXTENSION OF THE HALDANE TABLES TO SUIT DEPTHS UP TO FIFTY FATHOMS

The first thing to be ascertained was whether a simple extrapolation of the existing diving tables to cover the new and greater depths would provide safe decompression. Goats were chosen as the experimental animals, and the author provided two new steel chambers at his works in which they could be exposed to pressures equivalent to 50 fathoms depth and beyond. Means were also supplied for flushing out these chambers with oxygen, so that, when required, the animals could breathe that gas at 97 per cent purity.

Damant, assisted by the author's eldest son, R. W. Gorman Davis, subjected 12 goats to a standard "dive" of 30 minutes at 300 feet pressure, plus three minutes "to reach the bottom", and decompressed them, still breathing air, on the Haldane system, which gave the first stage at 120 feet pressure, and a total time of 122 minutes. Several of the animals developed compressed air illness, showing that the decompression was inadequate. The experiment was repeated with the goats breathing oxygen during their decompression, from the 60-feet stage onwards. The allowance for the oxygen effect reduced the length of the decompression to 64 minutes, and again the result was unsatisfactory, and it had to be accepted that at 50 fathoms, or ten atmospheres pressure, Haldane's two to one law no longer held good, a finding for which he had prepared us.

During the tests, it had been noticed that the first symptoms of illness often appeared at an early stage of the decompression, which suggested that the initial drop of pressure, from 300 to 120 feet, was too great. This could be remedied by calculating and using a Haldane stage decompression on the assumption that, for these greater depths, the safe pressure reduction was in the ratio of 1·75 to 1, instead of 2 to 1, as at lesser depths. When this was done, the decompression after a standard dive came out with the first stage at 150 feet and a duration of about three hours, if air were breathed throughout. This was for goats; for men the time would be still longer and almost impracticable in real diving from a ship. Evidently the decompression must be

* It is explained in a pamphlet "Calculating Decompressions on the late Professor J. S. Haldane's system", written by Captain G. C. C. Damant, and published by Siebe, Gorman & Co. Ltd. This was written with special reference to the case of tunnel workers at comparatively low pressures. As will be seen, other factors have to be used and allowances introduced for the high pressures to which deep divers are exposed, but the method of calculation is the same.

† Boycott, Damant and Haldane. Journal of Hygiene, Vol. VIII, 1908.

‡ Eggleton, Elsden, Fegler and Hebb. Journal of Physiology, Vol. 104, 1945.

shortened as much as possible by oxygen breathing which, it was calculated, would in this case reduce the duration to 87 minutes. When the new decompression was tested on 85 goats, much better results were obtained, and such symptoms as appeared, did so towards the end of or after decompression, when illness is more manageable than at the beginning. Nevertheless, perfect results were required, and to get them it was found necessary to make arbitrary additions to the calculated oxygen times. In Haldane's view, this difference between theory and practice depends on the fact that the breathing of oxygen at high pressures (from three atmospheres downwards) during decompression, slows up the circulation of the blood very considerably, and so hampers the discharge of gas from the lungs, though it still remains much more rapid than if air were being breathed. After a satisfactory table had been worked out for goats, it was modified and lengthened so as to suit men, who were then subjected to the same standard "dive" in the steel chambers as the goats had undergone, as well as other "dives" of various durations and pressures. The results were entirely satisfactory, none of the ten divers showing the slightest symptoms of compressed air illness. When the proceedings were translated from the steel chambers at the author's old works in London, to the waters of Loch Fyne, and real diving took place from H.M.S. *Tedworth* in 50 fathoms and below, it was found that some further modifications of the tables had to be made to suit the altered conditions. The final tables, giving decompressions while breathing oxygen at all depths from 120 to 300 feet, were adopted by the Admiralty, and were the first of their kind. They will be found on pages 160 to 179 of this book

In 1931, the tables, in conjunction with the author's submersible decompression chamber and injector helmet, were tested in a preliminary series of deep water dives from H.M.S. *Tedworth* in Loch Fyne. A confirmatory series took place in 1933, by which time a great number of successful dives had been made in depths of from 260 to 320 feet without any accident, and a standard Naval procedure evolved for controlling this specialised work.

The results of the second Admiralty Committee's work, in collaboration with Siebe, Gorman & Co. Ltd., were thus very successful and marked another milestone in the history of diving, adding greatly to the efficiency and range of diving in the Royal Navy and to the prestige of Great Britain as leader in the development of deep diving methods and appliances.

That the use of the two systems, the first initiated by the late Professor Haldane for depths to 210 feet, and the second by Siebe, Gorman & Co. Ltd., in association with Captain Damant, for depths to 300 feet, has been abundantly justified is proved by the fact that compressed air illness in the Royal Navy, and in foreign navies which have adopted the system, is now practically unknown. Any isolated cases which have occurred have been due to failure from one cause or another to carry out the instructions.

It is the practice on most deep diving works today to have available a recompression chamber for use in curing cases of compressed air illness which may occur as a result of inadequate decompression. If no chamber is available, the best plan is to send the diver down again till the symptoms disappear. But in that case very cautious ascent, in accordance with the instructions, is necessary to ensure his safety, because once bubbles of any great size have formed it takes a considerable time to redissolve them. This is dealt with in more detail later in the book.

## LATER EXPERIMENTAL WORK

Further experimental work was delayed by the Second World War, but it was resumed in 1946 by the newly-formed Admiralty Experimental Diving Unit, under the direction of Commander W. O. Shelford, R.N., *Superintendent of Diving. This unit, as explained more fully in a later chapter, had its origin in Siebe, Gorman & Co.'s Experimental Department at Tolworth, where much valuable work was done during the last three years of the war; after the war it was moved to H.M.S. *Vernon* at Portsmouth.

* Now Captain, R.N. (Retd.)

The new experiments had as their object a further extension of the maximum depth for flexible suited divers beyond the 300-feet limit established by the 1930-34 Deep Diving Committee. The experiments were largely based on the oxy-helium technique developed by the United States Navy.

In this method, helium, a light inert gas, is used to supplant the nitrogen content of ordinary air and thus serves to eliminate the adverse physical and mental effects of breathing nitrogen under great pressures. At the same time, the use of synthetic gas mixtures enables suitable reduction to be made in the oxygen content of the mixture breathed, so that the dangers of oxygen poisoning due to the high partial pressure of oxygen in air at over ten atmospheres pressure are also eliminated.

Preliminary experiments at Tolworth and Portsmouth resulted in the development of a technique for supplying oxy-helium mixtures to the Siebe, Gorman Standard Deep Diving Dress, and for using the Davis Submersible Decompression Chamber in conjunction with the United States tables.

In 1947, oxy-helium diving in open water was carried out for the first time in this country from H.M.S. *Deepwater* in Loch Fyne. Although unsuccessful in obtaining any increase in the maximum depth achieved, this series of trials taught many valuable lessons. From experiments conducted in the winter of 1947-8, under the technical supervision of Surgeon Lieutenant-Commander W. M. Davidson, R.N.* and Surgeon Lieutenant D. W. H. Barnes, R.N.V.R., it became evident that previously accepted standards of freedom from carbon-dioxide (see Chapter 2) in the deep-diving apparatus were inadequate for the great depths now envisaged, and further modification of the air-purification system of the dress became necessary and was carried out by Siebe, Gorman & Co. The necessity for re-working parts of the oxy-helium decompression tables was also shown.

Further and successful trials were carried out from the Royal Navy's new and specially designed deep diving vessel, H.M.S. *Reclaim*, in 1948, again in Loch Fyne. As a result of these trials, all previous depth records were broken when Petty Officer W. Bollard made a successful descent to 540 feet (90 fathoms), reaching the bottom of the loch at a depth never before achieved by a flexible-suited diver in open water, and which was in fact in excess of the designed depth of any existing armoured diving dress.

## USE OF OXYGEN FOR DECOMPRESSION AND ITS EFFECT AT HIGH PRESSURES

As already mentioned, Paul Bert was the first to give pure oxygen to animals with the object of accelerating the expulsion of nitrogen from the tissues after they had been exposed to high air pressure.

Much experimental work in this connection was carried out by Lorrain-Smith, von Schrotter, Bornstein and by Leonard Hill, and Damant in association with Siebe, Gorman & Co.

Paul Bert's pioneer work has withstood the test of time in the most impressive manner. He showed that oxygen at increased pressures was highly poisonous and that no living creature was exempt.† Larks exposed to 15-20 atmospheres of air convulsed and finally died. In a large series of experiments Bert showed that the amount of oxygen present was the decisive factor in the immediate effect of air or any mixture of nitrogen and oxygen. Lorrain-Smith (1899) next demonstrated that animals breathing oxygen at moderately high pressures over prolonged periods suffered severe and finally fatal lung damage. This is probably due to the direct effect of the oxygen upon the lung membranes, (See pages 12-13 regarding the effect on humans.)

With regard to human experiments, the first recorded case of oxygen poisoning was that of Bornstein (1912), who suffered spasms of the legs while exercising and breathing oxygen at three atmospheres absolute in the Elbe tunnel works. In 1933 two subjects‡ breathed oxygen at four atmospheres absolute in the decompression chamber on board H.M.S. *Tedworth* during experiments in Loch Fyne in collaboration with Siebe, Gorman & Co. Both had twitching of the face after 16 and 13 minutes

* Since promoted Surgeon Commander.

† Deep-sea fish secreting oxygen in the swim bladder must be immune so far as concerns the tissue of the bladder.

‡ Captain Damant, R.N. (retired) representing Siebe, Gorman & Co. Ltd., and Surgeon Lieutenant Phillips, R.N.

# THE LECTURE ROOM AT SIEBE, GORMAN & CO.'S WORKS

Fig. 2

The following appears over the entrance:

*"Welcome to all invited here;*
*We hope to make our lectures clear*
*on*
*Everything for safety everywhere,*
*On land, submerged and in the air*
*In earth's dark bowels, in ocean's depths,*
*In attenuated stratosphere,*
*In foul and poisonous atmosphere."* R.H.D.

# THE CHEMICAL LABORATORY

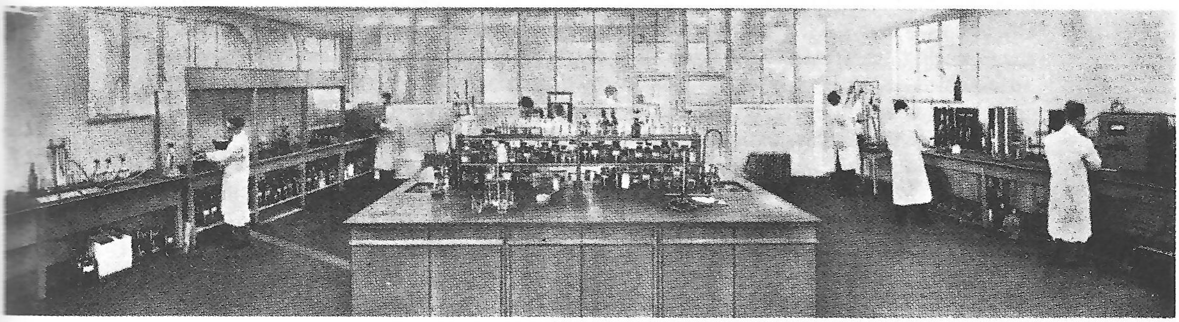


Fig. 3

respectively and one finally convulsed. This convulsion was indistinguishable from an epileptic attack. In 1934-6 Behnke and co-workers carried out a series of human experiments. Only two exposures were made at four atmospheres (99 feet sea-water), one subject collapsing after 43 minutes and the other convulsing after 44 minutes. At three atmospheres (66 feet sea-water) four subjects breathed oxygen for three hours without any demonstrable ill-effects. In a second series at this pressure the experiments were continued into the fourth hour, when three out of four subjects had dizziness and sickness (nausea). These results were published and obtained widespread recognition and acceptance. It was assumed that men at comparative rest, as in these experiments, were safe breathing oxygen for at least 30 minutes at four atmospheres (99 feet sea-water) and for at least three hours at three atmospheres (66 feet sea-water). In time, even the proviso concerning rest was omitted.

However, when the "human torpedo" oxygen divers were training in 1942 a number of cases of unconsciousness occurred in oxygen breathing apparatus at depths and in times which were then considered to be safe. Consequently a very large series of experiments were carried out by the Royal Navy in the experimental department of Siebe, Gorman & Co. As a result of over 2,000 experiments, supervised by Surgeon Lieutenant-Commander K. W. Donald, D.S.C., R.N., the knowledge concerning oxygen poisoning in man has been greatly enlarged. The most important finding was that if a diver is breathing pure oxygen under water he is more prone to oxygen poisoning than if he is breathing oxygen at the same pressure in a compression chamber, without his suit and surrounded by compressed air. It was shown to be unsafe to dive deeper than 33 feet (of sea-water) when breathing oxygen. In the Second World War oxygen divers did occasionally go deeper, but only for a short time. The limitation of oxygen divers to 33 feet did not greatly handicap the underwater commandos such as "human torpedoes", midget submarine divers, and underwater beach-clearance, demolition and sabotage parties. The reason why this limit had to be made absolute and that decreasing times of safety at increasing depths could not be given, was due to the extreme variation in normal healthy men's sensitivity to oxygen poisoning at depths over 33 feet. To make matters even worse the same diver may be safe for an hour or more at a certain depth one day and be acutely poisoned in about ten minutes at the same depth some days afterwards. It was also clearly shown that hard work increased the danger of oxygen poisoning considerably. Even at 33 feet an experienced diving officer will limit the periods of extremely hard work. Besides, if the absorbent canister has the slightest fault then there will be increased carbon-dioxide in the circuit and this is not only dangerous in itself, but will cause oxygen poisoning to occur far sooner. It is obvious, therefore, why the Royal Navy and Siebe, Gorman & Co. are so insistent that the canisters must be always serviced with scrupulous care. It has also been shown that if the water is very warm (87° F.) or very cold (40° F.), resistance to oxygen poisoning is slightly less.

The safety of breathing oxygen under increased air pressure becomes of considerable importance when oxygen is used in a surface or submerged decompression chamber to accelerate the elimination of nitrogen or helium after deep dives. The British procedure of getting the diver into the Davis submerged chamber is safer than the American method of pumping oxygen down to the diver on the shot rope, where he is far more prone to oxygen poisoning. Cases of poisoning have been reported in such instances. However, in the compressed air of the chamber the diver can breathe oxygen for reasonable periods even at depths of 60 feet. If he developed oxygen poisoning, and this has not happened, he would be safe, and with an attendant.

Special problems arose with underwater swimmers, or "Frogmen", and these are referred to in Chapter 15.

The symptoms of oxygen poisoning were first carefully studied in compressed air chambers, as the subjects can be easily observed under such conditions. Most people appear pale and under slight stress when breathing oxygen under pressure. The following symptoms are the most usual when acute poisoning is threatening:

lip-twitching, nausea, dizziness, apprehension, indifference, choking sensations, lights before the eyes and, occasionally, sounds such as knocking are heard. The most important warning symptom is that of lip-twitching which usually spreads over the face and, although this may occur a considerable time before acute poisoning, it means in most cases that convulsions are imminent. Twitching of other parts of the body can occur, but this is unusual. In a number of cases convulsions occurred without any warning whatsoever. The symptoms under water are a little different, but lip-twitching is usually the first trouble noticed by the diver, and less often he will complain of nausea and dizziness. The unusual equipment and surroundings appear to mask the more subtle feelings of abnormality, and thus he has less warning of approaching poisoning. All divers are agreed that even at considerable depths they remain clear-headed and are capable of efficient and hard work and, even though they are highly experienced, they are always surprised when they finally succumb, except when they have been warned by severe lip-twitching. If the diver works hard, nausea and dizziness are more frequent. Thus, although the signs and symptoms of oxygen poisoning are now well known, they vary so greatly that no particular instructions can be given that guarantee a reasonable margin of safety. This fact combined with the inability to give definite times of safety at different depths makes the use of undiluted oxygen at pressures where it is poisonous (over 33 feet sea-water, two atmospheres absolute) totally undesirable and very dangerous.

As a result of these conclusions, self-contained divers who go deeper than 33 feet have to use other types of apparatus. In escapes from submarines the use of oxygen breathing is justified as the exposures are usually relatively short (see Chapter 14). In chamber escapes the time of oxygen breathing at high pressure is only a minute or so. In compartment flooding escapes, oxygen may be breathed a little longer, but as the person's head and shoulders are above the water whilst waiting his turn the risk of oxygen poisoning is far less.

The damage to the lungs, which has been demonstrated in animals after long exposures to moderate pressures of oxygen, has been carefully considered in relation to diving. During the war it was possible to observe the lungs of men who dived to considerable depths on oxygen for several hours a week, over long periods. No lung damage of any sort was found and it can be said with confidence that oxygen breathing, as encountered in all types of diving, will not cause any harmful changes in the lungs. There is also a belief, particularly on the Continent, that frequent oxygen breathing will cause enlargement of the heart. This, too, has been shown to be untrue.

## GAS MIXTURES FOR DIVING

**Oxygen and Nitrogen.** The great advantage of oxygen breathing apparatus is that a self-contained diver can have a maximum endurance for a minimum load of apparatus carried by him. During the war it became necessary that self-contained divers should go deeper than 33 feet, particularly for mine disposal. Paul Bert had already discovered a fact that allowed this problem to be solved. He had stated that the effect of any gas upon a person could be accurately foretold by consideration of the pressure of that gas, either alone or in any mixture of gases. Now, if a mixture of oxygen is used (other than air, which is 21 per cent oxygen, 79 per cent nitrogen) it can be so adjusted that at any depth the partial pressure of oxygen is no more than that breathed by a diver at 33 feet. This, for depths up to 160 feet, allows considerably more oxygen to be used than is present in air and the diver can thus carry enough of this mixture to last him for a considerable time (90 minutes or more). The fact that there is less nitrogen in the mixture than in air allows him to dispense with decompression stops that would be necessary to prevent bends if he were diving on air. It is possible with any mixture at any depth to say what pressure of air his nitrogen pressure is equivalent to and what pressure of pure oxygen his oxygen pressure is equivalent to. Thus the risks of oxygen poisoning and bends are easily assessed and the decompression necessary can also be precisely determined, using the well-tried air tables.

An example that will illustrate how this works is the mixture used by the "P-parties" (human mine sweepers).* They breathed from a rubber bag (counter lung) into which was fed 3 litres of 75 per cent oxygen, 25 per cent nitrogen mixture per minute. If we assume an average oxygen consumption of one litre a minute, then it can be easily shown that they will be breathing 62·5 per cent oxygen from the bag. At a depth of 74 feet they will only be breathing the same amount of oxygen as a pure oxygen diver at 33 feet and thus they will not be in danger of oxygen poisoning up to the greater depth. Usually they average a higher oxygen consumption than this and will be safer to even greater depths. The same diver will be breathing 37·5 per cent nitrogen and he will be exposed to the same nitrogen pressure as an air diver at 14 feet. Thus there is no danger of "bends". If this diver worked harder and used more oxygen, the nitrogen in his breathing bag would go up and increase his equivalent air depth. However, he has, as shown, a considerable margin of safety.

It can be seen what an intriguing problem this mixture diving becomes. One has to calculate what is the most economical flow of gas, what percentage of oxygen must be used to avoid oxygen poisoning—but not to threaten a hard-working diver with shortage of oxygen—and what percentage of nitrogen can be safely employed that will allow immediate or rapid return to surface.

For deeper work in tidal waters, a rigid helmeted suit was used. The helmet was ventilated by an injector system (see Chapter 7), the whole suit comprising a self-contained mixture-breathing suit originated some years before the war by Sir Robert Davis, and in which the mixture was so regulated that the diver did not breathe more than two atmospheres absolute of oxygen at the depth in which he was working. These divers were supplied with two different mixtures at six litres per minute. The first was 55 per cent oxygen and 45 per cent nitrogen, with which there was no risk of oxygen poisoning down to 100 feet. At this depth the equivalent air depth was 58 feet, and only a brief stop for five minutes at 10 feet was necessary after a 30 minutes' dive. If there was any urgency owing to dangers of mine explosion this stop could be omitted with little risk of "bends". A 30-minute dive on air to this depth would necessitate stops totalling about 21 minutes safely to reach surface. For greater depths a 45 per cent oxygen, 55 per cent nitrogen mixture was used. This was safe as regards oxygen poisoning up to 160 feet. As, however, the percentage of nitrogen is higher the stops necessary are a little longer but still much less than with air. A dive to 120 feet for 30 minutes required three minutes' stop at 20 feet, and eight minutes at 10 feet (total 11). A similar dive on air would necessitate stops totalling 26 minutes.

One of the most difficult problems was to find a reducing valve which gave the same flow of mixture (as measured at atmospheric pressure) at any depth. If this flow varied, then the use of mixtures became fortuitous, complicated and somewhat dangerous. Fortunately, Siebe, Gorman & Co. designed and provided such a reducing valve, and great credit for the remarkable operational record of these gas mixture diving sets must go to the firm.

**Nitrogen Intoxication or Narcosis.** When the British Admiralty Deep Sea Diving Trials to 320 feet were commenced in 1930, new symptoms appeared which had not been previously reported in underwater work. Divers were on different occasions over-cheerful, hysterical or somewhat stupid and a number completely lost their memory and power of judgment. This was attributed to two factors: the increased pressure of oxygen and the excessive amount of carbon dioxide in the divers' helmets. Other workers attempted to explain these strange occurrences on psychological grounds (suppressed claustrophobia, etc.). In 1935 Behnke, in America, first advanced the theory that the increased pressure of nitrogen was the cause of these mental disturbances in deep dives on atmospheric air. It was also suggested that the reason why nitrogen acted in this way was the fact that the gas is far more soluble in fatty organs (i.e. brain and spinal cord) than in water (i.e. blood and tissue fluid). This theory had already been used to explain the particular effect of such anæsthetics as ether and chloroform.

* Now renamed "Clearance Divers".

There are alternatives to this theory, and the precise reasons for the effect of nitrogen at high pressures have yet to be established.*

In the Admiralty's Deep Diving Trials of 1946-48, it was clearly demonstrated that divers on oxy-helium mixtures, as opposed to those on air, remained far more rational and mentally efficient on the bottom at any depth over 240 feet, and showed no signs of mental deterioration down to depths as great as 540 feet. At the same time, it was also shown that *when ventilation and $CO_2$ elimination are efficient*, nitrogen narcosis will not necessarily give rise to any serious mental effects such as amnesia, disassociation or exaggerated claustrophobia.

**Oxygen and Hydrogen Mixtures.** The eminent American physicist and chemist, Elihu Thompson (of English parentage) (1853-1936), first proposed the breathing of hydrogen and oxygen, but, while perfect for

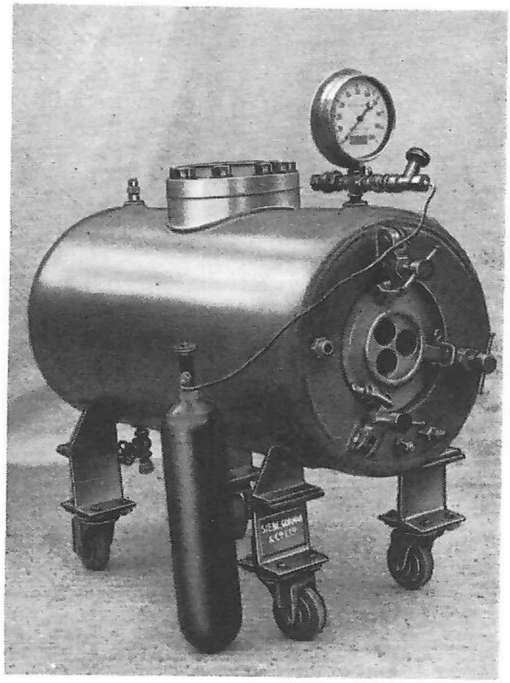


Fig. 4. High Pressure Experimental Chamber in Siebe, Gorman & Co.'s Works for small animals: Cats, Guinea-pigs, Rats, etc.

Fig. 5. Goat House and Pig Sties at Siebe, Gorman & Co.'s Works (insets: some of the subjects for experiment)

*Divers are often men with a sense of humour, hence the christening of strong-smelling goats with fragrant names such as "Lavender", "Rosemary", etc.*

* Some think that the intoxication is due to $CO_2$ retention in the body and not to excess of nitrogen.

respiration, this mixture might be liable to explosion unless the correct percentages were very strictly maintained for different depths of water.

The late Hermann von Schrotter, the Austrian physiologist, wrote a good deal on the subject and conducted a number of experiments and designed apparatus for supplying mixtures of hydrogen and oxygen to divers.

The most recent experiments were those carried out by Arne Zetterstrom, a Swedish experimentalist who, using mixtures of hydrogen and oxygen, made a number of dives. Unfortunately, this able young scientist was killed in a diving accident in 1944; his death was not, however, attributed to the use of hydrogen. Professor J. B. S. Haldane, F.R.S. (son of the late J. S. Haldane), before the Admiralty Experimental Diving Unit's work in Siebe, Gorman & Co.'s research department, also breathed a mixture of these gases.

**Oxygen and Helium Mixtures.** The first suggestion for the use of oxygen and helium as a breathing mixture for deep diving was again that of Elihu Thompson. It has enabled record-breaking dives in the flexible dress to be carried out, and is dealt with fully in Chapters 7 and 8.

## THEORETICAL ADVANTAGES OF ARMOURED (METAL) DIVING SUITS

In the foregoing, it has been assumed that the diver is wearing a flexible dress with metal helmet, on the principle invented by Augustus Siebe, and that he is breathing compressed air or mixtures. At the same time, it is obvious that if means could be found to enable a diver at great depth to breathe air at atmospheric pressure all danger of compressed air and other illnesses would vanish. Many attempts (see Chapter 10 and Part II, Chapter 4) have been made to accomplish this by means of what are generally called "Armoured Dresses".

The ideal diving apparatus would be one:

1. Capable of resisting external pressure of water at great depth, although containing air at atmospheric pressure only.
2. Enabling the wearer, by his own unaided efforts, to move freely about under water, and in a tideway; and to use tools, etc, in the same manner as a diver equipped with the Siebe flexible dress.

The first problem presents little difficulty, the second has yet to be solved.

During the past sixty years many metal diving dresses with articulated limbs have been designed, and some actually made, both in England and abroad, with the object of fulfilling these conditions; but nearly all of them have been so cumbersome and so lacking in flexibility that they have allowed the diver but very restricted movement on the sea-bed. They have, therefore, proved themselves but little more than observation chambers. One of the best of such suits produced was that designed by Gall in association with Neufeldt and Kuhnke. But, owing to its bulk and restricted movements, armour can never supplant the flexible diving dress for the great majority of diving operations.

The author in 1928 hired from the makers a set of the latest armour for his own examination and tests, and afterwards placed it at the disposal of the Admiralty for trials in deep water. The trials took place in a depth of nearly 300 feet, with results which were given in a full report by the Captain of H.M.S. *Excellent*, and which are summarized as follows:

"In tidal waters the dress proved of little value because in tides of over half-a-knot the diver was constantly swept away from his work. If he made himself heavy enough to withstand the tide, he sank in the mud and had great difficulty in moving. Only on a hard and level bottom could he attempt to carry out an elementary task. Little work could be accomplished, as the diver's immobility prevented him getting into and maintaining a satisfactory position to manipulate his handgrips. Lacking the all-important sense of touch of the hands, by means of which the flexible dress diver works, adequate light is essential with the armoured dress. The upkeep of the dress was also a constant cause of trouble and was costly. For observational purposes its advantages over the ordinary observation chamber are doubtful."

Since the war, the apparatus (precisely the same design) was acquired as a war claim from the Germans, and again tested by the Admiralty with the same results.

Another and more recent type of armoured dress was that designed by J. S. Peress. The main difference between the two types lies in the design of their articulated limbs. In the Neufeldt and Kuhnke dress, negative buoyancy is obtained by admitting water to a ballast-tank, the water being expelled by means of compressed air when the diver wishes to return to the surface. In the Peress dress negative buoyancy is obtained by a weight, which is so arranged as to be releasable when the diver wishes to ascend.

The bulkiness of the articulated limbs will be noticed in the illustrations in Chapter 10. The displacement of these is such as to give them neutral buoyancy and so to increase their mobility.*

As it has been said that the introduction of the metal diving armour would sound the death-knell of the flexible dress, we would point out how absurd such a statement is to those who know anything about the subject. For the great majority of diving operations the flexible dress will never be superseded. It has performed work, salved ships and recovered treasure worth untold millions, and it will do the same in the future. For depths then considered beyond the reach of the flexible dress, however, the metal armour has proved of some value in the past. For example, the wreck of the s.s. *Egypt*, sunk off Finisterre in 1922 with a million pounds' worth of gold and other specie on board, was located by means of this apparatus (see Part II, Chapter 1).

## DEEP SEA OBSERVATION CHAMBER (see Chapter 11)

The greater part of the work of the *Egypt* salvage, however, was carried out by the use of an observation and direction chamber on the principle of that designed by R. H. Davis over thirty-five years ago, models of which were exhibited by Siebe, Gorman & Co. Ltd., at the British Empire Exhibition in 1924. The man inside, at his lonely post 400 feet below, was the eye and brain of the operations. He was lowered to within a few feet of the wreck, and gave directions by telephone to those in charge on the salvage vessel—when and where to lower explosive charges for blasting a way through the decks to the bullion room, and how and when to operate the powerful grabs which were employed to tear away obstacles and to remove debris; while other devices were used for grabbing and hoisting the treasure itself to the surface.

A later, remarkable salvage feat achieved by means of the observation chamber was that carried out on the *Niagara* in 1941 at a depth of 438 feet off the New Zealand coast. This operation, in which gold to the value of over £2,000,000 sterling was recovered, is described in Part II, Chapter 1.

## DEVELOPMENTS IN USING THE FLEXIBLE DRESS

As already stated, the flexible diving dress gives the diver every freedom of action on the bottom, at whatever depth he may be working. He has unrestricted use of his limbs, and he is able to work in tidal waters up to about two knots—but this, of course, depends to some extent on the depth—and to perform in a few hours what it might take weeks to do in the metal armoured dress.

## THE DAVIS SUBMERSIBLE DECOMPRESSION CHAMBER

It seemed to us, therefore, that one of the immediate needs was to increase the scope of usefulness of the flexible dress by the adoption of means (1) to make it possible to go safely to greater depths; (2) to relieve the diver of the fatigue and tedium of waiting on the shot rope in mid-water during the long decompression periods; (3) to reduce to a minimum his exposure to cold and to strong currents; and (4) by shortening the actual decompression time (by giving the diver oxygen to breathe during this process) to make it possible to extend the period of useful work on the bottom. In furtherance of

* The design of Signor R. Galeazzi represents the latest form of this type of dress. Fitted with articulated limbs, in appearance similar to those of the Neufeldt & Kuhnke dress, and making use of water ballast tanks, it has been tested to over 800 feet, and is claimed to have overcome the disadvantages of the earlier suits.

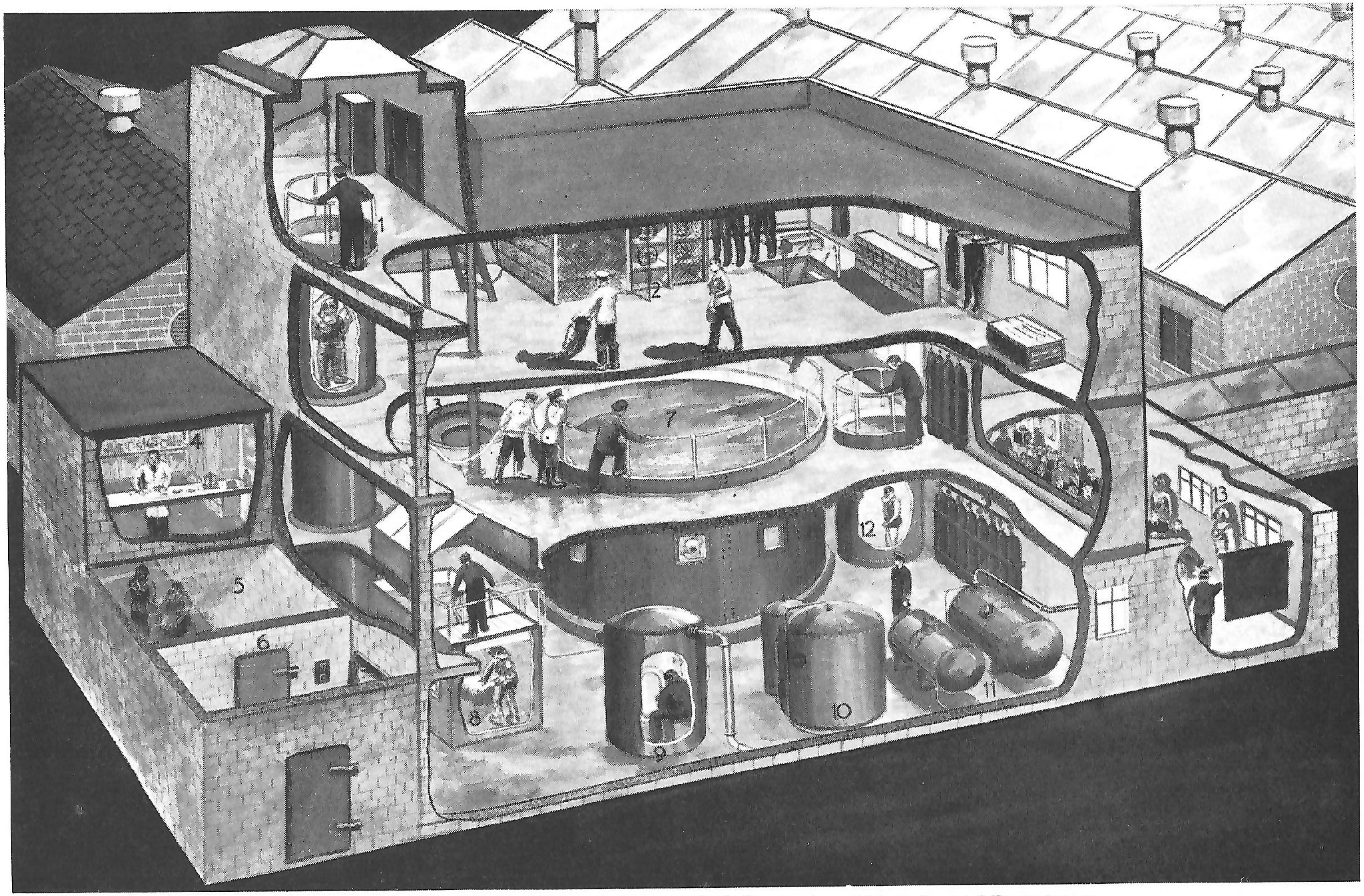



Fig. 6. A diagrammatic view of Siebe, Gorman & Co.'s Research and Experimental Department

1 Deep Diving Tank
2 Stores
3 Deep Diving Water and Air Pressure Chamber
4 Laboratory
5 Poison Gas Chamber
6 Gas Chamber Lock
7 Large Diving Tank
8 Underwater Cutting and Welding Tank
9 High Altitude Chamber
10 Pressure Chamber with Air-lock
11 Horizontal Pressure Chambers
12 Small Diving Tank
13 Lecture Room

these objects was the production, after much experiment, of the Davis submersible decompression chamber, which was submitted to the Admiralty in 1929, the preliminary trials taking place in Loch Long, Scotland, in that year.

A description of the chamber and of the method of using it is given in Chapter 7. Divers who have used it have told us what a comfort it is to know that, when they have finished their job at a great depth, they have got the submerged decompression chamber to look forward to as a sort of "halfway house", and what a relief to know that they have not to go through the long, monotonous, cold stops on the shot rope.

When the diving operations are on a large scale, Davis three-compartment stationary decompression chambers are installed in the salvage vessel to which the divers in the submersible chambers are transferred without interruption of the process, to complete their decompression. In this way, a number of divers can be kept going whenever diving is possible, for in diving operations one has to take the utmost advantage of fine weather in order to speed up the work.

## RESEARCH IN DEEP DIVING

Important experimental research work has for many years been conducted at Siebe, Gorman & Co.'s Experimental and Research Department inaugurated by Sir Robert Davis over fifty years ago in Westminster Bridge Road, London, and now located at Tolworth, Surbiton, Surrey. The establishment is unique of its kind; in no other private concern in the country can work of the varied character here undertaken be seen, and, as mentioned in other parts of the book, this department was placed at the disposal of the Admiralty during the Second World War. Here, with the aid of special plant and instruments, physiologist, physicist, chemist, mechanician and deep-diving specialists, collaborate in investigation of the various problems to be solved in connection with deep diving, work in poisonous atmosphere, high altitude flying, and the restoration of the sick (poliomyilitis, etc.) and injured. And here the apparatus required by the diver, the worker in dangerous atmospheres (the fireman, the sewerman, the gas worker, the chemical worker, the mine rescuer, the soldier, the sailor, the airman, etc.), as well as devices for the resuscitation of persons apparently drowned or asphyxiated are designed, produced and finally tested under as nearly as possible actual working conditions.

While much has been written about the exploits of users of self-contained breathing apparatus in underwater warfare, in poisonous atmospheres and at high altitudes, and praise and awards have rightly been bestowed upon them for their courage, fortitude and skill, the layman is inclined to forget the scientist whose knowledge and secret work have made the exploits of the other men possible. His courage, moreover, is no whit inferior, indeed, he runs great risk, since he has to make sure, by tests on himself and his assistants, that his theories are proved safe before the sailor, soldier, airman, miner, fireman or other worker in dangerous conditions, is allowed to wear the apparatus which scientific knowledge, research and practical experiment have evolved.

In all this work, equal credit should, we think, go to the men who undertook, at personal risk, the original experiments over the past sixty to seventy years. While due credit must be given to later experimentalists, we must remember that they have had the advantage of knowledge already gained, and of methods and appliances already tried by workers of an earlier date. The pioneers are too often forgotten when success has been ultimately achieved. Not all their work may have been entirely successful, but their failures or partial successes have often proved stepping-stones to success by later workers in the same field of research.

"*We often discover what will do by finding out what will not do.*"—*Samuel Smiles.*

Here the author would pay tribute to the men (most of whom have passed over) who took part in many of the earlier practical experiments in Siebe, Gorman & Co.'s research department: H. A. Fleuss, Alexander Lambert, E. Rayfield, W. R. Walker, J. Hines, J. Bateman, W. Webber, E. Martin, H. Sutcliffe, F. Utting, C. Oake, J. Hunt, C. H. Burwood, J. Murphy.

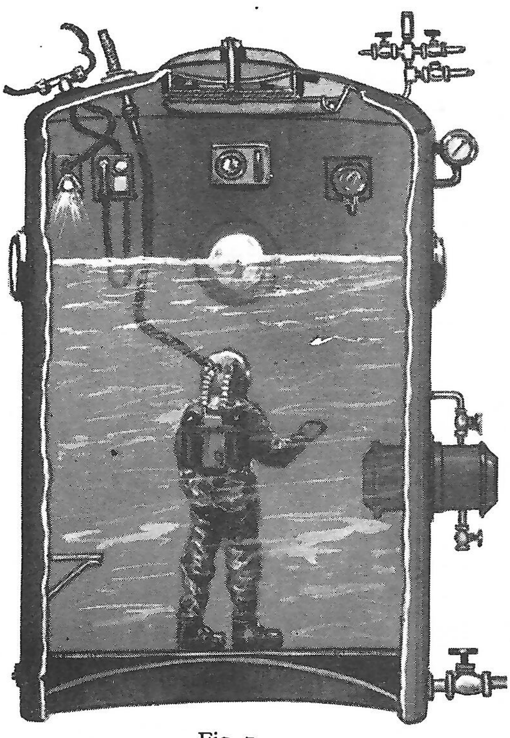


Fig. 7

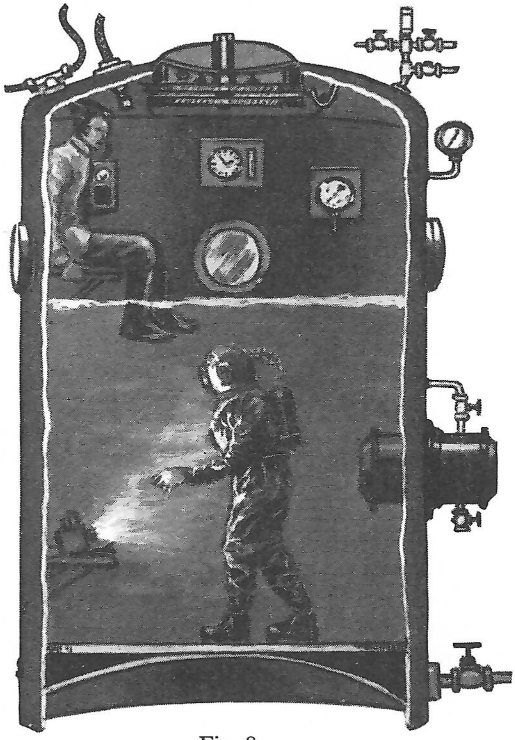


Fig. 8

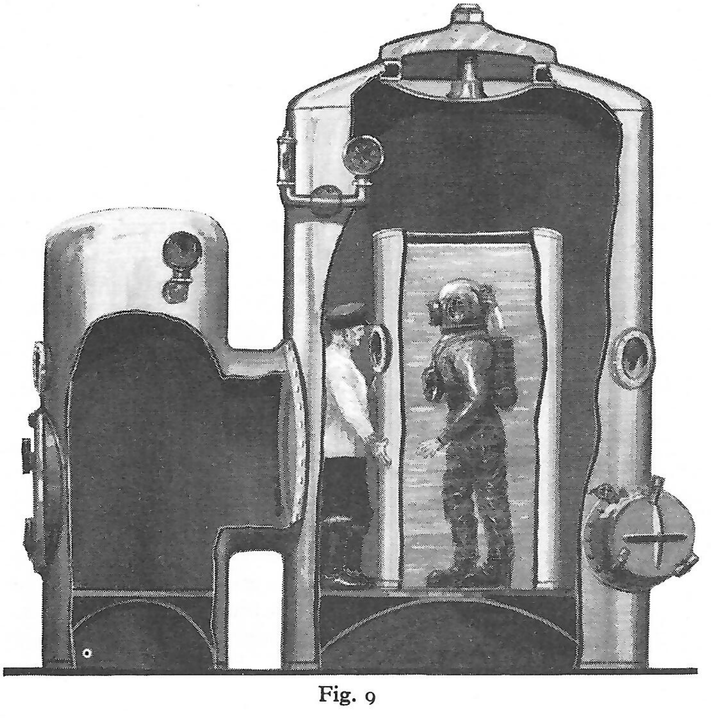


Fig. 9

When the disaster to the submarine *Thetis* occurred, J. B. S. Haldane told the author that he had a theory as to why not more than four men escaped, and offered to test it on himself. The author made the necessary preparations for the experiment in the same department.

For several days Haldane entered one of Siebe, Gorman & Co.'s test chambers and remained in it for a considerable time without fresh air, noting the gradually-rising concentration of carbon dioxide, increase of temperature and humidity, and the diminishing percentage of oxygen; his symptoms being recorded until they became unbearable and he was compelled to leave the chamber.

In this department of the Company's works training is also given in diving and in the use of breathing apparatus for work in poisonous atmosphere and high altitudes, by means of practical instruction and lectures.

It may also claim to have played its part in the lighter side of life, namely in that of the entertainment world. Frequent are the calls upon it for filming and broadcasting, including television, and not a few voices well-known to radio listeners have gone over the air from the Experimental Tank Room, both from above and below the water. A recent broadcast was that of the well-known Piddington thought-reading act, in which Mrs. Piddington performed her part submerged in a diving bell in one of the tanks whilst her husband carried out his part at the B.B.C. studio in London, fifteen miles away.

## DEEP DIVING EXPERIMENTS

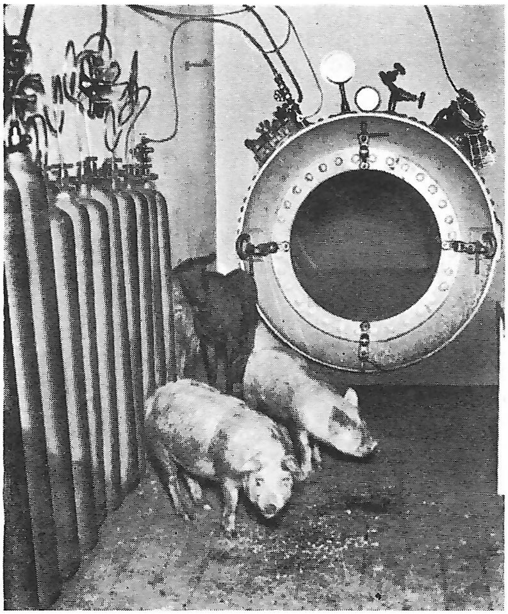
So as to avoid unnecessary risk to human life, it is our practice, before testing any new system of deep diving or decompression on men, to make preliminary tests on animals—from mice, rats and guinea pigs, to porkers, goats and baboons. In Figs. 10 and 11 is shown the entrance to one of the steel high-pressure chambers, with pigs and goats waiting their turn for treatment. Fig. 12 shows another chamber (large enough to hold several men comfortably) with its entrance door closed. Batteries of cylinders of compressed oxygen, nitrogen, helium and other gases are in the foreground. Fig. 6 gives a general impression of the Experimental Department and shows the diving tanks, used for experimental work and for testing new designs of diving and other appliances, including oxy-hydrogen and oxy-electric underwater steel cutting and welding torches, etc. Thick plate-glass windows in the lower part of the tanks enable the tests to be carefully watched by the experts. Submerged powerful electric lamps illuminate the operations.

## APPARATUS FOR TESTING DIVING APPLIANCES EXPERIMENTALLY AND FOR TRAINING MEN IN DEEP DIVING, WHEREBY ACTUAL PRESSURE AND DECOMPRESSION AND RECOMPRESSION CONDITIONS CAN BE REPRODUCED AND OBSERVED (Figs. 7, 8 and 9)

This apparatus was designed and patented many years ago by Robert H. Davis, and installed in Siebe, Gorman & Co.'s Research Department, for experiments on men using (a) diving apparatus of the type supplied with air from pumps and compressors or from highly charged cylinders of air, or mixtures of gases, and (b) apparatus of the self-contained regenerative type in which the diver carries his own supply of compressed oxygen, or mixtures of oxygen and nitrogen, or oxygen and helium, or oxygen and hydrogen, and $CO_2$ absorbent; it is also used for training men in deep water pressure conditions.

Entry into the chamber is through a manhole at the top, which is closed by a door opening inwards, so that internal pressure closes the door tightly on its seating.

In operating the chamber, it is usually filled with water to 70-75 per cent of its capacity. Compressed air is delivered through a non-return valve into the chamber itself, until the internal pressure is raised to the equivalent of the hydrostatic pressure to which the diver would be exposed at the depth of water which it is intended to simulate for the purpose of the experiment in hand.



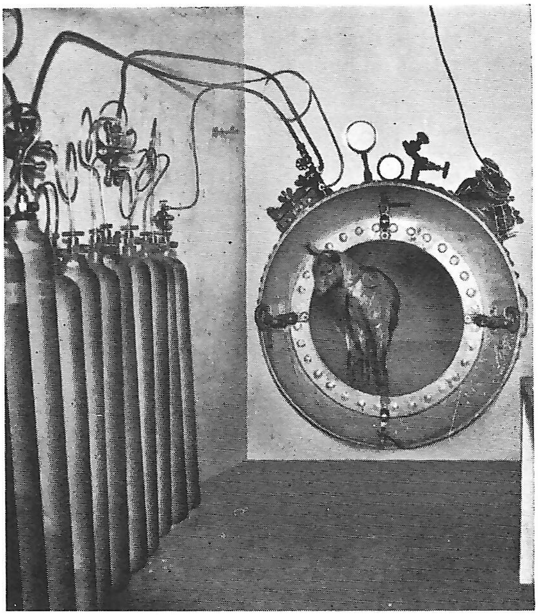


Fig. 10 Experimental Subjects Fig. 11

The pigs look a little apprehensive! "Lavender" takes a last look round!

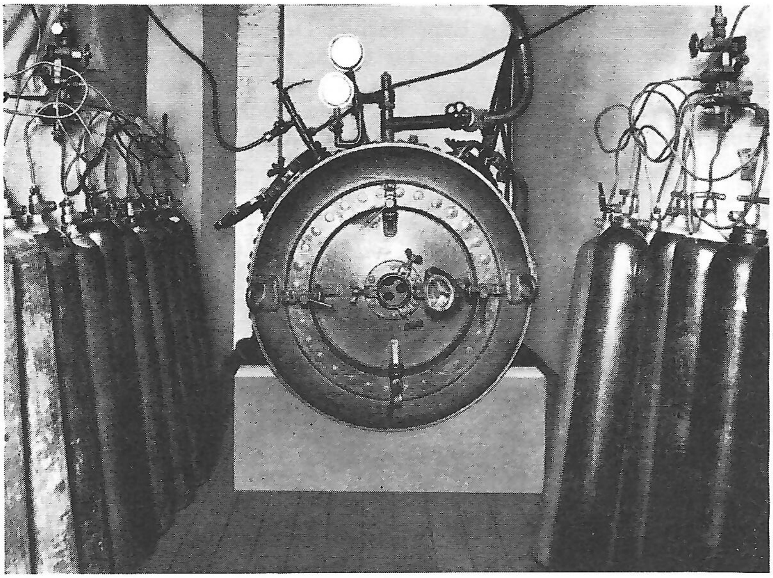


Fig. 12. Entrance to one of the High Pressure Chambers in which are several men undergoing experimental tests

In our earlier deep diving experiments, pigs were used as being physically representative of fat men, and goats as being more akin to leaner men. Fat takes longer to saturate with nitrogen, and longer to desaturate. Experience showed, however, that it was better to use goats exclusively, and this was done in all the later experiments

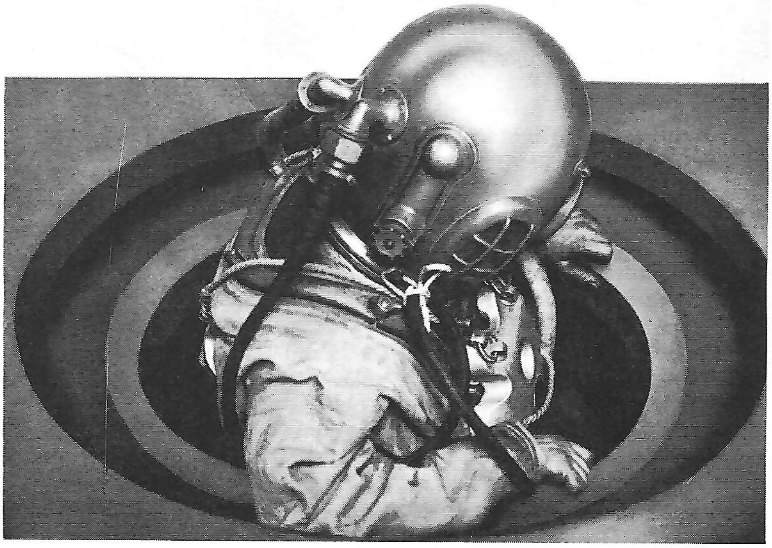


Fig. 13. Diver entering a High Pressure Water Chamber in which "deep sea" tests are carried out

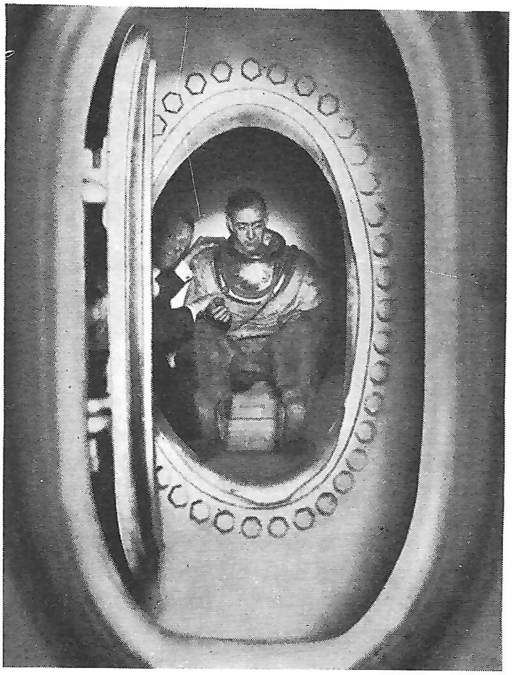


Fig. 14. Entrance to one of the High Pressure Air Chambers, with air-lock

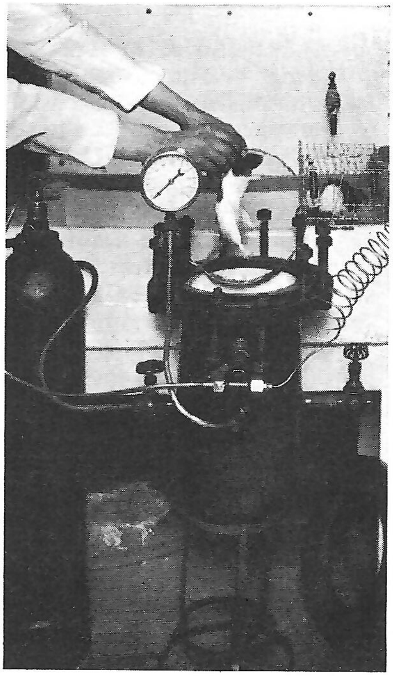


Fig. 15. Apparatus for tests on guinea-pigs, rats and other small animals

When experimenting with new types of diving apparatus on the self-contained system, using compressed oxygen or mixtures of oxygen and other gas, the diver's helmet is also adapted to be connected with a pump or with the compressed air cylinders through a connection in the wall of the chamber, so that, in the event of anything going wrong with the diver or his apparatus under test, air can be turned on immediately to ensure his safety.

The chamber is fitted with observation windows, a hand-lock to enable articles such as chemical test tubes, etc., to be passed in and out; air and hydraulic pressure gauges for internal and external readings; electric light, thermometer, etc.

Sometimes a diver's attendant works inside the chamber, being accommodated on a platform provided in the air space above the water. There is also telephonic intercommunication between the diver, his attendant and persons outside the chamber.

Instead of filling the chamber itself with water, a tank, large enough to submerge the diver (Fig. 9) may be installed and filled with water, the dry space between the two tanks then being used by the attendant for keeping watch on the diver during the experiment, instead of sitting in the air space above the water. The chamber with entrance lock as in Fig. 14 can also be used in the same way.

The chamber is also used for high-pressure water tests on underwater lamps, telephones, submarine cameras, etc.

It has been described by some divers of the Royal Navy who have used it as the "Wet Pot", and by others as "The Chamber of Horrors"; the latter, presumably, because some of the subjects who have been imprisoned in it have suffered from claustrophobia in addition to the ordeal of experimentation. Some men who would think little of diving to a depth of 300 feet or more at sea have been very unhappy when locked in the confines of this chamber, and have said that they felt much further from home than ever they did on the sea-bed, a typical case of psychological apprehension, since the subjects were always under careful observation during the experiments, and succour was immediately available in case of need.

It is not always necessary, however, to use the high-pressure water chamber for experiments on men. Most of the investigations can be carried out in one of the larger of the high-pressure air chambers. When we have evolved from exhaustive experiments on animals what we consider safe decompressions for divers, the next step is to try the system on men, and this is done in the high-pressure air chamber shown in Fig. 14. Attached to this chamber is an air-lock entrance through which a doctor or attendant may, during the experiment, enter or leave the main chamber without disturbing the pressure in the latter. Having safely passed this test, the men (trained divers) proceed to the final trials in deep water.

In Fig. 15 is seen one of our smallest chambers in which preliminary experiments are made on small animals such as cats, rats, mice, guinea-pigs, etc.

## A TYPICAL DEEP DIVING (PRELIMINARY) EXPERIMENT

The following is a typical scene at a preliminary experiment on men in one of our high-pressure chambers.

Twelve divers selected for the experiments were divided into groups of four, and the reader can imagine one of these little groups of strong young men, wearing thick, woollen sweaters, sitting on the floor of the chamber with their backs resting against its curving steel sides. In front of each man is the oxygen breathing apparatus which he has himself charged and tested and will begin to use at a certain stage of his decompression. Outside, stationed at the valves and observation windows, are the responsible officials and a surgeon. One of them stoops into the low doorway and asks: "Is everybody all right?" An answering chorus comes of "Yes, sir", and the heavy door is swung on to its seating, and the clamping screws are hove up with a clanking sound. As the moment arrives for the divers to "go down", an officer opens a valve, and a roaring noise is heard as compressed air rushes into the chamber, whirling up scraps of paper from the floor, and blowing the men's hair about. The pressure gauge needle climbs steadily. In former times, when such chambers were fed directly by compressors, it was impossible to reproduce the rapid descent of a modern diver, and allowances had to be made which complicated and reduced the accuracy of an experiment. But today, the air is delivered from a battery of steel cylinders, charged to a pressure of 120 atmospheres, which can send up the pressure at any rate desired. We are now imitating diving at 300 feet, and it is expected that, in the real thing, our men will be able to reach the bottom in that depth within three minutes of leaving the surface, so the pressure in the steel chamber is raised at the corresponding rate, and the valve controlled so that the gauge indicates 133 lbs. (corresponding to 300 feet) exactly three minutes after starting.

As the pressure rises, it gets much warmer in the chamber, and the men's faces begin to glisten. Some of them have been blowing their noses to clear their ears while "going down", but all are smiling and chaffing each other, notwithstanding the great pressure (higher than that in the boilers of many a steamship) to which their bodies are exposed. The "dive" is to be one of, say, half an hour at 300 feet pressure. Three minutes were spent in the "descent", and in the 27 minutes which remain, each diver has some little task to perform; pulses to be counted and recorded, a few simple questions to be answered, with paper and pencil, and so on. We know that the pressure produces no physical disability, but is it certain that it does not exercise any dulling effect on the intelligence or sensibility? These little tests will provide the answer.

The increased density of the air causes a number of interesting phenomena. Quite early in the compression it is no longer possible to whistle. The vocal cords find it equally difficult to adapt themselves to the increased weight and viscosity of the air. As a result of this the tone of the voice is modified (see page 35). At depths greater than about 200 feet, one becomes aware of the stream of air entering the mouth and going between the separate teeth. If one "pushes" a handful of air at another person several feet away, he will feel it strike him a little later. In rapid compression to considerable pressures, many people have a transient sensation of being "gassed" by the dentist. This usually passes off in a few seconds. At over 200 feet in depth the increased tension of nitrogen in the blood and brain causes the diver to feel abnormal. This is called nitrogen intoxication, as has been discussed earlier in this chapter, and it can be a danger to deep sea divers. This feeling is not dissimilar to moderate alcoholic intoxication, except that instead of the friendly, relaxed social atmosphere associated with the latter, the diver has arduous work to carry out and important minute to minute decisions to make. He is also faced with technical manipulation on which his and often other people's lives depend. As a result of this, the diver is aware of considerable strain in "holding himself together" and carrying out quite simple tasks. As with alcohol, divers vary enormously in their susceptibility to nitrogen intoxication. Despite the austere and arduous surroundings of either a compression chamber or of deep tidal water, a number become quite emotionally unstable. There may be hilarity, tears, or attempted violence to others. One well-trained diver had descended to a sunken submarine in which the crew were entombed but still alive. To the astonishment of those at the surface, instead of reporting the position and damage to the submarine, they heard hilarious singing while the diver beat out a rhythm on the submarine bell.

Another diver who was sent down, was heard giving vent to a string of nautical oaths. When he was bullied into a reasonable state of mind, he confessed that he had been trying to cut his life-line, as it was a nuisance to him.

All this makes it obvious why deep sea divers have to be carefully selected and tested in compression chambers before they work in open water. Those who are not suitable are rejected, but many can still be allowed to dive to more shallow depths, where the vast majority of underwater work is done.

It is now time to begin the decompression, and the officer in charge gives four heavy strokes with a spanner on the outside of the chamber—the signal to "Come up" —before opening the outlet valve. The escaping air makes a tremendous noise; the pressure gauge needle falls at the rate allowed for the first part of the divers' ascent, but nothing can be seen of the men inside, for the watchers at the observation windows are baffled by a dense fog arising in the chamber and hiding all it contains. This is caused by the sudden cooling of the air as it rapidly expands while the pressure is being reduced, and the chill strikes through the thick woollen clothing of the divers, and sets them shivering.

As the pressure falls still lower and approaches atmospheric, a keen look-out is kept for the slightest symptom that might indicate compressed air illness. During decompression, the clearing of the ears is unnecessary as the valve-like opening from the ear to the throat (Eustachian tube) allows the expanding gas to be released without effort and one is only aware of a not unpleasant bubbling sensation. The last stage seems long to the divers who have already been over two hours in the chamber, but it comes to an end at last, the door is unclamped and thrown open and the men clamber out cheerfully, and light up their cigarettes. Smoking is, of course, forbidden in compression chambers, in view of the danger of the increased tensions of oxygen. Very occasionally if the officer in charge was not looking or could not see because of the condensation during decompression someone has broken the rule. However, after a few "puffs" the offender desists. The smoke tastes acrid and unpleasant and the mist stings the eyes and throats of any other occupants, who take vigorous steps to see that he does not smoke again. The doctor examines each one; nothing is wrong, and the chamber is prepared for the next group of men.

After a deep dive all subjects are watched closely for about 30 minutes and are not allowed away from the compression chamber for several hours.

In this way the decompression table is tested at all the depths and durations of time likely to be encountered in practical diving, and if none of the 12 divers experiences any ill-effects, we feel justified in proceeding to the actual diving tests at sea which, in the case described, were carried out by the Royal Navy Diving School with such success that the new procedure can be recommended as safe and practical.

## HIGH PRESSURE AND LIFE

This interesting and instructive article by the author's friend, the eminent physiologist, Sir Leonard E. Hill, F.R.S., LL.D., M.B., with whom the author had the pleasure of working for many years experimentally on problems connected with Deep Diving and work in poisonous atmospheres, was written and presented to the author as a contribution to this volume.

"In a frog with its brain destroyed, so that it does not feel, the heart and circulation of blood go on normally. The web of one foot can be spread over the inside of the thick glass end of a small metal chamber; glass also closes the other end, so that a strong light can shine through and illuminate the web. With the aid of a microscope outside the chamber, the circulation in the capillaries of the web can be observed. By means of a cylinder of compressed air the pressure in the chamber can be very rapidly raised, say to 20 atmospheres or about 300 lb. to the square inch. The circulation in the delicate capillaries goes on unchanged, for the pressure is equally distributed all over the body, and so has no effect. If you take a tube in your mouth and go under water and try to breathe through it, you will find that you cannot do so when the water above your mouth becomes a foot or two in depth. This is because the pressure in the lungs is not equal to that exerted by the water on the body. Such inequality, if greater, is very dangerous and may cause bleeding in the lung. So, too, if air pressure is made greater in the lung than on the body, this may cause rupture of the lung and entry of air into the circulation, and death.

Divers have to be careful not suddenly to fall to a greater depth when the pressure in the helmet produced by the pump is less than that of the water; they would get a dangerous squeeze.

Similarly, men coming up from a submarine using the Davis escape dress must let excess of air in the lungs escape from their mouth or nose, in order to prevent danger of excess pressure on the lungs.

If the frog in the chamber is kept for sometime at, say, 20 atmospheres, and is then suddenly decompressed, bubbles may be seen to appear in the capillaries and to interrupt the circulation. These are due to excess of air, dissolved in the blood and tissues, which escapes just as gas effervesces off when a bottle of soda water is opened. On recompression the bubbles disappear and the blood flows again. If divers came up too quickly, the same may happen to them, and cause pains called "bends" or paralysis. Decompression has, therefore, to be carried out according to the established stages and times given in the present volume.

By breathing oxygen in a suitable dress under a positive pressure of a pound or two to the square inch it has been possible for a man to withstand evacuation of air, in a chamber installed by the author, till the barometric pressure became very little – equivalent to a height of

90,000 feet. Record heights of over 50,000 feet in aeroplanes have so far been reached. Pure oxygen without positive pressure ceases to be sufficient at 40,000 feet because of the carbon dioxide and water vapour in the depths of the lungs.

The positive pressure oxygen breathing apparatus and suit would allow the wearer to go to the moon, but he would not be able to come out of it, and enough oxygen and $CO_2$ absorbent for exhaled carbon dioxide would have to be carried to last for the journey there and return to earth, a very difficult problem, apart from that of the mechanics of the rocket apparatus for getting there and back, and of being able to eat and drink. With the much lessened pull of gravity on the moon, muscular action would be excessive and disordered.

Goldfish may be placed in a chamber partly filled with water and fitted with a strong glass window at either end. By means of a cylinder of compressed air, the pressure in the chamber is rapidly raised to 200 atmospheres. The goldfish at once sinks helplessly to the bottom of the water, this is because the gas in their swim bladders, by means of which they adjust their specific gravity to that of water, so as to swim about with least support, is compressed. Left until the next day the fish are found again swimming about. They have secreted air into their swim bladders against the very high pressure (a wonderful thing) and adjusted again their specific gravity. On then letting off the pressure in the chamber the fish come helplessly to the top, because their swim bladders are now over distended. Next day they will have adjusted this and be swimming normally. Fish live at great depths in the sea, and secrete oxygen – obtained out of that dissolved in sea water – into their bladders. A pressure of oxygen in excess of one atmosphere is poisonous, and causes convulsions in us and other terrestrial animals, but the deep-sea fish bladder has been evolved immune to oxygen poisoning.

When these deep-sea fish are hooked on a fishing line and started upwards, they "fall" helplessly to the top, as their swim bladders expand so much as to project out of their mouths (see page 542).

Deep-sea fish are immune to the high pressure of water, which equals hundreds of atmospheres, where living miles deep. Every 33 feet of water depth is equal to one atmosphere = 14·7 lb. per square inch, so you can easily calculate the pressure four miles deep; it would be about 600 atmospheres.

Terrestrial animals and surface sea animals are not immune to high pressures of water. If a frog or a surface fish is compressed to 300 atmospheres, the heart and circulation go on, but at about 400 atmospheres the living tissue, heart, muscles, become so rigid that their structure even breaks. The high pressure water coagulates the living protoplasm.

The late Sir Charles Parsons, of turbine fame, made a press which went up to 30,000 atmospheres. By this pressure and heat, he tried to make diamonds, but without any striking success. He allowed me to use this press. I found that, while all microbes were killed, their spores may be resistant to a pressure of 20,000 atmospheres. If milk could be sterilized at this pressure, said Parsons, it would possibly become a commercial process. The important microbe to kill in milk is the *Tubercle Bacillus*, but when, later, I wanted to test the pressure, particularly on this microbe, I found that Parsons had dismantled his press.

I found that oysters at 700 atmospheres pressure of water quietly opened, so there is a means of escaping the trouble of opening them with a knife, but rather too expensive a method for use in oyster bars.

In diving to depths of 300 feet = about 10 atmospheres of pressure, compressed air has an anaesthetic effect which has been attributed to the high pressure of Nitrogen. A mixture of Helium and Oxygen has allowed divers to descend to 540 feet. Nitrogen, and still more the heavier gas, Argon, impede the outlet of carbon dioxide from the lungs far more than the light Helium, and it is probably the excess of carbon dioxide in the tissues which causes the trouble. The saturation of the blood with oxygen also interferes with the transport of carbon dioxide from the tissues to the lungs by the blood. Sir Robert Davis, the submarine engineer, has greatly aided such researches."