Preface

Since it's first publication in 1969, 'Bennett & Elliott' has been regarded as the standard textbook in the field of diving physiology and medicine. It has been used as a reference text by scientists and by medical personnel, as well as by divers interested in the phenomena that underlies their reaction to the underwater world and the procedures used to prevent injury. It is thus, with considerable humility, that we tried to continue the tradition of providing an up to date review of the current state of knowledge which would be of use to all of those interested in the field. As in the previous editions, the different chapters have been written by acknowledged experts in the field. One effect of this is that there is some overlap in the chapters and there are differences in viewpoints and hypotheses. We hope this will provoke thought and stimulate ways to increase our knowledge about different aspects of 'living under water'.

In the previous editions of this book, the need for divers to perform underwater work was emphasized as a main reason for scientific studies related to diving. While such occupational endeavors are still imporant, increasingly, the development of automatic systems and underwater vehicles have replaced man. Still, however, man is the most versatile and efficient tool, and occupational diving will continue to be an important field for many years to come. In sport diving, new equipment has allowed divers to go deeper and stay longer than ever before. This has required new procedures and has challenged many of our accepted theories about diving physiology. As before, dedicated individuals have developed new techniques and tested old limits, often showing scientists that what they originally predicted could not be done, was possible. This continues to offer a challenge and an inspiration to develop new ideas and new approaches.

The 4th edition of this book was published nearly 10 years ago. In its preface the editors pointed to the lack of funding for research in this field in spite of the continuing need and interest in underwater activity. Today the situation has not changed. In spite of this, a large body of new knowledge has accumulated, which makes it timely to produce another edition. This is clearly demonstrated in many chapters in this book.

One of the strengths of the previous four editions was that each edition was different, demonstrating the particular interests of that era. In this edition we have focussed on the physiology of diving and the effects of pressure and gas composition as well as the clinical issues affecting divers. This has led us to include new chapters on diving physiology in different animal species, on basic pressure phenomena, on drowning, and on the biochemistry of oxygen under pressure. Additionally, one of the concerns of both divers and the general public in recent years has been that diving, even in the absence of clinical symptoms, may lead to impairment of the diver's health. This is a serious concern and we have therefore included chapters on the long term effects of diving.

Decompression disorders still remain a major field in diving. One editorial challenge has been the classification of the decompression disorders. In the 5th edition we have returned to an organization of chapters based upon physiologic mechanisms of injury. Since this book is primarily a book of medicine and physiology, the editors and the publishers felt that it was most appropriate to divide the chapters of the book along mechanistic lines. As a result, chapters are again divided in the classical fashion of being devoted to decompression sickness (i.e. those conditions resulting from the evolution of gas phase within the body from a supersaturated state) and air embolism (gas introduced into the vasculature secondary to pulmonary barotrauma). These conditions are separated primarily because the underlying pathophysiology of the conditions is different even though there are circumstances where clinical differentiation may be difficult. Therefore, except in the treatment chapter (since currently treatment for AGE and DCS is so similar) and the clinical manifestations chapter (where there can be considerable overlap between the syndromes), we have asked the authors of the various chapters to use a mechanistic nomenclature underscoring the physiologic differences between DCS, AGE and barotrauma. Some authors have recommended using the all-encompassing term of decompression illness (DCI) to describe all the forms of dysbarism. As noted above, since the treatment of DCS and AGE is, at least for the present, quite similar, the term DCI is used in the chapter on treatment. In the remaining chapters, the terms AGE and DCS are used predominantly. The term 'DCI' has been reserved for the situations where a portion of the text refers specifically to a reference where the term 'DCI' was used, or where the text refers to an undiagnosed heterogeneous population. In order to clarify the different classification systems to the reader, they have been described in detail at the start of the chapter on clinical manifestations of the decompression disorders. We hope this will not confuse our readers. Ultimately, it was the opinion of both the editors and the publishers, that the readers would be better served by a physiologic understanding of the differences between these conditions. This was the principal (but by no means the only) reason for the organizational change from the 4th to the 5th edition. In the new appendix, we have included information about physical laws, formulas and values that we feel would be useful to the reader. There are differences in pressure units and units of length used in Europe and in USA.

This book could not have been written without the support and enthusiasm of the authors of the various chapters. They have devoted a tremendous amount of time and effort into making this a truly comprehensive and up-to-date review. The work on this book has truly driven home the point that we need them more than they need us, the editors. We are particularly honored to have the introduction to this book written by Christian Lambertsen. He wrote the foreword to the two first editions and is thus a link to the past while he points us to the future in this field. Diving research will probably never be a major field of biomedical research, however, the study of the effects of pressure and pressure changes on the organism can give insight into basic phenomena in physiology and biochemistry, as well as benefiting divers by offering them better and safer procedures.

Trondheim/San Diego August 2001
Alf O Brubakk
Tom S Neuman

Introduction

Christian J Lambertsen

'The Changing Face of Diving Physiology' was the title of my Foreword to the first (1969) edition of this valuable book. The series of now five editions has provided renewing elaborations by internationally recognized experts of the large ranges of scientific and operational successes over the full prior century of expanding technologic and scientific advances in human underwater diving activities. The year 2003 is therefore the time to look back, and to look ahead.

LOOKING BACK AT THE 'HARD POINTS'

Although effective helmeted and suited compressed air diving was in use in mid-1800, diving was limited in depth and usefulness by the basic inadequacy of on-site means to pump air to high pressure, and by the high volumes required to limit CO_2 accumulation in the diving helmet and suit. The narcosis induced by compressed air diving, magnified to a hazardous degree by excesses of CO_2 accumulation, decreased working diver effectiveness even at depths now widely accessed by several million sport divers. Improved air pumps evolved, and Haldane's official actions circa 1900 imposed the increased helmet ventilation that opened the way to deeper air diving, albeit with increased degrees of exposure both to direct nitrogen narcosis and to decompression sickness (DCS).

The continuation of that period of thoughtful experiment 100 years ago therefore led the same UK giants to generate the imaginative concept of exponential uptake and elimination of nitrogen by undefined body 'tissues,' along with a less viable related concept of 'tolerable degrees of nitrogen supersaturation' that would not induce bubble formation and DCS. For nearly the first half of this past century the largely naval advances in air diving were guided by these principles, even with their evident incompleteness of validity in deep and prolonged exposures. Focus upon salvage requirements by leaders of US and UK diving medicine then led to prolonged oxygen use during in-water 'stage' decompression, to extensive investigations of human oxygen tolerance, and to systematic development of the bold and important procedure of 'surface decompression using oxygen' (i.e. Sur DO_2), which is, in reality, surface recompression and decompression using oxygen.

It was the naval initial trials of these operationally dynamic and physiologically appropriate uses of oxygen in air diving decompression that paved the way for the eventual broad technical successes of helium use in deep diving operations, as proposed by JH Hildebrand in 1924, and applied in the 1939 salvage of the submarine *Squalus* from a depth hazardous for air diving. (Hildebrand had previously, while in college, described by simple experiment that the formula for the now actively studied compound nitric oxide was NO rather than the then accepted N_2O_2.)

The *Squalus* salvage operations also included use of chemical absorption of CO_2 to limit the degree of waste of scarce helium in helmet ventilation. The accompanying methods of oxygen use, during both diving work and decompression, have progressively shortened and improved the decompression process into the modern period of industrial and naval surface-supplied $He–O_2$, air, and $N_2–O_2$ operations. The now well respected phenomenon of an O_2 induced convulsion in man had been discovered in exposures at 304 kPa (4 ATA, 30 msw, 100 fsw) O_2 in the UK Admiralty in 1933, and in the US Navy in 1936. The critical role of oxygen as the key to decompression success then led research attentions to fundamental and operationally limiting effects of oxygen itself, extending from the pioneering work of Paul Bert and

Lorraine Smith. These strong threads of early practical progress during the first half of 1900 were reinforced by World War II and have received description in the first and each subsequent edition of this volume.

BRIDGES TO THE PRESENT

With the end of World War II, there occurred a broad expansion of internationally productive diving physiologic research, scientific communication, and operational development. The impact of close academic, naval, and industrial 'research and development' interrelations brought forth specialized new research facilities in universities and government agencies. The result was rapid and well supported accomplishment in pioneering research, technologic applications, and consequent engineering expansions of offshore commercial or naval capabilities. The expanded international interests in undersea biomedical science spread out to assist the sister discipline of aerospace biomedical stress research. The result has been a still continuing cross-fertilization, worldwide.

Fractional examples of R&D 'accomplishments' during the past half century, each aided by the efforts of many, have included:

- New concepts for broad extensions of diving depth and duration and safety, including saturation and saturation–excursion diving and decompression.
- Development of improved commercial diving and decompression procedures for air, N_2–O_2, and He–O_2.
- The gross expansion of open system breathing equipment for use in underwater swimming and diving sport, and for use in hard work by shallow and deep commercial and military divers.
- R&D for 'ultimate' diving with hydrogen and helium at extreme pressures and in-water depths.
- Practical multiteam operational saturation diving systems of combined submersible decompression chamber and deck decompression chamber.
- Demonstrations of the distinct handicap of neurologic disruption by effects of high hydrostatic pressure (high pressure nervous syndrome).
- International developments and refinements of military circuit rebreathing 'self-contained underwater breathing apparatus' (closed system oxygen, semiclosed system mixed gas, closed system mixed gas).
- Neurologic O_2 exposure pressure/duration tolerance limits determinations in underwater swimming work.
- Investigations of roles of CO_2 and exercise in accelerating CNS O_2 poisoning.
- Accelerated decompression from surface-supplied and saturation He–O_2 diving by using air and O_2 during the ascent.
- Advances in O_2 sensors and microelectronics, allowing evolution of closed system mixed gas underwater breathing apparatus.
- Emergence of 'superficial and deep tissue isobaric inert gas counterdiffusion' gas phase evolution phenomena, and means of prevention in diving and decompression.
- Recognition and studies of tolerance of hypothermia and hyperthermia as generic amplifying stress factors in disruption of multiple forms of diving.
- Predictive modeling of gas phase evolution and resolution in diving and aviation decompression development.
- Definitions of respiratory–pulmonary hyperoxia tolerance prediction.
- Broad research expansion in biophysics of oxygen free radicals in biomedical systems.
- Adaptation of decompression procedures to 'wearable' decompression computers.
- Establishment of systems of interrupted hyperoxia for therapy of gas lesion incidents, and for extension of operational oxygen tolerance.
- Emergence of nitric oxide into the family of biologically influential 'gases,' along with O_2 radicals and CO_2 generated H^+ activity.
- Recognition of venous gas embolism/DCS correlations as components of decompression stress.

Such successes in research and technical communication have led universities, navies, and the offshore industry to improve safety and attain gross advances in the scope of human diving methods. They have also generated practical engineering support for deep undersea operations, in the extreme environmental stress situations in which physiologic adaptations alone could not provide for operational safety and effectiveness. A major advance has derived from the US Navy developments of helium saturation decompression and an 'unlimited duration helium saturation–excursion' procedure. Interest of navies has now expanded to improve competence in submarine rescue and in special forces' self-contained operations diving. Applications of decompression concepts to the 'space diving' of astronaut extravehicular activity has reawakened interest in the roles of exercise, cardiac output, and cardiovascular reflexes in hyperoxic denitrogenation. These concepts are being applied to develop acceleration nitrogen saturation decompression methods for escape from disabled submarines.

Throughout the desired improvements in safety and efficiency of diving and decompression in its multiple forms, the fundamental obstacles have remained: intolerance to oxygen poisoning at rest and in work; thermal stress; and the hydrostatic stress of high pressures. These, and essentially all other problems, are becoming progressively manageable at high ambient pressure by engineering of protective systems. The large advances in attainable depth now included in industrial diving, and in the performances of deep undersea construction and repair, have been accomplished through direct engineering design, and through developments of remotely controlled, unmanned systems. At moderate pressures, they remain as physiologic obstacles.

PROSPECTIVES

The scope and detail of past editions have reflected the gross expansions of military and industrial operational purposes and the severity of these exposures to physiologic stresses of underwater work. The discoveries of large reservoirs of oil and gas, at deep and shallow ocean depths, had initially generated a well recognized need for improved capabilities of direct manned subsea activity. In industry the hazards have necessarily been reduced by extensive engineering evolution of systems to provide precise support to the divers, working in essentially localized operations. However, military diving (especially special forces and submarine related) functions can be remote, isolated, and highly varied. By far the largest numbers of civilian divers will continue to be individuals engaged in open system recreational diving, with a few misplaced Everest climbers undertaking new undersea depth experiences with unique technologic adaptations of rebreathing equipment systems and ancillary support.

These patterns of current successes and future diving emphasis are unlikely to sustain the interest of research support agencies over the broad forms of individual biomedical research that have provided the giant steps to the present advanced capabilities. Research will largely focus on the detailed microchemical and biophysical investigations needed to define the bases and the dynamics of fundamental environmental stresses, not only related to diving but also to biomedical derangements in other stressful human exposures and pathophysiologic states. Interest will certainly persist indefinitely in the ultimate stresses of oxygen free radicals and the consequences of their systemic implications in hyperoxic and hypoxic states, including resulting neurologic toxicity.

Parallel interests should persist in the systemic phenomena involved in facilitating or interfering with decompression of all forms, including the origins and impact of venous gas embolism, the superimposed physiologic and toxic influences of oxygen on decompression, and the physiologic or pharmacologic modifications of inert gas elimination in diving and decompression. In the most demanding forms of free diving, stresses of both decreased and increased exposure temperatures will remain as important limitations which, like oxygen poisoning, are not solvable by physiologic adaptation.

With many decades of expert investigations and developments across the range of exposures to pressure and respirable gases and activity, emphasis in the period ahead should also be expected to include the integration of quantitative physiologic information and the results of newly evolving forms of 'molecular biology' research. The individual past efforts have been tremendous, and their referenced summarizations in volumes such as this will have a very large importance for their future correlation.

1

An Outline History of Diving Physiology and Medicine

David H Elliott and James Vorosmarti

As the techniques of diving continue to advance, it is natural to focus on what may come next, what research should be given priority, and how humans can further strive to develop their effectiveness, depth, duration, and safety underwater. This is only natural. Also natural is the observation, common to all sciences, that research builds upon previous publications, as too do those publications (and so on ad infinitum). All too often today the work of the earlier pioneers who addressed similar problems is ignored or quoted incorrectly. Although they had fewer technical resources to pursue their ideas, the early workers had many original thoughts and a few still remain untested. The medical profession also had valuable opportunities for observation, some of which continue, and they had opportunities for the clinical assessment of cases that can never be repeated.

A conventional history of diving begins with mythology, such as Alexander the Great at the siege of Tyre descending in a diving bell. It is likely to be illustrated by fanciful pictures, such as the diver standing on the sea bed (pictured in a 1511 edition of Vegetius *c.* AD 373) with an ax in one hand, fish in the other, while impossibly breathing via a tube to the surface. From such beginnings many histories have moved on in fascinating detail, through the bell, the caisson, and the helmet to the development of modern diving systems. Such histories (e.g. Bachrach 1982, Bevan 1996, Davis 1962, Dugan 1956) are important but most are predominantly technical. The purpose of this chapter is not to tread that path again but, rather, attempt a different emphasis: the development of diving physiology and medicine.

Although computerized searches are an invaluable tool, they only go back to 1966 and, in any case, search only specified journals. There is much work published earlier or in books or navy reports that remain valid but largely forgotten. A benefit of extending one's literature search beyond the limits of the computer is that many of the earlier publications are based on laboratory procedures that might no longer be approved by animal care committees, or are based on diving procedures that are no longer used. Many physicians of a 100 or so years ago were keen descriptive observers and, although anecdotal, their reports can challenge current thought. As an example, consider the spontaneous recovery of many severe cases of neurologic decompression sickness (DCS) that were described before the use of recompression.

There can never be sufficient space for a historical review of every aspect of diving medicine and physiology and so only the most important highlights will be selected. This brief review will use an approximately chronological approach and has the objective of linking the history of diving, and to some extent the history of compressed air work, to the contemporaneous development of hyperbaric applied physiology and medicine (Elliott 1993, 1999a, Vorosmarti 1997). An excellent and more detailed entry to all this is through the annotated bibliographies commissioned by the US Navy (Greenbaum & Hoff 1966, Hoff 1948, Hoff & Greenbaum 1954). Hopefully this review will stimulate the reader to revisit the original publications on which collective knowledge is based, and thus correct errors of interpretation, find a forgotten idea or merely admire the thinking of those who were present at the time of man's progressive exploration into unnatural environmental pressures.

The earliest divers had little or no understanding of physiology or the environment into which they descended, either breath-holding for shellfish or salvage or in a diving bell. In 1690, Halley (1716) was among the first to extend the underwater duration of a diving bell by sending down weighted barrels of air to replenish its atmosphere and he claims to have spent some 90 min at 18 msw (60 fsw). From such an apparatus, a diver could go out and be supplied through 4 mm (1/6th inch) hose with air siphoned from the bell (Dick 2000). In 1715 Lethbridge designed a barrel with a window which was shut at atmospheric pressure with him inside it, and with only his arms exposed to the pressure of the sea outside. He went down to 18 msw (60 fsw, 2.8 ATA) and used it for some 30 years to salvage valuables around the world, becoming a very rich man. A modern reproduction has confirmed at first hand its remarkable capabilities (Stenuit 2000).

Over the next 50–80 years, methods were developed of providing compressed air for the individual diver to breathe, but the number of divers remained small. During the nineteenth century, diving with a standard helmet became routine. A self-contained compressed air breathing apparatus with a demand valve was designed for use in flooded mines in the French Alps by Denyrouze and Rouquayrol, and a closed circuit oxygen breathing apparatus was designed by Fleuss in 1878 (Davis 1962). It provided oxygen on demand and caustic potash for removing CO_2. In 1882 this was used by Lambert to proceed 90 m (300 ft) in the dark along a flooded railway tunnel at 27 m (88 ft) at PaO_2 370 kPa (3.7 ATA) in order to save it by closing a vital sluice.

The use of compressed air to drive a 21 m (70 ft, 310 kPa 3.1 ATA) shaft down through quicksand to open a coal mine in France (Triger 1845) led to the employment of a great number of laborers. One consequence was reports of large numbers of cases of DCS that still warrant study. Indeed, in the history of diving and compressed air work, the history of DCS and decompression theory dominates the second half of the nineteenth century (Elliott 1999a).

EARLY STUDIES OF DECOMPRESSION AND DCS

The development of caisson work provides some of the first observations of the effects of raised environmental pressure on humans. Triger noted the increasingly nasal quality of speech with increasing depth and, on reaching around 3 atm, the loss of the ability to whistle. Previously reported by Halley (1716), Triger (1845) also described pains in the ears associated with compression. He further said of the workmen that

> ... they become much more tired when working in compressed air than in open air. We think that this is the result of the very great humidity ..., which hampers the insensible perspiration and promotes the more rapid secretion of sweat in those who have to exert their physical powers ... . Perhaps this humidity would also explain the somewhat severe pains in the articulations experienced by some workmen a few hours after leaving the shaft ... .

He also describes the case of two workmen who after

> ... seven consecutive hours in compressed air, experienced rather keen pains in the articulations, half an hour after leaving the shaft ... . Rubbing with spirits of wine soon relieved this pain in both men; they kept on working the following days.

At around the same time as these first descriptions of musculoskeletal DCS, the divers of the Royal Engineers were using helmets to try and salvage the *Royal George*, sunk at Portsmouth in 1782. In 1843 an account by Pasley of some of their diving incidents, quoted by Bevan (1996), includes the first of a buoyant ascent made by Corporal Jones, and the first description of a squeeze when the hose of Private Williams ruptured. Another of the divers sustained what seem to be the first neurologic manifestations following decompression. It is tempting to consider, in this first neurologic decompression injury, that it was a case of mixed pathology, clinical features of air embolism associated with the evolution of a gas phase due to dissolved gas.

> ... in consequence of his having been severely injured whilst diving, not by any accident but from his extraordinary zeal which induced him to overexert himself and remain too long underwater, which caused a sort of paralysis of one side ... .

Using the new method of compressed air to develop coal mines in Northern France one engineer (Blavier 1846) reported that a day after an exposure to around 2.6 to 3 atm on 5th December

> ... keen pains appeared in the left side, and we felt a rather severe painful discomfort for several days afterwards ... . After we were quite free from these pains, 28th December, we were anxious to try the experiment again ... at the same hour, that is, 20 hours after our exit from compressed air, we felt in the right side pains just like the former ones, which kept us numb for four or five days.

The maximum pressure there was around 425 kPa (4.2 ATA; equivalent to 32 msw, 105 fsw) with shifts twice daily of around 4 h, each with a 45 min compression phase, and each followed by a 30 min decompression. The superintendent of that mine had assured Blavier that the various symptoms of the workmen, including 'heaviness in the head or pains in the legs,' almost always coincided with 'some excess' committed by them between shifts. 'Only one of them experienced complete paralysis of arms and legs for 12 hours.' Of the 64 workmen, two died.

Dr Pol and Dr Watelle went to these mines in 1847 in order to examine these phenomena, but their study (Pol & Watelle 1854), upon their own admission, was not designed for publication. It was a collection of 'observations made without plan.' They established for the first time the relationship between the risk of DCS and increased pressure, time at depth, and rapidity of decompression. Nevertheless, from their observations, they deduced that

> the danger does not lie in entering a shaft containing compressed air; nor in remaining there a longer or shorter time; decompression alone is dangerous; pay only when leaving.

Among their case descriptions, one is struck by experiences of decompression which now are only rarely encountered. If they were to occur, they would be managed differently.

> an hour after leaving the shaft, ... he complained of distress; when placed in bed he lost consciousness. Pulse full and rapid, face congested, respiration short and stertorous; obscure sounds everywhere ... bled, purged, plastered. After 4 hours, return to consciousness. In 3 days, cured.

From among the 10 or so serious cases, i.e., those with more than just musculoskeletal pains, one notes a curious absence of what might be termed 'spinal' manifestations. They attributed the observed symptoms not to bubbles but to 'superoxygenation and congestion.' Nevertheless, they suggested that a sure and prompt means of relief would be to recompress immediately, then decompress very carefully. Indeed Bert (1878) reports that, at another mine in Belgium, some workers with severe attacks of articular pain were completely relieved by returning to work, but then found that the 'pains returned after leaving the apparatus.'

In 1851 with his two crewmen W Bauer escaped from the submarine *Brandtaucher* that had sank in 18 msw (60 fsw) a few hours previously. Wilhelm Bauer's own account of flooding their single compartment is the foundation stone for the history of submarine escape (Elliott 1999b). From the words of Bauer W, written just after his escape (Bauer J, 2000):

> Operated by Bauer and his two assistants, Witt and Thomsen, the submarine lost its horizontal stability at 9 a.m., after some 14 minutes running out to sea and shortly after flooding the flotation compartments. The tilt of stern's more rapid descent caused the horizontally-adjustable ballast to shift further towards the back, and the increasing pressure crushed the starboard side of the hull fracturing a propulsion drive wheel. The boat, now leaking water through several seams, came to rest stern lowermost at around 16 metres.
>
> The three men were trapped in a disabled and leaking submarine and seemed doomed to certain death. Bauer's frightened companions tried to plug the leaks and pump out the water but Bauer realised that the rising water level could be their salvation. He realised that when the trapped air became compressed to ambient pressure, it would be possible to open the hatch, escape outside and float to the surface. He then had to convince his two crewmen to stop plugging the leaks because this would only delay their escape and cause them to use up valuable oxygen. Instead he urged them to rest and conserve their energy.
>
> Some four or more hours later, when the three men were in the cold and near-dark of the compressed air remaining trapped in the uppermost bow, they heard chains and grappling hooks against the hull and Bauer became concerned that a salvage attempt might jeopardise or obstruct their escape. The water level was rising more slowly now and so they unscrewed an iron bar from the pump and used it to try and pry open the hatch. A frightening stream of cold water was their reward. The most powerful man of the three used his back against the hatch, it suddenly flew open and the escaping air swept him out into the sea. Instantly Bauer grabbed his other companion who was desperately trying to hold on, pulled him by the hair, and they were both swept out of the hatch by the remaining air stream.

They were rescued by the astonished crews of the salvage boats and, though cold and exhausted, there were no reports of any symptoms that might imply DCS or arterial gas embolism (AGE).

With the subsequent use of caissons in bridge building around Europe and then around the world, DCS among the workforce was reported time and time again. For example (Babington & Cuthbert 1863), symptoms

> ... were much worse when the change was made from caisson to the open air: serious, even fatal, symptoms appeared then.

They also described one worker who was

> ... completely prostrated ... unable to walk, hands and feet cold and without sensation. Was seated with his feet in the fire, so that several of his toes were burned without feeling the heat ... .Two days later he was cured except for his burns.

During the building of a bridge in Bayonne, a 20 year old engineer decompressed in 4 or 5 min after 60 min at 4 atm (gauge). Within a few minutes he had dizziness followed by unconsciousness. When he regained consciousness after 3 h he was paraplegic with also loss of sensation in the arms. After bedsores and other complications, function began to return after 7 weeks. Twelve years later he could climb one flight of stairs with difficulty (Bert 1878). Bert also quotes a mining student's description of his own decompression manifestations:

> During the decompression I felt a discomfort which I attributed to the cold. After I had come out, when I wished to raise my right arm, I could not make it reach a definite point. My sight was affected, and I saw … much as one perceives objects after whirling around several times. The paralysis grew worse … . I could not walk. I was dazzled and my eyes refused to serve me at all. My eyes were dull and glassy, they told me, and perceived only a white vaporous light. I recovered first the use of my leg, then of my arm; … and I saw distinctly for longer periods. Finally … my headache disappeared in the open air and I went home, having nothing but fatigue to remind me of my former experiences.

Many similar clinical observations continued to be made and were accompanied by various explanations of the underlying pathophysiology, many of which can now be dismissed as fanciful. In the absence of any facts, these interpretations were vehemently argued and then used by some, but with a totally incorrect logic, to justify a need for slow decompression.

Bert (1878) also reported that there were others who did not consider the rate of decompression to be important but said, for example, that the major factor was chilling during decompression:

> if the thick and icy mist, which is sure to appear, seems to be penetrating you, make haste!

But a few curious clues did emerge. For example, Bucquoy (1862) watched the use of dry cupping-glasses placed around a workman's painful knee. The cups had been applied properly by a skilful orderly but, repeatedly, after a certain time they fell off. He concluded that the elimination of free gases explained the prompt disappearance of the knee pain through repeated application. He went on to conclude that the gases of the blood are increased in quantity, and

> at the time of decompression, these gases tend to be liberated again, just as the carbonic acid escapes from charged water when the stopper is removed from the bottle containing it.

When the Scorff bridge was being built in France, decompression from unstated durations at 18 m (60 ft, 280 kPa, 2.8 ATA) were done in 10 s. One paraparetic worker sued his employer (another first in this field) but the arguments in the case by Pol and Watelle for a slower decompression were lost. Foley and the defendants won on what was reported as a relative technicality (Bert 1878).

Hoppe-Selyer's observation (1857) that decompression to altitude had caused bubbles in the heart and blood vessels of a rat, possibly led to a comment by Panum (1868) after studying dogs' blood pressure at depth, that the symptoms of decompression

> result from the fact that the air which has suddenly been liberated in the blood vessels … forms embolic obstructions in different vascular regions.

An engineering report (Combes et al 1867), based on some 10 locations around France, stated that the diseases caused by these accidents could be prevented by 'woollen garments in the lock chamber'. Tunellers should

> not to open the cock too quickly … . M. Triger requires that the decompression last 7 minutes, and states that then the symptoms disappear completely. It seems to us that this time should vary with the constitution of the workman.

One of the first bridges to be constructed in the USA using work in compressed air was over the Mississippi at St Louis where at the East pier a large number of workmen were exposed to pressure of 440 kPa (4.4 ATA, 34 m, 111 ft). With decompression in 3–4 min, 30 of the 352 men were seriously affected and 12 died. The clinical report on some of these cases (Bauer 1870) is interesting but adds little to the prevention of DCS. The report by the engineer, Captain Eads (Eads 1871) after whom the bridge is named, describes the use of 'galvanic rings' of zinc and silver which were worn by the majority of the workmen to stop attacks of paralysis or pains. He also mentions that the physician at the site was severely affected after $2^3/_4$ h at 27 m (90 ft) and, in Dr Jaminet's own words:

> We were only three minutes and a half in the air-lock to return to the shaft or normal atmosphere. … epigastric pain … dizzy. … I reached home … three quarters of an hour after leaving the caisson. The last effort brought me to my office where in a few minutes I became paralysed.

He was paralyzed in both legs and left arm and also had transient aphasia. Within 10 h or so his paralysis had gone, though he felt weak for another week or so (Jarcho 1968).

Some physicians, Eads says

> … maintained that a slower return to normal pressure would have been less dangerous; others blamed too rapid compression … we believe that the real cause lies in the long duration of the stay in this air … at pressure, and not the rapid changes to which it is exposed.

This belief appears to be based not on nitrogen uptake but was based on a 30–50% reduction of respiratory rates at pressure, and thus is a reaction

> against the introduction of oxygen in a proportion 2 to 3 times greater than in normal atmosphere.

As Eads stated elsewhere in his report:

> The duration of stay in the air chamber was gradually shortened from 4 hours, to 3, to 2, and finally to 1 hour.

After this period, there were no more fatalities.

About this time, Gal (1872) published his thesis on the diving illnesses of the sponge divers of Turkey. He classified DCS:

1 fleas – the skin manifestation that disappears without treatment.
2 arthritis that disappears after a few hours but may persist for 2 days.
3 pains in the ears.

He reported one paraplegia with 24 h latency. He saw one fatality, and some slow recoveries who continued diving. Méricourt (1869) had reported no deaths with the Rouquayrol and Denayrouse suit, but 10 deaths in 24 divers using the 12 English suits.

Many of these are among the observations and reports that formed the background to Paul Bert's experimental work. In 1878 he reported evidence to suggest that on decompression

> all the symptoms, from the slightest to those that bring on sudden death, are the consequences of the liberation of bubbles of nitrogen in the blood, and even in the tissues when compression has lasted long enough.

He made no hypotheses concerning the dynamics of the dissolved gases but concluded that

> The great protection is slowness in decompression; … from 3 to 4 atmospheres, one hour … . The longer the workmen remain in the caissons, the more slowly they should undergo decompression, for they must not only allow time for the nitrogen to escape from the blood, but also allow the nitrogen of the tissues time to pass into the blood.

These rates are between 0.5 and 1 m/min, similar to those proposed later by von Schrotter (1906), 20 min/atm. Bert also proposed that if a workman becomes stricken one should return him to 'a pressure greater than that from which he came, then make decompression very slowly'.

Paul Bert's clear conclusions in 1878, together with his pioneering work on oxygen neurotoxicity, are among the first scientific approaches to hyperbaric physiology and were the most thorough to date. One might expect such logical recommendations to be adopted by the doctors who had responsibilities for compressed air workers, but not so. Dissemination of knowledge and the subsequent conversion of the unconvinced took time and in the meanwhile much preventable morbidity continued.

In 1870 the workings of the Brooklyn Bridge in New York were at 20 m (66 ft; 320 kPa). Although Smith (1873) the doctor at that location, also recognised that re-exposure to compressed air would alleviate the symptoms, recompression was not made available for the 110 cases of serious DCS that did occur. Dr Smith had rejected the intravascular bubble theory because he considered that Bert's experimental work had been from a much greater pressure than that experienced by tunnel workers and also because he attributed the illness to the longstanding hypothesis of vascular congestion due to vasomotor paralysis.

When the construction of a tunnel under the Hudson was resumed in 1879, it reached 30 psig, 343 kPa (24 msw, 79 fsw). It provided some of the worst safety records ever encountered in industry. In 1880 excess pressure in the heading caused the tunnel to blow out into the river and 20 drowned. In 1882 there was a mortality of 25% of the workforce in the 1 year (Moir 1896) but then insufficient funds caused work to cease.

When work on the Hudson tunnel restarted in 1890,

> an air compartment like a boiler was made in which the men could be treated homeopathically, or re-immersed in compressed air. … The medical lock should be used at once, as it does not appear to have much effect after some time has elapsed.

By Moir's action in introducing the lock, the deaths were reduced to only two in 15 months, 1.5% (Boycott 1906).

Snell (1896) published his book, *Compressed Air Illness: Blackwall Tunnel*, but appears to omit the story that, in the early 1890s when the tunnel had completed a significant phase of its construction, the builders threw a champagne party for the dignitaries. Because of the raised environmental pressure, they could not get the champagne corks out. At last they succeeded by drilling holes through the corks but then of course they found that the champagne was flat. After all that effort to get the party going, they drank it anyway. There were some reports in the press about their uncomfortable decompression experiences but, no detailed accounts by the party goers exist.

The first reliable report with details of the pathology of DCS in humans appeared in 1897 when Heller et al published their findings of autopsies on deceased divers. They described the findings of gross bubbles in many tissues and the vasculature of most organs including the heart, and the finding of bubbles in the capillaries and finer arteries and veins of the spinal cord on microscopy. They also reported the findings of hemorrhages in the lungs and other organs.

In 1904 the Hudson river tunnel was completed after more than 30 years work and many deaths. This brings us to the time when Professor Haldane (Boycott et al 1908) was calculating tables for compressed air work. His principle was to decompress rapidly to half the absolute pressure in 3 min and then continue at a specified linear rate to the surface. For example, after working in compressed air at 366 kPa (40 psig) for 6 or more hours, ascent from 188 kPa (13 psig) was in 117 min. The response of employers in the construction industry (Hill 1912) could have been predicted: '... are these times practical?,' '... out of the question,' and 'it quite appals one to think of taking so long.'

Between 1906 and 1908 more tunnels were built under the East River in New York with twice daily exposures to pressures up to 380 kPa (42 psig, 28 msw, 92 fsw). Keays (1909) reported more than 3600 cases of DCS, including 20 fatalities. He described the association of abdominal girdle pain with serious spinal cord injury and several other clinical features. From some half a million decompressions, he analyzed the bends percentages in the first shift (0.35%) and the second (0.72%) of the two 3 h shifts in 1 day. Cumulatively this was 1.07%. From decompressions from more than 10 000 single 8 h shifts, the rate was 0.62%, clearly suggesting that one decompression might be better than two. Nevertheless, the 'split shift' continued for many more years.

It then became necessary to raise the pressure in the East River tunnels to 366 kPa (40 psig, 27 msw, 89 fsw). The shifts were 3 h, twice daily, with a 3 h interval between them (although it is not clear if this was a true surface interval or if it included the previous decompression time). Prolonged decompression stops were not welcomed by the workers because of the way that their pay was calculated, so the response of the contractor was to install an intermediate lock at 290 kPa absolute (28 psig, 19 msw, 62 fsw). The workmen had to spend 5 min in this and 8 min in another chamber at 185 kPa (12.5 psig, 9 msw, 28 fsw) and then take 15 min for the final decompression to surface (Hill 1912). The necessary intermediate stop time was introduced without it being noticed because the two chambers were some 305 m (1000 ft) apart in the length of the tunnel. By the time the stragglers walking from one chamber to the next had been rounded up, the total decompression time became 48 min. They used 330 men for this deep phase: *all* were experienced workers. At first, the workmen rebelled against the 15 min decompression to surface, but then agreed and no fatal or serious cases resulted.

Hill (1912) published his book on *Caisson Sickness and the Physiology of Work in Compressed Air* which was a landmark in the application of good physiologic science to a complex environment. He despaired of the many 'astounding hypotheses' that still abounded more than 30 years after Paul Bert's work. He methodically demolished each of these hypotheses and deplored the slowness of many doctors around the world to accept 'the magnificent work of the French school.' Hill also made the first quantitative analysis of nitrogen in blood and urine at pressure, reviewed the solution of the respiratory gases into the blood and their uptake into the tissues, and argued the importance of duration as a factor under pressure. He also emphasized the close concordance between the results of his own experimental work and those of Haldane but was concerned that the advantages of stages over continuous decompression might not be as great as Haldane had suggested.

Hill then used himself and Greenwood as subjects to pressures of up to 700 kPa (7.0 ATA, 60 msw, 196 fsw) but the decompression profiles are not detailed in his book. These experiments led Hill to believe in the value of moderate exercise during decompression and, at his suggestion, during the construction of the Greenwich tunnel the men were made to climb the ladder out of the shaft immediately after decompression to atmospheric pressure.

In spite of arising from a common stem, the subsequent development of safe decompression procedures for the shallow but prolonged dry exposures of compressed air workers has followed a different path from that for divers. The lessons to be learned by divers from caisson work today are few and, with tunneling now deeper than 50 m (600 kPa; 165 ft), the transfer is now in the other direction.

As reviewed by Behnke (1969) and Hempleman (1993), in place of the linear decompressions recommended by Bert (1878) and von Schrotter (1906), a staged decompression was introduced by Haldane (Boycott et al 1908; Admiralty Committee on Deep Water Diving 1907). It was based on five hypothetical compartments in the body (misleadingly called 'tissues') with half-times for gas uptake or elimination of 5, 10, 20, 40, and 75 min. A 75 min compartment was chosen because it becomes 95% saturated in 5 h and, as advised by Moir, compressed air workers did not appear to get an increased number of bends once they exceeded 5 h at pressure.

As reviewed further by Vann & Thalmann (1993), Haldane recommended an initial decompression, provided this was from less than 600 kPa (6.0 ATA, 50 msw, 163 fsw) to halve the absolute pressure, followed by an appropriate series of predetermined stops. Boycott et al (1908) also recognized that inadequate ventilation of the diver's helmet causes a build up of carbon dioxide and that it was necessary to increase the ventilation in proportion to the increased pressure at depth. Depth records, partly limited by the number of sailors needed to man the pump, exceeded 104 msw (340 fsw) on compressed air, even though there was one fatality and other divers were considered to be psychologically affected. This was somewhat improved by a further increase in the ventilation rates in order to reduce CO_2 in the helmets. It was not until 1935 that Al Behnke first described nitrogen narcosis (Behnke et al 1935).

In 1931 a fatality occurred during a 5 msw (16 fsw) training ascent with a Momsen submarine escape lung (Polak & Adams 1930) and this led to the recognition of pulmonary barotrauma as another cause of decompression-related injury.

In the UK, Damant and Davis also reduced the decompression ratios and, for dives between 36 and 100 msw (120 and 330 fsw), introduced oxygen stoppages (Admiralty Deep Diving and Ordinary Diving Committee, 1930). The subjects in a study in the USA by Hawkins et al (1935) made daily dives, 5 days a week, and the stated end-point in each of these runs was the 'production of caisson disease of severe enough nature to necessitate terminating the series,' an end-point difficult to judge. At about the same time Behnke et al (1936) introduced the use of oxygen in recompression therapy. In 1937 Yarborough revised the Construction & Repair tables, resulting in a bends incidence of 1.1%, but this percentage is not necessarily comparable with rates from other tables or other locations because the end-point for decompression safety had not yet been defined.

During World War II, there was much basic research on bubble nucleation and growth and on the pathophysiology of decompression in relation to high altitude and diving (see Fulton, 1951).

The US Navy reworked their tables and also developed 'surface decompression' tables (Van der Aue et al 1945, 1951), seemingly unaware that this procedure ('crash surfacing') had been used by Wotherspoon's divers in the cold waters of the St Lawrence during salvage operations on *The Empress of Ireland* in 1914 and again later by Damant during salvage of *Laurentic* (Baker, Personal Communication, Historical Diving Society, 1998). Behnke, subsequently (1951, 1967), drew attention to a disequilibrium in gas tensions, which he termed 'the oxygen window', but this with Workman's M-values (1969) and Hempleman's $P\sqrt{t}$ single tissue (1969) is reviewed by Vann & Thalmann (1993). Modern decompression theory is discussed in Chapter 10.1.

OXYGEN IN DECOMPRESSION AND TREATMENT

Bert theorized that oxygen and recompression would be useful in the treatment of DCS but did not recognize that oxygen might be useful during decompression. This may be because he found that oxygen caused central nervous system (CNS) toxicity. In addition, Lorraine Smith (Smith 1899) demonstrated that increased partial pressures of oxygen, even at 1 bar (101 kPa) were toxic to pulmonary tissues. It is probable that the interest in the use of oxygen in diving was not considered worthwhile since DCS was a minor risk in diving at depths shallower than around 33 msw (109 fsw) but oxygen poisoning was a real problem deeper than 18 msw (60 fsw, 2.8 ATA). Not until Ham & Hill (1906) and von Schrotter (1907) demonstrated that oxygen could prevent DCS did this technique begin to be taken seriously. The US Navy used oxygen in diving as early as 1915, although there were no standardized tables until the US Navy published them in 1924. In 1936 Behnke et al suggested oxygen be used in the treatment of DCS after they demonstrated that the use of oxygen at 3 bar (303 kPa, 20 msw, 66 fsw) greatly increased the recovery from DCS in dogs (Behnke et al 1936). However, it was not until 1965 that this use of oxygen became accepted in the US Navy (Goodman & Workman 1965) and around the world as the basis for the therapy of DCS.

Until the 1940s the use of oxygen during diving operations was not common because little work had been done on the optimal use of this gas and the problems of the inconsistent appearances of CNS toxicity. It was not until World War II that this problem was studied in a long series of exposures of humans to 100% oxygen under a variety of conditions (Donald 1947). These studies, along with a brief history of studies of oxygen toxicity and oxygen usage in diving, are included in Donald's book (1992). These studies performed under wartime conditions with important operational objectives could not be easily repeated. Donald investigated and defined the relationships of depth, exercise, carbon dioxide, and immersion in water with oxygen in this landmark series of experiments. Further work by many other workers has resulted in the common use of oxygen enriched mixtures in operational diving to decrease the time required for decompression and to prevent DCS. Unfortunately, none of the extensive research done in the past 50 years has delineated the cause of CNS oxygen toxicity or how to prevent it, except by limiting exposure. On the other hand the use of oxygen at increased partial pressures in relation to the effects on lung function has been thoroughly investigated by Clark & Lambertsen (1971a, 1971b). These studies, among others, led to the use of the 'unit pulmonary toxic dose' (UPTD) as a guideline for determining the maximum allowable amount of oxygen exposure that will result in no significant lung damage or loss of function (Wright 1972). The application of these guidelines has proved useful in saturation diving, which requires the use of increased partial pressures of oxygen over long periods, and also in treatment of complicated cases of diving casualties that require prolonged or multiple exposures to increased levels of oxygen at pressure.

THE DEVELOPMENT OF DEEP DIVING

In the period when CO_2 build up was thought to be responsible for adverse psychologic effects on the diver at depth, Thompson proposed the use of helium to the US Navy in 1919 (Thompson 1927) on the grounds that it would have less breathing resistance than compressed air. Studies on oxy-helium during the next 10 years failed to endorse this approach and the use of relatively safe air decompression tables further limited its use (Sayers et al 1925). Thus helium had a false dawn. It was a pair of non-naval pioneers, Nohl and End, who returned helium to the spotlight in 1937. Under the supervision of Dr End, Nohl made a 128 msw (420 fsw) solo dive with closed circuit breathing apparatus in Lake Michigan (Nohl 1938). The success of this well planned yet moderately hazardous dive stimulated the US Navy to conduct a large series of helium dives over the next 2 years to as deep as 152 msw (500 fsw) (Behnke & Yarbrough 1938, Yarbrough 1937). The salvage of the US submarine *Squalus* in 1939 was achieved by using a series of open sea heliox dives to 74 msw (243 fsw).

World War II imposed other priorities than deep diving to military development. There was much basic research on bubble nucleation and growth and on the pathophysiology of DCS in relation to both high altitude and diving by Fulton (1951); an excellent work that still deserves study.

The focus for operational diving was on clandestine operations using closed circuit oxygen breathing apparatus. Acute oxygen toxicity in such swimmers was a major hazard and studies in the Royal Navy by Donald (1947, 1992) did much to limit this risk. For clearing mines at depths deeper than permitted on oxygen, a semiclosed oxy-nitrogen ('nitrox') rebreather was routine.

After World War II the focus returned to deep diving. In 1945 Zetterstrom made an oxy-hydrogen dive to 160 msw (525 fsw) in Sweden that was overshadowed by his accidental death due to topside errors. The first ship built for deep diving development, *HMS Reclaim*, was commissioned in 1948. Using standard helmet dress, a dive was made to 165 msw (541 fsw) and in 1958 to 186 msw (610 fsw).

Under the medical supervision of Bühlmann (1969), a number of deep dives with sequential mixed gases were made in the Swiss lakes by Keller, followed in 1962 by a 305 msw (1000 fsw, 3.1 MPa) dive with a submersible compression chamber off Santa Catalina. The tragic death in the diving bell of the other diver, Small, plus the loss of a standby diver in an attempt to rectify a problem with the bell led to mixed conclusions. The fatalities dissuaded some observers from developing deep diving further and led in the USA to 1 atm sea bed habitats for servicing oil wells. However, the oil industry recognized the significance of Keller's deep dive and continued their funding of research into deep diving in the chambers of Zurich University. Using compression rates of 1 m/min to depths as great as 500 msw (1640 fsw) and with prolonged, yet relatively rapid decompression profiles, much knowledge was gained.

Although now this may be perceived as modest, another breakthrough in 1962 was a working surface-orientated helmet dive made by Wilson to 128 m for the oil industry. From this experience he, with Lindbergh, then developed the first submersible compression chamber specifically for commercial purposes. The Royal Navy also continued research into deep bounce diving, culminating in 1965 in 1 h dives to 183 msw (600 fsw) in depth at the limit of *HMS Reclaim*'s equipment. On one occasion, the onset of vertigo during decompression did not respond to recompression to the maximum pressure of the deck chamber equivalent to 91 msw (300 fsw) and the diver had to be lowered in the bell to 139 msw (455 fsw) in the sea to get relief. Other lessons were learned (Barnard & Elliott 1966, Elliott 1996) that were shortly to be applied to divers engaged in the development of the oil industry in the North Sea.

THE DEVELOPMENT OF SATURATION DIVING

The concept of a prolonged exposure in compressed air in order to reduce the costs of multiple shorter exposures with a similar total bottom time was first proposed by Behnke (1942).

> From the point of view of physiologic response and work output, the attempt to decompress men twice daily is not only potentially dangerous but also highly uneconomical … .

However, Kindwall (1990) reports that the first saturation exposure was made by End and Nohl in 1938. At that time, saturation was considered dangerous because it had proved impossible to decompress horses and mules after they had been used in lengthy tunneling operations. End and Nohl decompressed in 5 h from their 27 h in a chamber at 30 msw (98 fsw), with one of them needing recompression (Kindwall, personal communication, 2000).

The credit for turning into reality this concept of achieving inert gas equilibrium for deep divers belongs to George Bond. His original proposal in 1957 for the *Sealab* series of dives (Penzias & Goodman 1973) states:

> It is believed that successful completion of this research effort will provide a demonstration of man's capability for free-ranging existence under conditions of high ambient pressure such as might be encountered in life on the ocean floor of a continental shelf.

Animal studies called 'Project Genesis' (Workman et al 1962) preceded human exposures.

Dugan (1967) tells of a meeting in his apartment between Captain Bond and Jacques Cousteau in September 1959 when Bond explained his experiments and his ideas. This story is recounted by Bond who said:

> … in late 1959 Jacques Cousteau and I appeared together on an undersea programme in New York. Afterwards the undersea chronicler Jim Dugan invited me to his apartment for further talks with Cousteau. We discussed my concept of saturation diving. In fact, we talked until breakfast!

(Earle & Giddings 1980).

The first to take advantage of such developments was the 'Man-In-Sea' program (Link, 1973). It was largely concerned with underwater archaeology and wrecks, and was supported by the Smithsonian Institution. Based upon the initial work on saturation by the US Navy, Link began with a simple submersible decompression chamber (SDC) which would be used to return divers at pressure to the vessel from their sea bed habitat. In September 1962 Stenuit made a dive to 74 msw (243 fsw) from the chamber at 61 msw (200 fsw). Stenuit was very cold in the SDC overnight but, because of a shortage of helium, the bottom time was terminated after 24 h at depth. Only 4 days later, Cousteau began *Conshelf I*, a 7 day exposure for two men in a habitat at 10 m.

It was not until 1964 that the US Navy was able to mount *Sealab I*, in which four divers spent 10 days at 58 msw (190 fsw) (MacInnis & Bond 1969). In the interim, Cousteau's *Conshelf II* had been home to seven divers at 11 msw (36 fsw), five of them living there for 1 month (Chouteau 1969). A year later, in June 1964, Ed Link used his SDC to take two divers down to their inflatable house ('SPID') at 132 msw (433 fsw) for 48 h.

In the US Navy's *Sealab I* there was an apparent slowing of all gross physiologic and motor functions, but it was also noted that when oxygen levels were held at 4% (Po_2 0.27 kPa) or greater at 59 msw (193 fsw), the aquanauts reported an improved sense of well-being. In the US Navy's *Sealab II* in September 1965, there were extensive physiologic investigations while, for 45 days, three teams of 10 men occupied the habitat at 62 msw (203 fsw). *Sealab II* involved a whole new habitat and surface support vessel in order to more adequately serve the many underwater experiments and physiologic studies which were carried out in an environment much more representative of most ocean floor conditions than those encountered in *Sealab I*. This phase of the *Sealab* series was now to prove that humans could both live and do useful underwater work as opposed to simply determining if they were able to survive. The physiologic studies included biochemistry, electrocardiography, electroencephalography, behavioral, and respiratory studies. Following dives into cold water, a marked reduction in temperature of the extremities and the slight rise of the core temperature was recorded. On return to the elevated temperature of *Sealab* and, particularly following a hot shower, rectal temperatures fell sharply. This fall was due to peripheral vasodilatation and partially explained the 'paradoxical shivering,' a subjective feeling of being warm, coupled with an objective pronounced shivering observed by several divers. There were no significant changes noted in any of the studies done. In spite of the stress involved in this setting, the amount of work done was high compared with the expected degradation of performance because of the conditions. The concurrent *Conshelf* dives led, in 1965, to *Conshelf III* at 100 msw (328 fsw). The habitat was home for six men for 30 days and there were no reported adverse effects.

Sealab III was planned as an ambitious continuation of *Sealab II* to investigate new methods of underwater search and recovery construction, tools, and marine biology. It was to have been conducted near San Clemente Island off Long Beach California at a depth of 183 msw (600 fsw). The habitat was the extensively modified *Sealab II* habitat, and a larger surface support ship with dual saturation diving systems and closed diving bells (PTCs) with a specially designed handling system. Plans were to have five teams of eight men each spend 12 days on the ocean floor. Included in this effort was an extensive biomedical investigation, including newly developed biochemical tests of muscle metabolism, red blood cell survival studies, and studies of respiratory function and exercise physiology. In preparation for the sea floor program a series of dives were made at the US Navy Experimental Diving Unit in Washington, DC, where many of these studies were accomplished during dives at 61–251 msw (200–825 fsw) between mid-1966 and mid-1968. The 251 msw (825 fsw) dive included an excursion to 312 msw (1025 fsw), a record at that time. Again, no unexpected problems were found. One notable respiratory study used neon–oxygen mixes for the first time for respiratory studies to simulate gas densities 15 times the density of air at 1 bar (101 kPa). Also included were studies of performance, hearing, vision, memory, and speech intelligibility. Unfortunately, the habitat developed a leak after being placed on the bottom and one of the aquanauts died in an attempt to repair the problem. Although the Navy continued to do saturation diving after this, both operationally and in land-based chambers, the habitat program was never resumed.

The first commercial saturation dive was conducted in 1965 by Marine Contractors of Connecticut with technical hardware provided by Westinghouse. The divers spent up to 5 days at 61 m (200 ft) working on the Smith Mountain Dam in Virginia (Zinkowski 1978). The following year the same contractors again used the Cachalot diving system in the first saturation dive for the oil industry. This dive to 73 m (240 ft) was to remove parts of a platform destroyed by a hurricane.

In subsequent years, research diving continued to progress in depth and duration, whereas dives conducted as commercial diving contracts made much slower progress. Among the significant commercial dives to follow was the recovery of oil well equipment by Comex from 326 m (1070 ft) of water in 1975. For the installation of the oil platform *Cognac*, Taylor Diving undertook saturation dives over two seasons which totaled more than 14 000 man hours in saturation at depths greater than 290 m (951 ft). Though somewhat shallower at 240 msw (787 fsw), the salvage in 1981 of gold from the wreck of *HMS Edinburgh* by the diving company 2W is remarkable for the amount of hard physical work undertaken by well-motivated divers at the performance limit of their breathing apparatus.

These operational experiences tend to be overshadowed by the deep test dives, in the laboratory and in the sea, that occurred in the USA, UK, France, and Norway during this time (reviewed by Bennett & Rostain 1993). Following a dive in 1992 on hydrogen–helium–oxygen mixtures to 701 msw (2300 fsw) by Comex, one might ask why operational diving has never exceeded around half the depth achieved in such trials. One answer might be that breathing apparatus design, communication systems, and engineering requirements to support such deep dives have not yet been fully developed at those depths to the standard required for health and safety. A more relevant answer is simply that there is currently no work at such deep depths. However, in spite of the excellent progress made in the design of remotely operated vehicles (ROVs) to eliminate the need for deep diving, there are still a number of tasks for which the human hand and eye are needed. As long as there is the possibility that just one diver will need to lock out at a great depth, all the supporting services and the research for health and safety must be provided.

This limited account has not been able to cover much of the development of surface-orientated diving for recreational and working divers, nor has it touched on the worldwide experience of shallow oxy-nitrogen and air saturation diving. Even though the names of many important pioneers have not even mentioned, it is hoped that this overview will encourage others to recognize the value of the contributions made by so many dedicated and enthusiastic researchers and diving pioneers in the last 150 years or so. It is important for tomorrow's divers and researchers to realize that diving is based on an extensive foundation of multidisciplinary development. There is a wealth of important data and original thought in the historical archives – work that can continue to enhance the health and safety of future diving.

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2

Diving Methods

2.1 Compressed Air Work

Eric P Kindwall

Compressed air is used in civil engineering when tunneling or sinking bridge piers considerably below the local water table. This permits mining and excavation to proceed unhampered by the ingress of water. Almost all compressed air work is carried out in soft ground, whereas when tunneling in rock, pumps usually manage water ingress. Compressed air is used in rock tunneling only rarely and then only when there are multiple fractures or the rock is of poor quality and flooding is severe.

Compressed air other than for caissons was first used by the French mining engineer Triger to force water from a coal mine at Chalons, France in 1841. It was Triger who was the first to report a case of decompression sickness (DCS) in man (Triger 1845).

It was on the Brooklyn Bridge project that the word 'bends' was coined for DCS. A stilted way of walking effected by fashionable ladies of the era was termed 'the Grecian Bend.' When the 'sandhogs,' or caisson workers showed signs of DCS, their painful gait suggested the Grecian Bend. The term was shortened to 'doing the bend' and finally 'bends' or 'bent' became legitimized by use (McCallum 1967b). 'Sandhog' is a US term; in the UK, caisson and tunnel workers are termed 'navvies.'

Fig. 2.1.1 View of pressure bulkhead, Baltimore Subway. The lower square door is for use of the muck train, which can be decompressed in the lock seen beyond. Above it is a rectangular door to the separate man lock. Pipes to the left carry water for the fire main and ventilation to the face of the tunnel. The large flexible ventilation tubing is in use prior to starting pressurization of the tunnel. (Courtesy of Kiewit/Shea Contractors)

THE PHYSICAL PLANT

CAISSONS

Caissons are generally used for sinking bridge piers or structural building foundations and provide a means of removing silt and clay underwater so that bedrock may be reached on which is placed the bridge foundation. The edges of the caisson are beveled so as to cut into the soft bottom as weight is applied from above. Today, caissons are usually made of steel and concrete, constructed in dry docks and then towed to the construction site supported by their own buoyancy. When the caisson has been located at its approximate final position, construction on top is continued, adding weight to the bridge pier until the caisson touches the bottom with the rising and falling tide. It is positioned accurately and then buoyancy chambers within the caisson are flooded. The working chamber at the bottom of the caisson is filled with compressed air to force out the water and the weight of the caisson forces it into the mud as the workers commence digging and send the excavated material to the surface. Two shafts extend from the surface into the caisson: one for removal of muck and the other for use by the workmen. A muck lock is placed atop the muck shaft to allow for removal of muck and a small decompression chamber or blister lock is placed at the top of the man shaft.

Decanting

The blister locks on top of the caisson are usually quite small. Because of the physical constraints at the work site, large decompression chambers cannot easily be attached to the man shafts from the caisson. When decompression times exceed 30 min, workers rapidly decompress in the blister locks, and then with a large excess nitrogen load, quickly run to a large chamber located nearby where they first recompress and then slowly bleed off the pressure to complete their decompression. This procedure is known as decanting. The surface interval in free air should not exceed 5 min. The 5 min free air interval corresponds to the 5 min surface interval permitted by the US Navy during the surface decompression of divers. However, this process can be dangerous, and decanting in caisson work is not permitted in the USA.

Automated Caisson Systems

The Japanese have now devised a fully automated system in which a hydraulically powered scoop can reach all corners of the caisson. The scoop delivers the muck to a hopper, which removes it from the caisson. An operator using a closed circuit TV camera directs the scoop. Thus, nobody need be exposed to the compressed air environment in the caisson itself. Only when the scoop needs maintenance or when boulders impede excavation, are workers required to enter the caisson working pressure.

The automated caisson has already been used in Japan to pressures of 600 kPa (73.4 psig) and work is planned to 800 kPa (103 psig). Workers entering the caisson for maintenance breathe a tri-mix gas of N_2–He–O_2. Decompression, after 1 h shifts, is accomplished using decompression tables developed by Nashimoto and Sterk. Automated caissons now have

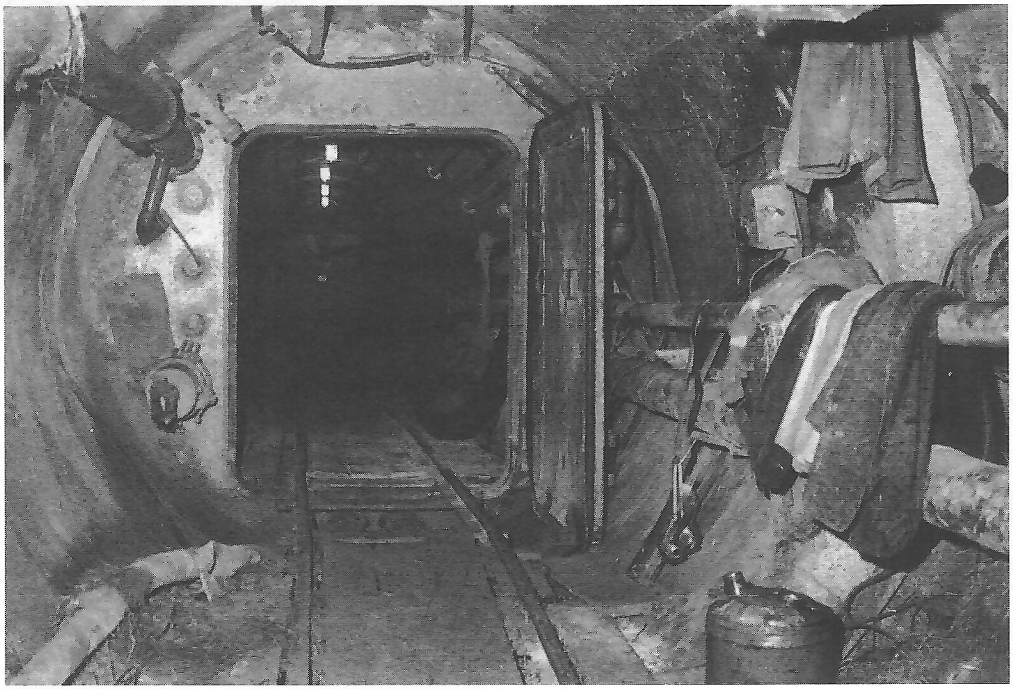

Fig. 2.1.2 View from the pressurized heading into the combination lock which is used for both the muck trains and for decompression of the workers. Combination locks are permitted in smaller tunnels such as this 2.4 m (8 ft) finished bore tunnel. A removable track section allows closure of the door. (Courtesy of Wisconsin Department of Health)

become the norm in Japan (Nashimoto, personal communication, 2001).

COMPRESSED AIR TUNNELING

When the sand or muck becomes porous or the tunnel runs under a river or lake, there is often no practical way of keeping the water out except for considerable air pressure in the tunnel. Recently developed pressure balanced shields have often allowed tunneling without the use of compressed air, with soil and water pressure being maintained ahead of the shield. Tunnel driving at extreme depths has been carried out using this method.

All compressed air tunnels are excavated using a shield which is driven forward by hydraulic jacks around its circumference. The direction of the tunnel ('line and grade') is determined by differential jacking of the shield perimeter. Openings in the shield allow removal of the mined muck, usually with the aid of automated machinery and conveyor belts. Some shields are equipped with cutting heads rotating the full circumference of the tunnel as the shield moves forward. The tunnel is lined with either steel or concrete liner plates for its entire circumference or with rings made of circular I-beams that support wooden lagging (Fig. 2.1.3).

Although 10 kPa of pressure for each meter of water head is the theoretical requirement, soil resistance to water flow generally reduces the air pressure required by 10–30% depending on the depth of the tunnel and the characteristics of the ground (Richardson & Mayo 1975). Methane is rarely found in compressed air tunnels, as the pressure generally keeps it out. Only when compressed air is removed from a tunnel does methane become a serious threat if it is present in the ground.

SAFETY REQUIREMENTS IN CAISSON AND TUNNEL WORK

FIRE

Fires rarely occur in caissons because of their all-steel construction, and because there is usually no flammable material present. However, hydraulic fluid and electrical insulation can present a fire hazard, although the most serious fire danger occurs in tunnels lined with wooden lagging, where straw is used to caulk the

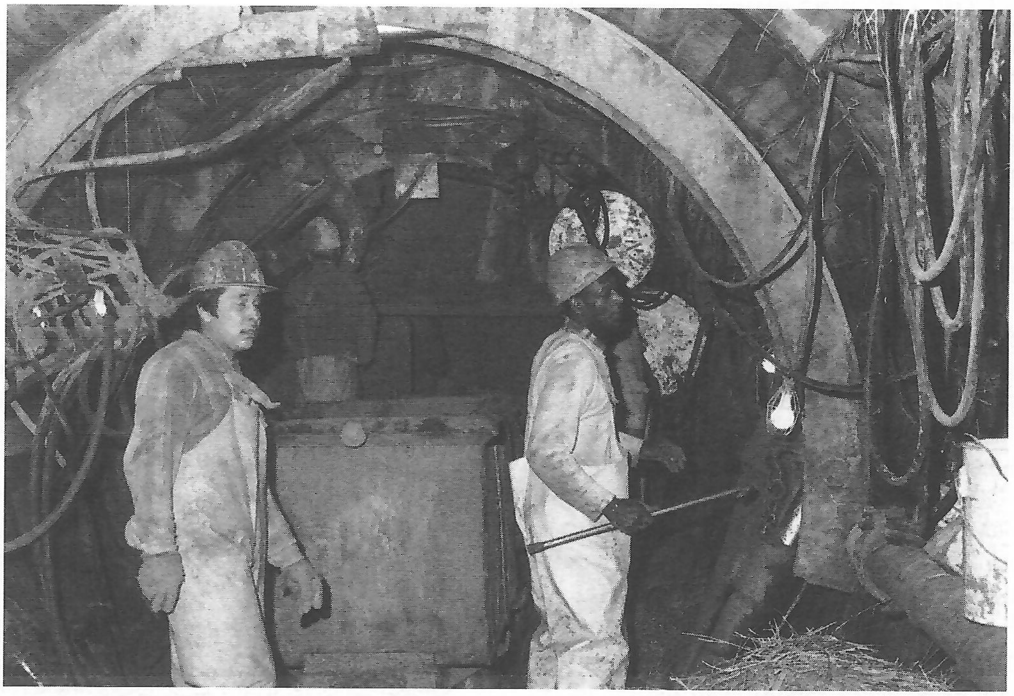

Fig. 2.1.3 Workmen at the face of an 2.4 m (8 ft) finished bore sewer tunnel being driven under 394 kPa (43 psig) pressure. The tunnel lining is made up of 1.2 m (4 ft) sections of maple heart timbers supported by steel ribs. The straw is used for caulking the invert. Hydraulic fluid, straw and wooden planking present serious fire hazards. (Courtesy of Wisconsin Department of Health)

seams at the invert. A wet fire main should extend all the way to the heading with sufficient pressure to overcome the air pressure within the tunnel. Outlets should be provided every 60 m (200 ft) with 30 m (100 ft) of rot-proof hose attached to the fire main at each fire point. A fire main and hoses must also be provided in the decompression lock. Chemical and CO_2 fire extinguishers are prohibited because of the danger of contamination in confined spaces.

On some compressed air jobs, workers are provided with Mine Safety Appliances (MSA) 'self-rescue units', which are hermetically sealed and worn on the belt. In the event of fire and smoke, the units can be broken open and the men breathe through a Hopcalite catalyst which removes carbon monoxide (CO) and other contaminants. The capacity of these units is limited, the catchphrase being 'one man, one hour, one way, one percent (CO)'. For instance, 2% CO would reduce functioning time to 30 min, and so on. The compressed air environment makes it difficult to open the units, as the two halves are forced together by the increased ambient pressure. A sharp blow is often necessary to break the seal and separate the two halves. Draeger makes a self-rescue unit that has a plastic tear plug, which opens the unit, relieving the pressure imbalance.

AIR SUPPLY FOR CAISSONS AND COMPRESSED AIR TUNNELS

The supply of air must be sufficient to carry off pollutants in the air and to accommodate the air lost during the periodic decompression of the muck lock. Because caissons are tightly closed structures, open only at the bottom, air supply requirements are modest compared to tunnels, and can be accurately predicted, as long as sufficient allowance is made for air loss due to opening and closing the muck lock, and decompressing the workers. A ventilation rate of 0.85 m^3/man/min (30 cu. ft) should be sufficient to carry off contaminants and keep the working chamber comfortable.

The contaminants that must be closely monitored are CO_2, CO, oxides of nitrogen, oil vapors, and methane. Today, large rotary compressors are typically used to supply the necessary volumes. The intakes for the air must be located away from sources of CO and oxides of nitrogen such as auto and truck exhausts. *This also applies to the intakes of the air compressors for high-pressure tools, which exhaust into the tunnel.* In tunnels, the supply of air that is required is considerably greater than in caissons, and may vary widely, depending on the porosity of the ground, the type of tunnel lining and how much of the concrete lining has been completed at any given time. Large air receivers or volume tanks are generally interposed between the compressors and the tunnel. These are at a higher pressure than the tunnel and serve not only as a small air reserve, but allow for cooling of the air after compression and smooth out any pulsations if piston compressors are used.

An additional factor is the amount of CO_2 present in the tunnel. Certain kinds of muck ferment to produce CO_2 and occasionally iron containing soils catalyze a reaction which produces CO_2. The more CO_2 that is produced, the greater the ventilation requirement. Carbon dioxide generated in the soil by compressed air tunneling in populated areas has produced problems on occasion, by seeping into nearby basements, layering near the floor and putting out pilot lights in furnaces and water heaters.

As an absolute safety requirement, there must be two separate sources of compressed air available. Emergency diesel generated lighting must be provided as well as emergency power for man hoists. There should be two independent supply pipes to the tunnel of sufficient size to minimize pressure drop and there must be wholly independent power supplies. In the event of electric power failure, the secondary compressor plant is immediately activated. Back-up air is an absolute requirement, because loss of air pressure may lead to flooding and loss of the tunnel, and a whole shift may experience DCS. In the UK, the Construction Industry Research and Information Association (CIRIA) Code of Practice requires the standby air source to be at least 50% of the primary source, whereas in the USA the Occupational Safety and Health Administration (OSHA) states it must be of equal capacity.

Gauges showing the pressure in the heading and the decompression locks should be installed in the compressor house and at the lock tender's station outside the decompression locks. Care must be taken to ensure the gauge lines are dry and not 'water bound,' which would give a spuriously low reading on the surface in the compressor house and cause the permanent recording graphs to read low. They must also be tested periodically for leaks as well as the presence of water. Recording charts are a necessity for documenting pressure exposures to the workers. Circular charts with recording pens having 24 h rotation are satisfactory. Charts must be kept for the heading pressures as well as the man lock.

Unless one is using two locks in series for decompression, the door to the heading must be kept closed so that in the event the entire working crew is incapacitated, the decompression lock can be decompressed and entered by a rescue team. A handy method of ensuring this is to rig a door spring or bungee cord to hold the inner door bumped shut. Using this arrangement, the door from the lock to the heading is not dogged shut, which allows quick access to the lock from the tunnel in an emergency, yet it is closed and will seal if the lock is decompressed.

An air supply pipe from the compressor plant should be continued all the way to the heading or working face. Most of the air should be delivered there to maximize air quality for the workers. Additionally, there should be smaller vent holes in the supply pipe at 60 m (200 ft) intervals for the length of the tunnel to eliminate pockets of 'dead air.' Throughput of the compressed air is usually assured by the porosity of the ground, but in very tight tunnels, mop lines, opened at the face, may be necessary to ensure adequate ventilation. All air supply openings in the chamber should be equipped with flapper valves so that the tunnel will not be depressurized should the operative air supply pipe be accidentally broken at the surface.

During decompression, it is vital that the decompression lock is ventilated to prevent the build up of CO_2. It is critical that effective silencers or mufflers are provided to the supply of air so that near continuous venting of fresh air into the lock is not prohibitively noisy.

MONITORING THE ATMOSPHERE

It is recommended minimal standards for air composition and purity be maintained in the caisson or tunnel (see Table 2.1.1).

Carbon dioxide dramatically increases the incidence of DCS and although 0.25% is given as a maximum, it is highly desirable to maintain CO_2 below this level if at all feasible.

The shift foreman or the project safety engineer usually carries out air sampling once every 8 h. If standard color tube indicators supplied by MSA, Bachrach, Draeger or Kitigawa are used in the tunnel, they are accurate when read in the compressed air environment. These color tubes indicate the level of contamination for a given volume of gas. This corresponds to the amount delivered to the lungs with each breath. Therefore, no compensatory calculation is required. If, however, a gas sample is taken in an evacuated test cylinder in the compressed air environment, and subsequently analyzed in the laboratory, the reading will be spuriously low. That is because decompression dilutes the number of contaminant molecules in proportion to the pressure. Therefore, the laboratory result must be multiplied by the number of absolute atmospheres present in the working atmosphere. The same caveat applies to continuous monitoring equipment on the surface, drawing samples from the tunnel. For example, if a methane monitor at the surface is continually sampling air from a tunnel being driven at a pressure of 202 kPa (14.7 psig), the monitor should be set to read 200 ppm when calibrated with 100 ppm calibration gas on the surface. At present, there are no commercially available continuous reading electronic methane monitors which function when the monitor itself is taken into the compressed air environment.

Table 2.1.1 Minimal standards for air composition.

Component	Quantity
Oxygen	20–22%
Carbon monoxide	< 50 ppm (by volume)
Carbon dioxide	< 0.25% (by volume)
Oil or particulate matter	5 mg/m^3 for environments between 200 and 300 kPa (1 and 2 bar gauge pressure)
Methane	< 10% of the lower explosive limit

SUPERVISION OF WORKERS

The project engineer and shift foremen should be knowledgeable in the use of compressed air and familiar with the basic physiologic problems attendant to its use. They should be thoroughly familiar with the decompression tables in use, the symptoms and signs of DCS and barotrauma, and where to refer workers should DCS occur. They should be able to instruct workers in ear clearing and how to avoid injury when working in the compressed air environment. They should be responsible for maintaining proper logs, records of decompression, be familiar with the hazards of fire in the compressed air environment and the provisions of all safety codes being enforced on the project. A single individual should have overall responsibility for the compressed air aspects of the project, including ultimate enforcement of the rules and preservation of records. Typically, this would be the project engineer or safety engineer. Some jurisdictions have required licensing of this individual as an 'air master.' In the event that compressed air regulations are not followed, the air master is subject to loss of his license, thus causing the work to be suspended until another air master could be installed. This has been shown to put 'teeth' into the enforcement of regulations. This individual is also responsible for assuring that gauges are accurate, gauge lines have been inspected for leaks or flooding, and that the required physical examinations for the workers are current.

DECOMPRESSION FOR CAISSON AND TUNNEL WORK

Even though stage decompression tables are available, continuous decompression tables are still used in the USA based on historical precedent. This complicates matters, as it is very difficult to control such decompressions by hand. Thus, a computer or cam-controlled exhaust mechanism is required. (If stage decompression is used, there is no such requirement.) The slow bleed-off method is also inefficient and wasteful. For example, if the last stage from 127 kPa (4 psig) to the surface were to take 1 h, at least half of the time is spent at a pressure less than 114 kPa (2 psig), which provides no meaningful bubble suppression. This is not an efficient use of decompression time. In the UK, France, Germany, and Brazil, the more efficient stage decompression procedures have been adopted.

SHIFT LENGTH AND SATURATION EXPOSURES

Working shift lengths are typically divisible into 24 h as tunneling usually proceeds round the clock. Shifts of 8, 6 and 4 h are used, the latter at the higher pressures. The French drastically shorten the permissible shift length as pressures rise, so as to increase safety. In the UK, work shifts tend to be longer, as it is permissible for decompression time to be added to a full 8 h work shift. The 1982 CIRIA regulations stipulated only that there be a 12 h surface interval between exposures and that the total of the combined work and decompression exposures be limited to 10 h/day. It is clear that if the present theory regarding the half time for the slowest tissues is correct, employees are not completely free of work-absorbed nitrogen when re-entering compressed air after the first shift of the week.

In the USA, all work – including decompression – must be completed within an 8 h shift, guaranteeing a 16 h surface interval. Behnke (1980) has suggested construction of saturation habitats in tunnels with storage pressures up to 250 kPa (22 psig). This would be the pressure limit because of the cumulative effect of oxygen toxicity from compressed air. At that pressure, the effective percentage of inhaled oxygen (F_{IO_2}) would be equivalent to 53% O_2 at the surface. Much deeper, 8 h excursions to working pressure could be made without a decompression obligation. A major problem with saturation exposures is the space required for the workers' living quarters and securing co-operation for these exposures. Saturation would be feasible only on the largest projects. To date, it has not been utilized.

ENFORCED DECOMPRESSION CODES

See Bennett & Elliott (1993) for a detailed history of decompression regulations. In the UK, decompression tables using continuous decompression were devised in 1936. No decompression stops were required at pressures up to 250 kPa (22 psig) if 'sensitive individuals were eliminated.' It was concluded that saturation occurred at 4 h and that for any exposure longer than 6 h no additional decompression was required (Walder 1982). In 1958, Paton and Damant (Paton 1967) devised improved tables. However, when these tables were put into use on the Clyde tunnels, they were found to produce a 19% incidence of aseptic necrosis of the bone (McCallum 1967a). This was an indication that further modifications would have to be made.

FURTHER DEVELOPMENTS

In 1966, Hempleman devised new tables which were first used at Blackpool and came to be known by that name. The Blackpool Tables were much longer, adopted stage decompression, and required decompression for all exposures greater than 202 kPa (14 psig) (Hempleman 1973). The Blackpool Tables represented a quantum leap in improvement in the decompression schedules, but still produced DCS. Unfortunately, they also continued to produce aseptic necrosis. Of the 59 workers on the Dungeness SB Power Station contract five developed bone disease on the Blackpool Tables (Trowbridge 1977). KP Yau (personal communication, 1987) reported that 83% of the men working on the Hong Kong subway project reported DCS in association with the Blackpool schedules. However, the 'official' bends rate, derived from those who actually received treatment, was low (Lam & Yau 1988). Bone necrosis was also reported on the Hong Kong project. The incidence was possibly worsened by engineers and other 'short stay' personnel visiting the tunnel several times a day and 'adding up' their decompression times to be taken all at once, at the end of the day (DN Walder, personal communication, 1987).

In the USA, the only major decompression schedules in widespread use were the 1922 New York Tables, which continued to be used until Duffner devised the

Washington State Tables in 1963. The Washington State Tables abolished the split shift, greatly extended the decompression time, but only took three compartments – the 30, 60 and 120 min tissues into consideration for a Haldanian calculation. Continuous decompression at varying rates was retained instead of stage decompression, as Duffner found the contractors and workers refused to stray from tradition (GJ Duffner, personal communication, 1983).

The Washington State Tables also have another major flaw. For each 14 kPa increment (2 psig pressure change), a decompression time is provided for shift lengths 'over 8 h'. This would be dangerous if used. For example, at 236 kPa (20 psig), if an emergency occurred causing a foreman to work two 8-h shifts totaling 16 h, his decompression requirement using the Washington State Code would be *only 113 min.* In commercial saturation diving, such an exposure calls for over 14-h decompression.

The Washington State Tables were used in Seattle on a water tunnel project and later on the San Francisco Bay Area Rapid Transit Subway Project. In Seattle, they were used at pressures up to 330 kPa (34 psig), whereas in San Francisco they were rarely used above 216 kPa (16 psig), except for a 2 week interval under the Embarcadero, where pressures rose to 348 kPa (36.5 psig). Ten years later, Sealey surveyed 83 men who had taken part in the construction of the Seattle tunnel and found that none of these individuals had aseptic necrosis of the humoral or femoral head. Four men were found to have shaft lesions in the proximal tibia, one of these being bilateral (Sealey 1975). Annual X-rays of the men working on the Bay Area Rapid Transit project during the duration of the project failed to reveal any evidence of aseptic necrosis, but it must be remembered that there was only one 2 week period when they were exposed to pressures at which this could occur. Dysbaric osteonecrosis is unknown at pressures less than 216 kPa (17 psig) (DN Walder, personal communication, 1971).

DYSBARIC OSTEONECROSIS IN US TUNNELERS

In Milwaukee, X-ray surveys were initiated in 1969 of all the compressed air workers treated for DCS. At that time, the State of Wisconsin was using a split shift schedule, a modification of the 1922 New York Code. It was found that 35% of the men had radiographic evidence of aseptic necrosis of the bone. This finding prompted the adoption of the Washington State Tables.

At that time, there had been no report of aseptic necrosis in conjunction with their use. In 1971, the Washington State Tables were adopted as the Federal Code under the newly created OSHA (US Bureau of Labor Standards, 1971). No further cases of aseptic necrosis were reported in Milwaukee until 2 years after the completion of a sewer tunnel section in which pressures of up to 392 kPa (43 psig) had been necessary. At that time, two workers presented with dysbaric osteonecrosis as a consequence of decompressing on the OSHA enforced tables. A subsequent survey of the workers involved in that project revealed a 33% incidence of dysbaric osteonecrosis using the federally enforced schedules (Kindwall et al 1982). The OSHA table had never previously been used at pressures greater than 348 kPa (36.5 psig).

THE INCIDENCE OF DCS

The reported incidence of DCS as manifested by the number of workers appearing for treatment is always artificially low. Typically, workers tend to 'tough out' minor symptoms of bends and only report for treatment when the symptoms are unbearable. Too frequent treatment for DCS might risk their jobs in the tunnel and cause them a loss of pressure pay. Therefore, the true incidence of symptoms associated with DCS can only be obtained by the use of an anonymous reporting system. On the tunnel jobs in Milwaukee, a system has been used whereby the individual workers simply write an X or an O on a slip of paper along with the date and the shift, which was then deposited in a box when going on shift. If a worker had symptoms after coming off the previous shift, he wrote an X; if he has had no symptoms, he wrote an O. Using this method, it was discovered that up to 26% of a shift might have DCS without any workers reporting for treatment and, at pressures between 229 and 310 kPa (19 and 31 psig) one or more individuals in the workforce was affected on 42.5% of the working days. Nevertheless, the official DCS rate for that project was only 1.44% This was based on the number of workers treated.

The appearance of DCS in tunnel workers seems to be capricious and sporadic. The same anonymous reporting system revealed that, conversely, DCS was not experienced by any tunneler on over 50% of the working days. This was despite the use of tables known to be grossly 'inadequate'. If any meaningful statistics are to be generated, it is probably required that compressed air projects adopt an anonymous symptom reporting system.

In the past, it had been customary to adopt a rather cavalier attitude towards minor musculoskeletal pain, with the feeling that selected workers should be tough enough to put up with this kind of discomfort. However, this ignored other research which suggests that there may be measurable long term damage associated with 'pain only' DCS (see Ch. 13).

DEVELOPMENT OF THE MILWAUKEE TABLES

When it was discovered that the present OSHA decompression tables produced dysbaric osteonecrosis, work on new tables commenced in 1979. As all of the previous decompression models based on mathematical theories had proved to be inadequate at the deeper depths and especially with longer exposures, an empirical approach based on practical experience was utilized. A set of decompression tables labeled Autodec 3 was developed using a database of exposures from the commercial diving sector (Kindwall et al 1983).

Unfortunately, the Autodec 3 air tables were too long to be commercially useful. For this reason, oxygen breathing was introduced at the shallow stops. By way of comparison, the OSHA decompression table called for 4 h of decompression following 4 h of work at 400 kPa (44 psig). The Autodec 3 air decompression table called for 10 h 46 min following a similar exposure. The oxygen variant of Autodec 3, however, called for only 3 h 21 min decompression.

The new oxygen tables were tested at 14 kPa (2 psig) increments, from 195 to 413 kPa (14 to 46 psig). There was no reported incident of DCS in any of the test subjects. A bone scan and follow-up X-ray 6 months after the last exposure failed to reveal any dysbaric osteonecrosis. Decompressions were made from the longest shift possible at each pressure, which could be carried out within an 8 h shift when combined with the decompression time. These are the only shifts, which will be used, in actual practice. Only two or three test exposures were made at each pressure, making it impossible to predict the incidence of DCS. However, catastrophic error was ruled out in the computation of these tables. It should be noted that these caisson tables were the first to have any kind of laboratory testing before being recommended for use in industry. The final tables and a summary of their development were delivered to the National Institute of Health (NIOSH) on 1 December 1983 (Kindwall et al 1983). Nevertheless, the 1971 OSHA schedules still remain in force in the USA.

THE USE OF OXYGEN DECOMPRESSION INTERNATIONALLY

Oxygen decompression was first used experimentally for the decompression of tunnel workers in 1959 in Japan (Nashimoto 1967), but this work ceased when a fire killed six men undergoing decompression. Oxygen decompression was put into use on a regular basis in Germany in 1972, when the first oxygen tables for caisson workers were promulgated there. It appears 'the rates of DCS decreased remarkably in spite of longer shifts' (A Altner, personal communication, 1986).

Recent German experience with new oxygen tables developed by Faesecke (Faesecke, personal communication, 1991) has been excellent. These tables have been used on the Kiel Canal tunnel at pressures up to 480 kPa (56 psig), with an overall DCS rate of 0.5% (19 cases in approximately 4000 man decompressions). There were no neurologic findings and all responded completely to treatment on US Navy Table 5. At 430 kPa (50 psig), a new 3 h work shift produced a rash of eight cases despite 2 h oxygen decompression at 9 m (33 ft). When the work shift was shortened to 150 min, using the same decompression, no further cases were seen (K Faesecke, personal communication, 1991).

The French adopted oxygen decompression tables for tunnel workers in 1974, but these remain to be tested on a large project (JC Le Pechon, personal communication, 1987). Brazil used oxygen decompression successfully in 1976 in the construction of the São Paulo subway with a nearly 80% reduction in DCS. Because of the Japanese incident, there has been resistance on the part of the UK and US regulating bodies to adopt oxygen decompression. This is despite the experience of approximately 14 000 experimental oxygen decompressions carried out without mishap in 1938 and 1939 in the city of New York during the construction of the Queen's Midtown Tunnel (Jones et al 1940). There were no fires and there were no serious cases of DCS among the workers who breathed oxygen.

REGULATORY ACTION

Historically, regulatory bodies in the UK were adamant in refusing to accept any change in the tunneling decompression schedules until it could be assured that 'no new risk was added.' However, in 1996 decompression risk factors using the Blackpool Tables were studied (Flook, personal communication, 1998) and suggestions made for options for health risk reduction. It was reported that the Blackpool Tables were inadequate for no-stop decompression from 0.95 bar (95 kPa). It was recommended that no-stop decompression be reduced to exposures of 0.5 bar (50 kPa) or less. Switching to oxygen at the 0.6 bar (60 kPa) stop was predicted not to produce adverse health effects and therefore recommended. It was further suggested that treatment for DCS using the air treatment tables (recommended by the CIRIA 1982 guidelines) cannot remove sufficient inert gas from fat, and bubble formation on return to normal pressure is an inevitable consequence (Flook 1999). A secondary finding was that the Blackpool Tables produced such a high gas loading, that bubbles would recur in an individual even after 8 h of oxygen breathing as provided by a fully extended US Navy Treatment Table 6 (RN Table 62). This would not occur to the same extent using oxygen decompression tables when decompressing from shift work. More recent work (Flook et al 2001) compared air decompression vs oxygen decompression using the Blackpool Table following an exposure to 1.85 kg/cm^2 gauge (27 psig) for 4 h. The median maximal precordial Doppler bubble grade at rest following air decompressions was 3 and for oxygen decompressions, 0. An attempt to bring UK regulations into line with those of the European Union is currently in progress.

In the USA, the Office of Variance Determination of the OSHA concluded that 'oxygen decompression may be feasible' and that contractors will be permitted to use this method under an 'interim order.' It was further noted that oxygen decompression can be very safe as proven by the German, French and Brazilian experience. In summary, oxygen decompression is long overdue in caisson work.' (Yodaiken, OSHA internal memo, 1988).

ACCLIMATIZATION

It has been consistently noted that workers acclimatize or habituate to the compressed air environment and become less prone to DCS after 7–10 days of daily exposures. Should a worker take a 2 week vacation, acclimatization is lost and DCS may occur following the first work shift after the return. In one contract with 290 kPa (28 psig) in the tunnel from the first working day, there was an 8.57% incidence of *treated* DCS during the first week of the contract. By the second week, after acclimatization had occurred, the rate of DCS fell to 1.44%, which was the average of *treated* cases for the entire contract. An outbreak of DCS often occurs when the pressure is raised by 14–21 kPa (2–3 psig). The workers then have to acclimatize to the new pressure. An explanation of these observations is not forthcoming, though possible causes include loss of platelets and/or consumption of complement, a decrease in circulation bubble nuclei, or simply some selection bias creating only a perceived acclimitization.

POSSIBLE CENTRAL NERVOUS SYSTEM DAMAGE IN COMPRESSED AIR WORKERS

Rozashegyi (1967) reported that 42% of 31 caisson workers who had never suffered from manifest DCS of the central nervous system (CNS) had abnormal electroencephalograms (EEGs). Of 179 individuals who had suffered from DCS and who could be examined after 4 years or more, sequela of lesions caused by decompression could be found in 130, and in about half of all of these cases the sequelae were serious. Rozashegyi went on to point out that EEG records showed 'pathologic' changes in two-thirds of 57 subjects who had suffered from DCS of the CNS many years before. A borderline EEG record was found in an additional 10% and a completely normal record was found in only one-quarter of all cases (see also Ch. 11).

In 1988, magnetic resonance imaging (MRI) was used to look for brain damage in compressed air workers in Milwaukee (Fueredi et al 1991). MRI was performed on 30 subjects who had been engaged in tunnel work, of whom 19 had been exposed to various degrees of compressed air, whereas 11 were age-matched controls who belonged to the same labor union but who had never been exposed to hyperbaric air. The MR scanning was undertaken using a 1.5-Tesla Phillips MRI unit, obtaining axial, sagittal and coronal T-1, proton density and T-2 weighted images. Ventricular size was measured objectively. Foci of increased T-2 intensity, also known as 'unidentified bright objects' (UBOs), deep within white matter tracts, were evaluated as to their number and location. Psychometric testing was carried out on both groups to exclude pre-existing brain disease.

The 19 subjects in the compressed air group has a statistically higher number of white matter lesions (more than 152) than the control group (22 lesions) ($p = 0.05$). Altogether, 37% of the compressed air group had more than 20 white matter lesions each (seven of the 19 subjects), whereas only 18% of the control group has 10 or 11 lesions each. The experimental group were five times more likely than the control group of having high grade lesions and a high statistical correlation was found between the number and severity of lesions in the compressed air group as compared with the control group when linear trend analysis was performed ($p = 0.02$). Ventricular size was normal in all the subjects. The distribution of white matter lesions was 100% in the centrum semiovale and 50% in the optic radiations. Additionally, three subjects in the compressed air group had two internal capsule lesions and one basal ganglia lesion. There were no statistical differences in the psychologic testing between the two groups.

MEDICAL TREATMENT LOCKS

In the UK, medical locks for the treatment of DCS must be available in the ratio of 1 to 100 compressed air workers on site, whenever the working pressure is 202 kPa (2 ATA) or above, and for 24 h after the last man-lock decompression from such pressures (Walder 1982). In the USA, a recompression chamber must be available whenever pressures exceed 182 kPa (12 psig). As workers are seldom stricken with DCS at the actual job site, but typically after they go home, a central location for the recompression chamber in the city near the job site is generally considered appropriate. The requirements for the medical lock are similar in most countries, specifying minimum headroom and seating and that it must consist of two compartments. Minimally, each chamber should be equipped with proper heating, lighting and a communications system with the exterior. In the USA, the chamber must be capable of reaching a maximum pressure of 610 kPa (75 psig), so that a maximum treatment depth of 607 kPa (6 ATA) can thus be utilized. In the USA and most other countries, it is mandatory that the medical lock be equipped with overboard dump masks for oxygen breathing. In the UK, however, this is a requirement only when tunnel pressures exceed 1 bar (101 kPa).

Fire safety in the treatment chamber is an essential requirement. Cigarettes, matches and lighters are excluded. Flammable material, unless required for the treatment of the patient, should not be allowed in the chamber. The mattress should be covered with a fire retardant flash cover, and the blankets, sheets, and pillows should be treated with a fire retardant. A fire extinguishing system in the form of a water hose is a minimal requirement. Chemical extinguishers are unacceptable because they contaminate the atmosphere.

TREATMENT OF DCS

Today, most countries in the world, except those under UK jurisdiction, mandate low pressure oxygen recompression for DCS in tunnel workers. The tables used are versions of the US Navy Tables 5 and 6 (US Navy 1967). In the UK, the CIRIA 1982 Code of Practice recommends low air pressure recompression as developed by Griffiths (1960). This practice is continued in the 1996 Guide to the Work in Compressed Air Regulations published by Health and Safety Executive (HSE). Detailed air treatment tables are provided, but oxygen treatment tables are omitted. The use of oxygen treatment is permitted, however, at the discretion of 'contract medical advisors.' These air treatment methods appear to be little different from those employed by Moir in 1889, except that the decompression times have been somewhat lengthened. In spite of this guidance from the HSE, air recompression is probably an inappropriate form of treatment under most circumstances, given the current state of our knowledge. For a history of the development of treatment tables for compressed air workers, see the fourth edition of this book.

PHYSICAL STANDARDS FOR COMPRESSED AIR WORKERS

Physical examinations of prospective compressed air workers are a universal requirement. The examining physician should choose individuals who are capable of hard, sustained physical work. In addition, changes in atmospheric pressure experienced by tunnel workers and caisson workers impose additional physical requirements that may differ considerably from the requirements of commercial, scientific, recreational, and military divers (Kindwall 1988).

PRESSURE TESTING

Candidates for work in compressed air should be given a 303 kPa (30 psig) pressure test. This is adequate for most purposes. If an individual cannot clear his ears or sinuses at the first attempt, he need not be disqualified. However, if on three occasions the applicant fails to clear his ears, he should generally be disqualified. Applicants should not have any known allergies or colds when attempting a pressure test. Highly motivated applicants have sometimes had pressure equalization tubes placed through the eardrums when they have experienced an absolute ear block, and have retained them for the duration of the contract.

RECORDS

The pressure recording graphs for the tunnel and decompression lock must be retained. Usually, this is required by law. It is the company's responsibility to place these in company archives and, should a company subsequently cease operations, they must be transferred to a government authority. This is in the event that workers subsequently develop medical problems that could be related to their tunnel work. The lock keeper must also maintain a log of all entrances into the compressed air environment of each worker. Each worker must be suitably identified by name or number. The log should include the maximum pressure for each shift and the exposure time. The decompression table used must also be recorded. If decanting is used, this must be noted.

Workers' records should include results of a completed history and physical examination and the results of any laboratory tests. Skeletal radiographs are obtained as a baseline for employment and should be retained. On jobs progressing under high pressure, these should be repeated at yearly intervals. Skeletal radiographs may be omitted if work is not to exceed 209 kPa (16 psig).

Any cases of DCS must be recorded and reported to the local regulatory authorities if the local jurisdiction requires this. In any case, the results of any medical treatment for DCS should be maintained in the physician's files.

SUMMARY

Compressed air work presents many potential hazards. However, with present-day knowledge of the mechanisms of their production, and with insistence that sound physiologic principles be obeyed with regard to compressed air exposure, and subsequent decompression, these hazards may be minimized. The cooperation of a physician knowledgeable in compressed air matters is a requirement when any compressed air project is undertaken.

A consistent problem over the years has been the lag time from physiologic advances, improvements in decompression and treatment methods before their application to tunneling and caisson work. Historically, this lag period has typically been of the order of 20 years or more, because of poor communication between physiologists and supervising engineers, unwieldy bureaucratic mechanisms for regulatory change and an unwillingness to change established methods of procedure. Compressed air is a powerful tool used in underground and subaqueous construction. It is to be hoped that regulatory means may be developed internationally to optimize safety and the working environment of those engaged in the industry.

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2

2.2 Commercial Diving

Michael L Gernhardt and Christian J Lambertsen

Nick Zinkowski summed up the first chapter of his 1971 book '*Commercial oilfield diving*' with two themes:

'A commercial diver is a man who can use tools and perform work underwater'

'The more you know the longer you live' (Tom Angel, Sanford Marine Services).

Commercial divers, like military salvage divers, are a unique breed of individuals who are distinguished from recreational and scientific divers by the work that they do, the environmental extremes in which they work, their dependency upon umbilical hoses and topside crew, as well as a number of personal characteristics including strong mechanical aptitudes and extreme perseverance. Without attempting to espouse the motivations of the individual diver, commercial diving is also distinguished from sport and scientific diving by the fact that the incentive to dive is the economical accomplishment of a work task on the bottom and not the dive itself. If tasks can be accomplished more economically with remote operated vehicles (ROVs), they are. In spite of improvements in ROV technology and operational methods, it is a tribute to human perception, judgment and dexterity that divers remain the most cost effective solution to a wide range of tasks across a depth range from 0 to 300 msw (0–984 fsw). Recent increases in natural gas prices have increased the demand for divers over ROVs, since it is now economical to produce wells over shorter time periods and the upfront costs of ROV interface engineering is typically not justified. It seems clear that divers will remain an important and viable part of commercial subsea activities for years to come so long as scientists, engineers, and operators continue to provide solutions that improve diver safety and performance. In the past, many of those improvements have been driven by operational personnel who understood the available scientific information and applied it in full to the unique aspects of their diving operations. In order for the scientists and engineers to better contribute to the improvement process, it is important to understand the complex interrelationships between the work tasks, environmental parameters, human physiologic and psychologic stresses and their interfaces with diving equipment and methods (Fig. 2.2.1).

Fig. 2.2.1 Despite improvements to ROV technology, divers remain the most cost effective solution for a wide range of tasks in the 0–300 msw (0–984 fsw) depth range. (Courtesy of Oceaneering International.)

This chapter will only attempt to provide medical and research personnel a brief glimpse of that complex human work system: the commercial diver, his tools and support equipment.

ENVIRONMENT

Commercial diving occurs in water depths from 0 to 300 msw (0–984 fsw), sea states from calm to 10 m waves and gale force winds, currents from 0 to 7 knots (river diving), underwater visibility from 0 to 100 m (328 ft), temperatures from –2°C to +50°C, habitat humidities from 40 to 95%, salinities from 0 to 42 ppt, altitudes from sea level to 4400 m (14 436 ft), toxicological conditions ranging from nuclear, biological, and chemical contaminants to potable water stowage systems that require divers to be decontaminated prior to diving. These wide ranges of environments impose significant and interrelated physiologic and psychologic stresses on the humans operating in them. The subsea workplace is also a dynamic environment, capable of radical changes over short time periods, and thus imposes additional constraints on both primary and contingency operations planning.

FUNDAMENTAL TASK ELEMENTS

Before describing details of commercial diving tasks and equipment, it is important to first consider some of the fundamental requirements of information and assets, which must be provided for a diver to successfully complete a task. Later in this chapter, these elements will be discussed in relation to the physiologic and environmental stresses acting on the diver, and how these stresses can be controlled with proper equipment and procedures.

INFORMATION

The diver must have information of what specific actions are required for successful task completion. It is preferable that this information be known prior to the dive. However, in many cases, this is not possible, and it is necessary to deploy ROVs or perform inspection dives to gather the requisite information to determine the task and the tools required to accomplish it. In many cases, real time changes and decisions are necessary, underscoring the importance of reliable communications between divers and surface support crews.

PERCEPTION AND COGNITION

Sufficient sensory perception of the work task and workspace must be provided to the diver through a combination of sight, sound, touch, and proprioception. In zero visibility conditions, the diver must integrate on-site tactile and proprioceptive information with verbal communications from topside crews, into a detailed mental picture of the task and workspace. The requirement for keen sensory perception and thought imposes significant challenges to the control of environmental and physiologic stresses.

STRENGTH

Divers must have sufficient muscular strength for task completion, in addition to counteracting the external forces imposed by the environment. This imposes qualitative requirements upon the gas delivery and breathing systems to meet the oxygen consumption requirements of the working diver, which can exceed 3 L/min (Morrison & Reimers 1982).

ENDURANCE

Sufficient energy reserves must be available to supply the physical and mental resources necessary to accomplish the task. The endurance requirements are directly related to the number of divers available, the chosen diving/decompression method, the available bottom time, the environmental parameters and the capability to provide supplemental heating, hydration, and nourishment.

PHYSICAL ACCESS AND DEXTERITY

Even with optimal control of environmental and physiologic stresses, if the diver cannot physically access the work task and apply the forces and torques necessary, the task cannot be accomplished. Physical access also includes the methods for safely entering and exiting the water. Physical access along with the manual dexterity requirements of the task are important considerations in both the design of subsea equipment and diver life support equipment, tools, restraint systems, and deployment/recovery systems.

FLEXIBILITY, ADAPTABILITY, AND SITUATIONAL AWARENESS

Knowledge and experience of the dynamics of the tasks and environment, along with the situational awareness to anticipate problems, comprise a vital real-time skill of the successful commercial diver. The ingredients of a successful dive are both mental and physical, although those proportions can vary with the individual capabilities of the diver. It is important to recognize that there is no one 'right way' to perform a given operation, and maintaining a degree of flexibility and adaptability is an important consideration in diver selection and training as well as in the planning of commercial diving operations.

The role of scientists and engineers is to combine knowledge of the uncontrollable environmental parameters with an understanding of the controllable physiologic stresses and the task parameters into life support systems, tools, tasks and diving methods that increase diver safety and performance. Experience has shown that no single scientific or engineering approach will solve all the problems. Instead, improvements are most likely within the framework of an integrated systems approach.

COMMERCIAL DIVING TASKS

Subsea activities currently being performed by divers tend to be those jobs that require a wide range of individual tasks and tools, each of which requires a degree of perception and manipulation in a relatively unstructured and ill-defined environment. Such jobs are not generally adaptable to ROVs, which are better utilized in performing specific, well-defined and repeatable tasks. A hyperbaric-welding repair of an offshore platform is one example that illustrates the wide range of tasks that commercial divers perform.

In a hyperbaric-welding repair, the objective is to perform code-quality welding repairs in a dry environment to return the platform to its original condition or better. In order to achieve this objective, first a customized dry welding habitat must be fabricated and installed over the damaged portion of the platform truss so that the water can be evacuated to permit welding in a dry environment (Fig. 2.2.2a, b). Detailed inspection dives are often necessary, along with high pressure water blasting. Sophisticated rigging operations are required to install and seal the habitat in multiple pieces around the complex node geometries.

Table 2.2.1 lists subjective ratings of the elemental task requirements against generic commercial diving tasks. Of all the subtasks, rigging can be the most demanding. Rigging generally includes free swimming, high workloads, strength, endurance, and dexterity to manipulate the large slings and shackles associated with positioning heavy subsea equipment in currents and surge (Fig. 2.2.3).

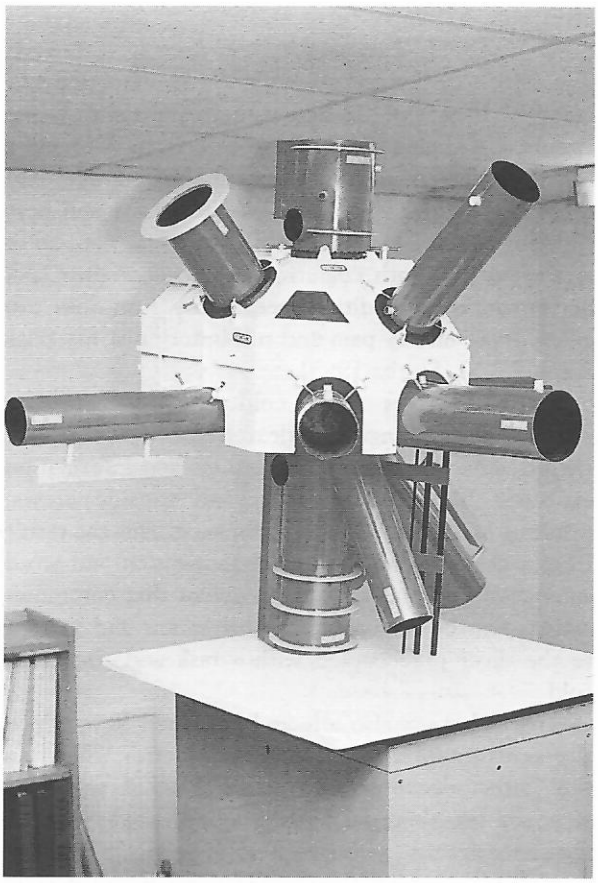


Fig. 2.2.2a Model of a hyperbaric welding habitat.

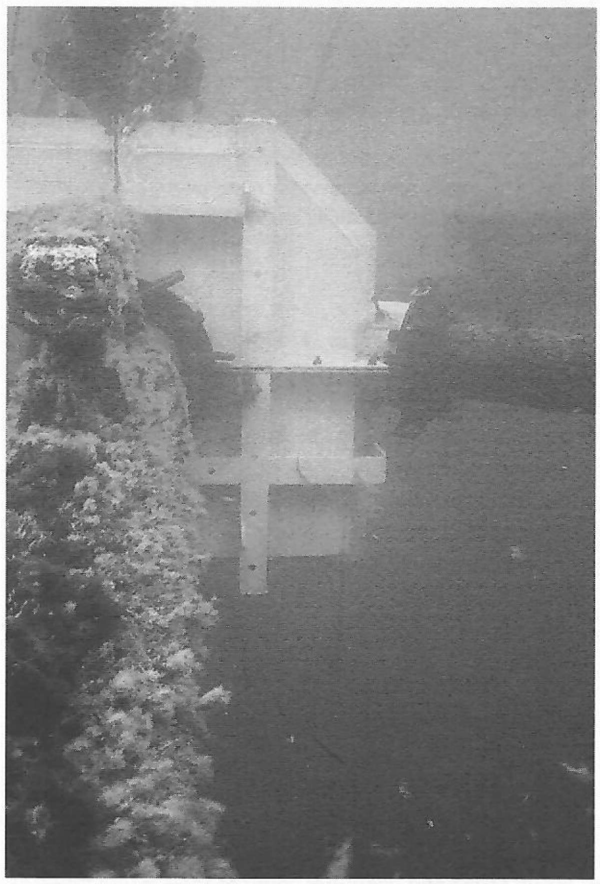


Fig. 2.2.2b Welding habitat installed and sealed around a platform. (Courtesy of Oceaneering International.)

Table 2.2.1 Subjective ratings of the task requirements associated with generic commercial diving tasks.

Generic tasks	Information	Perception	Strength	Dexterity	Endurance	Situational awareness
Water blastings	Low	Medium	Medium	Low	Medium	Medium
Jetting	Low	Medium	High	Low	Medium	High
Burning	High	High	Low	High	Medium	Medium
Welding	High	High	Low	High	Medium	Medium
Rigging	High	High	High	High	High	High
Photography/inspection	Low	Medium	Low	Low	Low	Low
Nondestructive testing	Medium	Medium	Low	Medium	Low	Medium
Grinding	Medium	Medium	Medium	Medium	Low	Medium
Torquing	Medium	Medium	Medium	Medium	Medium	Medium

Fig. 2.2.3 Subsea rigging of welding habitat. In commercial diving, high forces and workloads create physiologic stresses that far exceed those normally encountered in recreational or scientific diving.

Rigging also requires a high degree of personal situational awareness to direct up to six or more crane or winch lines to position the subsea equipment. Situational awareness of the location of these lines and the umbilical hose and other lines is vital to diver safety and task completion. It is not uncommon to discover, once in the water, that currents, vessel heave, or other factors have invalidated the original plan, requiring on the spot rethinking and rerigging, frequently against limited bottom time.

PHYSIOLOGIC STRESS

Discrete physiologic stress affecting diver performance is discussed in great detail in other chapters of this book. This section intends to introduce the scope of individual types of stress and examines some of their interactions, in the context of how they can affect the overall performance and safety of the commercial diver as a living work system. The physiologic stress that can affect diver performance and safety includes, but is not limited to:

1 Thermal stress;
2 Workload stress (physical and metabolic);
3 Oxygen stress;
4 Inert gas stress;
5 Decompression stress.

THERMAL STRESS

The effects of thermal stress on divers are varied and complex. In general, the biggest thermal problem facing commercial diving is heat loss, both from convective heat transfer to the surrounding environment and through breathing cold gases, whose density and heat capacities increase with depth. Heat loss can cause decrements in both cognitive and psychomotor task performance. In addition, respiratory heat loss can cause upper airway pain and respiratory distress (Figs 2.2.4, 2.2.5) (Sterba 1993).

Thermal stress from cold environments can decrease diver strength and dexterity, as well as reduce the effectiveness of communications and information exchange between the diver and topside crews, resulting in degraded task performance. This can result from a combination of degraded cognition and word annunciation, along with the problem that communications can be an unwanted distraction and irritant to the diver preoccupied with a task and also being cold.

Thermal stress also affects local blood flow, which alters patterns of inert gas exchange kinetics, which can then affect decompression stress. Use of hot-water suits and breathing gas heaters are effective countermeasures against excessive heat loss. However, hot-water suits have been shown to increase decompression stress, presumably by increasing the inert gas uptake in some tissues (Shields & Lee 1986).

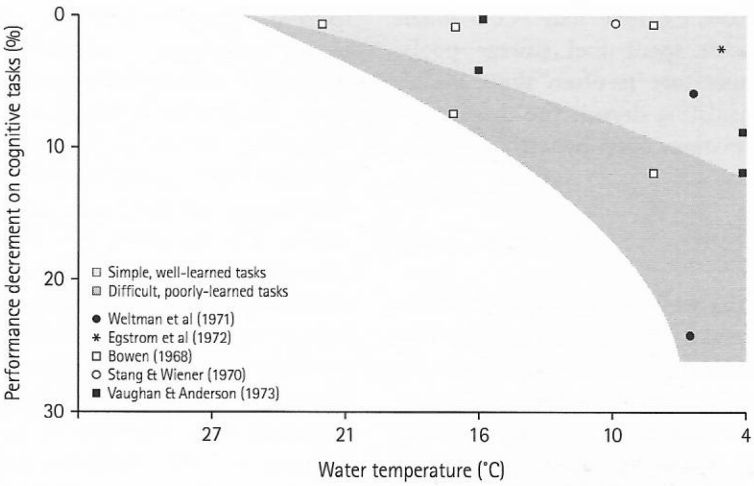


Fig. 2.2.4 The effect of water temperature on cognitive task performance. (Egstrom & Weltman 1974)

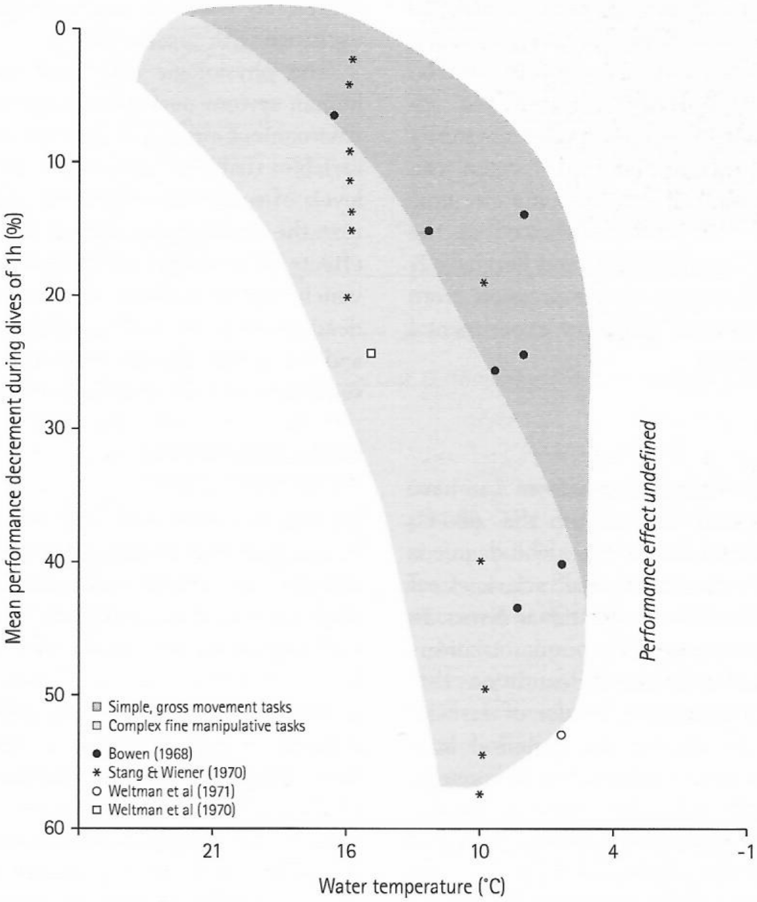


Fig. 2.2.5 The average decrement in psychomotor performance during 1 h exposure to cold water. (Egstrom & Weltman 1974)

A unique temperature extreme may occur when diving in nuclear reactor spent fuel storage pools, where the water temperature is often above 32°C. Exacerbated by the insulating drysuit the diver must wear to avoid contamination, deep hyperthermia is a real and present danger.

OXYGEN STRESS

Although oxygen has the well-known physical effects of reducing inert gas uptake during the exposure phase of a dive and increasing inert gas elimination during the decompression, it simultaneously has toxic effects on divers' lungs and other organs. In addition to symptoms of acute oxygen toxicity, physiologic effects of increased inspired oxygen partial pressure can influence inert gas uptake and elimination kinetics, which can indirectly affect decompression stress.

In commercial diving, it is desirable to use as high a partial pressure of oxygen as safely possible, in order to minimize the decompression penalty. At blood oxygen partial pressures above approximately 100 mmHg, hemoglobin becomes completely saturated and additionally, a considerable excess of oxygen physically *dissolves* in plasma. Excess dissolved oxygen can theoretically act as an inert gas under some circumstances. Some evidence of this is suggested in the animal experiments of Donald (1955) and Berghage & McCraken (1979) and oxygen decompression from shallow air saturation dives at the Navy experimental dive unit (Flynn et al 1999).

WORKLOAD STRESS

The level of physical activity 'on the bottom' can have profound and compound effects on the diver's physiologic state and performance. Workload degree is a major distinction between normal activities of commercial divers and sport or recreational divers. In addition to working at deeper depths, commercial divers routinely work in current and sea state conditions that scuba divers would not consider. The use of surface-supplied breathing gases through an umbilical hose removes any requirement to move slowly or conserve air. The motivation is to work as fast and efficiently as possible to maximize the amount of work accomplished in a limited bottom time. Commercial divers work on massive subsea equipment with heavy tools, frequently on the bottom in mud or clay. These conditions further increase workload requirements, which can approach maximum aerobic capacity for short periods of time.

Increased workload increases oxygen consumption, heart rate, cardiac output, local blood flow to the exercising muscles, and generates heat, carbon dioxide, lactate, and other metabolites which can induce physiologic effects that persist longer than the exercise itself. These include effects on blood pH, respiration, pulmonary ventilation/perfusion ratios, patterns of systemic and localized blood flow, inert gas uptake and elimination kinetics, and subsequent decompression stress. The temperature, density and the partial pressure of oxygen in the inspired breathing gas, as well as the temperature of the external environment further complicate the effects of metabolic work. Excess CO_2 resulting from high workloads can have effects on thermoregulation, where heat production can be impaired while heat loss is accelerated (Lanphier & Camporesi 1982). Excess inspired CO_2 during work can also affect diver susceptibility to neurologic oxygen toxicity and inert gas narcosis, as well as his psychologic state, and cognitive and psychomotor performance. The demands of high workloads can severely reduce or completely eliminate communication and information exchange with topside crews.

The physiologic effects of workload on practical human system performance in the commercial diving environment are so complex and influenced by so many variables that they are largely unpredictable at current levels of scientific integration. In the operational context the rational approach is to control and limit the effects of workload by utilizing breathing equipment which minimizes the work of breathing and physiologic dead space, to use well-conditioned and trained divers, and to design subsea tasks that minimize the consequences of high workload stress.

INERT GAS STRESS

The narcotic effects of air increase with depth and can be compounded by superimposed effects of breathing resistance, CO_2 levels, thermal conditions, workload, respiratory heat loss, and other stresses including poor visibility, the complexity of the task and the experience level of the diver.

Fig. 2.2.6 illustrates that decrements in performance are more pronounced for difficult and unfamiliar tasks. These data support the anecdotal experience of working divers who frequently report better performance and doing well-learned and repeated tasks in daylight and clear water conditions at depths of 60 msw (197 fsw) or more, whereas the same divers complain about the effects of narcosis while performing complicated tasks such as pipeline tie-ins in low visibility conditions. Under those conditions, narcosis can decrease situational awareness, spatial awareness and judgment, as well as cognitive and psychomotor

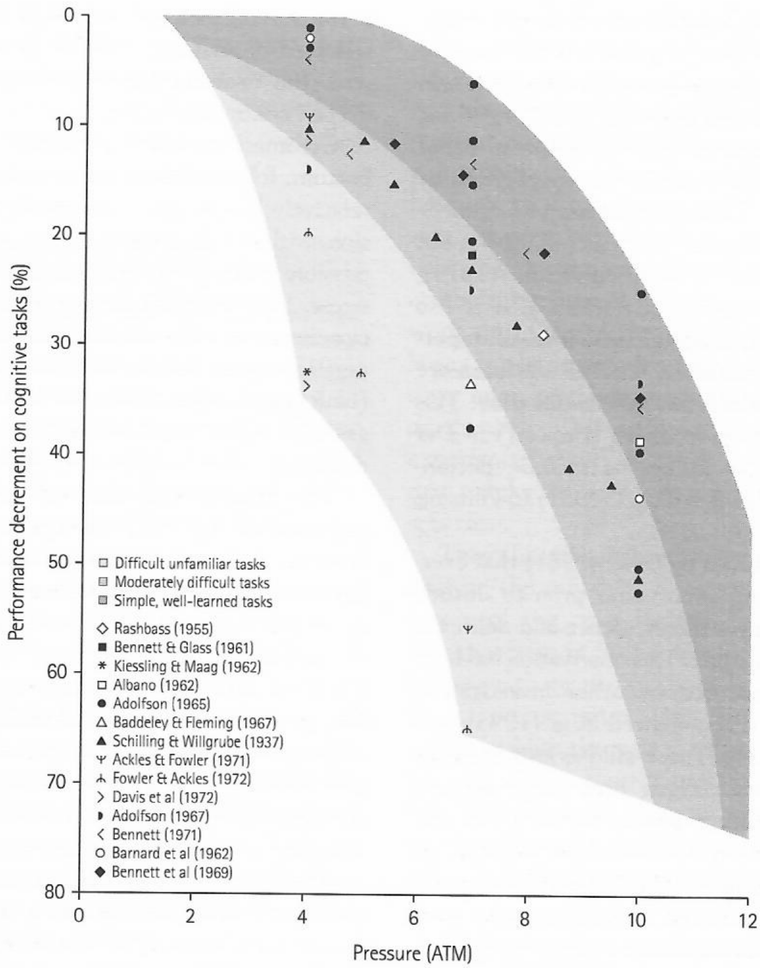


Fig. 2.2.6 Narcotic effect of air at high pressure on cognitive task performance. (Egstrom & Weltman 1974)

performance. Some divers can experience personality changes as a result of nitrogen narcosis, placing additional burden on the communications systems and the topside crew to carefully monitor the diver's performance and real-time decision making.

DECOMPRESSION STRESS

A variety of interrelated physiologic stress types that occur during the exposure or decompression phase of a dive can affect the degree of decompression stress. These include workload, thermal, oxygen and immersion stresses, all of which can unpredictably alter patterns of systemic or local blood flow and affect the kinetics of inert gas uptake and elimination. Additionally, workload and the degree of musculoskeletal activity can potentially affect the number, size, and distribution of gas nuclei, which are theoretically the sites for initial gas phase separation and growth that can result in the symptoms of decompression sickness (DCS). The distribution and size of these theoretical nuclei could conceivably be influenced by a variety of mechanical effects related to diver activities and are discussed in detail in Chapter 10.

It is an important, if not obvious point that none of these conceived stress types themselves causes clinical DCS. It would be possible to experience a combination of multiple such stress types and still have a symptom free decompression. Questions of whether and how any of these potential stress types contribute to actual decompression stress are reflective of limited data and the inability of decompression models and procedures to properly account for them. The two factors that are likely to have the largest effect on decompression safety in commercial diving are workload and thermal stress.

Diver workload can have both positive and negative effects on decompression stress depending on the severity, duration, time course, and level of tissue supersaturation. It has been appreciated for decades that work during the exposure phase of the dive can increase cardiac output and local blood flow, resulting in increased uptake of inert gas and consequent higher decompression stress. The concept was appreciated by Boycott et al (1908) and the observations of a number of other investigators over the years, including, but not limited to Van Der Aue (1949), Buhlmann (1975), Vann (1982), and Weathersby et al (1987). It is also well known that exercise in the presence of supersaturation after decompression can increase the incidence and severity of DCS, and reduce the onset time. This has been observed in no-stop diving studies (Van Der Aue et al 1949) and in numerous altitude decompression studies, from Ferris & Engel (1951) to Pilmanis & Webb (1994).

Conversely, it was shown by Balke (1951) that exercise during use of 'oxygen prebreathe' prior to altitude decompression can reduce the incidence and delay the onset time of DCS at altitude. This observation has been more recently demonstrated by other investigators, including Vann et al (1989), Powell et al (1995), and Webb & Pilmanis (1994). These studies provided the rationale for developing oxygen prebreathe exercise protocols for performing space walks from the international space station (Gernhardt et al 2000). In these oxygen prebreathe studies a combination of initial heavy exercise followed by light exercise were employed to reduce the incidence of hypobaric DCS. These studies combining oxygen and exercise suggest an increased perfusion carryover effect from the initial period of heavy exercise, which couples with the effect of light exercise, resulting in increased inert gas washout over a longer duration.

Such a carryover effect could potentially play a role in the efficacy of in-water oxygen decompression following surface-based commercial dives. In most parts of the world, complete in-water decompression is not commonly used in commercial diving because it is preferable to get the diver out of the water promptly to perform surface decompression on oxygen in the safer and more controllable environment of a deck decompression chamber.

Analysis of the decompression stress associated with in-water decompression, using a tissue bubble dynamics model predicted relatively high decompression stress for standard in-water procedures, compared with equivalent depth-duration diving with air (Sur-D-O_2) methods. This analysis provided a significant prediction and goodness of fit (Hosmer & Lemeshow, 1989) with over 6500 laboratory decompression trials. However, in contrast to the prediction, a study published by Imbert & Montbarbon (1991) reported a relatively low DCS incidence associated with the in-water decompression practices used by French commercial divers.

Commercial divers with high workloads on the bottom, followed by continuous light workloads at the relatively low levels of supersaturation during immersion with long in-water decompression steps, could possibly make use of exercise to reduce decompression stress. Laboratory studies have shown that light exercise during in-water decompression can reduce decompression stress, as measured by the incidence of VGE (Lauckner & Nishi 1984). Under these conditions inert gas elimination would likely be enhanced relative to resting in a dry deck decompression chamber.

The special situation of 'multilevel' diving is represented by offshore operational dive records (Ocean Systems, Subsea International, Oceaneering International), which indicate an extremely low (if not zero) incidence of DCS associated with 'repet-up' dives that are commonly used by commercial divers. On these dives, the diver begins at the deepest depth and progressively works at shallower depths, maintaining a relatively constant workload throughout the dive profile, while simultaneously experiencing levels of supersaturation that are lower than for conventional US Navy in-water decompression.

The limited laboratory data and operational records do indicate that exercise during decompression at zero (oxygen prebreathe) or low levels of supersaturation can reduce decompression stress. What is not clear, at this time, are the mechanisms by which exercise at higher levels of supersaturation can increase decompression stress.

Thermal stress experienced by commercial divers can include exposure to hot-water suits during the inert gas uptake phase on the bottom and exposure to cold air in a cold deck decompression chamber during inert gas elimination while performing surface decompression breathing oxygen. Conversely, in warm climates, divers can experience heat loss conditions during the exposure phase of long and deep air or heliox dives, and then be exposed to hot and humid conditions while undergoing surface decompression. Evidence that thermal stresses can affect decompression stress in commercial diving is seen in the epidemiologic studies of North Sea diving, which suggest increased decompression stress in divers using hot-water suits (Shields et al, 1989). Additional evidence is also suggested in two sets of laboratory trials of surface decompression on oxygen tables based on tissue bubble dynamics (Lambersten et al 1992).

While thermal and workload stress types have the largest effects on decompression stress and diver performance during the working phase of the dive, all of these interrelated stress types are important and can have significant consequences if not properly controlled with equipment and operational methods.

COMMERCIAL DIVING EQUIPMENT AND METHODS

The basic methods and support equipment of commercial diving were developed throughout the 1970s and 1980s. Incremental refinements in methods and equipment continue, and are now extremely varied based on depth and geographic locations. However, some equipment components are common to all forms of commercial diving.

UMBILICAL HOSE

The most common and distinguishing component of most commercial diving operations is the umbilical hose. The umbilical hose typically contains the main breathing gas supply line, a hardwire line for communications, a pneumofathomer hose and a strength member. It can optionally contain a coaxial cable for video and power, a hot-water hose and a return line hose if hot-water suits and/or gas reclaim systems are used.

A commercial diver must learn to use the umbilical hose to the fullest advantage. The many advantages to using an umbilical hose over scuba include providing an unlimited amount of breathing gas and reliable communications. The umbilical hose also provides the ability for the surface tender or bellman to pull the diver back to the surface or over to a subsea work site. This is a significant advantage in high-current conditions, where scuba divers could be 'blown off' the work site, because of current or sea state conditions, and not be able to swim back to the work site or the support vessel. The umbilical hose is also a means to locate the diver on the bottom. In many cases commercial divers work with only one diver in the water, which is desirable for a number of reasons, including not having to co-ordinate between two divers and surface support crews during complicated rigging and lifting operations. Instead of using the 'buddy' system, commercial divers use the standby diver or bellman that is on station ready to perform assistance at a moments notice. Should standby divers be required, they quickly enter the water and follow the prime diver's umbilical hose to find him, frequently in low or zero visibility conditions. The umbilical hose can also be used as a tool transfer device. Topside crews can pull the hose tight, then tie on a tool, (welding or burning lead, etc.), which the diver on the bottom can pull to him and remove. In some cases, the umbilical hose can be used as a work site restraint, in much the same way as a mountain climber, with the diver balancing the tension in the umbilical hose with his legs on the subsea structure to provide a stable hands-free work site. One of the disadvantages of the umbilical hose is the possibility of fouling. Ultimately the diver must keep his umbilical hose clear to the surface or the bell. This becomes second nature with the experienced diver constantly asking the tender or bellman to take a strain in the umbilical hose to ensure that it is clear.

The other major disadvantage is the effect of water drag on the umbilical hose, which increases with the square of the cross section. In some cases can be a consideration in using hot-water suits or wetsuits. However, there are operational methods for minimizing the effect of water drag, including fair-leading the umbilical hose through the dive stage or open bottom bell, or using a shorter umbilical hose from a closed bell. The diver can also coil up a length of umbilical hose and then play it out as he translates, which has the effect of decoupling much of the drag.

DIVING HELMETS

As discussed earlier, the most effective way to deal with high diver workloads is to use breathing equipment that minimizes the work of breathing and the respiratory dead space. There are a wide variety of diving helmets and masks in use throughout the commercial diving industry.

One of the common components of most modern helmets is an oronasal mask to reduce the helmet dead space to prevent CO_2 reinhalation and build up. The masks typically incorporate a nominal demand breathing system through the oronasal mask along with a maximum rate free flow capability for high workloads. The oronasal mask also includes a microphone for communications as well as a nose block device for ear and sinus equalization. These helmets have a valve assembly for both primary and secondary breathing gas supplies which can range from scuba tanks to semi-closed and closed circuit rebreathers depending on the depth of the dive. Typically it is desirable to have approximately 30 min of reserve breathing gas, although the duration depends on many variables and 30 min is not always practical.

The main advantages of the helmets over 'band masks' are that they keep the diver's head clean and dry, providing better communications and possibly reducing the risk of ear infections. They also provide physical protection to the head, as well as containing mounting fixtures for attaching lights or video cameras. Band masks, which are held to the diver's head with rubber 'spider' straps, are lighter, easier to put on, and provide better visual cues since the mask moves with the diver's head versus the hard helmet where the diver's head can move inside the helmet. Band masks also have less surface area and therefore are easier to swim with. Individual diver preference and job specific details dictate the selection, although the majority of commercial divers prefer hard helmets (Fig 2.2.7).

HOT-WATER SUITS AND GAS HEATING

Hot-water suits are required for deep helium–oxygen saturation diving and are frequently used in the air diving range, based on the environmental considerations including both the temperature and current, since the

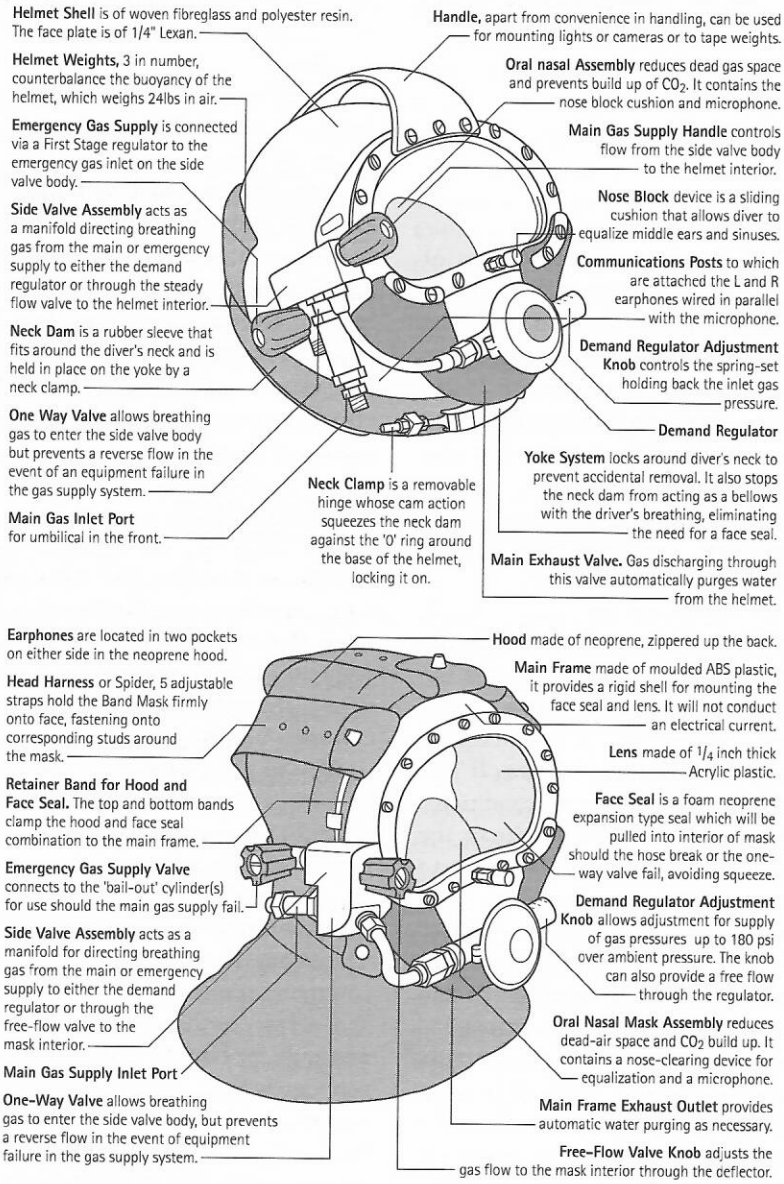


Fig. 2.2.7 Typical diving helmet and band mask. (Sisman 1982)

hose and suit can add increased drag, making swimming more difficult. The hot-water suit is a loose-fitting neoprene suit, which usually includes gloves and boots and in some cases a heated hood. Hot water is generally produced with heaters on the surface or the bell and then pumped to the diver, who controls the open loop flow using a bypass valve along with a control valve to proportion the flow to the upper or lower body.

Some additional considerations associated with hot-water suits include proper control of the injection water temperature at the suit so that the diver does not get scalded. The appropriate supply temperature is a function of the length of the hose and the temperature and current of the water as it relates to heat loss through the umbilical hose. These parameters must be carefully monitored, as frequently the diver is not aware of gradual changes in temperature. If back-up heater systems are not available, many divers elect to wear thin wetsuits underneath the hot-water suit, to provide a degree of protection in the event of a heater failure, which could result in rapid hypothermia due to the loose-fitting suit.

Diver breathing gas heaters are used for deep heliox saturation diving to avoid respiratory heat loss from breathing dense gas with its high heat capacity. These heaters can be mounted on the helmet, the umbilical hose, or the bell and typically use the suit hot-water supply to heat the breathing gas through a heat exchanger.

There are established guidelines for breathing gas temperatures. Tests should demonstrate the ability to achieve the following gas temperatures:

- 150 m (492 ft) 20 ± 2 °C
- 200 m (656 ft) 20 ± 2 °C
- 300 m (984 ft) 25 ± 2 °C
- 400 m (1312 ft) 30 ± 2 °C

In the North Sea these recommendations are detailed in the Norwegian Petroleum Directorate Guidelines (1991), which state that the temperature of humid gas should never exceed 37°C or dry gas exceed 32°C.

GAS RECOVERY SYSTEMS

Saturation diving in excess of 50 msw (164 fsw) requires the use of heliox breathing mixtures. The majority of the helium in the world comes from mines in the USA. The cost of helium can range from 15 dollars/ft^3 in the Gulf of Mexico to almost 1 dollar/ft^3 in Brazil. A typical commercial diver will have a surface consumption rate of 1.5 ft^3/min. A 200 msw (656 fsw) saturation dive using open circuit diving would cost approximately 250 to 1800 dollars/h, resulting in helium costs of up to 1 million dollars/month. The additional problems associated with logistics and stowage dictate the use of gas recovery systems for deep saturation diving.

There are a number of different types of gas recovery systems in use throughout the commercial diving industry. Without going into detail, for most of these systems the diver is supplied with breathing gas from the surface. The gas is exhaled through a non-return exhaust control valve and then returned to the bell and/or surface. The gas is then dehumidified, filtered and scrubbed of carbon dioxide, enriched with oxygen and compressed. After careful gas monitoring and analysis, it is then reused.

Additionally, there are chamber gas recovery systems to reclaim the helium from the deck decompression chamber. The diver and chamber recovery systems typically recover 85–95% of the helium.

COMMERCIAL DIVING METHODS

Commercial diving methods and the associated support equipment can be broadly classified into surface-based and saturation diving. In surface-based diving, the diver descends to the working depth, performs a limited amount of work consistent with the bottom time restrictions of the chosen breathing gas and decompression method, and then decompresses back to surface pressure.

In saturation diving, a team of divers is compressed to the given storage depth in a deck decompression chamber. They remain under pressure for up to 30 days or longer, working in two- or three-man shifts around the clock, using a diving bell as an elevator to transfer, under pressure, from the deck of the vessel or platform to the subsea work site.

They then lock out of the bell and typically work an 8 h shift, after which they return to the bell and transfer, still under pressure, back to the deck decompression chamber. Saturation diving operations typically provide approximately 20 h/day of bottom time, accounting for bell deployment and recovery overhead. Advanced diving systems installed on dynamically positioned diving support vessels employing two three-person bells can achieve a constant 24 hr/day working bottom times. The second bell is deployed before the first is recovered. The second two-person team locks out while the first team is still working and effectively 'shakes hands' with the team they replace as the job is transferred. In this method, launch and recovery overhead is eliminated. After completion of the job, the diving crew is then slowly decompressed back to sea level pressure over several days, depending on the depth of the dive. A rough guideline of the decompression time required for a saturation dive is 1 day for every 30 msw (100 fsw) of storage depth plus 1 day.

The two basic diving methods can be further divided into air, nitrox, or helium–oxygen breathing mixtures, each of which has its own set of support equipment requirements. Whether a diving bell is used, and the type of bell, open or closed, further classifies surface-based diving.

Fig. 2.2.8, shows an overview of the various diving methods against the associated depth limitations. It should be recognized that these are approximations and that specific depth and bottom time limitations vary according to local governmental regulations and diving contractor procedures and policies.

In the surface to approximately 50 msw (164 fsw) depth range, where the majority of commercial diving is performed there is considerable overlap between the various diving methods, with the specific details of the job governing the selected method. Some resourceful diving contractors, in special circumstances, use hybrid forms of diving that combine different bottom breathing gases with decompression gases and bell systems that further complicate this overlap. Examples include but are not limited to: air and heliox surface dives, followed by nitrox decompressions in open and closed bells; nitrox saturation dives with air lock outs; and use of closed 'mini-bells' in shallow water to allow a transfer under pressure and extend bottom time limits beyond the limits of surface decompression tables.

Additionally, in saturation diving the living or storage depth can be decreased at various points throughout the 30 day exposure. This, combined with the unlimited excursion up or down limits, provides coverage of a wide range of working depths in offshore structures, in addition to reducing the unproductive decompression time.

SURFACE DIVING EQUIPMENT

Most surface diving operations use diving helmets or band masks, which incorporate both demand and free flow breathing apparatus as described earlier. Frequently surface diving operations can include air and mixed gas breathing mixtures (heliox or nitrox). Typically the gas supplies are mixed on site with a variety of commercially available gas mixers or blenders. These devices typically mix pure oxygen with the diluent gas using a series of three oxygen sensors. The gas is mixed in volume tanks, which are then independently monitored with a separate gas analyzer, before being supplied to the diver. In some locations, use of 100% inert gases has sensibly been discontinued for gas mixing because of the possibility of inadvertently supplying the diver with pure inert gas. There are minimum oxygen concentrations that are provided in the inert gas supply that vary as a function of depth, with North Sea regulations specifying a 2% oxygen minimum. Another important consideration for operations that involve a number of different gas mixtures is to ensure that there is clear identification of the gas mixtures in the diver bailout bottles. Implications of using the wrong bailout bottle range from acute central nervous system (CNS) oxygen toxicity to hypoxia, depending on the depth of the dive.

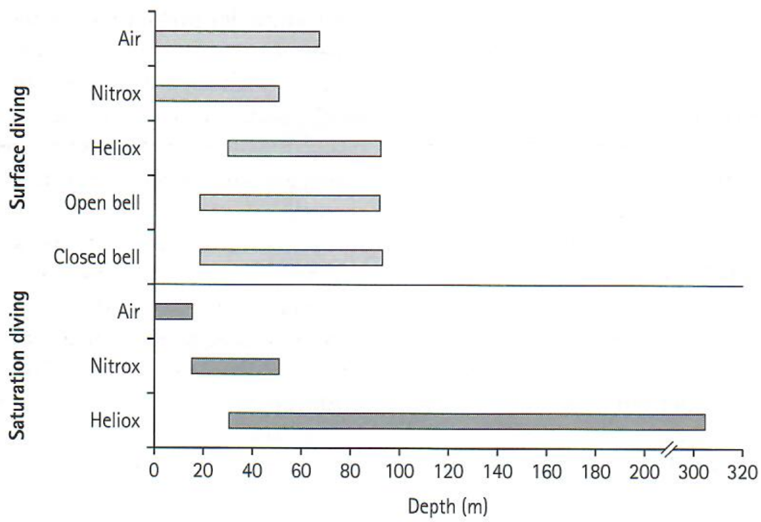


Fig. 2.2.8 Diving method versus depth.

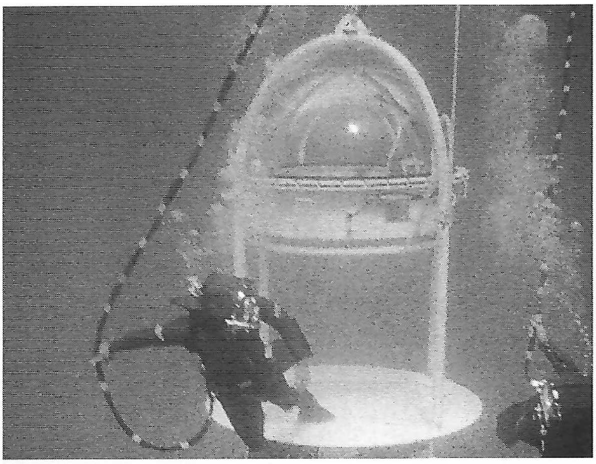


Fig. 2.2.9 Open bottom bell system.

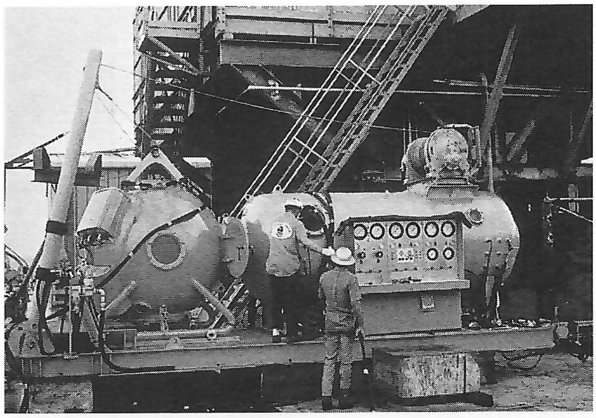


Fig. 2.2.10 Closed bell diving system.

Many commercial diving contractors are now using a 50/50 nitrox mix for the in-water decompression phase following long deep air or heliox dives. The 50/50 decompression mix is typically premixed and placed into the gas control rack only after the diver leaves bottom and arrives at his 27–30 msw (89–98 fsw) decompression stop.

In surface diving operations deeper than approximately 50 msw (164 fsw) depending on location, open bottom diving bells are used, as shown in Fig. 2.2.9.

An open bottom bell is configured with a dry dome of breathing gas at head level. The bell is supplied with an umbilical hose for breathing gas and with communications. It also carries on-board emergency breathing gas.

In a contingency involving loss of air supply, the diver can abort to the bell and have two sources of breathing gas as well as communications. Open bells become necessary when the depth and bottom times are such that abort to the surface on the bailout bottle could result in serious DCS.

Some open bells are equipped with shorter 'excursion' umbilical hoses, which reduce the drag, however, most divers elect to use an umbilical hose from the surface, which they may fairlead through the bell. This has the same advantage of reducing drag and provides protection against problems with the bell deployment and the recovery system, which are significant considerations when motion compensation systems are not used.

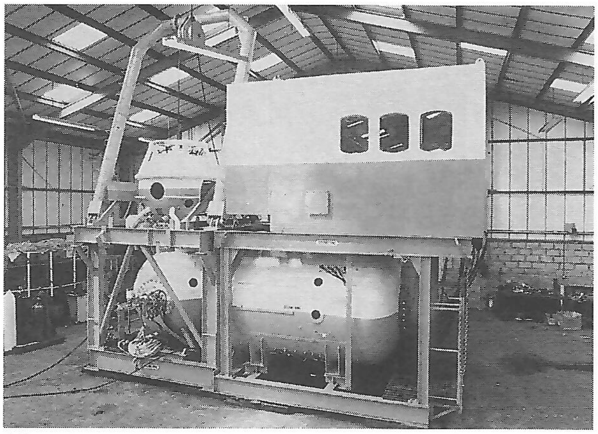
Some diving contractors utilize closed bell systems (Fig. 2.2.10) for surface diving operations to provide for a transfer under pressure to the deck decompression chamber. This permits longer and deeper dives than could be accomplished using surface decompression methods.

SATURATION DIVING EQUIPMENT

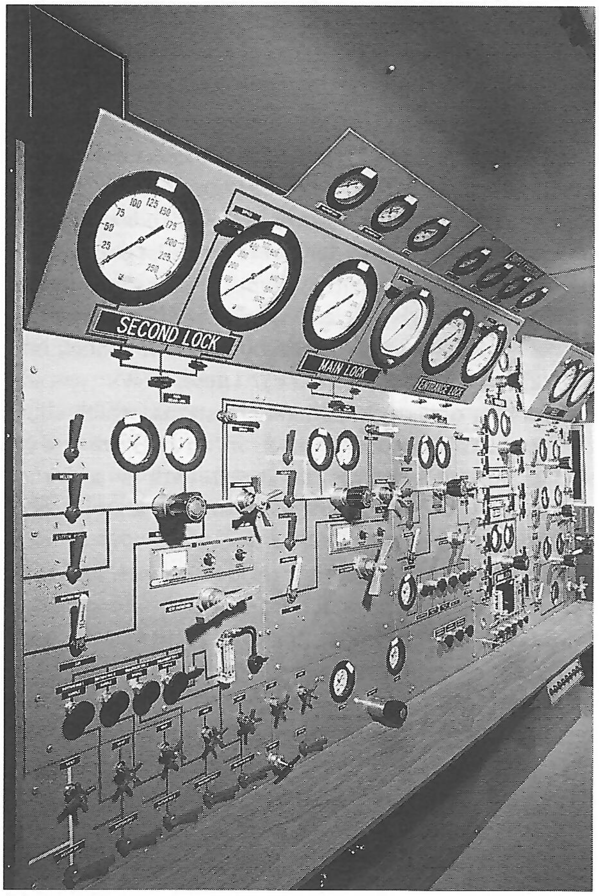
In saturation diving the divers live in a deck decompression chamber and transfer under pressure through a transfer lock (which may contain the shower and toilet facilities) into the diving bell, which is used as an elevator to transfer under pressure to and from the subsea worksite. Saturation diving systems vary in size and complexity. Fig. 2.2.11 shows a 16-person saturation diving system, which is built in below deck into a diving support vessel (DSV). These DSVs typically incorporate dynamic positioning systems, which allow the vessel to maintain position in up to 10 m (33 ft) seas. These vessels are equipped with a series of thrusters, which are controlled to maintain position within approximately 5 m (16ft).

The position keeping is provided from a real-time computer controller, which integrates local navigation information, and sensors for wind, current and sea state, with inertial dynamics models of the vessel to compute the thruster commands necessary to maintain position without having to use anchors. In these DSVs the bell is typically launched through a retractable moon pool in the bottom of the vessel to eliminate the effect of surface sea conditions on deployment and recovery of the bell.

Details of the life support systems of these saturation systems are beyond the scope of this chapter. However, it is important to note that the life support requirements are demanding and increase in complexity with the depth of the dive. For a 300 msw (984 fsw) saturation dive the life support requirements are much more complex than those associated with human spacecraft. The breathing gas is less than 1% oxygen, and a variance of less than 1% can mean the difference between oxygen toxicity and hypoxia. There are also very rigorous demands on the levels of carbon dioxide,



(a)



(b)

Fig. 2.2.11 Typical deployable saturation diving system. (a) Chamber complex with diving bell (left) and control cabin (right) on top. (b) Control panel for diving system.

which are typically controlled, to less than 0.4–0.7 kPa (3–5 mmHg). Gas contaminants also must be rigorously controlled with careful materials selection. Even trace levels of toxic gases can be lethal at these depths. It is also recognized that contaminant gases can be introduced into the system from the subsea work sites. This dictates the use of electronic instrumentation and/or chemcial color changing tubes to monitor for toxic levels of contaminant gases. All chambers of the system are outfitted with built in breathing systems (BIBS), which can be used in the event of any problem with the chamber breathing gas. Temperature and humidity control also have tolerances that become tighter as a function at depth. At 300 msw (984 fsw) a 1 degree change in the temperature can cause discomfort and 5 degrees can cause hyper or hypothermia, depending on the humidity which must also be tightly controlled.

EVOLUTION OF CURRENT OPERATIONAL DECOMPRESSION METHODS

Whereas many deep saturation dives are performed around the world, the majority of commercial diving occurs in the 0–50 msw (0–164 fsw) range. For this reason the dominant decompression method used in commercial diving is surface decompression on oxygen. 'No Stop' (No D) diving with air or N_2–O_2 is used extensively for work involving limited depth and duration situations.

While hydrostatic forces and the effects of O_2 are the same in the N_2- and He-based gases, the difference in their physical and biophysical characteristics lead to differences in the scope of diving and decompression methods. In all methods the key to accelerating decompression is the effectively controlled and timely use of the toxic oxygen as an inert gas diluent or substitute. The initial Navy research and developments of the Sur-D-O_2 diving method, for air diving and for helium–oxygen diving, were therefore paralleled with exposures to determine occurrences of nervous system oxygen poisoning and convulsions (Ch. 9.4). At the outset of the commercial diving expansion for offshore petroleum recovery, industry gained from the important new US Navy concepts of helium saturation-excursion and decompression developments for deep work, but leaned upon the pre-existing US Navy air Sur-D-O_2 'tables' for shallower regions such as the Gulf of Mexico and the southern UK North Sea gas fields. While these air Sur-D-O_2 tables were useful for naval related activities of short duration and shallow depth, the expanding scope of commercial diving entailed deeper and more prolonged open sea exposures, which resulted in an increased occurrence and severity of DCS incidents.

To counter the existing hazard, corporations independently inserted changes to the basic US Navy

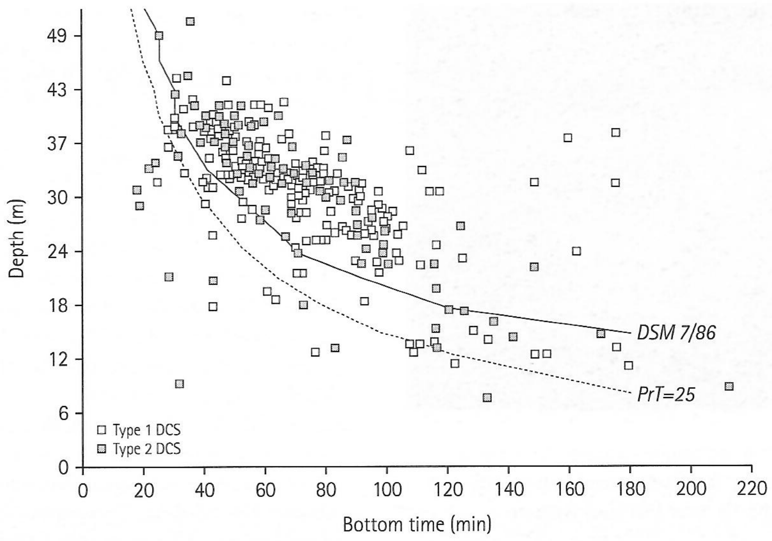


Fig. 2.2.12 Distribution of DCS incidents by depth and time. North Sea commercial diving operations 1982–1990 (Shields et al 1994). (Pr T = P √ T where P is pressure in bar and T is bottom time in minutes).

tables, e.g. increasing the durations of 'in-water' decompression stops and increasing oxygen recompression exposures (considered as 'treating' imminent DCS). British Government surveys (Shields 1986, 1989) made it obvious that the use of the primary air Sur-D-O_2 tables, with or without attempted improvement, imposed hazards, and a policy of restricted depths and durations for air diving was officially imposed upon the UK industrial offshore operations (Fig. 2.2.12).

Improvements in Sur-D-O_2 techniques resulting in increased bottom times with low DCS risk have been made and implemented. These improvements include but are not limited to: changes to the depth and duration of in-water decompression stops; generally performing deeper stops to reduce gas phase separation and growth prior to the surface interval; and improvements to the control of the surface decompression phase including deeper initial compression to control gas phase, followed by subsequently lower chamber pressures to control oxygen toxicity doses (Lambertsen et al 1992).

INTERSECTIONS OF SEA AND SPACE OPERATIONS AND ENVIRONMENTAL STRESS

The commercial ocean diver and the space 'diver' in extravehicular activity (EVA), work effectively in extremely different environmental circumstances, but with common physiologic systems. Each worker is subject to multiple physiologic stresses of long duration exposures, and potential hazards of severe degree. Gross differences exist in ambient and inspiratory gas pressures, in multiple forms of thermal exposures, in susceptibility to varied decompression incidents, and in patterns of exposure to hyperoxia.

Special physiologic cross links occur in the measures for prevention of hyperbaric and hypobaric DCS. The ocean diver accumulates dissolved inert gas at work while the oxygen-breathing astronaut loses it during prolonged EVA. However, EVA carries the potential risk of DCS, as this is performed at a lower pressure than that of the space vehicle (30 and 100 kPa respectively).

These now familiar connections of ocean, aviation and space activity are related to the awareness that the astronaut must exit the present space station from a physiologic state of saturation in an atmospheric equivalent to breathing air at 101 kPa (1.0 ATA). The familiar Tektite and US Navy Sea Lab undersea programs had their origins in concepts of saturation exposures and saturation decompression research (Ch. 1, 10.2). The commercial diving industry, with large research investments by academic institutions, has greatly expanded the scope of the original saturation and non-saturation diving for manned undersea working exposures, through literally millions of hours of practical operational experience. These evolutions blended both research and operational procedure for use in current undersea and aerospace activity. Well established relations of commercial diving to aerospace activity in this evolution include the use

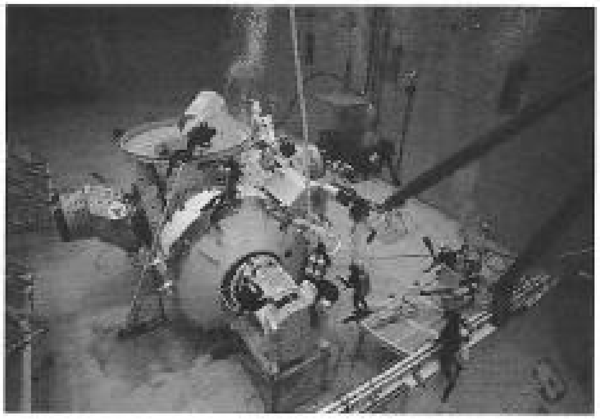


Fig. 2.2.13 Nitrox diving techniques applied to astronaut training in neutral buoyancy facilities provide up to 400 min bottom times at depths of 15 msw (50 fsw) with no decompression penalty.

of sophisticated nitrox diving procedures within the NASA deep, water-filled 'Neutral Buoyancy Laboratory' for detailed premission operational training for the 6 h EVA exposures and complex work required in present construction of the International Space Station. The ongoing extensive methods of deep subsea work by commercial divers with ROVs has also influenced design of the unique tools, methods, and tasks enabling human space station assembly and maintenance.

The recognition is therefore well established that efficiency of nitrogen saturation decompression is the primary limitation to accelerated preparation for safe exit from spacecraft, or from disabled submarines. Advances in these capabilities are now occurring, based on pooled awareness of the uses of oxygen and exercise to accelerate elimination of nitrogen from hyperbaric and hypobaric nitrogen saturated states. These gains in understanding will, as in the past, affect commercial diving.

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