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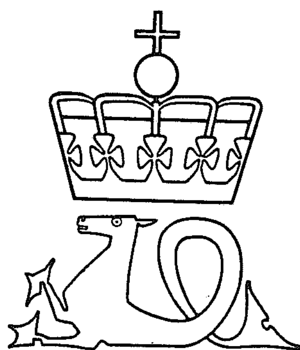

The Safety Evaluation of Saturation Decompression Tables

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1 INTRODUCTION

Ensuring the safety of divers during the decompression phase of a saturation dive involves the examination of a very wide range of techiques and practice. If many cases apparently unrelated matters such as fire hazard and the rate of decompression have a common interest, which in this particular instance is the oxygen pressure in the chamber during the shallow part of the decompression. Conflicts of judgement can occur, especially in emergency incidents, and for many situations, due to human ignorance, any course of action must necessarily involve some guesswork. This lack of knowledge has led to an uneasy feeling amongst many people closely connected with diving work that perhaps the current procedures could be causing long term damage to sensitive tissues particularly the nervous system. The situation is not helped by persistent rumours of divers who are said to have suffered serious, permanent, memory impairment and personality changes as a result of their diving employment.

Deciding whether such psychological changes have occurred and are attributable to diving activities as a task of great complexity and it will undouptedly take many more years of intensive effort to establish an agreed answer.

Even more time will be required to ascertain whether the decompression phase of the dive, which is the subject of this report, is responsible for any of these long term problems. Therefore to minimise the possibility of the decompression phase being involved in any short term or long term tissue damage a very cautious approach is essential until the necessary research has been completed.

It will be assumed that all decompressions take place in pressure chambers with strict codes of diving practice being correctly followed and, except in certain emergency situations, factors of critical importance for properly

controlled decompression such as pressure, gas composition, temperature etc., can be accurately monitored. Furthermore, no consideration will be given to decompression from depths exceeding 360 m (1200 ft). Depths in excess of this magnitude are rarely performed and must be regarded as purely experimental, and outside the scope of this document.

Before proceeding with this analysis of ways to assess the safety levels of saturation decompression procedures it will be helpful to give a brief outline of the present situation in the relevant aspects of decompression theory and practice. From this account it is hoped that the reasoning behind many subsequent statements will be clear and not require further detailed explanations.

2 THE PRESENT SITUATION

(a)

Since 1670, when decompression sickness was first observed by subjecting a viper to reduced atmospheric pressure, there have not emerged any agree quantitative ideas on the aetiology of decompression sickness as found in human beings. The vast majority of experiments to establish the underlaying mechanisms involved in the onset of decompression sickness have been undertaken using animals, and generally small animals. The forms of decompression sickness exhibited by small animals are certainly not those normally found in man as a result of inadequate decompression.

Death or severe paralysis have been the signs used in small animal work, but these extreme and violent forms of decompression sickness are fortunately rare in human work, where a pain in a knee, or weakness in a limb are typical of the nature of the problems encountered. The reasons why most research has been performed on small animals are quite

clear. In the first place it is a way of acquiring large numbers of statistically significant result for the least cost. Pressure chambers to accommodate large animals, or men, are very expensive to buy and operate. Secondly the ethical problems associated with using small rodents eg rats and mice, are far less troublesome than those which arise from using healthy young human volunteers in experiments that have no direct benefit to them, and may even permanently and seriously damage their health. From the point of view of reaching quantitative concepts about human manifestations of decompression sickness the vast majority of the background animal research is at best crude, and at worst misleading. The only relevant animal work leading to quantitative ideas has been performed on large animals, mainly goats. However, when considering the special case of saturation decompression procedures the contribution from large animal research is very small. Once again it is easy to see the causes for this lack of effort. Keeping large animals in pressure chambers for prolonged periods, such as two or three weeks, requires a highly efficient and specialised form of life support system. Such a system is very expensive to install and run. Furthermore, when an experimental decompression is in progress it is impossible to know when the animal is having mild symptoms of decompression sickness, and so it becomes necessary to wait for undoubted signs to develop before the outcome of a procedure is assessed. Finally, it is impossible for animals locked inside pressure chambers to co-operate with the numerous techniques necessary for modern experimental investigations eg blood sampling, ultrasonic scanning. All told it is not surprising to find that using large animals has not been a popular technique for studying saturation decompression procedures.

(b)

Thus nearly all relevant knowlegde concerning saturation diving has been obtained from using human volunteers. At this point it becomes necessary to define what is meant by the term "saturation". For the purposes of this report no

dive will be considered a saturation dive unless at least 24 hours have been spent at depth before decompression commences. This particular statement is the first of several that serve to illustrate the lack of firm data, as it is not certain that the tissues of the body are fully equilibrated ("saturated") with a raised pressure of inert gas after 24 hours, but this has been taken as a reasonable estimate. From a decompression standpoint the assumption that there is a fixed "saturation" time could be misleading because there will be changes in basic physiological processed occurring at pressure over a much longer time-scale, and these changes could influence the success of a decompression schedule. Perhaps a successful deompression routine from a bottom time of 1 day would not necessarily be successful when following a 2 day or 3 day bottom time. There is insufficient experimental evidence to settle such doubts. Once again the reasons for the lack of experimental evidence are quite easily seen. The costs of mounting a series of definitive experimental saturation dives are huge. Each experiment requires a large pressure chamber facility eg USN at Washington, COMEX at Marseille. It is useless expecting any statistically significant results from less than 10 trials with 3 men per trial. Thus one single experiment occupies the whole chamber complex for at least a year to settle one point only, ie the effect, if any, of a bottom time of 1 day or of 2 days on the decompression requirements from some fixed bottom pressure.

Should some-one suggest that the result would not be quite the same at a different pressure, or using a different oxygen partial pressure in the breathing mixture, then the whole experiment needs repeating taking these additional factors into account. At least a further 4 years intensive work, employing the services of many fit young volounteers (not readily obtainable), small teams of skilled people prepared to work all hours of the day and night, specialist medical advisers available throughout the experimental period, large and expensive gas systems, etc.

If the procedures need to be tested at sea before being

released for general use then a suitable ship, plus crew of course, with most of the workforce engaged on the shore-based experiments will attempt to repeat the procedures. If all goes well a typical sea trial would be completed in a few weeks, at a cost which is worrying to contemplate.

(c)

From what has just been stated it will be quite obvious that the necessary experimentation to enable a satisfactory number of definite quantitative statements to be made would require resources of NASA-like magnitude. The alternative is that some person of unusual intelligence and insight provides an explanation of what is occurring during decompression, and that this answer is sufficiently comprehensive to acceptable without too many exploratory tests of its effectiveness. Neither large sums of money nor the arrival of a comprehensive aetiology of decompression sickness are immediately likely possibilities, so it must be assumed that, as in the last several decades, there will be slowly improving levels of understanding, often based upon the outcome of routines used by working divers.

(d)

The purpose of the brief review given above is to emphasize the fact that due to lack of adequate background experimentation there are large areas of ignorance in the present understanding of many fundamental issues relating to the problem of decompression. For example although it is highly likely that bubbles of gas in the tissues cause decompression sickness no-one has ever proved this to be true in cases of the various forms of "bends" (Type 1 and most Type 2). Even supposing that the "bubble hypothesis" is true it is not known which tissue contains the offending bubble (or bubbles), what shape they are (spherical or cylindrical or thin films), their rate of growth under different conditions, how long they can persist after formation, etc. etc. Despite this massive ignorance on many fundamental points it is nevertheless possible to construct

successful decompression procedures for a wide variety of bottom times and depths. This success has been achieved by process of trial and error over a number of years which has led to the gradual evolution of simple mathematical models to act as bases for calculating decompression tables. It is very important to realize that nearly all current decompression procedures are based upon mathematical models which have almost no physiological content, they are simply calculating systems.

This provides the first guide-line to the assessment of decompression procedures, that examining the theoretical framework used to calculate the procedures will not be of prime importance. The mathematical model being used may be temporarily unsatisfactory, in that it yields troublesome procedures, but it is merely a matter of altering the value of one or two constants in the mathematical functions and a whole new set of procedures can be generated.

If a mathematical model of blood flow down a blood vessel was being contemplated then the dimensions of the blood vessels, the viscosity of blood, the pressure gradients, would be examples of fundamental constraints placed upon any attempts at modelling. Further, the value of these constraints would be known, within well defined limits, for the various types of blood vessels that may be under consideration. Any acceptable model must therefore incorporate these fundamental physiological features. In the case of the decompression models, as has just been pointed out, there are no basic physiological costraints of this kind. It is an example of the "Black Box" situation. Some procedure is performed and the black box either responds (bends) or it remains silent. By performing sufficient number of tests the rules whereby the box responds, or not, gradually became clearer. Any assessment of saturation decompression schedules will therefore be forced to ask only the simple question "how well does it avoid having to treat the diver for signs and symptoms of decompression sickness?", rather than the more desirable "how well does it minimise interference with normal tissue

function throughout the duration of the decompression?" This latter question, if answered, would show whether the diver's tissues were being subjected to the same level of interference throughout the whole decompression time, and an attempt could be made to optimize the procedures. As it is, no-one knows wether a "bend-free" pressure-time course is grossly oversafe at some points and nearly unsafe at others.

3 DETECTION SYSTEMS

(a)

Attempts have been made to use techniques such as pulsed ultra-sound to detect the presence of separated gas in tissues put so far no method has been envolved which could be relied upon for prognosis or diagnosis. Undoubtedly these techniques can successfully detect separated gas but gas can be detected without this meaning that decompression sickness is present or will follow shortly, also gas is sometimes not detected but nevertheless decompression sickness ensues. The principal reasons for the failure of these physical methods are explained by the statements previously given, namely that no-one knows the location of the relevant tissue (or tissues), and it may be that because the size of the bubble (or bubbles) responsible for bends pains is also unknown the methods used not sufficiently sensitive.

(b)

There have also been attempts to use bio-medical measurements to assess the effects of decompression. Undoubtedly there are changes occurring during the course of a dive and afterwards, but due to the multiplicity of possible interpretations of these changes no reliable indicators, specifically attributable to decompression, have become available. This means that there are no suitable objective

tests, ether physical or biological, for assessing the effectiveness of a decompression procedure.

All evidence of adequacy, or inadequacy, of a decompression procedure rests upon the subjective response of the diver of a clinical judgement by the doctor. Both these ways of obtaining a result are liable to error and introduce an uncertainty into any data collected for analysis.

4 DATA COLLECTION AND ANALYSIS

(a)

The magnitude of the problem can be seen when it is realized that because diving is a relatively safe practice the mumber of decompression sickness incidents in any tests will be small, and errors in small numbers can be seriously misleading. In the case of decompression sickness this is even more troublesome because there is an "all of none" endpoint assessed on the basis of symptoms, ie the diver reports pains or he doesn't. This means that a single incident near the start of a series of test dives is only of potential significance, and even if usually severe of obviously true, eg accompanied by objective signs of neurological involvement, needs more supporting data to be considered as statistically significant. Thus to obtain a first estimate of the success of a schedule it will be necessary to provoke a minimum of two incidents. This will therefore become one of the basic rules adopted for assessing the safety of a proposed decompression procedure.

(b)

Having decided on the number of incidents involved in the analysis it is now necessary to decide how many men and how many divers are needed. This raises issues which have been seriously neglected by previous analyses of decompression data. To speak of less than 1.0 % incidence of decompres-

sion sickness as a desirable practical result normally refers to an average of 1 incident per 100 divers, but there is a much more revealing percentage incidence obtained by referring to the percentage of divers affected. The difference in assessment can be hugely dependent on which forms of data analysis are used. For axample it may be stated by engineers constructing a tunnel and using compressed air workers that as a result of many thousands of exposures to compressed air only 0.5 % of the exposures resulted in decompression sickness. Viewed from the engineers standpoint this looks a very good result. It means that for only 0.5 % of the enties into compressed air did they need to spend unprofitable time recompressing one of their workforce. Obviously they would prefer an even lower incidence of trouble but realize that this implies a longer period spent decompressing, and decompression is, like therapeutic recompression, non-productive.

For the statistician there can be no doubts that given such large numbers of observations, typicallly 100,000 entries into pressure and 500 attacks of bends at a medium sized compressed air contract with working pressures in excess of 2.2 bar, confidence in the validity of the 0.5 % incidence is extremely high. So, all is apparently satisfactory with a decompression sickness incidence well below the agreed maximum value of 1.0 %.

Now re-examine the data from the other aspect, not the engineer´s or contractor´s, but the compressed air worker´s. A radically different picture is presented. Assume the contract took three years to be completed, and during that time a large number of workers came and went, but that about 150 men stayed with the work throughout the entire period. Say that over half the bends were experienced by the temporary workers and the rest by the permanent workers, then approximately 200 bends were suffered by 150 men, a bends rate well in excess of 100 %. The situation can never be considered in such simple terms, as the detailed examination of data from any suitably recorded contract will soon reveal. Invariably it will be

found that a few men incurred a disproportionate number of bends. Some men could well have had as many as 17 bends, whereas most men would have had no bends.

It is not profitable to continue much further with this analysis of a hypothetical situation but hopefully it can now be appreciated that from the worker's standpoint the risk of an attack of decompression sickness is far from negligible if the continues to work under pressure of a prolonged period. Depending upon the working pressures encountered it would not be surprising to find that 20 % of the regular workers experienced bends at some time during the course of a contract which lasted three or four years. The point being established is that this 20 % rate is a more sensitive indicator of the success of the decompression procedures than the 0.5 %. This is a mainly technical matter of reaching a more potent index, but it can be seen to have greater moral force to be examining the data from the divers standpoint. Thus the next rule which will be adopted is that the best measure of the success of an established decompression procedure is the incidence of bends amongst the diving population. The number of troublefree divers is also obviously relevant but of secondary importance.

(c)

A further matter relating to the nature of decompression data will be made before proceeding to assemble a set of rules. Examination of experimental observations on goats and human beings reveals remarkably skew distributions in their sensitivity to changes in time at pressure, or pressure itself. The latter can be best illustrated by some experiments reported in J. Physiology (Jan.1985). Twenty subjects were compressed to 1.7 bar and remained there for 48 hours breathing oxy-nitrogen, with admixture of 0.02 bar carbon dioxide in some cases, and following this saturation exposure they were decompressed back to 1.0 bar in 2 min. No cases of decompression sickness were reported. however on repeating exactly the same environmental conditions,

except for a small increase in the nitrogen partial pressure to give a total pressure of 1.8 bar, there were 4 cases of decompression sickness amongst 25 volunteers following the decompression to 1.0 bar. A mere a increase of 0.1 bar ie 1 metre depth had changed the bends percentage of these saturation dives from 0 to 16. There is no doubt from such observations that if a sensitive subject suffers an attack of bends following a particular procedure then many other divers are not far removed from also reporting troubles when using that procedure. This is a very fortunate finding for practical diving because it means that if a procedure is rendered safe for the sensitive man it is not ridiculously over-safe for the bulk of the population. It also has theoretical significance by revealing that the distribution of sensitivity to decompression sickness is markedly skew with regard to pressure and therefore simple statistical analysis based upon the Gaussian distribution will be incorrect.

(d)

Finally a philosophical point needs to be stated. As mentioned earlier, no-one adequately understands the basic physical and physiological mechanisms that cause decompression sickness and therefore it will be safest to assume that the worst possible situation applies. This means that the relevant tissue (or tissues) always possesses separated gas in some form, either as gas nuclei or trapped in crevices etc. Using this philosophy no decompressions are free of gas, it is merely that som decompressions may yield more separated gas than others and, although it is possible that there is a critical volume of gas required to cause decompression sickness, there can be no critical pressure change that causes its formation or significantly increases the likelihood of this occurring. All men are equal in this respect and so are all decompression schedules.

5 THE HYPERBARIC ENVIRONMENT

Having settled, in general terms, the manner in which the information will be analysed it is essential that the evidence being submitted for analysis is gathered using a set of rules that give confidence in the value of the conclusions reached. Attention has already been directed towards the subjective nature of evidence concerned with reporting mild attacks of decompression sickness, and unfortunately little can be done to improve confidence in this particular contribution to the data at the present time. However there are numerous other factors contributing to the reliability of the decompression data, and many of them can be satisfactorily controlled within agreed limits. In this way the variabilities between one decompression and another, using the same (or different) pressure-time courses, can be reduced and thus help to make comparisons more realistic.

(a)

It is quite well known to everyone that body warmth is important to the distribution of blood. Cold hands and feet can be seen to have poor circulation of blood. Knowledge of the detailed physiology of achieving thermal balance is unnecessary for making the broad general statement that keeping the diver comfortably warm will help maintain a satisfactory blood circulation. Further, the elimination of excess dissolved tissue gas, vital to successful decompression, can only be achieved via the blood circulation. So quite clearly it is necessary to ensure the circulation is changed as little as possible by alterations in thermal exchange. It is important to note that some forms of abnormal circulatory responses may actually be beneficial to the decompression process, but until the nature of these changes is established and satisfactory evidence is available the aim will be to interfere with the normal physiological mechanisms as little as possible.

When deep oxy-helium saturation diving was undertaken it was observed that the body, not surprisingly, altered its responses when subjected to such a considerable change in its environment. One factor that was observed early in this work was the very considerable body heat loss occurring at all pressures, but which became a serious problem at pressures in excess of about 150 m. Since those days experimentation has successfully continued to depths approaching 700 m and from a practical viewpoint the problem of maintaining thermal balance has been overcome.

The pattern of heat loss alters at depth as the result of a remarkably large proportion of the total body heat production being lost via respiration. Normally only about 10 % is lost in this way, but at 180 m for example, when breathing oxy-helium, about 50 % is lost in this way. Another noticeable alteration at depth is the lowered amount of heat lost via evaporation of moisture on the skin. Despite these major shifts in the heat exchange mechanisms of the body it is still possible to supply adequate external heat to maintain thermal balance without disruption to the diver's well-being.

The question that used to worry many physiologists was whether the body could maintain its thermo-regulatory mechanisms when exposed to raised pressures for prolonged periods. In simple terms this worry can be stated as "Would the diver know if he was maintaining heat balance, or would his normal responses be so affected by the grossly changed environment encountered at depth that he gradually moved into a hypotermic or hyperthermic state?" The question was answered by the practical experience that if a diver reported feeling cold, or hot, in the pressure chamber then the environment was adjusted until he no longer complained. As a result of these adjustments it became clear that his thermal balance was not being shifted into a dangerous condition. This simple reliance on the diver's own estimate of his needs proved to be entirely reliable for very deep dives and for prolonged periods of many weeks under pressure. Therefore it can be confidently asserted that the

body's sensitivity to the heat exchange requirements are not impaired by the marked changes induced by the hyperbaric environment. The regulatory mechanisms involved have fortunately remained unaffected.

This removes one possible burden to the life support systems but there are still difficulties left regarding methods of supplying the heat energy requirements of the diver and also keeping careful temperature control. The five physical features of the environment that control body heat loss are:

a) The gass composition ie helium or air,
b) The gas temperature,
c) The velocity of gas flow in the vicinity of the diver,
d) The humidity ie water vapour pressure,
e) The radiant temperature of the surroundings.

For nearly all the time spent under pressure the gas being breathed is oxy-helium and this removes the need to consider the first of the variables just mentioned. From a physiological standpoint it is better to have as large an input of radiant heat as possible. Such a requirement can only be satisfied by keeping the pressure chamber walls at a raised temperature. The warm walls bring an additional advantage by minimising condensation but have the disadvantage that, due to the large mass of metal involved, their temperatures cannot be rapidly adjusted to the diver's demands. The method of choice is therefore a combination of warm walls for all normal situations but with gas heating, and cooling, available in the ventilatory system to respond to any quick adjustments that may be needed. The dry bulb temperature of the helium environment which is accepted as comfortable by the diver varies with the depth, and also his level of activity, but the very noticeable feature of his thermal comfort at depths in excess of around 150 m is the narrowness of his range of tolerance to temperature changes. A change of two degree Celcius will be capable of causing a shift from a state of comfort to one of acute discomfort at pressures in excess of 300 m (31

bar). Accurate temperature measurement and control is therefore a pre-requisite for all saturation decompression procedures.

For several reasons it is desirable to keep the relative humidity to values between 25 % and 75 %. Outside these limits the exposed skin becomes either too dehydrated or too wet and if maintained for prolonged periods, renders the skin easy to damage mechanically and increases the risk of infections, sores, and irritations. Despite high standards of hygiene there are therefore small, but definete, possibilities of confusing skin rashes, general discomfort, etc. with minor manifestation of decompression sickness, especially if no suitable qualified person is present. However a more important reason for maintaining a low humidity in the chamber is to promote increased evaporation of moisture from the skin. This helps to compensate for the reduction in evaporation that occurs in the hyperbaric environment and which can contribute to alterations in body water exchange. This in turn is important to the distribution and elimination of dissolved tissue gases, and of course would be expected to have some influence on the decompression process. To reduce such possible complications and to keep the divers in a more comfortable bodily state it is better to avoid extremes of humidity.

(b)

Many years experience of working in the closed environments encountered in nuclear submarines has led to the conclusion that keeping the carbon dioxide partial pressure below 5 millibar is desirable for all prolonged exposures. At greater concentrations of carbon dioxide there are alterations in the acid-base balance of the body, and these alterations often persist for several weeks after the exposure to the raised levels of carbon dioxide has ceased. Although the pressure chamber environment is not the same as that of the submarine it would be sensible to take notice of this limitation on the carbon dioxide pressure

and apply it to the decompression gas composition. Fortunately it is not a technically difficult life-support system requirement to ask for low carbon dioxide concentrations in chamber atmospheres. The principal problem is finding a robust and accurate method of measuring such small partial pressures.

Abnormally high pressures of oxygen are breathed by the diver during most of his time at pressure. When considering the diver's health, how much high pressure oxygen breathing can be safely tolerated? The true answer to this question is not yet available and therefore certain simple and somewhat crude rules need to be adopted. The oxygen pressures breathed for prolonged periods during saturation diving are below 1.0 bar and therefore not those which would lead to serious neurological signs and syptoms in a short time. The results of breathing oxygen pressures between 0.21 bar and 1.0 bar have been thoroughly examined for their effects on pulmonary function, and it is generally agreed that no harmful changes can be detected at pressures less than 0.5 bar, even after several days of continuous exposure. This observation is fundamental to the concept of the Unit Pulmonary Toxicity Dose, UPTD (definded later in the section concerned with units) which is a useful attempt at measurement of the seriousness of pulmonary oxygen toxicity. However there are two areas of concern to be considered before accepting the 0.5 bar oxygen pressure as totally safe for men to breathe for long periods in pressure chambers.

All the research on these oxygen partial pressures was carried out at total ambient pressures no greater than 1.0 bar. As just mentioned when considering a suitable carbon dioxide partial pressure the diver is subjected to very high pressures of helium, and there is no certainty that results obtained at 1.0 bar will apply to his high pressure environment. The second source of concern is that nearly all the careful measurements of physiological change have been confined to tests of pulmonary function. More recently there have been detailed haematological investigations

conducted throughout the course of very prolonged deep dives and there is reason to believe that even 0.4 bar oxygen when breathed in a hyperbaric environment for four of five weeks shows quite large effects on the red cell count. These changes are reversible without any apparent adverse effects on the diver's health, but complete return to normally takes some weeks post-dive. It hardly needs stressing that quite severely anaemic, mentally and physically very tired, divers do not represent a desirable end result of saturation diving. These findings are from extreme experimental exposures but nevertheless lead to conclusion that for all ordinary commercial diving the partial pressure of oxygen should not exceed 0.4 bar throughout the whole decompression, thus staying well away from the possibility that oxygen breathing during the work period, or for therapy, might summate and give a lower than desirable state of vitality post-dive.

Before leaving the oxygen breathing problem it must be noted that what happens during the working period at depth can influence the success of a decompression. In particular the diver must not enter the decompression phase of the dive with his lung functions impaired as a result of breathing too high a concentration of oxygen whilst at work. From a practical viewpoint this means not exceeding 600 UPTD at any 24 hour period. Attempts to have two sessions per 24 hours, each session of 6 hours during with a UPTD value of 600, and a 6 hour interval between these "excursions" with the diver at rest in low oxygen levels, will result in serious pulmonary function changes and obvious signs of distress after 5 such "excursions" into the higher oxygen levels. Thus to maintain healthy divers and to avoid the possibility of lung damage interfering with the elimination of excess gas during the decompression period it is advisable to halve this dose not exceed 600 UPTD in an 24 hour period. This UPTD measurement of the oxygen toxicity risk is unfortunately relatively crude and does not allow for complex pressure/time profiles. Until a more versatile system is established the oxygen dose acquired in one exposure must be added to the oxygen dose

of any subsequent exposures and this total UPTD dose must not exceed 600 for any 24 hour period. Such a rule is probably over-safe but until considerably more research involving breathing raised partial pressures of oxygen at high ambient pressures has been performed it is the best available.

(c)

In association with an appropriate partial pressure of oxygen there are only four gases that can be used to supply part, or all, of the pressure required for diving work. These are helium, nitrogen, hydrogen and neon. Of these gases helium is so clearly superior in the depth range 15 m to 360 m that from a practical standpoint it is pointless considering the use of any other gas or mixture of gases. Nitrogen is seven times denser, has undesirable narcotic properties, is much more soluble in both fat and watery tissues, has a diffusion coefficient 2.6 times greater than that of helium. Similar, but less marked, considerations of density, solubility, and diffusion properties apply to neon. Hydrogen has the major drawback that it needs extremely careful safety measures to avoid explosion hazards, otherwise this could be a potentially useful gas.

Once the limit saturation air diving has been reached at 15 m the need for a life support system and artificial atmospheres is unavoidable. Oxygen-helium has mixtures automatically become the first choice unless there are helium supply problems, when it is possible to contemplate dives as deep as 60 m on oxygen-nitrogen mixtures, but this is not recommended practice.

(d)

There are many occasions when divers lose their appetite during the actual dive time or subsequently when being decompressed. This does not seem to be important to the success of the decompression procedure unless accompanied by a lack of fluid intake, which can sometimes be

exacerbated by vomiting. It is important that the water balance of the tissues should remain as near normal as possible, otherwise the resultant shifts in osmotic balance and ion exchange begin to influence the whole of the divers's physiology. In particular there is a diminished output of urine an a consequent drop in through-put of water. Although no human experimentation has examined this problem it is "a prior" obvious that a diminution in both the input and output of body water must be relevant to the mechanisms involved with eliminating the excess gases dissolved in tissue fluids. Therefore it is advised that a diver should drink at least a litre of water per day.

(e)

Finally attention needs to be given to the problems of sleeping in pressure chambers during decompression. The diver must not be allowed to feel cold prior to going to sleep, or when attempting to go to sleep. As mentioned earlier coldness leads to undesirable blood circulation changes. Further he must be provided with a dry and comfortable mattress or bunk bed as this will help to reduce the effects of awkward sleeping positions such as the potentially troublesome habit that some men have of sleeping with their body weight resting on an arm, which, with hard surfaces to sleep on, considerably impedes blood flow in that arm.

6 UNITS OF MEASUREMENT

SI units of measurement will normally be used but the Kelvin scale for temperature will not be employed as this is not familiar to many in practical diving.

The fundamental pressure unit is the Newton per square metre (N/m^2), however by common consent the Bar ie 10^5 N/m^2 is the most convenient unit to be used for diving physiology purposes. It so happens that a vertical column

of 10 metres of standard sea water exerts a pressure of exactly 1 bar. This is highly convenient for arithmetic purposes, but it must not be forgotten that sea water is not of constant density eg near river outlets, and only pressure measured in terms of the bar is reliable. Fortunately these measurement difficulities are not likely to arise in the pressure chamber during saturation decompression, where all pressures are read in fundamental units by calibrated gauges. For most practical diving purposes 1 bar is equivalent to 1 Atmosphere Absolute ie 1 ATA. Being totally accurate a bar = 0.98692 ATA, which is slightly over 1 % difference. Such small differences only become important at the maximum pressures being considered.

The oxygen toxicity unit to be used is termed the Unit Pulmonary Toxicity Dose. It is defined as the degree of pulmonary toxicity produced by breathing oxygen at a partial pressure of 1 ATA for one minute. The vital capacity of the lungs is used as the measure of the pulmonary oxygen toxicity effects of breathing raised pressures of oxygen. Suppose that a fixed small decrement in vital capacity is taken as a standard of impairment due to oxygen breathing, then using this fixed decrement as an end-point for all oxygen breathing it is found that for various pressures of oxygen (P ATA) for different durations of exposure (t min) there is a relationship between P and t of the form:

$$P - 0.5 = b \cdot t^{-1.2}$$

If now it is wished to express any exposure to hyperbaric oxygen (P_1) in terms of an equivalent exposure to oxygen at 1.0 ATA then eliminating the constant b in the above equation a relationship is obtained:

$$t_1 = t \left(\left(P_1 - 0.5 \right) / 0.5 \right)^{1.2}$$

where t is the duration of exposure to pressure P_1 and t_1 is the duration of exposure to 1 ATA which would give the same decrement in vital capacity, ie the UPTD value for this particular exposure when time is expressed in minutes.

Total UPTD units for consecutive exposures to more than one oxygen pressure are obtained by adding the units acquired at each pressure. For practical purposes using 1 bar = 1 ATA will not introduce any significant errors into these calculations.

As stated elsewhere in this report the UPTD as a crude measure of oxygen toxicity and other more versatile measures have been proposed but until far more basic research at high ambient pressures has been undertaken these are also open to adverse criticism.

7 SAFETY RECOMMENDATIONS

(a) The pressure chamber environment

The diver's physiological processes are unavoidably affected by the hyperbaric environment, but must remain within the limits of what is acceptable for him at one bar breathing pure air (see Section 5). To help achieve this level of normality:

1) The carbon dioxide partial pressure should not exeed 5 m/bar.

2) The relative humidity should lie between 25 % and 75 %. Preferable near to 50 %.

3) The oxygen partial pressure should not exceed 0.42 bar, or 22 % (by volume) of the chamber gas composition. This is more than USN Tables recommend but less than most commercial practice.

4) If high oxygen partial pressures are breathed during the working time before decompression, then no diver must exceed 600 UPTD in any 24 hours period.

5) The nitrogen partial pressure should not exceed that of ordinary pure air ie 0.8 bar.

6) For all saturation diving at depths between 15 m and 360 m the only gases injected into the chamber should be either oxygen or helium (or both together). See 5) above.

7) Thermal balance must be carefully maintained by ensuring that the diver is never either too warm or too cold.

8) Fluid balance requires an intake of at least 1 litre of water per 24 hours period.

9) Well presented, properly cooked meals; sound sleep; opportunities for total privacy; some entertainment (video films etc.); mental and physical exercise; are among the more important factors that help to maintain a proper state of well-being during the many boring hours of decompression.

(b) Excursion diving

If an excursion has taken place to a depth greater than the storage depth then the tissues will have acquired extra dissolved gas and therefore a period of rest will be necessary at the saturation dive depth before a standard decompression procedure can be started. The difficulty is deciding upon the duration of this rest period when bearing in mind the depth and duration of the excursion dive.

Physiologically speaking the practice of excursion diving should be discouraged until more is understood about the effects of the presence of "silent" bubbles ie ultra-sonically detectable separated gas which is undoubtedly present after most diving procedures but which is apparently harmless unless provoked by further decompres-sion. Starting a prolonged saturation decompression with a good supply of "silent" bubbles seems undesirable, even if

the bubbles continue to remain "silent".

Variations in pressure are unavoidable in the course of normal diving procedures but these should be not greater than 10 m, either deeper or shallower, than the saturation dive depth. If an excursion (up or down) is greater than 6 m but not in excess of the permitted 10 m maximum than wait 6 hours at the saturation depth before commencing decompression.

(c) New decompression procedures

New schedules are obtained by making alterations in the calculating basis of the old schedules or by adopting of procedures that some-one else has apparently used with great success. This latter approach is not bringing any new initiative to the problem of decompression and will be considered later.

If a diving organisation wishes to introduce new procedures then it is necessary to demonstrate that these new procedures will constitute an advance. This demonstration is sometimes attempted in suitably equipped shore-based hyperbaric research establishments. Clearly this is preferable for a number of reasons, but it is not logical to judge the results of various ways of proving the effectiveness of new schedules according to the location of the test chambers, and therefore everyone should be asked to meet the following minimum standards.

1) A strict code of diving practice is to be followed.

2) All divers who take part in the tests must be made aware that they are being asked to volunteer for an experiment. The nature of test and any hazards must be fully explained to them by a medically qualified person experienced in diving medicine. They must be given the right to withdraw from the tests, and coercion must not be used. Written consent must be obtained.

3) Unless convincing evidence is obtained modifying the basic environmental requirements, mentioned above, these conditions must be met.

4) The proposed schedules will normally cover a wide working pressure range. Until the schedules have been established as safe to use at the extremes of their range and at one intermediate value the whole set cannot be accepted. If excursion diving is proposed then the maximum permitted excursion, plus appropriate rest period at saturation depth, must be attempted prior to the schedule testing.

5) At least 15 volunteers must participate in a trial, and each man would be expected to take part in two dives. No more than three volunteers are tested in the chamber on any particular dive, otherwise too much data is list when a dive has to be stopped if one diver has decompression sickness before reaching surface pressure. The other volunteers with him are thereby prevented from demonstrating their own response to the schedule.

6) The first decompression sickness incident in any trial, however serious, is temporarily ignored, and the trial continues. If there are no further incidents in the two exposures of each of the fifteen men involved (30 dives in all) then the particular procedure under test is deemed safe enough for general use as non-experimental.

7) If a second incident occurs before 15 men have completed their first dives then the trial must cease and the procedure is regarded as unsuccessful.

8) If a second incident occurs after 15 men have completed the first half of the trial, and if this incident involves the same man as the first

incident, then continue with the trial but extend the number of different volunteers to a total of 20 (40 dives). If a further incident occurs then the trial must be abandoned. If another incident does not occur then the practical procedure under test can be regarded as nonexperimental and safe enough for general release.

9) If a second incident occurs after 15 men have completed the first half of the trial and this incident does not involve the same man responsible for the first incident then the procedure under test is failure.

10) If the schedule testing satisfies the above criteria regarding overt (ie therapy required) attacks of decompression sickness but nevertheless the volunteers report several episodes of persistent (over 2 hours duration), or recurring, minor aches and pains in the final 20 m of decompression, or post-dive, then the schedule is in need of modification and re-trial.

(d) Emergency procedures

Emergencies arise as a result of serious and unexpected medical or mechanical difficulties. In both cases the main problem that usually confronts the dive control team is how to get the divers out of the pressure chamber, or to a much lower pressure, in as short a time as possible consistent with a reasonable chance of not given them serious decompression schedules are designed to cope with this kind of situation.

After a diver has entered a pressure chamber at great depths for long times his tissues contain several potentially lethal doses of dissolved gas. However it will be sensible to consider the minimum pressure to which the chamber can be reduced in a relatively short time without too great a risk of serious decompression sickness

complications. This will be called the "target pressure" for the emergency procedure and may be surface pressure, or any dive pressure, depending upon the depth at which the emergency happened.

An important question to be answered is "What is an acceptable risk in such a situation?" the view taken here is that about a 1 in 3 risk of mild decompression sickness is tolerable. Once the divers are at the lower pressure this must surely improve the overall situation and perhaps they can then be rapidly transferred under pressure to another chamber, or given appropriate therapy whilst resting at the target pressure. However it must be remembered that if a doctor or other skilled person is licked in to the chamber to render assistance of some kind this cannot be achieved rapidly at pressures greater than 150 m. Otherwise the person transferred in to the chamber may suffer impairment of performance due to HPNS and become more of a nuisance than a help.

Testing emergency schedules for their suitability is clearly potentially more hazardous to the volunteers than ordinary schedule testing, but if carried out under close medical scrutiny with experienced men this is not the case. If any event it is ridiculous promulgating untried emergency procedures that may be more dangerous than the emergency that brought them into use.

For this much more difficult trial only 6 experienced volunteers are needed. See (c), 1), 2), 3), above. Clearly any experimental dive carrying this level of risk must cease when one of the volunteers encounters decompression sickness. All attacks will be carefully observed by the man himself and also en experienced physician, when means that the incidents observed will be only brief and marginal. The affected volunteer must then receive the best possible theraphy for his attack. These entirely unavoidable humanitarian requirements mean that sometimes the trial cannot be pursued to the target pressure at which greater discomfort would be encountered. Therefore when testing the

proposed schedules:

1) The schedule must be abandoned if decompression sickness is encountered deeper than 24 m above the target pressure of the emergency schedule.

2) Only two volunteers at a time are tested, see (b) 5 above.

3) If one incident occurs in the first 6 dives, but see 1) above, proceed to a second set of 6 dives, using the same volunteers. If only one incident occurs in the second attempt by these 5 volunteers and it is the same man that is responsible for both incidents, then this can be accepted as a suitable emergency procedure. If one or two further incidents occur to other men during the second set of 6 dives then the procedure may be acceptable depending upon the nature of the decompression sickness encountered. If more than one of the incidents occur 18 m deeper than the target depth, or are serious and difficult to treat then this schedule is not acceptable.

4) If two incidents are encountered in the first six attempts then this procedure is a failure, unless the decompression sickness is of a mild nature, in which case it is ethically justifiable to continue with a second group of 6 volunteers and see whether another one or two mild attacks are again provoked. If so the schedule is acceptable for emergency use, but if serious forms of decompression sickness appear, then the suggested procedure is a failure. Mild decompression is defined for present purposes as "limb pain only" forms of deompression sickness (Type 1) ie no neurological complications, or sub-sternal distress, etc.

5) If no incidents occur after 6 men have attempted the emergency schedule on two seperate occasions

then the schedule may be too safe for emergency use. Try another 6 men for 6 dives, and unless one incident occurs on this extension of the trial the schedule must be abandoned as unsuitable.

6) All emergency procedures must be tested following a saturation dive at the highest working pressure for which they are designed, as well as at some lesser value. If they are stated to offer help when the emergency arises during the course of a normal saturation decompression then an extreme case of these circumstances should be tested.

7) Despite the obvious decompression advantage of using oxygen rich breathing mixtures no schedule should require the diver to breathe a partial pressure in excess of 1.0 for longer than 12 hours or 0.8 bar for longer than 24 hours. For more prolonged breathing the oxygen partial pressure should not exceed 0.6 bar. Otherwise there is a risk of lung damage, which could affect any subsequent theraphy.

8) Specially reserved supplies of oxy-helium gas, available on a built-in breathing system, must be part of the whole pressure chamber safety plan. Air is sometimes advocated as part of the emergency breathing gas mixture, but has serious decompression disadvantages if breathed at high pressures for prolonged periods. The increased breathing gas density of air mixtures unnecessarily and adversely affects diving casualties already afflicted with respiratory problems.

(d) Existing Schedules

No information is currently available on the numbers of dives performed, the depths of these dives, and the identities of the men who took part in these dives. It is not necessary to know the actual names of divers involved

as this could be sensitive information, code names would suffice. Without this basic information all quantitative statements are quite impossible because it is the proportion of divers adversely affected by the repeated use of a particular schedule that is the measure of that schedule's safety.

The unfortunate fact, statistically speaking, that has become clear when examining the forms returned by the various diving contractors is that three of them started new procedures in 1984! Why did they change their schedules ie on what basis were they not satisfied with what they were using the previous year?

The simple procedures for estimating the effectivness of saturation decompression tables already in use are as follows:

1) Divide the total pressure range ie 0 m to 360 m into 6 groups, 0 m to 60 m, 60 m to 120 m, 120 m to 180 m, 180 m to 240 m, 240 m to 300 m, and 300 m to 360 m. If the tables do not cover such a wide range of diving depths then take only the range given by the tables and use an appropriate number of these 60 m (200 ft) increments.

2) Note the number of decompression incidents reported in each of these depth increments. For these purposes an incident is any decompression sickness that needed therapy, ie recompression, or altering the decompression in progress, or breathing special gas mixtures, or medication (eg analgesics). All minor persistent, or recurrent, aches and pains that did not receive treatment are also important, although it is not likely that such evidence (niggles) has been recorded.

3) Note which men were responsible for these incidents and how many dives they had completed in each increment.

4) Repeat 3) but this time record all those who did not report any problems during their decompressions.

5) If less than 30 men have dived within any depth increment then more information is needed to take a firm judgement on that particular section of the diving table. However if less than 30 but more than 10 are recorded and there were more than 3 men requiring therapy ofr decompression sickness this section of the table is clearly in need of modification. This statement is independent of the total number of dives recorded.

6) If more than 30 men have dived within a particular increment and the number of different men who needed therapy as a result of using a given schedule does not exeed 2, or 5 % for 40 or more men, then this could be regarded as accepable but 5 % or over would be unacceptable. A schedule given repeated incidents involving one or two senisitive men, although passing the above test of effectiveness, would not be considered wholly satisfactory. Also a schedule that caused numerous "niggles" would need modification.

In view of the situation that has become exposed by the recent questionnaire there is no benefit to be gained by attempting to apply the above criteria for judging current schedule effectiveness when the necessary minimum basic for the assessment is unfortunately not obtainable. The best course of action is to abandon ideas of depending upon the contractors, and move into the future, relying entirely upon yourselves as Project managers.

1) As soon as possible commence sending around to all contractors forms which request the relevant information. Each form should cover a month's diving activity and be completed and returned in

the week following the collection of the data for that month.

2) Some knowledgeable person(s) must also interview the divers and ascertain, as near as possible for such a difficult problem, the extent of the sub-clinical decompression sickness ("niggles") encountered by the various schedules. Other problems such as post-dive fatigue, and depression, could also be included in the work for this investigation. Only linking the decompression phenomena with these immidiate post-dive effects can any improvements be given credibility.

3) The data obtained must be recorded and stored in such a way that confidentiality is maintained but allows versatile data handling. After two seasons of data acquisition there will probably be sufficient information to reach a few definte conclutions on the effectiveness of the various precdedures.

4) Research into some objective measures of the saturation decompression is a prime practical requirement. The reliance on recognition of overt decompression sickness, and the less obvious "niggles", by the diver or doctor is very unsatisfactory for accurate appraisal of the effectiveness of schedules. This is especially true if no-one bothers to mention minor aches, even although these can persist with varying levels of discomfort for many hours or days.

8 CONCLUSION

Confinement inside a pressure chamber, breathing high pressure of synthetic gas mixtures for days or even weeks at a time, must have unvoidable effects upon the saturation

diver but it is essential that the decompression procedures do not add to his difficulties and are proved to be not detrimental to his short term or long term physical and mental health. This will eventually require much more detailed information than that sought in this report, but it is hoped that the suggestions given there represent a significant start to realising this aim.