THE DYNAMICS OF DECOMPRESSION WORKBOOK

FIRST EDITION

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DISCLAIMER

Neither the author or The University of Michigan will accept responsibility for accidents or injuries resulting from use of the materials contained herein or the activity of scuba diving.

Scuba diving is an activity that has inherent risks. An individual may experience injury that can result in disability or death. Variations in individual physiology and medical fitness can lead to serious injury even with adherence to accepted standards.

Trained and certified divers are informed of the risks associated with scuba diving and ultimately bear responsibility for their own actions.

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Author's Note

This workbook is designed to be used along with the *DYNAMICS OF DECOMPRESSION WORKSHOP* which has evolved over the past six years. The workshop started out as a three hour seminar and is now commonly presented as a full day program. It has also been given once as an extremely thorough two day workshop. Since the content of the material presented in each workshop will vary due to time constraints and the number of workshop attendees, this workbook was designed to provide the participants not only with the information presented in the workshop, but with supplemental information that may not have been covered in their workshop.

The concept "Dynamics of Decompression" does not just apply to the dynamic process of compression/decompression physiology and the models developed to describe this activity, but also to the field of decompression research. This field has been continually in flux since, and before, Haldane presented his model and tables in the early 1900s. It is not uncommon to find more disagreement than agreement among scientists, researchers, and decompression model/table developers, even though they have the common goal of developing techniques for safe effective decompression. Due to the dynamic nature of decompression research, this workbook and workshop are also dynamic entities. As new information becomes available it will be included into both the workshop and workbook.

It is not the intent of this workshop to provide definite answers in areas where none yet exist, but to provide up to date information which you can use to make educated decisions about how you will determine your own decompression status.

Karl E. Huggins - October 1991

Additional Note

Last year when I started the process of writing this workbook I thought that I could complete it by the end of November. Since that time I have discovered that a task such as this requires much more time and effort than originally estimated. In addition there is the urge to add new information to previous chapters that have been completed. I wish to apologize to those who have waited up to 6 months for this publication to become available. I hope that it will be informative and beneficial.

Karl E. Huggins - May 1992

Acknowledgement

My deepest appreciation to Mike Emmerman, for taking time out from his vacation in Maine to review this workbook, and for his comma-sense.

INTRO

WORKBOOK INTRODUCTION

Ever since humans started working under pressure they have been plagued with the problem of decompression sickness (DCS) or the bends. Throughout the years there have been many theories and techniques developed to deal with DCS. In the 1950s, when recreational diving started to take hold in this country, the U.S. Navy Repetitive Diving Tables were the defacto tables for use. These tables, in their original and various "easy to read" formats, were incorporated into recreational diving instruction as various certifying agencies started to form and propagate. This lead to the U.S. Navy tables becoming the "Standard of the Community" for determining the decompression status for recreational divers in the United States and many parts of the world.

Over the past ten years a revolution has taken place. The U.S. Recreational Diving Community has been moving away from the established U.S. Navy tables and, as in most revolutions, there now exists a state of confusion. Todays diver now has a choice of over thirty different tables or dive computers to determine their decompression status. Depending on the table or computer that is being used the "no-decompression," or "no-stop," limits can vary greatly. For instance, a dive to 100 fsw this limit may be 25 minutes, 8 minutes, or somewhere in between (Table I.1). Which of these options is the correct one? There is no pat answer. Of the options presented in Table I.1 one can only say that a diver should be at less risk for developing DCS if the 8 minute limit is observed instead of the 25 minute limit. This poses a potential problem within the boundaries of recreational scuba diving, rigidly defined by the certifying agencies, manufacturers, and resort operators. Since all recreational dives are to be "no-decompression," would a diver using the 1% Risk tables be chastised for performing a dive to 100 fsw for 15 minutes, which would require decompression? Would another diver who has backed off 5 minutes from the U.S. Navy limits be accepted with a dive to 100 fsw for 20 minutes since the "no-decompression" rule had been observed? What exactly is the standard?

My hope is that, with all the various options available to them, divers will make an attempt at

TABLE I.1
NO-STOP LIMITS FOR 100 FSW

U.S. Navy Tables	25 minutes
NAUI	22 minutes
PADI, BSAC, Jeppesen, Huggins	20 minutes
Suunto Dive Computer	18 minutes
German Tables	17 minutes
DCIEM Tables	15 minutes
Dacor Microbrain Dive Computer	12 minutes
Dacor Microbrain Pro Plus Dive Computer	11 minutes
Computek Dive Computer	9 minutes
Maximum Likelihood 1% Risk Tables	8 minutes

being more informed consumers with a better understanding of the underlying concepts of decompression tables and how dive computers compute decompression status. The primary objective of this workbook, and the workshop associated with it, is to allow divers to understand that all dive computers, decompression tables, and decompression models have limitations that need to be considered in the planning and execution of any dive.

TRUTH

"If of the many truths you select just one, and follow it blindly, it will become a falsehood, and you a fanatic."

Some training agencies dictate which decompression tables should be used by exposing their students to only one of the available tables. If any of the other options are discussed, it is generally in a disparaging light. All this does is to lure newly trained divers in to the false sense of security that the technique they are taught is the ***"truth."*** They are not exposed to other theories, models, tables, and debates which exist in the decompression field that are needed to make educated and knowledgeable decisions regarding their own decompression needs.

Chapter 1 presents a brief overview of some of the basic definitions, physics, and concepts that are used throughout the workbook. In addition, brief descriptions of DCS, its treatment, and early attempts at eliminating its occurrence are presented.

This workbook deals primarily with, what has come to be known as, the Haldanian approach to decompression modeling. The majority of the dive computers and most decompression tables available today are based on Haldanian concepts. Chapter 2 looks at Haldane's theory and the testing done prior to publishing his decompression tables.

In the years following Haldane's table development, the U.S. Navy generated various versions of their own table from 1915 to 1957. Chapter 3 examines the historical experience of U.S. Navy table development focusing heavily on how the 1957 Repetitive Air Decompression Tables were calculated.

Chapter 4 presents an overview of other theories, models, and tables. These range from simple modifications of the U.S. Navy tables, through newer Haldanian tables (like the new PADI tables), and finally to non-Haldanian concepts and models. Reasons why a single decompression model can produce a wide variety of decompression tables are explored, showing why a table, based on a model more conservative than the U.S. Navy model, can allow more bottom time for repetitive dives than the U.S. Navy tables.

Theories and techniques behind Multi-Level diving are presented in Chapter 5. Both table and model based procedures are examined. Decompression device development began in the 1950s based upon the introduction of scuba. The loss of surface contact and greater three dimensional freedom scuba permitted generated a need for an alternate method of determining decompression status. Chapter 6 presents a history of these decompression devices which have evolved into the dive computers that are available to us today.

In Chapter 7 the function of current dive computers is explored. How do these devices come up with their decompression status and what their perception of the world?. Benefits and limitations of dive computers are covered along with why it is difficult to compare a dive computer to a set of tables. A technique for adding safety factors, and American Academy of Underwater Sciences recommendations, for dive computer use are also included.

Divers' uses and abuses of dive computers are presented in Chapter 8. General abuses as well as case histories demonstrate that the dive computer is only just one additional tool that the diver can use to make informed decisions about a dive.

Other decompression problems that face the recreational diving community are discussed in Chapter 9. These problems include, deep air diving, oxygen decompression, nitrox, heliox, trimix, and closed circuit rebreathing systems. All of these techniques and technologies are out in the fringes of recreational diving, but are gradually gaining ground. An overview of both the benefits and dangers of these techniques is covered.

Chapter 10 examines how decompression models and tables are validated. How "safe" are the models and tables currently out in the field? How much testing needs to be done in order to be confident that a table or model is "safe?" What is the definition of *safe*?

It is my hope that the information contained within this workbook, and the corresponding workshops, will help you raise more questions than are answered. Decompression is a area where you discover that, *the more you learn, the more you know that you really don't know what is going on.* For behind the "black-and-white" exactness of table entries, the second-by-second countdowns of dive computers, and beneath the mathematical purity of decompression models, lurks a dark and mysterious physiological jungle that has barely been explored.

1
INTRODUCTION TO DECOMPRESSION THEORY

DECOMPRESSION SICKNESS

Ever since humans started working under pressure they have been plagued with the problem of decompression sickness (DCS) or the bends. During a hyperbaric exposure increased gas pressures cause gas molecules to be transported through the lungs and become dissolved in the body tissues. Di-nitrogen (N_2), the major component of air, is a physiologically inert gas and its pressure in the body gradually increases, or decreases, until it equals the N_2 pressure in the lungs. DCS is the result of excess nitrogen (or other inert gases in the case of mixed gas diving) coming out of solution in the body tissues when there is a rapid decrease in ambient pressure, just as carbon dioxide bubbles are released from solution when a carbonated beverage is opened.

There are many factors that can increase the probability that a diver may develop DCS, besides the pressure exposure (Table 1.1). In addition, there are areas within a diver that are considered more susceptible to bubble formation than others. These sites may include joints, areas that have been previously injured, and areas where blood reservoirs exist and flow is reduced (such as venous return from the spinal column). Once gas bubbles form within the blood and tissues they can produce a wide range of physiological problems as the body reacts to this "invasion." Pain and neurological detriment are the most well know, but not the only, symptoms associated with DCS. Table 1.2 lists some of the major signs and symptoms of DCS.

DCS is normally separated into two types, Type I and Type II. The primary symptoms of Type I (pain only) DCS are, limb and/or joint pain, and itching. Type II (serious) DCS manifests itself with, neurological involvement (such as visual disturbances, quadriplegia, paraplegia, etc.), skin rash, and sometimes lung involvement (the chokes). Although Type II DCS has been labled as serious it does not mean that Type I DCS isn't a serious condition that required attention.

In general, if bubbles enter the venous return system they are transported, via the heart, to the lungs and filtered out. However, in some people these venous bubbles could migrate over to arterial circulation and pose additional problems. A certain portion of the population has a condition known as "Patent Foramen Ovale," a defect in the heart that may allow venous blood to be shunted over to arterial flow. If bubbles, present in the venous blood, are shunted to arterial blood they may be pumped to the brain, causing cerebral DCS. Another mechanism proposed for

TABLE 1.1
SOME FACTORS THAT CAN CHANGE SUSCEPTIBILITY TO DCS

Environmental	Physiological
Depth/Time Profile	Hydration Level
Ascent Rate	Physical Condition
Water Temperature	Exercise Level
Current Activity	Age
Profile Sequence	Alcohol/Drug Use
	Body Composition

TABLE 1.2
SOME SIGNS AND SYMPTOMS OF DECOMPRESSION SICKNESS

Signs	Symptoms
Blotchy Skin Rash	Skin Itch
Paralysis, weakness	Numbness, tingling and paralysis
Staggering	Dizziness
Coughing Spasms	Shortness of Breath
Collapse or unconsciousness	Unusual Fatigue
	Joint Pain

"pumping" venous bubbles to the arterial side is a short bounce dive following a normal dive. If venous bubbles produced from a dive are trapped in the lungs then a short dive (ie. to free an anchor line) may compress the bubbles to a point where they travel through the aviolar capillaries to the arterial side. When the diver ascends these bubbles will expand and can cause problems.

CASE HISTORY

Female tourist treated at Townsville, Australia. Diagnosed with cerebral DCS. Successfully treated, clinically. Admitted to not feeling her normal self. Feeling of depression that improved over following months. Feelings of extreme paranoia during, and just after, treatment. At the time of the treatment she did not like being alone because space creatures were going to get her. These creatures had been in a book she had been reading at the time she went diving.

Another unresolved issue, currently under investigation, is that of neuropsychological changes associated with DCS. An article by Chris Acott in the South Pacific Underwater Medical Society Journal sites a study where all Type II cases of DCS had cerebral perfusion deficits, or changes to the blood flow in the brain.[1] Anecdotal reports associated with albalone divers imply that, *"shellers who remain in the boat...could differentiate the depth of the dive on the mood and personality change seen in the abalone diver upon surfacing."* Confused states were associated with deeper dives while longer shallower dives tended to produce abusive behavior. The major concern expressed by Acott in his article is that:

> *Failure to recognize that there is something wrong may, in fact, be a manifestation of the disease. Unrealistic or perhaps, in some instances, a paranoid reaction to the symptoms may in part be part of the disease itself. This is sort of a "Catch 22" situation. To recognize that one has DCS one must recognize the symptoms, but one of the symptoms of DCS is that one does not recognize that one has got it.*

As indicated previously, this area of study is unresolved at this time. However, Acott reports several cases of severe psychologic changes in divers who have developed DCS. Not only should you be aware of your own physical and psychologic state following a dive, but you should also be aware of your buddy's state. They may be showing signs of DCS which they either will not, or can not, recognize.

TREATMENT OF DECOMPRESSION SICKNESS

The management and treatment of DCS is covered in many texts, articles, and courses on diving accident management.[2,3,7,8] Early recognition of the signs and symptoms of DCS and seeking help are immediate concerns. The primary response should be the administration of oxygen in as high a concentration as possible, preferably via a demand mask, and as soon as possible. All attempts need to be made to transport the victim to hospital for further evaluation and treatment as rapidly as possible.

Treatment of DCS involves recompression within a hyperbaric chamber. There are various treatment schedules which are used to reverse the effects of DCS depending on the seriousness of the case and the reaction to initial treatment. Recompression is no guarantee for complete recovery. Divers may have residual symptoms even after ten or more treatments. The chance of eliminating all symptoms is related to the delay between developing DCS and being treated. The longer the delay, the lower the chance of resolving all symptoms.

The old adage, *"An ounce of prevention, is worth a pound of cure"* truely applies to DCS. Understanding of the mechanics of DCS, factors that can increase a diver's susceptibility to DCS, decompression theory, and how tables and computers work will give divers the ability to make educated decisions that may be used to help reduce (but not totaly eliminate) the possibility of developing DCS.

GAS DYNAMICS AND PRESSURE

Since the problem of DCS deals with the release of inert gas (normally nitrogen) from solution in the body's tissues and fluids, decompression models attempt to model the flow of gases in and out of the body. To better understand these models a review of some basic physics dealing with gases and various definitions of pressure representations follows.

Pressure and Depth

Pressure is a measurement of force per unit area. We live at the bottom of a sea of air that is approximately 50 miles thick. The pressure the air exerts at sea level is about 14.7 pounds per square inch (psi) or one atmosphere absolute (ATA). The *standard* atmosphere can be represented using different units in both English and Metric systems as shown below:

1 atm	= 14.7 psi
	= 2,116.8 pounds per square foot (psf)
	= 29.92 inches of mercury @ 0^o C*
	= 406.8 inches of pure water @ 4^o C*
	= 33.9 feet of pure water @ 4^o C*
	= 33.08 feet of sea water (fsw) @ 4^o C & 1.02478 gm/cm^3*
	= 1,013,000 (1.013 x 10^6) dynes per square centimeter
	= 1.013 x 10^5 Newtons per square meter
	= 1.013 bar
	= 1,013 millibars
	= 760 millimeters of mercury (torr) @ 0^o C*
	= 10.33 meters of pure water @ 1.02478 gm/cm^3*
	= 10.08 meters of sea water (msw) @ 1.02478 gm/cm^3*

*With standard acceleration of gravity of 9.80665 meters/sec^2

The approximate definitions of the standard atmosphere used in this book are:

1 ATA	= 14.7 psi	= 34 feet of fresh water (ffw)
	= 1.013 ba	= 10 msw
	= 33 fsw	= 10.3 meters of fresh water (mfw)

The ability to represent pressure as a height of a non-compressible fluid such as water or mercury depends upon standardized conditions. The density of pure water at 4^o C is 1 gm/cm^3 and a column that is 1 inch x 1 inch x 33.9 feet high will weigh 14.7 pounds (under standard gravitational acceleration) and will balance the weight of the standard air column at sea level (1 ATA). Since depth gauges measure pressure, against a depth scale, a measured depth will not always match pressure represented in fsw units. If, for example, a diver was at a measured depth

TABLE 1.3
COMPOSITION OF DRY AIR

Nitrogen	78.080%
Oxygen	20.950%
Argon	0.934%
Carbon Dioxide	0.031%
Trace Gases	0.005%

of 50 feet in high salinity water with a density of 1.2 gm/cm^3, a gauge calibrated for standard sea water would display a depth of 58 fsw. In this case the diver would be at higher risk if the measured depth was used to calculate decompression status instead of the gauge depth. Most decompression models and tables assume standard sea water for their depth entries. However, some do use fresh water or an average between standard salt and fresh water.

Atmospheric pressure is not constant. Sea level pressure can vary due to atmospheric conditions. Low pressure systems produced by hurricanes can reduce air pressure to as low as 13.5 psi at sea level. Atmospheric pressure also depends upon altitude. As altitude increases air pressure decreases since there are fewer molecules exerting their weight over an area. This decrease is not linear. Since air is compressible its density is greater at sea level than it is at the top of the atmosphere. At an altitude of 18,000 ft. the average pressure is 0.50 ATA, while the average pressure at 48,000 ft is 0.13 ATA.

Dalton's Law of Partial Pressure

Air is a mixture of gases (Table 1.3). Each gas in the mix exerts part of the total pressure. Dalton's Law of Partial Pressures states that the pressure exerted by any component gas is related to its fraction in the mix. For dry air 78.08% of the total pressure is exerted by nitrogen. To make calculations simpler it is assumed that air consists of 79% nitrogen and 21% oxygen. In decompression theory the major concern is how this nitrogen is absorbed and eliminated by the body throughout the dive.

Pressure Representations

There are different ways to represent the pressure a diver is exposed to. Any one of these representation can be converted to the others. Three representations used in this book are:

- **Total Ambient Pressure** - The total, or absolute, pressure the diver is exposed to. It is the sum of the atmospheric pressure and the water pressure at the depth of the diver.
- **Ambient Nitrogen Pressure** - The total nitrogen pressure the diver is exposed to. It is the Total Ambient, or Absolute, Pressure times the fraction of nitrogen in the breathing gas (0.79 for air).
- **Gauge Pressure** - This is the additional pressure, over atmospheric, that the diver is exposed to. It is the Total Ambient, or Absolute, Pressure minus the surface pressure, or the pressure exerted by the water column (depth).

At a depth of 80 fswg (g=Gauge Pressure) the Total Ambient Pressure would be 80 fswg + 33 fswa atmospheric pressure or 113 fswa (a=Absolute Pressure). Of this Total Ambient Pressure 79% or 89.3 fswa is exerted by nitrogen. Therefore the Ambient Nitrogen Pressure of air at 80 fswg is 89.3 fswa. If a diver starts out saturated at sea level then there is a nitrogen pressure of 26.1 fswa (33 fswa x 0.79) in the diver's tissues. When the diver reaches 80 fswg a driving force of 63.2 fsw (89.3 fswa - 26.1 fswa N_2 pressure) between the nitrogen pressure in the lungs and the nitrogen pressure in the tissues causes nitrogen molecules to diffuse from the lungs, to the blood, to the tissues (Figure 1.1).

Gas Absorption and Elimination

> **SATURATION**
>
> Saturation exists when the nitrogen pressure in the tissues equals the nitrogen pressure in the breathing gas.

Some tissues absorb nitrogen rapidly while others take a longer period of time. The body is made up of a wide spectrum of tissues that absorb and eliminate nitrogen at different rates. Some of the "fast" tissues may already be saturated at the new nitrogen pressure before some of the "slow" tissues even start to show a nitrogen pressure increase. Figures 1.2 shows how a range of tissues can go from being saturated at 1 ATA (N_2 pressure = 0.79 ATA) and gradually reach a new state of saturation at 2 ATA (N_2 pressure = 1.58 ATA). These graphs also show how a "tissue" can be saturated even though the entire body has not reached a state of saturation at the new pressure.

Upon surfacing from a dive the excess nitrogen that has been absorbed by the tissues must be released in some manner. Hopefully, the nitrogen remains in solution and the molecules migrate from the tissues, to the blood, and back to the lungs by diffusion. However, whenever the nitrogen pressure in the tissues exceed the total ambient pressure supersaturation occurs and conditions exist for the nitrogen to come out of solution in the form of bubbles.

Figure 1.3 shows how a diver becomes supersaturated upon surfacing from a saturation dive to 2 ATA. When the diver reaches the surface the conditions exist for bubble formation since the nitrogen pressure (1.58 ATA) is greater than the ambient pressure (1 ATA).

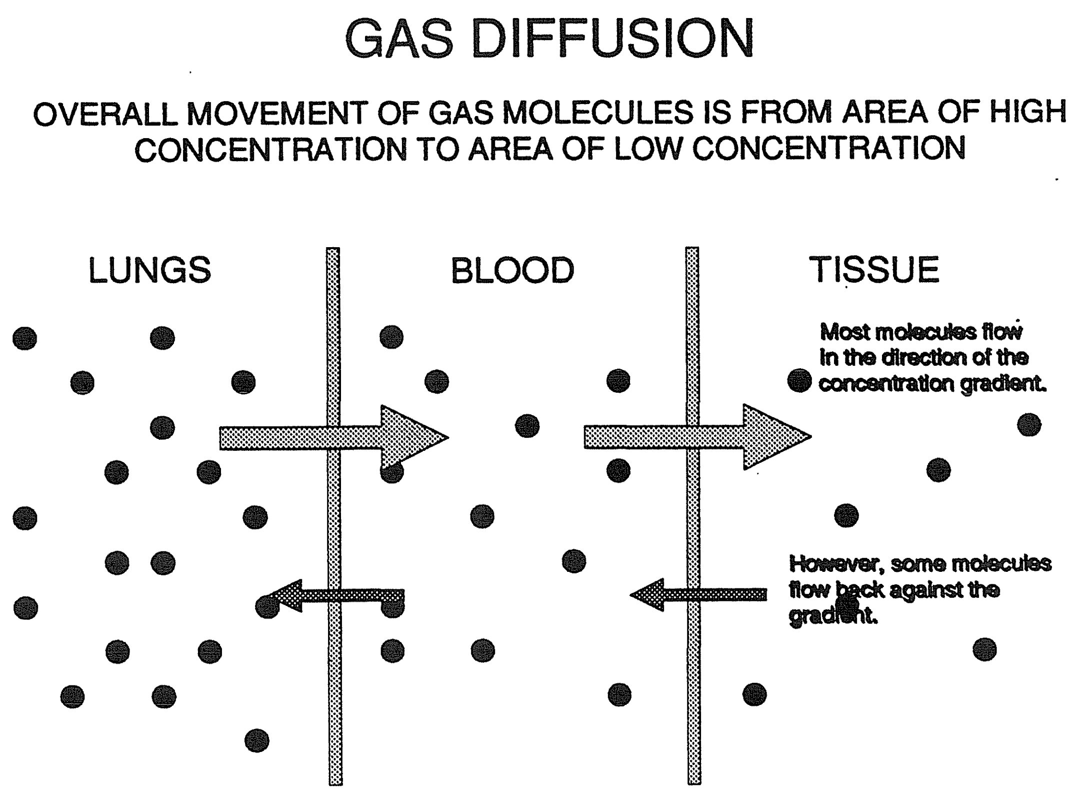

Figure 1.1. Gas Diffusion.

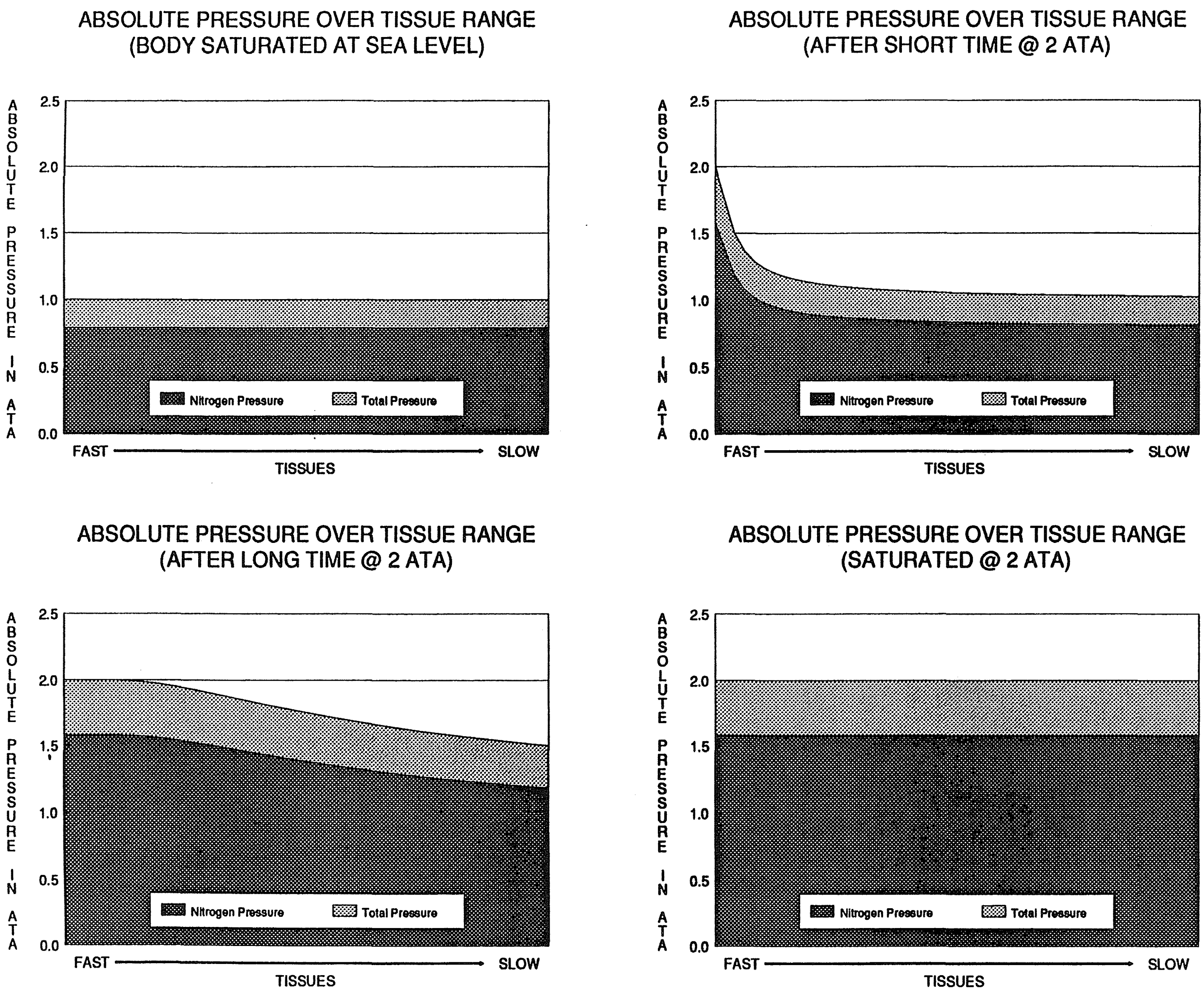

Figure 1.2. Tissue Pressure Build-up during an exposure to 2 ATA.

Based on this concept of supersaturation it is possible to calculate the maximum saturation depth a diver can be exposed to without becoming supersaturated upon surfacing. This would be the depth where the ambient N_2 pressure would equal 1 ATA (33 fswa). If the nitrogen pressure is 33 fswa then the total pressure is 41.8 fswa (33 fswa / 0.79), or a depth of 8.8 fswg (41.8 fswa - 33 fswa surface pressure). According to our definition of supersaturation, anytime a diver descends below 8.8 fswg there is a possibility of bubble formation upon ascent which could lead to DCS. Since divers routinely perform no-stop dives to depths greater than 9 fswg, without any apparent problems, there seems to be some level of supersaturation that the tissues in the body can withstand. Just how high a level of supersaturation can be withstood is still a topic of debate that has driven the development of many decompression techniques over the years.

> **SUPERSATURATION**
>
> Supersaturation exists when the nitrogen pressure in a tissue exceeds the total ambient pressure exerted on the body.

In a recent paper, Eckenhoff presents data which show bubble formation occurring in over 50% of subjects exposed to 12 fsw for 48 hours.[4] He also states that, *"...it suggests that bubbles should be detectable in at least some subjects after decompression from saturation at between 5 and 8 fswg."*

EARLY DECOMPRESSION RESEARCH/THEORY

Research into the theory of decompression can be traced back to 1670 when Robert Boyle first described DCS. While exposing animals to decreased pressures, he observed a bubble moving in the eye of a viper. The snake was, *"tortured furiously by the formation of bubbles in the blood*

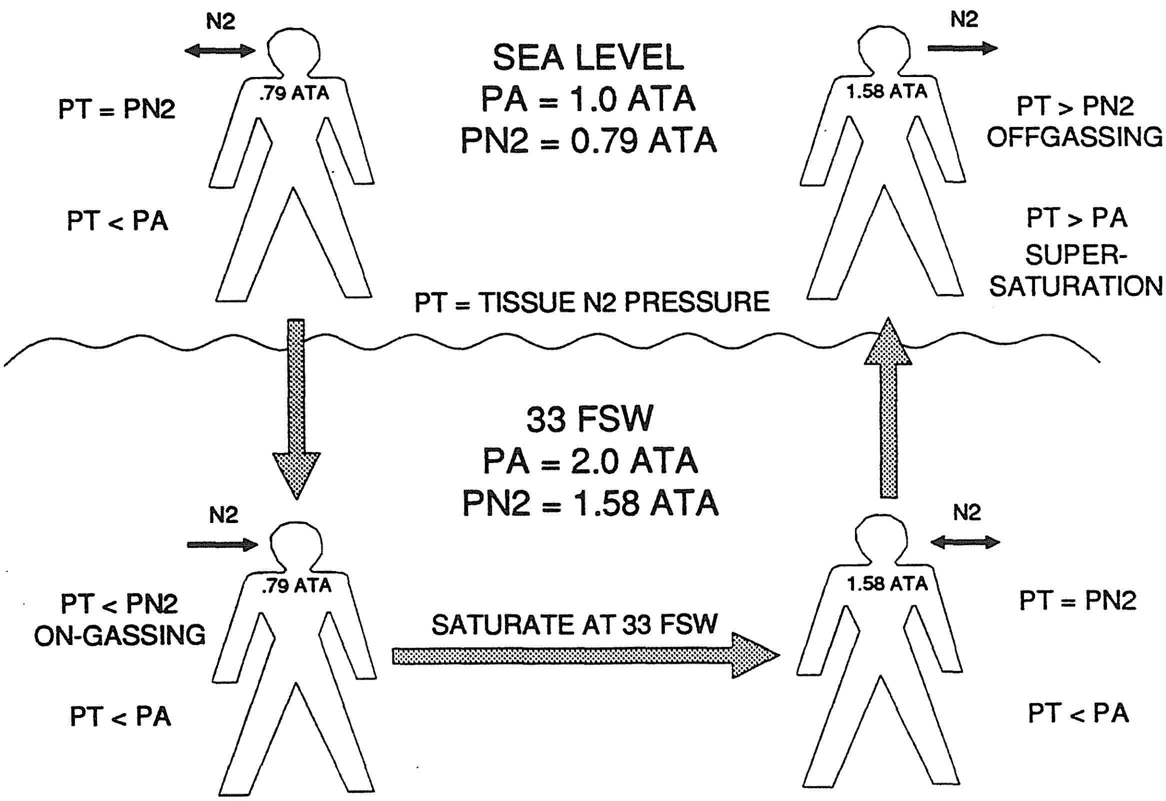

Figure 1.3. Pressure Dynamics of a 2 ATA Dive.

juyces [sic] and soft parts of the body."[5]

The description of DCS in man was first presented in 1841. The victims were coal miners who worked in mines that were pressurized to keep out water.[6]

As construction caissons and hardhat diving systems were developed in the 1800s the problem of DCS in man became more prominent. In 1857 Hoppe-Seyler repeated Boyle's experiments and suggested that cases of sudden death in compressed air workers were caused by the release of bubbles. To remedy this problem he recommended recompression.

Smith, in 1873, described "caisson disease" or "compressed air illness" as a disease which depends upon increased atmospheric pressure but always develops after reduction of the pressure. Five years later Paul Bert determined that DCS was the result of nitrogen gas bubbles which were released from tissues and blood during or following decompression. He also showed the advantages of breathing oxygen following the development of DCS and proposed its use in recompression therapy.

In the early 1900s there was controversy regarding the rate and manner of decompression of caisson workers and divers. In 1906 V. Schrotter suggested a uniform (linear) decompression of 20 minutes per atmosphere (or 1.65 fsw/min). Figure 1.4 shows Schrotter's linear decompression requirement for a dive to 100 fswg for 20 minutes. This dive, which many models and tables would consider a no-stop dive, would require a little over one hour of linear decompression. 1906 was also the same year that the English physiologist J.S. Haldane was commissioned by the British Admiralty to examine the problem of DCS and formulate a solution to this problem that plagued their divers.

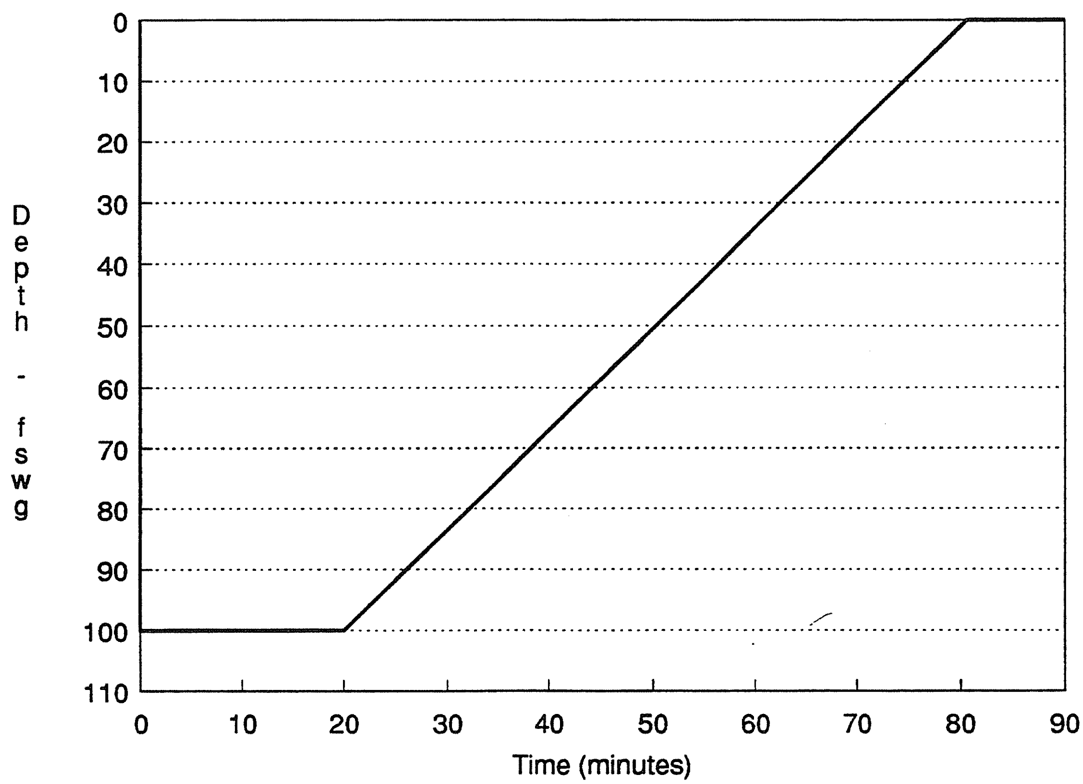

Figure 1.4. Linear Decompression from a 100 fsw / 20 minute dive.

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2
HALDANE'S THEORY AND TABLES

HALDANE'S THEORY

At the time Haldane was commissioned by the British Admiralty to develop a safe decompression technique, linear decompression was the prevailing method used. Haldane expressed concern that a slow linear decompression could result in additional nitrogen buildup during the initial stages of ascent. Haldane's concept was that a diver could ascend immediately to a depth where the level of supersaturation was "safe." This would produce a large pressure gradient for nitrogen off-gassing and eliminate the buildup of additional nitrogen at deeper depths associated with linear decompression. The diver would remain at this *decompression stop* until he could ascend another 10 fsw. This process would be repeated until it was "safe" for the diver to reach the surface. This type of *staged decompression* was a drastic departure from *linear decompression* techniques, which Haldane took issue with in his publications.[1,2]

> **CRITICAL SUPERSATURATION**
>
> The maximum nitrogen pressure that a tissue can tolerate at any given ambient pressure. Generally expressed in terms of a ratio of tissue nitrogen pressure (PN_2) and ambient pressure (P_a).
>
> $$\text{Critical Ratio} = PN_2 / P_a$$

Starting in 1906 Haldane, along with A.E. Boycott and C.C. Damant, worked with goats to determine this "safe" level of supersaturation, or what Haldane called **Critical Supersaturation.** According to his theory, if the tissue nitrogen pressure was below this level the nitrogen would diffuse harmlessly out of the body. However, if this level was exceeded then bubbles would form and the diver would develop DCS.

HALDANE'S TESTS

Haldane's tests were set up to determine this critical supersaturation ratio. Goats were exposed to various pressures for three hours in order to "saturate" them at the new pressure (Haldane theorized that man, being a larger animal, reached saturation after five hours, as opposed to the three hours, he theorized was, needed for goats). Following the exposure, the goats were rapidly decompressed to surface pressure and examined for signs of DCS.

What observations indicated to Haldane that his goats had developed DCS? The following are results of a dive evaluating linear decompression from a dive to 168 fsw for 2 hours (surfacing at 2:32 p.m.):

> *[Goat]XVIA came out with bad bends left hind and right fore-legs; could hardly walk and kept head twisted round to left; much better at 2:50. [Goat]XIXA urine at 2:34 full of froth; bends right fore-leg. [Goat]XA began bleating at 2:38 but showed nothing till 2:44 when he had complete foot-drop right fore-leg and bends left hind-leg; at 2:50 right fore-leg paralysed [sic], could not stand up, left fore-leg also week; urine at 2:50 a little froth. [Goat]XXVA cried out a bit, belly very*

tight, refuses to move, evidently far from well: died between 8 and 8:30 a.m. next day: a good many bubbles in right heart...

It was found that goats "saturated" at a pressure of 2.25 ATA (41 fswg) or less, would show no signs of DCS. Haldane also found that goats "saturated" at 6 ATA (165 fswg) and decompressed to 2.6 ATA (53 fswg), a 2.3:1 pressure reduction, showed no signs of DCS. He concluded that:

...bubbles of nitrogen are not liberated within the body unless the supersaturation corresponds to a decompression from a total pressure of more than 2-1/4 atmospheres. ...Hence, it seemed to me probable that it would be just as safe to diminish the pressure rapidly from 4 atmospheres to 2, or 6 atmospheres to 3, as from 2 atmospheres to 1.

This established the concept of the 2:1 pressure reduction ratio. This ratio is more commonly presented as unlimited dive time allowance for depths less than 33 fsw, which has been propagated for decades in the recreational diving community.

HALDANE'S MODEL

Based on his studies Haldane formulated his decompression model, which included the following assumptions:

- The time in which an animal or man exposed to compressed air becomes saturated with nitrogen varied in different parts of the body from a few minutes to several hours. The progress of saturation follows in general the line of a logarithmic curve and is approximately complete in about five hours in man and in a goat in about three hours.
- The curve of desaturation after decompression is the same as that of saturation provided no bubbles have formed.
- Those parts of the body which saturate and desaturate slowly are of great importance in reference to the production of symptoms after decompression.
- No symptoms are produced by rapid decompression from an excess pressure of 15 pounds [1 ATA or 33 fsw], or a little more, to atmospheric pressure, i.e. from two atmospheres absolute to one. In the same way it is safe to quickly reduce the absolute pressure to one-half in any part of the pressure scale up to at least about seven atmospheres: e.g. from six atmospheres (75 pounds [psi] in excess) to three (30 pounds), or from four atmospheres to two.
- Decompression is not safe if the pressure of nitrogen inside the body becomes much more than twice that of the atmospheric nitrogen.
- In decompressing men or animals from high pressures, the first part should consist of rapidly halving the absolute pressure: subsequently the rate of decompression must become slower and slower, so that the nitrogen pressure in no part of the body ever becomes more than about twice that of air. A safe rate of decompression can be calculated with considerable accuracy.

Haldane designated the "different parts of the body" as tissue groups with different "half-times," or the time it would take the tissue group to reach one-half of the pressure difference between the initial tissue nitrogen pressure and the ambient nitrogen pressure (Figure 2.1). Mathematically, as the exponential curve shows, a tissue group in this half-time model would never reach a point of equilibrium with the ambient nitrogen pressure. Saturation could only occur following an infinite time. Haldane stated that tissue pressures are close enough to the ambient pressure after four half-times (94% saturated) to be considered saturated. Most models today consider a tissue saturated after six half-times (98.5% saturated).

Haldane selected five tissue groups, or compartments, for his model. These tissues had half-times of 5, 10, 20, 40, and 75 minutes. The 75-minute tissue was selected because it would be "saturated" after five hours, which he considered to be the time it would take to equilibrate a man to a new ambient pressure. The model that Haldane used to create his tables can be reduced to two assumptions:

- The body can be represented by five tissue groups (compartments) with half-times of 5, 10, 20, 40, and 75 minutes.
- Each of the tissue groups can withstand a pressure reduction ratio of 2:1.

HALDANE'S TABLES

Using the above model Haldane computed a set of decompression tables (Figure 2.3). In general, the technique involved computing the pressure buildup in the five compartments during the dive and then stepping the diver back to the surface without producing a total pressure ratio in excess of 2:1 in any compartment. Figure 2.2 shows the calculated decompression schedule for a dive to 100 fswg for 20 minutes along with the pressure buildup in the five compartments. The steps used to calculate this schedule are as follows:

1. The tissue pressures for the five compartments are computed for the exposure to 100 fswg (133 fswa) for 20 minutes.
2. The highest pressure produced, 126.8 fswa, is in the 5-minute compartment and corresponds to the compartment being saturated at a depth of 93.8 fswg (126.8 - 33).
3. Using the 2:1 ratio the 5-minute compartment could withstand a pressure drop to 63.4 fswa (126.8 / 2). This corresponds to a depth of 30.4 fswg (63.4 - 33). Since

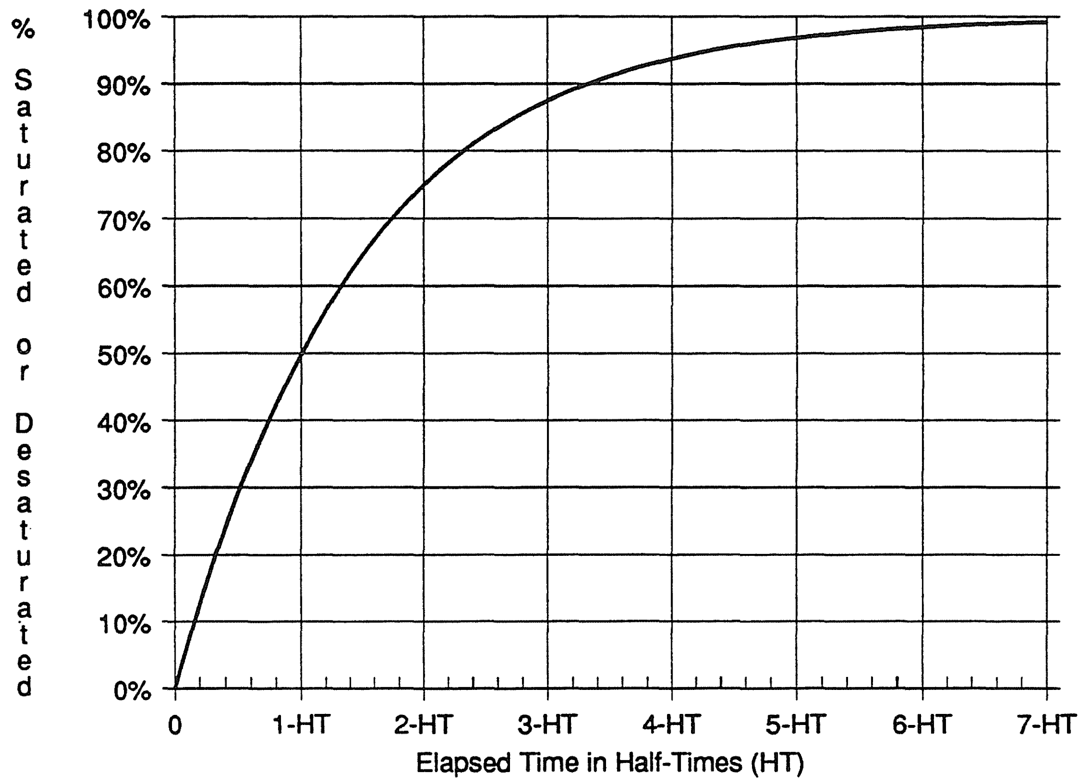

Figure 2.1. Definition of Half-Time.

decompression stops are in 10 fsw increments the first stop in the decompression will be at 40 fswg.

4. The diver then spends enough time at 40 fswg to allow the compartment pressures to drop to a level which will allow an ascent to 30 fswg. In order to ascend to 30 fswg all compartment pressures must be at, or below, 126 fswa (30 + 33 = 63, 63 x 2 = 126). After 1 minute all compartments can be brought to up to 30 fswg.
5. Before ascending from 30 fswg to 20 fswg all five compartment pressures must fall below 106 fswa. Once again the 5-minute compartment controls the stop time. It drops below 106 fswa after 3 minutes at 30 fsw.
6. During the 20 fswg stop the 10-minute compartment takes control. After 3 minutes the 5-minute compartment says it is safe to ascend to 10 fswg. However, the 10-minute compartment needs 4 minutes to reach a pressure of 86 fswa which is considered safe at 10 fswg (10 + 33 = 43, 43 x 2 = 86).
7. Time required at the final stop of 10 fswg is controlled by the 20-minute compartment which requires 10 minutes to drop to a pressure of 66 fswa or less. Following this stop the diver can surface and none of the compartments will exceed Haldane's 2:1 critical ratio.

This example shows that the staged decompression technique allowed the diver to surface with only 18 minutes of decompression, as opposed to the one hour linear decompression requirement. It also shows how control of the decompression is "passed" from fast to slower compartments. The 5-minute compartment determined the depth and time of the first stop, but when the final stop was reached, it was the 20-minute compartment which had the final control.

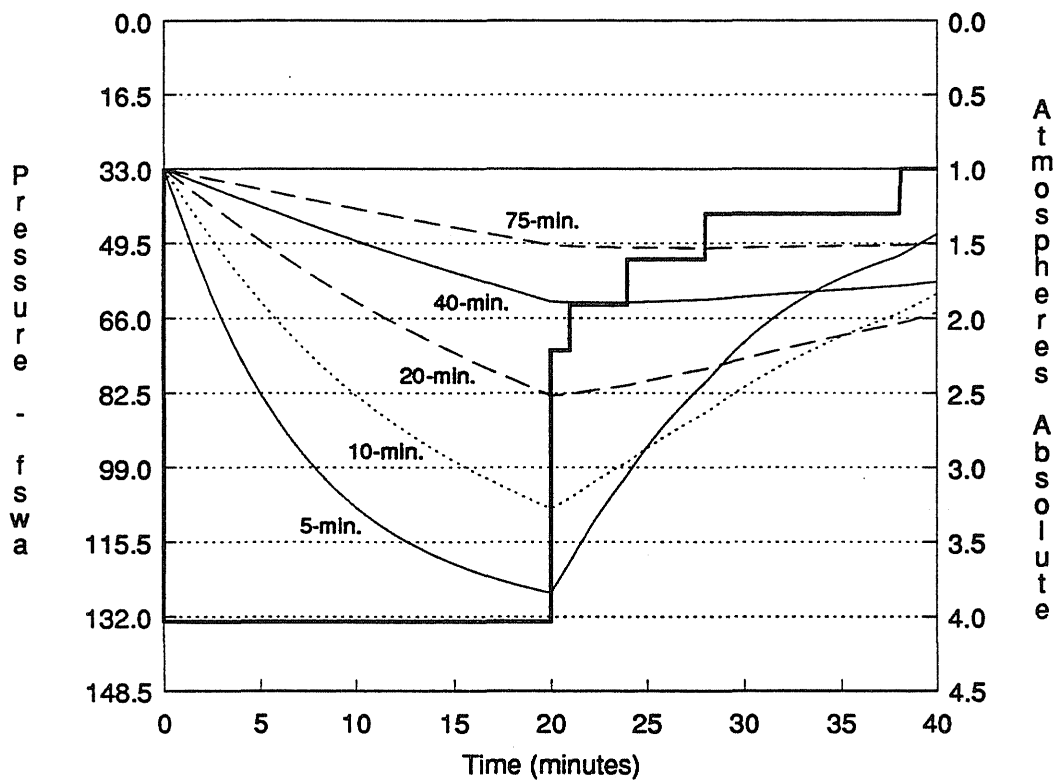

Figure 2.2. Haldane Decompression Schedule for 100 fsw / 20 minute dive.

STOPPAGES DURING THE ASCENT OF A DIVER AFTER ORDINARY LIMITS OF TIME FROM SURFACE

Depth: Feet	Depth: Fathoms	Pressure — Pounds per square inch	Time from surface to beginning of ascent	Approximate time to first stop	Stoppages in minutes at different depths[1]: 60 ft.	50 ft.	40 ft.	30 ft.	20 ft.	10 ft.	Total time for ascent in mins.
0–36	0–6	0–16	No limit	1	—	—	—	—	—	—	0–1
36–42	6–7	16–18½	Over 3 hours	1	—	—	—	—	—	5	6
42–48	7–8	18½–21	Up to 1 hour	—	—	—	—	—	—	—	1½
			1–3 hours	1½	—	—	—	—	—	5	6½
			Over 3 hours	1½	—	—	—	—	—	10	11½
48–54	8–9	21–24	Up to ½ hour	—	—	—	—	—	—	—	2
			½–1½ hours	2	—	—	—	—	—	5	7
			1½–3 hours	2	—	—	—	—	—	10	12
			Over 3 hours	2	—	—	—	—	—	20	22
54–60	9–10	24–26½	Up to 20 mins.	—	—	—	—	—	—	—	2
			20–45 mins.	2	—	—	—	—	—	5	7
			¾–1½ hours	2	—	—	—	—	—	10	12
			1½–3 hours	2	—	—	—	—	5	15	22
			Over 3 hours	2	—	—	—	—	10	20	32
60–66	10–11	26½–29½	Up to ¼ hour	2	—	—	—	—	—	—	2
			¼–½ hour	2	—	—	—	—	—	5	7
			½–1 hour	2	—	—	—	—	3	10	15
			1–2 hours	2	—	—	—	—	5	15	22
			2–3 hours	2	—	—	—	—	10	20	32
66–72	11–12	29½–32	Up to ¼ hour	2	—	—	—	—	—	2	4
			¼–½ hour	2	—	—	—	—	3	5	10
			½–1 hour	2	—	—	—	—	5	12	19
			1–2 hours	2	—	—	—	—	10	20	32
72–78	12–13	32–34½	Up to 20 mins.	2	—	—	—	—	—	5	7
			20–45 mins.	2	—	—	—	—	5	10	17
			¾–1½ hours	2	—	—	—	—	10	20	32
78–84	13–14	34½–37	Up to 20 mins.	2	—	—	—	—	—	5	7
			20–45 mins.	2	—	—	—	—	5	15	22
			¾–1¼ hours	2	—	—	—	—	10	20	32
84–90	14–15	37–40	Up to 10 mins.	2	—	—	—	—	—	3	5
			10–20 mins.	2	—	—	—	—	3	5	10
			20–40 mins.	2	—	—	—	—	5	15	22
			40–60 mins.	2	—	—	—	3	10	15	30
90–96	15–16	40–42½	Up to 10 mins.	3	—	—	—	—	—	3	6
			10–20 mins.	2	—	—	—	—	3	5	10
			20–35 mins.	2	—	—	—	—	5	15	22
			35–55 mins.	2	—	—	—	3	10	15	30
96–108	16–18	42½–48	Up to 15 mins.	3	—	—	—	—	3	5	11
			15–30 mins.	3	—	—	—	3	7	10	23
			30–40 mins.	3	—	—	—	5	10	15	33
108–120	18–20	48–53½	Up to 15 mins	3	—	—	—	2	3	7	15
			15–25 mins.	3	—	—	—	5	5	10	23
			25–35 mins.	3	—	—	—	5	10	15	33
120–132	20–22	53½–59	Up to 15 mins.	3	—	—	—	2	5	7	17
			15–30 mins.	3	—	—	—	5	10	15	33
132–144	22–24	59–64½	Up to 12 mins.	3	—	—	—	3	5	5	16
			12–25 mins.	3	—	—	2	5	10	12	32

Figure 2.3. Haldane's Decompression Tables.

It is interesting to note that in some cases Haldane allowed the ratio of 2.3:1 to occur on the final decompression step to the surface. This causes a slight discrepancy between schedules that are calculated using the 2:1 ratio and Haldane's published tables. This type of table "*tweaking*" is not at all uncommon in the development of decompression tables. Remember that in his assumptions Haldane states that, "*No symptoms are produced by rapid decompression from an excess pressure of 15 pounds, or a little more, to atmospheric pressure...*" In his model he took a conservative approach by making the ratio 2:1, but in the calculation of the tables he takes advantage of the "*little more*" that his tests showed could be withstood.

In July of 1906 chamber tests were performed using Lieutenant Damant and Mr. A.Y. Catto as subjects. The series of seven dives, which ran from July 25th to July 31st, included two days with repetitive dives and culminated with a dive to 180 fsw for a 'virtual' exposure of 34 minutes (44 minutes decent time and 12 minutes of bottom time) with required 51 minutes of decompression. No symptoms were observed except for some skin itches. From August 20th through September 3rd open water test dives were conducted off the H.M.S. Spanker. Once again Lieutenant Damant and Mr. Catto were the subjects making 20 staged decompression dives. Lieutenant Damant had previously never dived beyond 114 fsw and Mr. Catto had never been deeper than 144 fsw. During the test series both of the divers reached a depth of 210 fsw and were successfully decompressed from all of the dives.

The Haldane tables were adopted by the Royal Navy in 1908 and are considered to be the first true set of decompression tables. Their use helped reduce the incidence of DCS in hardhat divers and caisson workers. Haldane's concept of modeling the body as a group of theoretical compartments that can withstand certain levels of critical supersaturation is still in widespread use today in various models, tables, and dive computers.

REFERENCES

1. Boycott, A., Damant, G., and Haldane, J., "The Prevention of Compressed-Air Illness," in *Journal of Hygiene (Cambridge)*, vol. viii, no. 3, 342-443, 1908.
2. Haldane, J., *Respiration* (New Haven: Yale University Press, 1922).

3
U.S. NAVY DECOMPRESSION TABLES

EARLY TABLES

The first U.S. Navy tables were produced by the Bureau of Construction and Repair in 1915. Called the C & R tables, they were based on Haldane's model, included the use of oxygen during decompression, and allowed dives to depths of 300 fsw. Later that year they were successfully used in the salvage of the submarine F-4 at depths up to 306 fsw, well beyond today's accepted depth limitations for use of air. During this salvage 11 dives were made to depths between 270 and 306 fsw with 20 minutes bottom time and about 110 minutes of decompression. The only major decompression problem during the operation involved a diver who became fouled at a depth of 250 fsw and was stuck for three hours before being freed. A description of the incident by Assistant Surgeon French U.S.N. was presented by Haldane and shows how aggressive treatment and rapid recompression can mean the difference between life and death:[5]

> *When [the diver] was freed he came up beyond the proper stopping places, disregarding the telephoned orders. Possibly he was partly stupefied by the prolonged action of the high pressure of oxygen. At forty feet from the surface he collapsed. This was about 40 minutes after starting the ascent. He was then pulled up to surface, where he was still able to say a few words before becoming unconscious. His dress was quickly ripped off and he was hurried into the recompression chamber along with the two doctors and the other diver who had rescued him. By this time he was black in the face, his breathing had ceased, and no pulse could be felt at the wrist. Artificial respiration [1915 style] was at once applied, and at the same time the [chamber] pressure was run up to 75 lbs. [168 fsw] in 3 1/2 minutes, which ruptured both the eardrums of one of the doctors. As 75 lbs. pressure was reached the patient suddenly recovered and sat up, feeling all right again. He was then gradually decompressed to 20 lbs. [45 fsw] in about 1 1/2 hours, but at this point severe pain developed, so that the pressure had to be raised again. For the next five hours many attempts at decompression below 20 pounds had to be given up. At last he was very gradually decompressed in about 3 hours in spite of the pain. Soon after being taken from the chamber he was in a very precarious condition, with the pulse no longer palpable. In spite of haematuria [blood in urine], almost complete suppression of urine, extreme pain, and other threatening symptoms, he recovered gradually; and when it was possible to examine his lungs he was found to have double broncho-pneumonia, the result, presumably, of the very high oxygen pressure... In a few weeks he had completely recovered [by 1915 standards].*

In subsequent years information from the Navy's submarine escape training program suggested the possibility of changing Haldane's model to make decompression more efficient. Research on methods of submarine escape were conducted, and submariners were trained in various escape techniques, at submarine escape towers. These towers were about 100 feet tall and filled with water. The submariner qould enter an air lock at the bottom of the tower, don a submarine escape hood, allow the lock to pressurize, exit the lock, and then ascend directly to the surface. During

SUPERSATURATION RATIO REPRESENTATIONS

As indicated in the previous chapter, the super-saturation ratio is generally expressed in terms of a ratio of tissue nitrogen pressure (PN_2) to ambient pressure (P_a). This has not always been the case. Much of the early literature presents the ratio as total pressure (P_t) to P_a. Therefore Haldane's supersaturation ratio can either be expressed as 2:1 (P_t / P_a) or 1.58:1 (PN_2 / P_a). To be consistent PN_2 / P_a values will be used herein unless otherwise indicated.

training, cases of air embolism occurred, but DCS was not a problem. However, when nitrogen pressures in the five compartments of Haldane's model were calculated, based on pressure exposure in the air lock before ascending, the fast compartments had pressures well in excess of Haldane's supersaturation ratio.

In the 1930s, Hawkins, Shilling, and Hansen conducted 2,143 experimental dives over a period of 3 years to determine allowable supersaturation ratios for Haldane's half-time compartments.[6] The dives "titrated" the occurrence of DCS for depths of 100, 150, 167, 185, and 200 fsw. By calculating the nitrogen loading in the five Haldanian compartments, for the exposures prior to the first occurrence of DCS, they derived higher allowable supersaturation ratios (Table 3.1). Since the ratios for the 5- and 10-minute compartments were so high they concluded that, "*...it is evident that the saturation of the 5- and the 10-minute tissues has no relationship to the production of caisson disease.*"

Based on their conclusions a set of tables was calculated which did not consider the 5- and 10-minute compartments. The supersaturation ratio for the 20-minute compartment was set at 2.21:1 and the 40- and 75-minute ratios remained at 1.58:1, even though they stated that a 2.37:1 ratio would be safe for the 20-minute compartment and a 1.82:1 would be acceptable, from the last decompression stop, for the 40- and 75-minute compartments. The rational for allowing the 1.82:1 ratio was that Haldane permitted surfacing ratios of that degree in some of his decompression schedules.

Later Yarborough used these three compartments (20-, 40-, and 75-minutes), with modified supersaturation ratios (Table 3.1), to compute a set of tables. Yarborough's reduction of the ratios was based on dives which involved exercise.[4] These tables (Appendix A) were released to the U.S. Navy in 1937 and operationally had a DCS incidence of 1.1% in the following years.

These 1937 tables had no real provision for repetitive diving since operations consisted of surface supplied hard-hat diving. A diver could work until the job was done, the table limit was reached, or the diver could not continue, therefore repetitive diving was not much of a consideration. However, if a repetitive dive was performed, the maximum depth of both dives would determine the depth entry and the sum of the two bottom times would give the time entry for the table. No account was made for off-gassing during the surface interval. The ascent rate for these tables was set at 25 fsw/min. (fpm) because it was an reasonable rate for the tenders to

TABLE 3.1
MODIFIED SUPERSATURATION RATIOS

COMPARTMENT HALF-TIMES	HAWKINS, SHILLING & HANSEN	YARBOROUGH
5 min.	3.00 - 4.35:1	----
10 min.	2.92 - 3.71:1	----
20 min.	2.37 - 3.00:1	1.94 - 2.21:1
40 min.	1.74 - 2.21:1	1.38 - 1.58:1
75 min.	1.34 - 1.66:1	1.38 - 1.58:1

TABLE 3.2
EVALUATION OF 1937 U.S. NAVY DECOMPRESSION SCHEDULES

DEPTH	BOTTOM TIME	NUMBER SUBJECTS	# SUBJECTS WITH DCS	DCS OCCURRENCE
100 fsw	85 min.	18	9	50.0%
130 fsw	55 min.	22	4	18.2%
150 fsw	38 min.	21	4	19.0%
170 fsw	30 min.	20	3	15.0%

pull hard-hat divers up at.

CURRENT TABLES

Background:

The current U.S. Navy Tables were developed in the 1950s to accommodate the limited air supply of the newly developed technology of scuba and to improve upon the 1937 tables.

In the early 1950s Van der Aue, while developing procedures for surface decompression and oxygen use, showed that there were problems with some of the 1937 table's long duration dive schedules. Table 3.2 shows some of his test results. His analysis indicated that in some cases the 5- and 10-minute compartments would control decompression, even when the high supersaturation ratios calculated by Hawkens, et. al. were used. In addition to reintroducing the faster compartments into the model, Van der Aue added a slower compartment with a half-time of 120-minutes to take care of problems associated with long duration dives.

Another consequence of these studies was the conclusion that the critical supersaturation ratio was depth dependent. In other words, the critical supersaturation ratio for a compartment was less at 30 fsw than it was at the surface. Analysis of 609 dives by DesGranges, Dwyer, and Workman in 1956 determined "safe" supersaturation ratios for the six compartments at various depths. For example, the 40-minute compartment could withstand supersaturation ratios of 1.90:1 at sea level, 1.55:1 at 40 fsw, and 1.52:1 at 80 fsw.

U.S. Navy Model (1956):

In 1956 the decompression model to be used in the calculation of the current U.S. Navy Decompression Tables was developed.[1,2,3] The new model used information gathered from the previous studies and operational needs. The model is a modified Haldanian model that includes the following basic assumptions:

- The body can be approximated by six compartments that absorb and eliminate nitrogen in an exponential manner.
- Each compartment has a different half-time which is the same for on-gassing as it is for off-gassing.
- The compartment half-times are; 5-, 10-, 20-, 40-, 80, and 120- minutes.
- Each compartment can withstand a certain level of nitrogen supersaturation (PN_2:P_a). This ratio decreases as ambient pressure increases.

This model assumes that a compartment is saturated, or desaturated, following an exposure time of six half-times, or when it is 98.4% saturated. The slowest, 120-minute, compartment is considered saturated, or desaturated, in 12 hours.

The basic formula used in the calculation of compartment nitrogen pressures in the U.S. Navy model (as well as other Haldanian models) is the simple exponential function:

$$P_t = P_i + (P_a - P_i) \times (1 - e^{(\ln(.5)t / T_{1/2})})$$

or,

$$P_t = P_a + (P_i - P_a) \times 0.5^{(t / T_{1/2})}$$

Where:

P_t = Final Nitrogen Pressure in Compartment
P_i = Initial Nitrogen Pressure in Compartment
P_a = Ambient Nitrogen Pressure
t = Time that Compartment is Exposed to P_a
$T_{1/2}$ = Half-Time of the Compartment

SATURATION TIME VS. HALF-TIME

There is an easy way to figure out how long it will take a compartment, with a specific half-time, to saturate or desaturate, based on the six half-time assumption. If the half-time is presented in minutes, just divide it by 10 and consider the result to be in hours. For example, a 40-minute compartment would saturate in 4 hours and the 5-minute compartment in 0.5 hours, or 30 minutes.

M-Values:

In order to handle the concept of decreasing supersaturation ratios in the model as depth increases the "M-value" system was developed. All this system does is convert the allowable supersaturation ratios to allowable absolute nitrogen pressures (presented in fswa). The M-value for a specific depth can be calculated using the following formula:

$$\text{M-Value} = M_o + (\Delta M \times \text{Depth})$$

M_o is the M-value that corresponds to the supersaturation ratio permitted at sea level. To obtain the critical surfacing supersaturation ratio associated with a specific M_o value simply divide the M_o value by 33 fswa (sea level pressure). For example, since the M_o value for the 5-minute compartment is 104 fswa the critical supersaturation ratio is 104 fswa/ 33 fswa, or 3.15:1. The change in the M value per foot of sea water is referred to as ΔM (Delta M). The M_o and ΔM values for the six tissue groups are listed in Table 3.3 with the corresponding critical supersaturation ratios for surfacing.

In addition, the "No-Decompression Depth" limit is shown for each compartment. This is the depth where the inspired nitrogen pressure in air is equal to the M_o value. In the case of the 5-minute compartment the M_o value is 104 fswa N_2. Since the nitrogen percent in air is 79%, an inspired nitrogen pressure of 104 fswa exists when the total ambient pressure is 132 fswa (104

TABLE 3.3
U.S. NAVY M_o, ΔM VALUES, AND CRITICAL SUPERSATURATION RATIOS

HALF-TIME	SUPERSATURATION RATIO AT SURFACE	M_o	ΔM	NO-D DEPTH
5 min.	3.15:1	104 fswa N_2	2.27	99 fsw
10 min.	2.67:1	88 fswa N_2	2.00	78 fsw
20 min.	2.18:1	72 fswa N_2	1.71	58 fsw
40 min.	1.76:1	58 fswa N_2	1.40	40 fsw
80 min.	1.58:1	52 fswa N_2	1.29	33 fsw
120 min.	1.55:1	51 fswa N_2	1.27	31 fsw

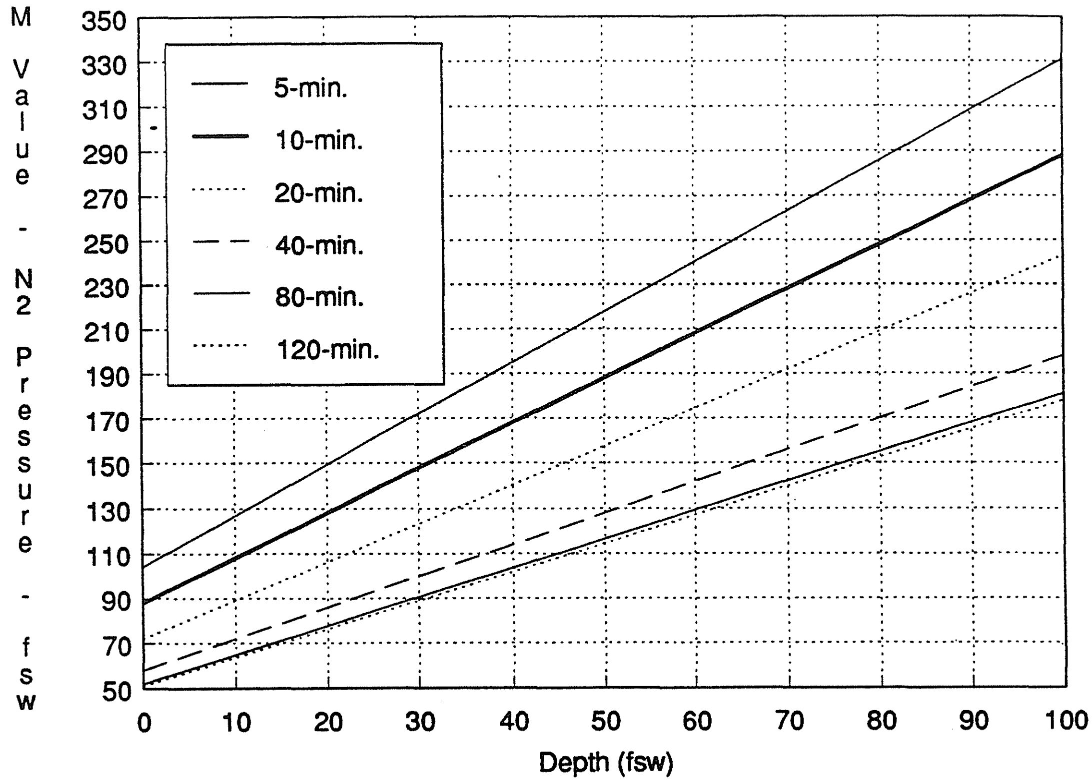

Figure 3.1. U.S. Navy M-Values vs. Depth.

fswa / 0.79). Since this is 132 fsw **absolute** the depth which exerts this pressure is 99 fsw (132 fswa - 33 fswa surface pressure). This indicates, according to the model, that the 5-minute compartment could saturate at 99 fsw or shallower and not require any decompression to return directly to the surface.

Although the M-values for the six compartments increase as depth increases (Figure 3.1) the critical supersaturation ratios decrease as depth increases (Figure 3.2).

No-Decompression (No-Stop) U.S. Navy Limits:

The no-decompression limits for the tables were determined using the six compartment half-times and their respective M_0 values. To calculate no-decompression limits the compartments are initialized at surface pressure and then "exposed" to the depth in question. A "race" begins in which the first compartment to reach its M_0 value controls the no-decompression limit for that depth. If the depth in question is less than the "No-Decompression Depth" for a compartment, then the compartment need not be considered in the race since it will never reach its M_0 value. For example, at depths shallower than 78 fsw there is no need to consider the 5- and 10-minute compartments in the race since the 10-minute compartment can only exceed its M_0 value at depths greater than 78 fsw and the 5-minute compartment requires a depth greater than 99 fsw.

Calculation of the 60 fsw No-Decompression Limit

One way to calculate no-decompression times is graphically. Using the values in Table 3.3, and knowledge of half-time curves, no-decompression limits can be approximated from curves representing the response of the compartments to the depth in question. For this exercise, Figure 3.3 is a blank graph on which you can plot curves which will determine the U.S. Navy no-decompression limit for 60 fsw.

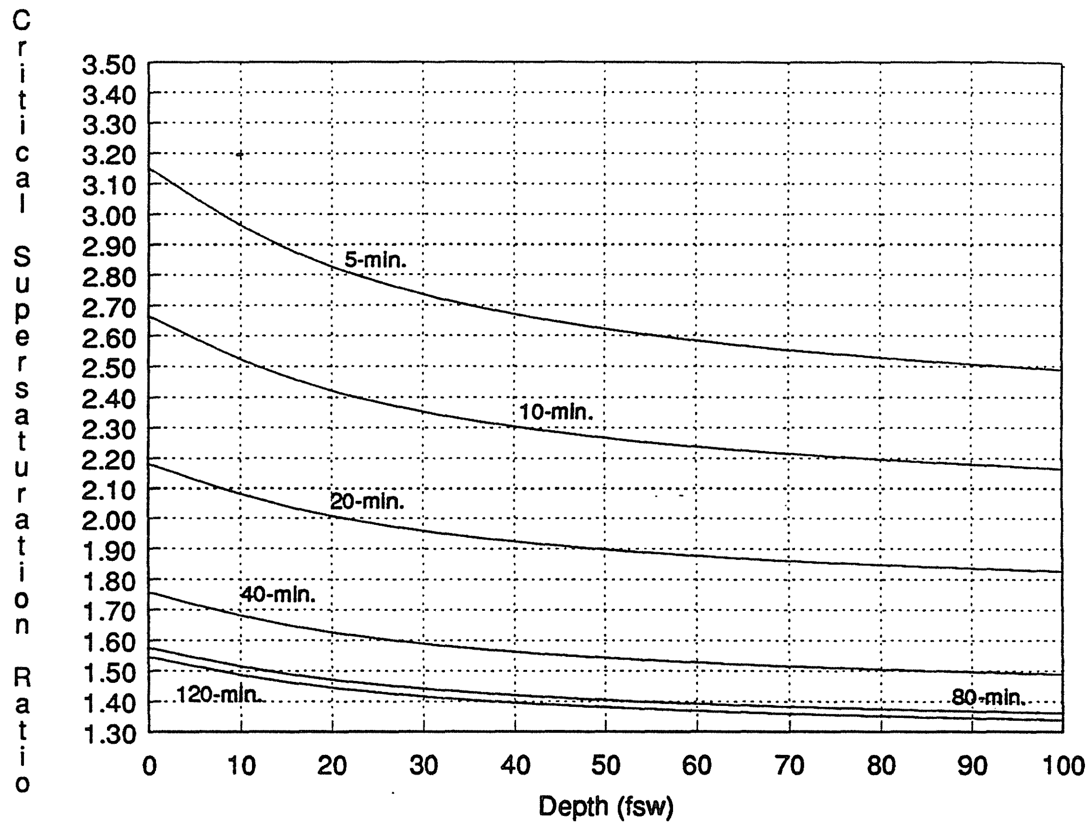

Figure 3.2. U.S. Navy Critical Supersaturation Ratios vs. Depth.

The pressure in this exercise is expressed in equivalent depth. This means that all the compartments start saturated at sea level, or an equivalent depth of 0 fsw. If the compartments were allowed to saturate at 60 fsw then their equivalent depth pressure would also be 60 fsw. The limits which the compartments are "racing" to must also be presented in equivalent depth units, not M_o value pressures. These values are just the "No-D Depth" values presented in Table 3.3 (eg. the **equivalent depth limit** for the 40-minute compartment is 40 fsw, not 58 fswa).

Since the depth under consideration is 60 fsw there is no need to include the 5- and 10-minute compartments in the "race," since they will never be able to reach their M_o values at 60 fsw. In Figure 3.3 there are lines drawn which show the limits for the 20-, 40-, and 80-minute compartments at equivalent depths of 58, 40, and 33 fsw respectively. The time at which the curve of a compartment crosses its limit line represents the no-decompression limit for that compartment. The following steps describe how to calculate the points to plot on the graph which will determine the curves:

1. Since all the compartments are starting at sea level pressure, plot a point at the origin of the graph (0,0) where depth=0 and time=0.
2. Start with the 20-minute compartment. After 20 minutes, or one half-time, its pressure will be half way between its starting pressure of 0 fsw and the final pressure of 60 fsw. This puts the pressure at 30 fsw. Plot a point where time=20 and depth=30 (20,30).
3. At 40 minutes, after another half-time of 20 minutes, the pressure will be 75% of the way to being saturated at 60 fsw or half way between where it was at 20 minutes and its final pressure. The pressure now is at 45 fsw. Plot the point (40,45).
4. After 60 minutes the pressure has reached half way between 45 and 60 fsw, which is 52.5 fsw (60-45=15, 15/2=7.5, 45+7.5=52.5). Plot a point at (60,52.5). Twenty

minutes later (80 minutes) the pressure is at 56.25 fsw. At 100 minutes it has reached 58.13 fsw and has finally crossed its limit line at 58 fsw.

5. Since the 120-minute compartment will not have reached its limit of 31 fsw after 100 minutes (why?), it does not need to be considered further in the calculations.
6. Draw a smooth line through the points that were plotted (so that it looks like the half-time curve in Figure 2.1). Then draw a line straight down from the point where the curve crosses the 20-minute limit line. This will give the no-decompression limit for the 20-minute compartment at a depth of 60 fsw which should be a little less than 100 minutes.
7. Repeat the previous steps for the 40-minute compartment. The difference will be that it will reach a pressure of 30 fsw after 40 minutes, and a pressure of 45 fsw after 80 minutes. Plot all four half-time points that will fit on the graph and then draw a smooth curve through them. Once again draw a line down from where the 40-minute curve crosses its limit line to get the no-decompression limit for the 40-minute compartment (approximately 60 - 65 minutes).
8. Do the same for the 80-minute compartment to determine its no-decompression limit for 60 fsw (about 90 minutes). By now it is evident that the 40-minute compartment produces the shortest no-decompression time and will control the no-decompression limit for 60 fsw.

Based on this technique, the no-decompression limit for 60 fsw has been calculated to be approximately 65 minutes (64.5 minutes by exact calculation). Using the U.S. Navy's "Woolworth Factor," which rounds a result down to the nearest 5 or 10, the no-decompression limit for 60 fsw becomes 60 minutes. A computer generated graph of the curves for this determination is shown in Appendix B.

Figure 3.4 shows another representation of this "race." It shows all of the compartments of the U.S. Navy model and their pressures at various times during the exposure. Notice how the 5- and 10-minute compartments reach the 60 fsw level and stay there since they have become saturated.

Figure 3.4 also shows that even though the 20-minute compartment was faster in building up pressure it had further to go, giving the 40-minute compartment time to reach its limit. In addition the 80-minute compartment had a shorter distance to travel, but it wasn't fast enough to reach its limit before the 40-minute compartment did.

In general, no-decompression limits for shallower depths are controlled by slower compartments while those at deeper depths are controlled by faster compartments. Other than by doing the calculations it is sometimes difficult to guess which compartment will actually control the limit for a specific depth.

Calculation of the 120 fsw No-Decompression (No-Stop) Limit

Following the same procedure, the no-decompression limit for 120 fsw can be calculated. Based on the values from Table 3.3, all of the compartments can reach their M_o values at 120 fsw. Figure 3.5 presents the same type of information as Figure 3.4 only in different pressure units. In Figure 3.5 pressure is presented as absolute nitrogen pressure. This means that all the compartments start out with a pressure of 26.07 fsw in them (33 fswa surface pressure x 0.79). Since absolute nitrogen pressures are considered, the limits for the compartments are their M_o values. The nitrogen pressure that the compartments are trying to equilibrate at 120.87 fswa ([120 fswg + 33 fswa] x 0.79). The graphs show that after 12.4 minutes the 5-minute compartment has reached its M_o value. However, the no-decompression limit for 120 fsw on the U.S. Navy tables is 15 minutes. Why is 15 minutes allowed when the model reaches its limit after 12.4 minutes?

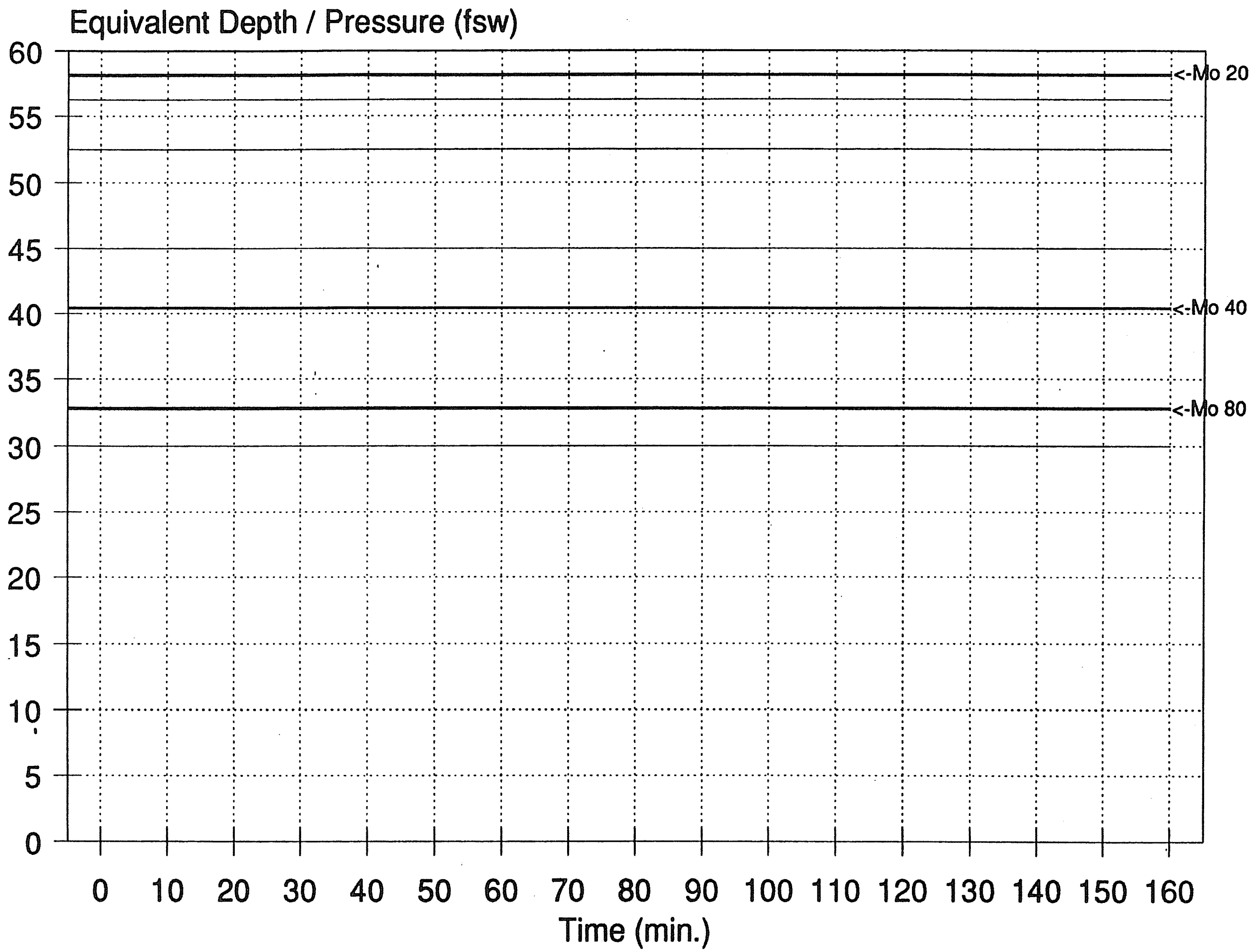

Figure 3.3. Graph for Determination of 60 fsw No-Decompression Limit

If the compartments are kept at 120 fsw for 15 minutes the 5-minute compartment exceeds its M_o value and will require decompression before reaching the surface. This decompression is provided by ascending at a rate of 60 fpm. Upon reaching the surface the pressure in the 5-minute compartment has off-gassed enough nitrogen to be below its M_o value. This example shows that the ascent rate of 60 fpm was included in the calculation of the tables and that the term "no-decompression" is deceptive. If the ascent rate was faster than 60 fpm then the 5-minute compartment might not have decompressed enough by the time the surface was reached. The term "*no-stop*" is more representative in that it indicates that a direct ascent can be made to the surface, at a specific rate, without required staged decompression. Since off-gassing occurs during ascent from all dives it can even be argued that, ***there is no such thing as a no-decompression dive.***

60 fsw/min. Ascent Rate:

The decision to use an ascent rate of 60 fsw/min. in the calculation of the U.S. Navy tables came from a compromise between the two main U.S. Navy diving groups that existed in the 1950s. Ed Lanphier presented the following description of a meeting, to discuss the new U.S. Navy Diving Manual, in which the two sides reached a consensus:[7]

> *Decompression was definitely not the primary topic of discussion [at the meeting], but the main reason for having a new diving manual at that point was to put forth the new air decompression tables that Officer-in-Charge Maino des Granges and his merry band had been working on. In any case, the proposed rate of ascent in the new tables became a hot topic of discussion.*
>
> *CDR Doug Fane, representing his West-coast Underwater Demolition Team, was adamant in saying that his frogmen couldn't possibly observe anything as slow as 25 ft/min. What they wanted was more like 100 ft/min - or even faster. The hard-hat types insisted that nothing of the sort would be practical for hauling up divers in suit and helmet.*
>
> *Those involved in calculating the tables insisted that ascent was an important element in decompression and that two complete sets of schedules would have to be produced for different rates of ascent - and that doing so would be utterly impractical...*
>
> *In that setting, the two sides decided to compromise on 60 fsw/min. That had the merit of being one foot per second, and it seemed possible for a hard-hat diver to be hauled up that rapidly and for a scuba diver to come up that slowly. Anyhow, the group decided on 60 ft/min, and the calculations proceeded on that basis.*

This example illustrates that many of the decisions in the development of models and tables are based on operational considerations, not necessarily physiological information.

U.S. Navy Decompression Tables:

Using the M_o and ΔM values in Table 3.3, and an ascent rate of 60 fpm, the current U.S. Navy Standard Air Decompression Tables were calculated. The calculation procedure was basically the same as the one Haldane utilized in computing his tables. The only procedural difference was that instead of using critical supersaturation ratios the M-value system determined the depth of the first stop and when it was "safe" to ascend to the next stop. A major computational difference was in the utilization of an early UNIVAC computer to help with the decompression calculations.

To validate the calculated decompression schedules, Des Grange selected 88 profiles to test. If no DCS occurred following six dives on a particular schedule it was considered "safe." There were 564 man-exposures done during these tests, resulting in 27 cases of DCS. In a review of U.S. Navy table validation, Thalmann states:[10]

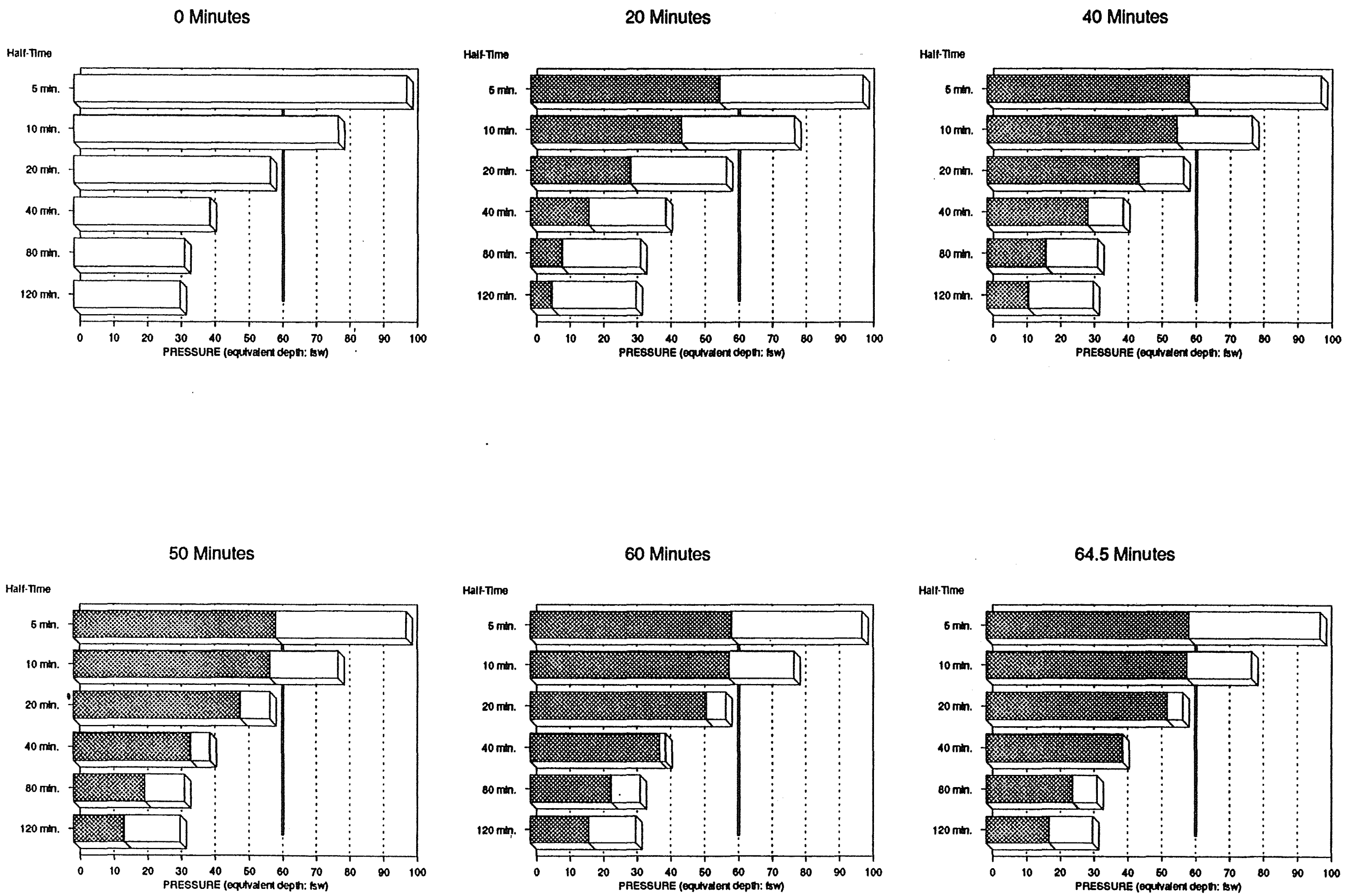

Figure 3.4. Determination of 60 fsw No-Decompression Limit

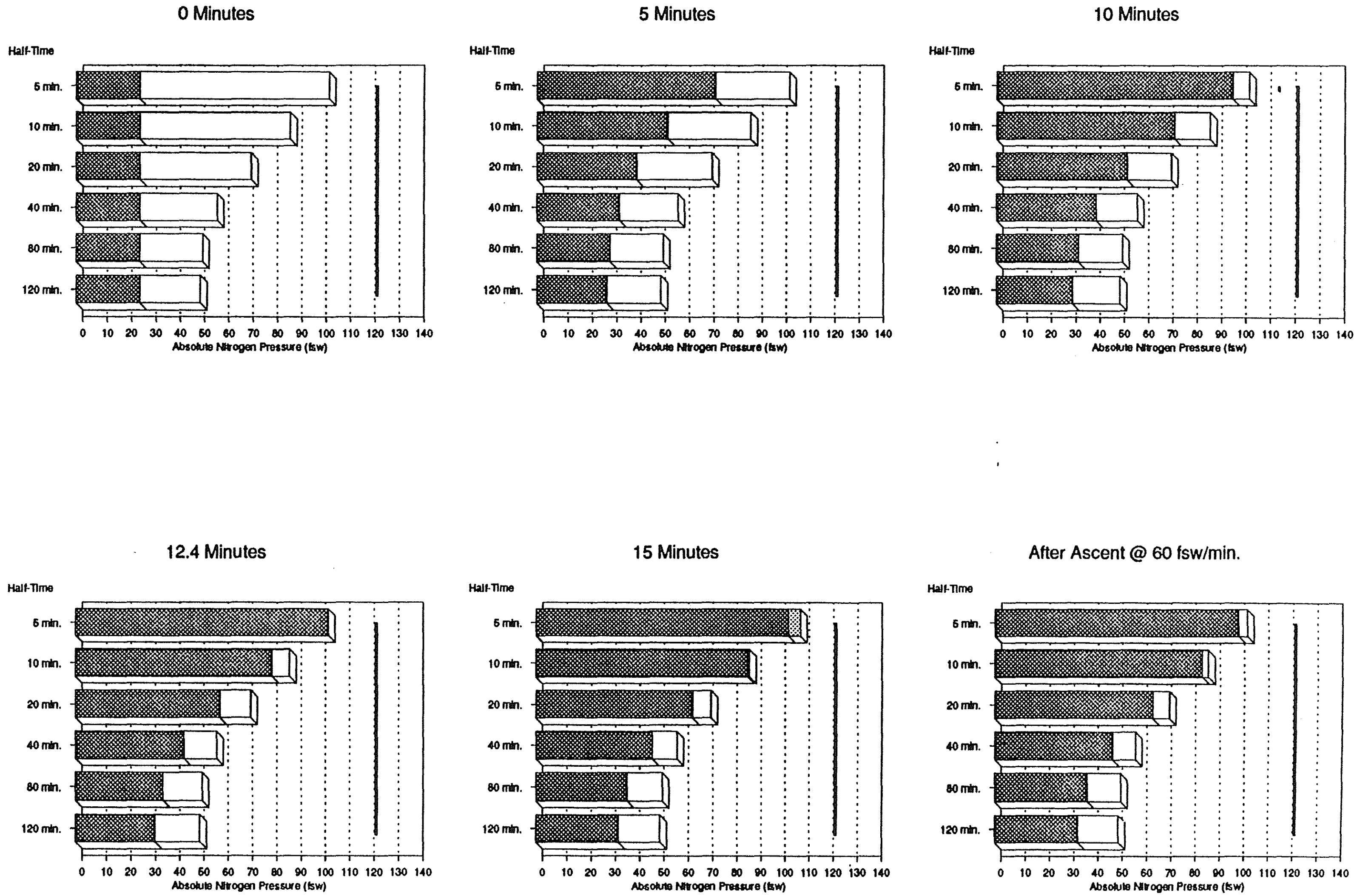

Figure 3.5. Determination of 120 fsw No-Stop Limit

In the end, however, empirical modifications were made to some schedules in order to reduce the incidence of DCS. Thus, the Current Standard Air Tables cannot all be calculated directly from the mathematical model initially used to program the UNIVAC.

Repetitive Diving Tables:

In addition to the standard decompression tables, it was necessary to create a set of tables that would allow divers to perform repetitive dives. Ideally, for the tables to track the entire model, a system needed to be developed that kept track of the nitrogen pressure in all six compartments. Divers could then compute the levels of remaining (residual) nitrogen in the compartments following a dive and the subsequent surface interval. These residual nitrogen levels would then affect repetitive dive times. The idea initially explored was to compute repetitive dive tables for all six compartments. However, running through six sets of tables was considered to be far too complex for normal diving operations. A simpler technique needed to be devised that would be easy to use in field operations yet would keep the divers within the limits of the model.

It was decided that a single set of repetitive tables would be calculated, using one of the six compartments to control surface off-gassing. The compartment selected was the 120-minute compartment, since it retained nitrogen for the longest period of time. The technique also had to prevent any of the other five compartments from controlling a repetitive dive. Calculations were made to determine how long of a surface interval was required for the other five compartments to off-gas to levels where the 120-minute compartment would have a controlling effect on a repetitive dive. The longest time generated in these calculations was 9.7 minutes, for the 40-minute compartment to pass control to the 120-minute compartment. For this reason the Surface Interval Table cannot be entered unless the surface interval is greater than 10 minutes. Any repetitive dive done within 10 minutes of surfacing is considered part of the original dive.

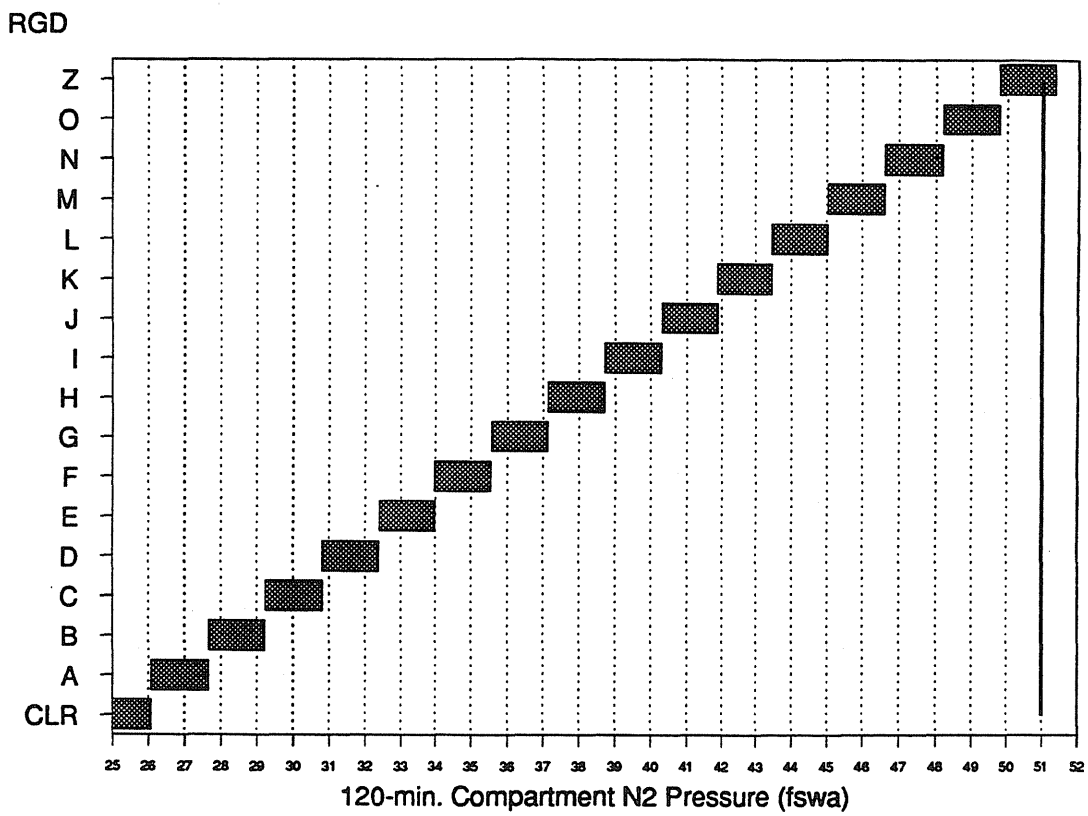

Figure 3.6. Definition of U.S. Navy Repetitive Group Designators

The solution developed for computing repetitive dives utilized a Repetitive Group Designation system. The U.S. Navy Repetitive Group Designators "A" to "O" and "Z" just represent increasing levels of residual nitrogen pressure in the 120-minute compartment. Each group represents a nitrogen pressure range of approximately 1.58 fsw. For example, Group A represents a nitrogen pressure in the 120-minute compartment between 26.07 and 27.65 fswa (Figure 3.6).

Figure 3.7 shows the pressure in the 120-minute compartment following exposure to the longest time entry for each depth in the no-decompression table. The wedge shape of this graph resembles the shape of the U.S. Navy No-Decompression table (Appendix C, Page C-2). Since the no-decompression limits for the deeper depths are controlled by the fast compartments, the 120-minute compartment does not have much time to build up extra nitrogen, hence the low RGD, even though the no-decompression limit has been reached. As the depths decrease the medium speed compartments start to control, giving the 120-minute compartment more time to build up nitrogen, producing larger RGDs. At 35 fsw the 120-minute compartment has enough time to nearly reach its M_0 value, producing the highest RGD on the table. At depths of 30 fsw and shallower there is not enough ambient nitrogen pressure to reach the M_0 value of the 120-minute compartment so the RGDs of the maximum times decrease with depth.

This repetitive system allows multiple dives to be performed without violating the underlying decompression model. Following a dive (either no-stop or decompression), the diver's status is represented on the table by a Group Designator (A-O, or Z. However, if the group designator at the end of a dive is "Z" then no repetitive diving is allowed). By using the initial Group Designator and the time spent at the surface, a new Group Designator is obtained using the Surface Interval Table. The time penalty that the first dive places on the second dive is obtained using the Residual Nitrogen Time table. This translates the new Group Designator to the time it would take, at the repetitive dive depth, to reach the nitrogen pressure in the 120-minute

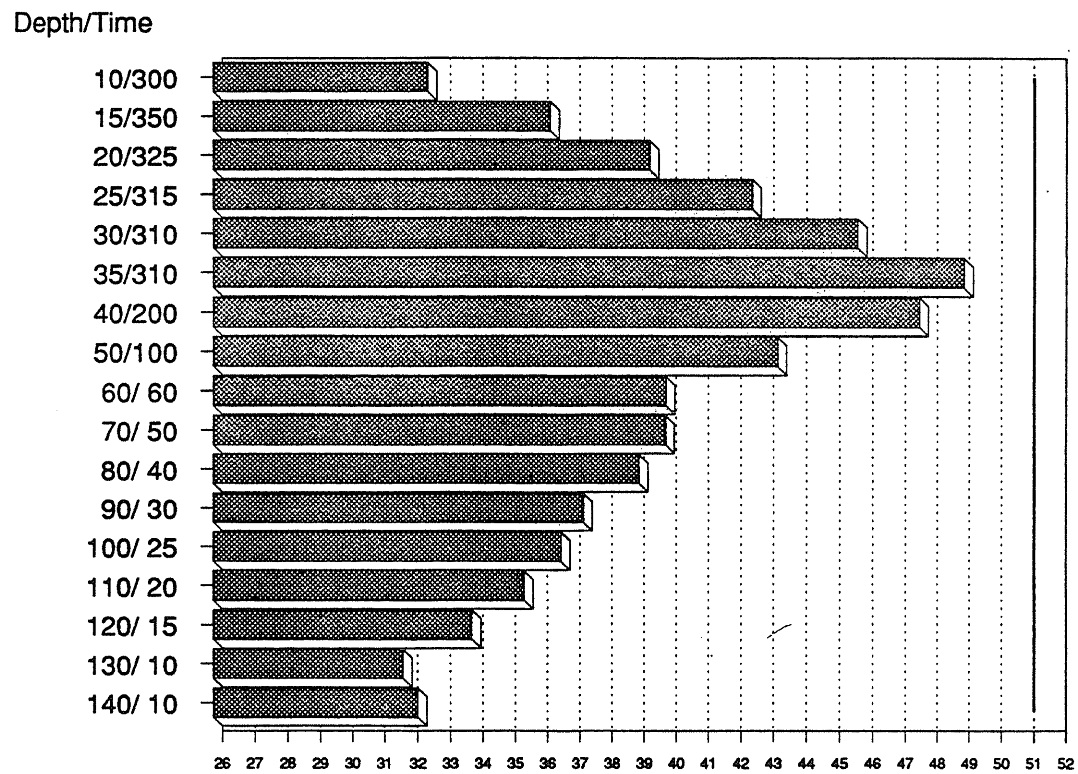

Figure 3.7. 120-Minute Compartment Pressures vs. No-Decompression Time Entries

compartment that is equivalent to the present Group Designation. This Residual Nitrogen Time (RNT) is then added to the Actual Bottom Time (ABT) of the repetitive dive to determine an Equivalent Single Dive Time (ESDT), which is then used in computing the decompression requirements of the second dive (ESDT = RNT + ABT). A third dive can be computed by following the same procedure since the ESDT in essence combines the first and second dive into a single dive used to enter the tables.

To test the repetitive diving tables, 58 repetitive dive combinations were devised. A total of 121 test dives were performed using these profiles, resulting in 3 cases of decompression sickness.[1] A review of these repetitive dives show that over half of them had a surface interval of only six minutes and only four fall within the currently "acceptable" range of recreational diving (Figures 3.8 and 3.9). In his report Des Grange explained the rational behind some of the restrictions placed upon repetitive diving using these tables:

> *After close association and observation of innumerable exposures, the decision to limit the instructions for repetitive dives to 190 feet and to emphasize the inherent dangers of excessive depths seems logical and necessary. The Experimental Diving Unit made several deep repetitive dives with no surface interval, with 60 feet per minute rate of ascent and decent. Regardless of the method of computation, the massive changes of pressure appear more than the body desires to accommodate. A diver accomplishing useful work on air at depths greater than 200 feet is tired physically and mentally and not prepared for repetitive dives.*

Following a successful operational evaluation of the tables at Enewetak Atoll, the tables were promulgated to the Navy for use.[8] At that time these U.S. Navy Repetitive Decompression Tables were picked up by a fledgling sport diving community and have since been used successfully by millions of divers (military, commercial, scientific, and recreational) around the

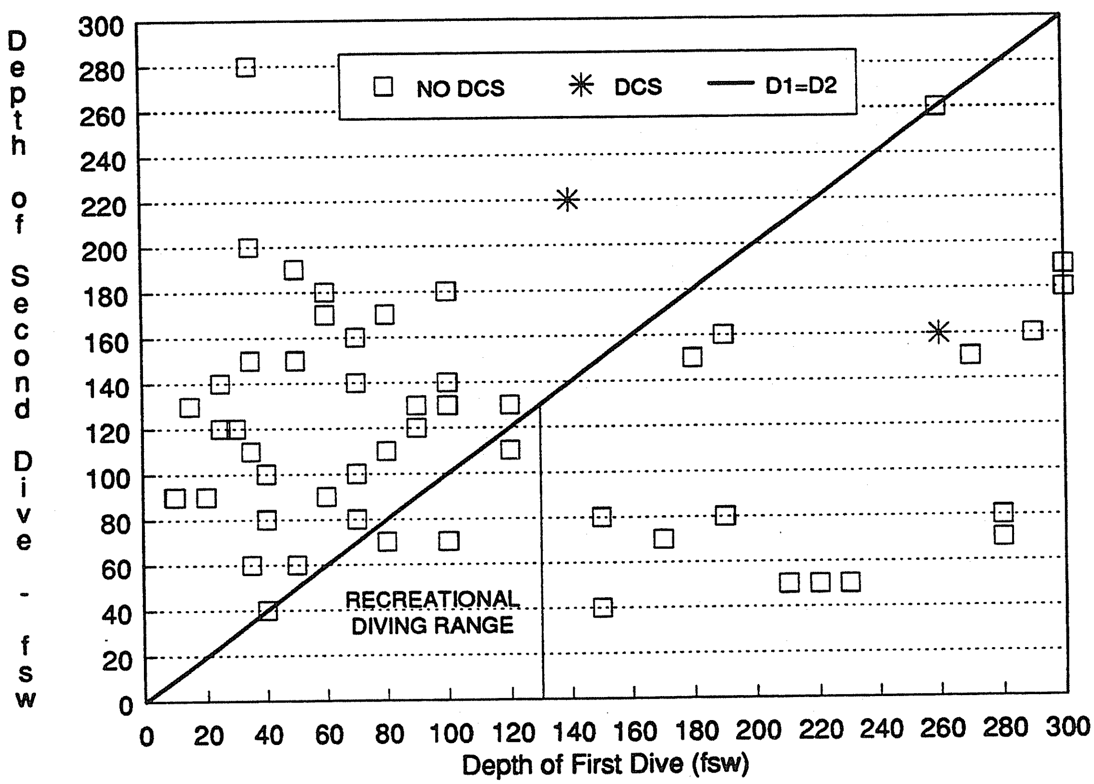

Figure 3.8. U.S. Navy Repetitive Dive Test (1957) - Depth of 1st Dive vs. Depth of 2nd Dive.

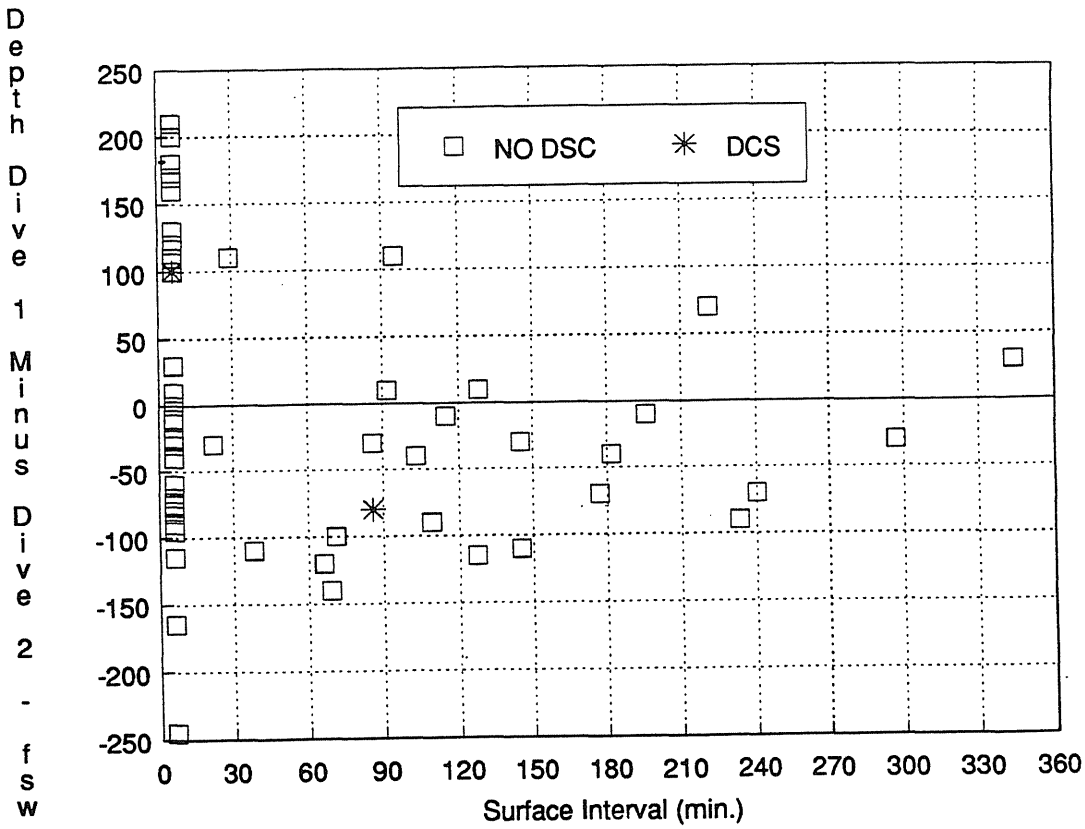

Figure 3.9. U.S. Navy Repetitive Dive Test (1957) - Depth of 1st Dive minus Depth of 2nd Dive vs. Surface Interval.

world.

A recalculation of the U.S. Navy tables by the Navy Experimental Diving Unit, in 1983, found some computational and transcriptional errors.[9] This was a surprise to some divers who assumed that the U.S. Navy tables were "carved in stone". But it must be remembered that in the 1950s only the earliest computers existed and most of the numerical entries of the U.S. Navy tables were derived through manual computations. The major transcriptional error occurs in the no-decompression table. Every value in the table at a depth of 30 fsw and shallower is shifted one column to the left. For example, after a dive to 30 fsw the table indicates a Repetitive Group Designation of "G" while the group should actually be "H".

However, even with these transcriptional and computational errors, the U.S. Navy tables have successfully served all types of divers in many different diving situations, around the world, for over 35 years. It has only been during the last decade or so that other tables have started to erode the foothold that the U.S. Navy tables have had within the U.S. recreational diving community.

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4
OTHER DECOMPRESSION THEORIES, MODELS, AND TABLES

INTRODUCTION

Although the U.S. Navy Tables were the tables of choice in the U.S. from the inception of recreational scuba diving in the 1950s, to the 1980s it would be egocentric to think that they were the only tables available to divers. Since the introduction of Haldane's theory and tables, other decompression theories, models, and tables had been progressing along alternate evolutionary paths. Before the table explosion of the 80s most of these alternates came from other countries including England, Switzerland, and Canada.

This chapter explores some of the alternative tables, models, and theories that have been, and are currently, available to divers. In general, they fall into the following categories:

- **Modified U.S. Navy Tables** - Tables which use the U.S. Navy Tables as their base with some degree of modification.
- **Haldanian Models & Tables** - Tables and models which used the basic Haldanian model concepts with half-times and/or M-values (or critical supersaturation ratios) which differ from the U.S. Navy model.
- **Pseudo-Haldanian Models & Tables** - Tables and models in which a Haldanian model plays only one role in the determination of decompression status.
- **Non-Haldanian Models & Tables** - Tables and models that use theories and assumptions altogether different from a Haldanian model.

EARLY ALTERNATIVES

U.S. Navy Exceptional Exposure Tables

Shortly after the introduction of the current U.S. Navy tables it was discovered that their decompression schedules for dives of 2-4 hours at depths deeper than 100 fsw were not adequate. To eliminate the problems associated with these extended dives, Workman developed a model which included compartment half-times of 160 and 240-minutes. In addition this model changed some of the M_0 values and reduced the ΔM values of the 5- to 120-minute compartments (Table 4.1).

These values were used to generate a set of decompression tables for exposures which were deep and of long duration. To test the tables six divers were exposed to a single dive to 140 fsw for 360 minutes. Three of the subjects (50%) developed DCS. Two contracted limb bends (of a severity which was not treated by the Navy at that time but which would currently receive treatment) The other subject was recompressed and treated.[6] Despite the limited amount of testing, and the bends rate associated with the test, the tables were released to the fleet for EMERGENCY USE ONLY! One can only imagine the problems associated with the standard tables in these ranges if these Exceptional Exposure tables reduced the risk.

TABLE 4.1
U.S. NAVY EXCEPTIONAL EXPOSURE M_o, AND ΔM VALUES

HALF-TIME	M_o	ΔM
5 minutes	104 fswa N_2	1.80
10 minutes	88 fswa N_2	1.60
20 minutes	72 fswa N_2	1.50
40 minutes	56 fswa N_2	1.40
80 minutes	54 fswa N_2	1.30
120 minutes	52 fswa N_2	1.20
160 minutes	51 fswa N_2	1.15
240 minutes	50 fswa N_2	1.10

The Exceptional Exposure tables were added to the bottom of the regular U.S. Navy regular decompression schedules and yield repetitive group codes of "**" (earlier versions of the tables showed repetitive groups of "Z" occurring after some exceptional exposure dives, however this was corrected in the 1988 U.S. Navy Diving Manual) indicating that, "NO REPETITIVE DIVING IS PERMITTED FOLLOWING AN EXCEPTIONAL EXPOSURE DIVE."[37] Regardless of the fact that these tables are considered hazardous they have been used by some recreational groups (cave and deep wreck divers) to determine decompression requirements from long deep dives.

U.S. Navy Table Reorganization

The earliest modifications to the U.S. Navy tables by the recreational diving community involved changes to their layout. Many recreational diving companies created their own versions of the Standard U.S. Navy tables. These included The "Nu-Way" Repetitive Dive Tables, Dacor (Reuter) "No Calculation Dive Tables", PADI Dive Tables, NAUI Tables, Jeppesen tables, etc. These table layouts were designed to make single and repetitive dive calculations easier to perform. Many listed adjusted no-decompression times for repetitive dives eliminating the need to subtract the residual nitrogen time from the no-stop time. In the 1960s and 70s, additional attempts to make U.S. Navy table calculations easier placed the tables in a circular calculator format where a diver could "dial-a-dive" to determine decompression status.

Swiss (Buhlmann) Model

In the early 1960s Professor A.A. Buhlmann of the Laboratory of Hyperbaric Physiology of the Medical Clinic of the University of Zurich started to develop the Swiss, or Buhlmann,

TABLE 4.2
SWISS MODEL HALF-TIMES AND CONSTANTS

COMPARTMENT HALF-TIME	a	b	COMPARTMENT HALF-TIME	a	b
2.65 min.	2.200	0.820	114.0 min.	0.455	0.890
7.94 min.	1.500	0.820	146.0 min.	0.455	0.934
12.2 min.	1.080	0.825	185.0 min.	0.455	0.934
18.5 min.	0.900	0.835	238.0 min.	0.380	0.944
26.5 min.	0.750	0.845	304.0 min.	0.255	0.962
37.0 min.	0.580	0.860	397.0 min.	0.255	0.962
53.0 min.	0.470	0.870	503.0 min.	0.255	0.962
79.0 min.	0.455	0.890	635.0 min.	0.255	0.962

decompression model.[3] This model, which is Haldanian in nature, has undergone various adjustments over the years in order to accommodate new data. Buhlmann's model uses sixteen compartments with a half-time range of 2.65- to 635-minutes which are allowed certain levels of inert gas pressure supersaturation (Table 4.2). The formulas and values used to compute allowable compartment pressures utilize bar pressure units, as opposed to fsw. In this way the model is not restricted to use at sea level which makes sense since all diving in Switzerland is done at altitude. "Safe" ascent pressures are determined by the following formula:

$$P_{amb.tot.} = (P_{i.g.t.} - a) \times b$$

Where:

$P_{amb.tot.}$ = Total ambient pressure (in bars) to which the compartment with pressure $P_{i.g.t.}$ can be safely decompressed
$P_{i.g.t.}$ = Total nitrogen pressure (in bars) in the compartment
a & b = Constants corresponding to the specific compartment

Rearranging the previous equation creates an equation that will compute the allowed $P_{i.g.t.}$ at a specific $P_{amb.tot}$:

$$P_{i.g.t.} = a + (P_{amb.tot.} / b)$$

This equation allows supersaturation pressures ($P_{i.g.t.}$) to be calculated for any ambient pressure. For example, the allowable pressure at sea level (1 ATA) for the 7.94-minute compartment would be:

$$\begin{aligned} P_{i.g.t.} &= 1.500 + ((1 \text{ ATA} \times 1.01325 \text{ bar per ATA}) / 0.820) \\ &= 1.500 + (1.01325 / 0.820) \\ &= 1.500 + 1.236 \\ &= 2.736 \text{ bar} \end{aligned}$$

This pressure is equal to 2.700 ATA (2.736 bar / 1.01325 bar/ATA) which can be converted to an M_o value equal to 89.31 $fswN_2$. The corresponding ΔM value is found to be 1.22. In this manner a complete set of Mo and ΔM values, for sea level, can be generated (Table 4.3).

Currently the full set of Swiss Tables consist of four tables for various altitude ranges (0-700m, 701-1500m, 1501-2500m, and 2501-3500m). The no-stop limits and decompression schedules are generally more conservative than the U.S. Navy Tables for a single dive. The repetitive dive system for these tables utilizes a Repetitive Group and Surface Interval Table system similar to the U.S. Navy Tables. However, dive time allowance on repetitive dives tend to be less conservative than the U.S. Navy tables due to the fact that the tables utilize an 80-minute compartment in the control of repetitive dive calculations (vs. the 120-minute compartment used

TABLE 4.3
SWISS MODEL SEA LEVEL M-VALUES

COMPARTMENT HALF-TIME	M_o	ΔM	COMPARTMENT HALF-TIME	M_o	ΔM
2.65 min.	112.16	1.220	114.0 min.	52.02	1.124
7.94 min.	89.31	1.220	146.0 min.	50.27	1.071
12.2 min.	75.35	1.212	185.0 min.	50.27	1.071
18.5 min.	69.00	1.198	238.0 min.	47.45	1.059
26.5 min.	63.63	1.183	304.0 min.	42.71	1.040
37.0 min.	57.40	1.163	397.0 min.	42.71	1.040
53.0 min.	53.37	1.149	503.0 min.	42.71	1.040
79.0 min.	52.02	1.124	635.0 min.	42.71	1.040

in the U.S. Navy system).

British (Royal Navy Physiological Laboratory) Model

In the early 1950s Hempleman developed a different type of decompression model. His model was based on the *diffusion* of nitrogen from the blood into tissue.[10] By contrast, the Haldanian models were considered *perfusion* models (based on the amount of blood flow to the tissues). The base of Hempleman's model was a capillary surrounded by tissue (Figure 4.1). Nitrogen would diffuse radially into the tissue from the capillary. By placing more and more of these capillary/tissue units together he eventually developed a "sandwich" of tissue and blood. Also known as "slab diffusion" model, it looks at the linear bulk diffusion of gas into the tissue slabs.[7] As inert gas pressure increases in the blood, it migrates through the slabs. As long as the inert gas pressure does not exceed a specific level with respect to the ambient pressure, decompression sickness theoretically will not develop.

Using established no-stop limits, Hempleman determined the limits permitted by his model. As long as the product of the depth (in fswg units) and the square root of the time did not exceed 475 units the dive did not require decompression. The following equation can be used to calculate the no-stop limit for any depth:

$$\text{No-Stop Limit (min.)} = (475 / \text{Depth [fswg]})^2$$

Figure 4.2 presents a graph of the no-stop limits computed by this formula for depths between 40 and 200 fsw.

The 1972 Royal Navy Physiological Laboratory (RNPL) tables were based on a modified version of Hempleman's tissue slab model, and are more conservative than the U.S. Navy tables.[5] A version of the RNPL tables was used by the British Sub Aqua Club[34,36] (the RNPL/BSAC tables) up until the recent production of the BSAC '88 tables.

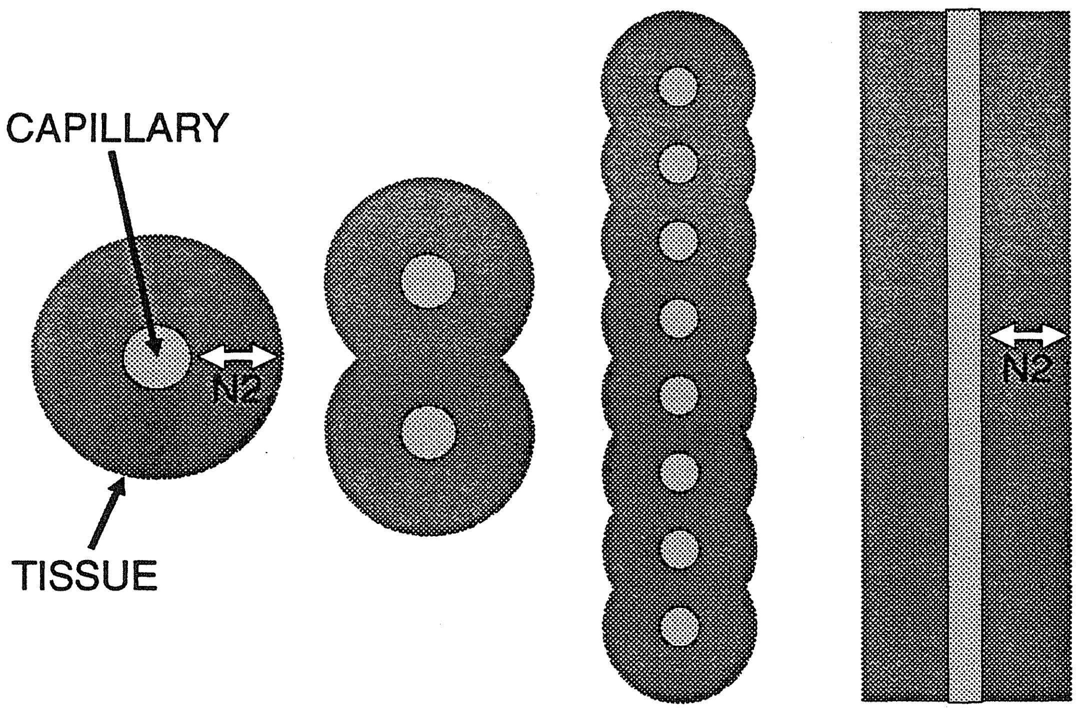

Figure 4.1. Hempleman's tissue slab model development.

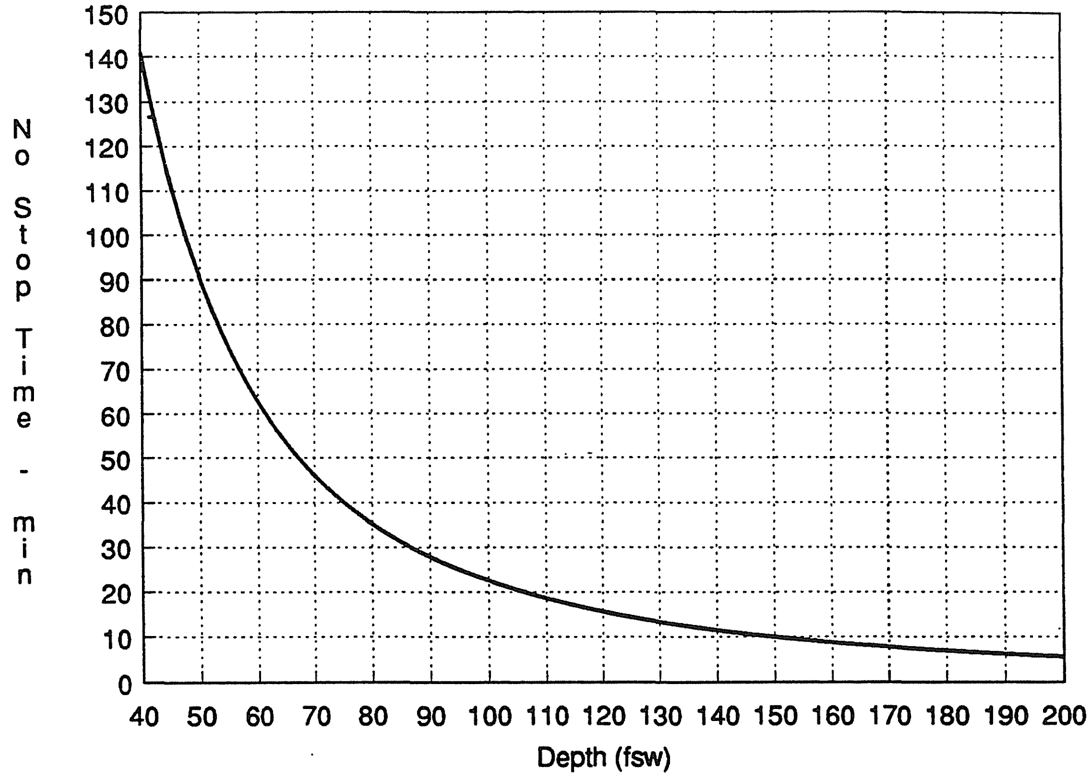

Figure 4.2. Hempleman's no-stop limits [t = (475 / Depth)²].

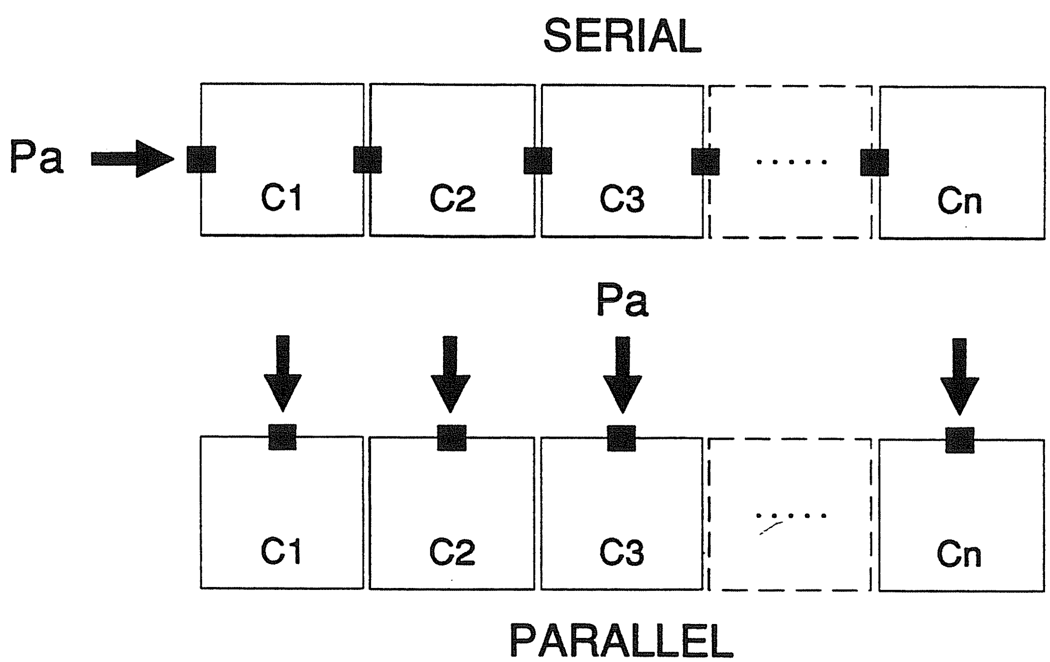

Figure 4.3. Parallel Model vs. Serial Model

DCIEM Model & Tables

In the mid-1960s the Defence and Civil Institute of Environmental Medicine (DCIEM) in Canada began work on developing a pneumatic analog dive computer (see Chapter 6). In the process of this development they developed a new type of *serial* decompression model called the Kidd/Stubbs model. Haldanian models are parallel models, which assume all compartments are exposed to the ambient pressure and no "communication" occurs between compartments. A serial model assumes that all the compartments are connected in a series, with only one exposed to the ambient pressure. Figure 4.3 compares the serial and parallel models. This type of serial model is basically a compartmentalized version of the British bulk diffusion slab model.

The DCIEM Kidd/Stubbs model is a serial model with four compartments.[19] Each of the four compartments in the model have the same half-time of approximately 21 minutes. The allowable surfacing supersaturation ratios considered are 1.92 and 1.73 for the initial two compartments in the series. The pressure levels in the last two compartments are not considered in the computation of the diver's safe ascent depth.

DCIEM has continually been evaluating and modifying their decompression model since its inception. Recently their analysis has been based on ultrasonic Doppler studies. In September of 1984 DCIEM released their new No-Decompression and Decompression Tables. The DCIEM tables are based on thousands of Doppler evaluated man-dives. DCIEM's primary goal with these recent modifications was to upgrade the decompression model programmed into their decompression computers (Chapter 6).[14,15,16]

PADUA Model

The PADUA (Pennsylvania Analysis of Decompression for Undersea and Aerospace) model was developed by the Institute for Environmental Medicine at the University of Pennsylvania as part of a computer program to analyze decompression profiles.[2] The model differs from the U.S. Navy model in that it considers ten compartment half-times (up to 480 minutes) and has more conservative M_o and ΔM values. Table 4.4 presents the compartment half-times, Mo, and ΔM values for the PADUA model. Depending upon the assumptions used, the PADUA model could produce tables which are more conservative than the U.S. Navy tables. However, at this time no such tables have been produced for publication.

THE DOPPLER REVOLUTION

In 1976 Dr. Merrill Spencer of the Institute of Applied Physiology and Medicine in Seattle published a report recommending that the present no-decompression limits be reduced, based on Doppler ultrasonic bubble detection studies.[23,24] He found that divers who were exposed to the U.S. Navy no-decompression limits developed large counts of venous gas emboli (VGE) or "silent bubbles". These bubbles are thought to be nitrogen bubbles that have been released from solution during ascent. They are detected with an ultrasonic probe that distinguishes gas bubbles

TABLE 4.4
PADUA MODEL PARAMETERS

COMPARTMENT HALF-TIME	M_o	ΔM	COMPARTMENT HALF-TIME	M_o	ΔM
5 min.	100	1.6	120 min.	51	1.1
10 min.	84	1.5	160 min.	50	1.1
20 min.	68	1.4	240 min.	49	1.0
40 min.	53	1.3	320 min.	49	1.0
80 min.	52	1.2	480 min.	48	1.0

TABLE 4.5
DOPPLER BASED NO-STOP LIMITS vs. U.S. NAVY LIMITS

DEPTH*	U.S.N.	DOPPLER	DEPTH	U.S.N.	DOPPLER
30 fsw	none	225 min.	80 fsw	40 min.	30 min.
35 fsw	310 min.	165 min.	90 fsw	30 min.	25 min.
40 fsw	200 min.	135 min.	100 fsw	25 min.	20 min.
50 fsw	100 min.	75 min.	110 fsw	20 min.	15 min.
60 fsw	60 min.	50 min.	120 fsw	15 min.	10 min.
70 fsw	50 min.	40 min.	130 fsw	10 min.	5 min.

by the reflection of the ultrasonic wave off the bubble surfaces. Spencer modified Hempleman's square-root equation and computed reduced no-decompression limits which would hopefully hold VGE formation to 10 - 20% of the time:

No-D Limit $= (465/D)^2$

Where:

No-D Limit = No-Decompression Limit for Depth D in minutes
D = Depth in fsw

Further studies by Dr. Andrew Pilmanis at the Catalina Marine Science Center confirmed the presence of high degrees of VGE following "no-decompression" dives in open water. Pilmanis found VGE formation in all his subjects who were exposed to 100 fsw for 25 minutes (the U.S. Navy no-decompression limit for that depth).[20] Doppler work by Dr. Bruce Bassett while studying flying after diving for the Air Force also produced suggestions for reducing the no-stop

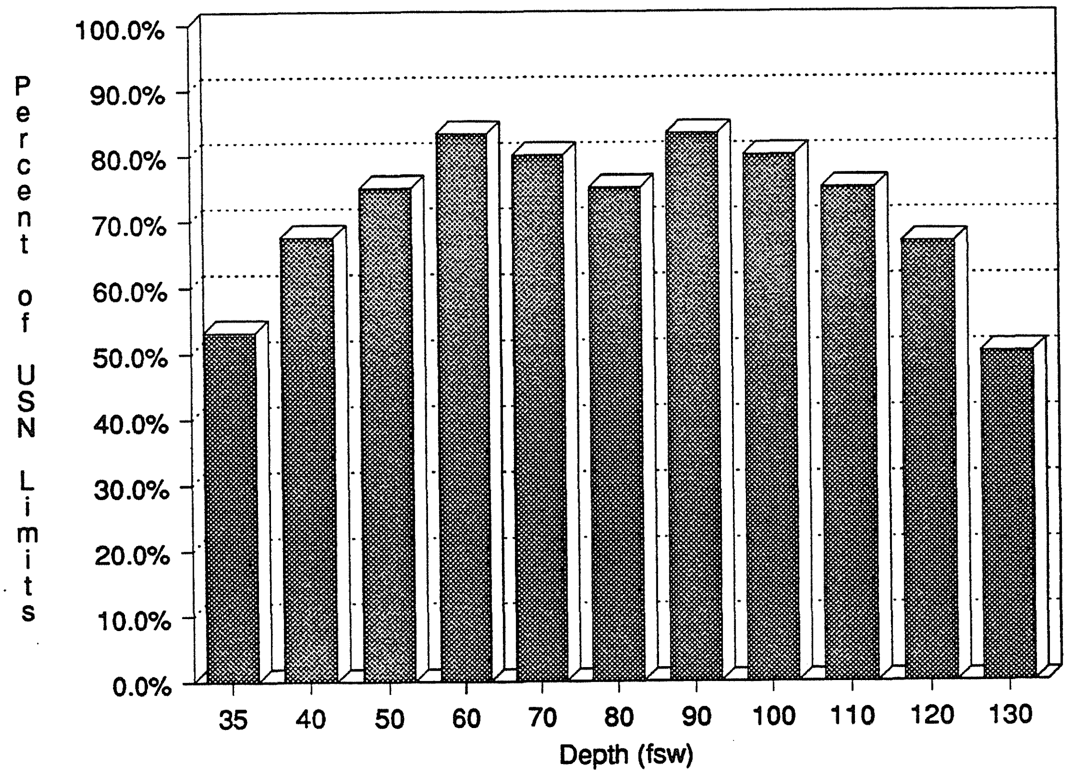

Figure 4.4. Percent of U.S. Navy Limits represented by the Doppler Limits.

limits of the U.S. Navy tables.[1] These studies and recommendations along with Spencer's work produced the new no-stop limits (Table 4.5).

The largest reductions in the no-stop times are in the shallow depths. However, when the new limits are compared as a percent of the U.S. Navy limits the percent reduction is about 50% at 35 fsw while only about 17% at 60 fsw. Moving to the deeper depths the percent reduction starts to increase until it reaches 50% again at 130 fsw (Figure 4.4). In my opinion, the work of Spencer, and others, in the area of Doppler bubble detection was the major influence in starting the current decompression table revolution.

WHY CHANGE TABLES?

If the U.S. Navy Tables had been used by the recreational diving community for over 35 years, why has there been such a large movement away from them in the past decade? Over the years U.S. Navy Table "bashing" has been practiced by many diving authorities (including myself for awhile) who have called the U.S. Navy tables anywhere from inappropriate to dangerous for use by recreational divers. In all fairness, the U.S. Navy tables have served the recreational diving community well for all these years, even though they were never designed, or tested, for the types of diving performed by recreational divers.

As the previous chapters show, decompression theory is not an exact science. As more information becomes available, theories and models can be changed and then used to generate new models and tables. Hopefully, the result of this evolution is a better understanding of the process of decompression, and safer models and tables.

There are many reasons why tables are changed or new ones developed. Some tables and models add additional safety to diving while others allow more dive time, reducing some of the safety factors that were built into the U.S. Navy tables, while still keeping the diver within a "safe" envelope. On the side for making more conservative tables and models there are:

- **Doppler Research** - Tables and models developed using bubble formation as an endpoint instead of DCS should, theoretically, be safer for use. The recommended changes to the no-stop limits proposed by Merill Spencer in 1976 was a major catalyst for table modification and new table development.
- **Safety Stops** - Studies done by Andy Pilmanis showed that the addition of a safety stop following a no-stop dive greatly reduced bubble formation in divers.
- **Slower Ascent Rates** - Many tables indicate an ascent rate that is slower than the 60 fpm rate stated by the U.S. Navy Tables. The Swiss tables indicate an ascent rate of 10 msw/min., or about 33 fpm. Slowing the ascent rate reduces the stress which is placed upon the diver during ascent and also serves as a impetus to maintain good buoyancy control.
- **Shorter Repetitive Dives** - There have been concerns regarding the safety of repetitive dives on the U.S. Navy tables, since they had only been tested for a single repetitive dive before being released. However, recreational divers have been using them for three, four, and sometimes more dives in a single day. Because of these concerns some tables were developed to reduce the allowable bottom time for repetitive dives.
- **Longer Nitrogen Retention** - Since the U.S. Navy tables were designed, and tested, for at most two dives a day there were concerns whether or not the model could adequately handle more than two dives a day (let alone five consecutive days of diving three to four dives a day). The addition to models of longer half-times compartments allows the possibility for a previous day of diving to have some effect on the calculation of decompression status the following day.

Some of the reasons for change attempt to give divers more of what they want... **More Dive Time:**

- **Multi-Level Diving Credit** - Most tables assume the entire dive time was spent at the deepest depth attained during a dive. A diver who spent only a fraction of the dive time at the deepest depth would have the same decompression status as a diver with the same dive time who spent the entirety of the time at the maximum depth. Tables and models that penalize the divers only with the time spent at various depth levels could greatly extend dive times (Chapter 5).
- **Lengthen Repetitive Dives / Shorten Surface Interval** - Some table developers believe that the use of the 120-minute compartment by the U.S. Navy to control repetitive dives is unduly restrictive to recreational divers. If a faster compartment is used, the tables would show a more rapid elimination of residual nitrogen and therefore allow longer repetitive dives or shorten the surface interval required to perform a specified dive.

The final reasons listed here may offend some members of the diving community, however, they are presented in an attempt to produce a more holistic view:

- **Community Status** - There currently seems to be a need on the part of all the U.S. certifying agencies to have their own set of tables. All of these tables are different in some way or another. With the loss of the U.S. Navy table as the "standard of the community" there seems to be a competition between which set of tables will inherit that position. According to some experts the "standard of the community" depends upon the sub-community.[4,9] For example the standard for a PADI instructor is the Recreational Dive Planner, for a NAUI instructor it is the NAUI tables, etc. If any one of this plethora of tables rises above the chaos and confusion, and is established as the "New Standard" then the group that developed them will obtain additional status in the community.
- **Profit** - In a market economy, profit motives generally play a part in any decision that a company makes. One would hope that diver safety plays the primary role in the determination to switch tables, if not for the obvious ethical reasons then for the liabilities associated with the introduction of a product that may not be adequately safe. The retail price of a set of tables ranges from $8.95 for a set of NAUI tables to $39.95 for a PADI Wheel.[32,33] Even if the profit margin on the tables is only $2-$3 dollars, "retrofitting" the current population of approximately 2-3 million divers represents a sizeable profit opportunity.

MODIFIED U.S. NAVY TABLES

As additional information on diving safety became available, such as Doppler research, benefits of safety stops, etc. various groups began to modify more than just the format of the U.S. Navy tables. Changes were made to the no-decompression limits, table entries, surfacing protocols, rules, etc.

The Jeppesen Tables

The simplest modification to the U.S. Navy tables was done by Jeppesen. Based on the above recommendations a red line was drawn on their version of the U.S. Navy tables. This line represented where the new no-stop limit occurred on the table and divers were recommended to stay within the line. If one of the new time limits was not listed on the U.S. Navy table, the next shorter table entry was selected. In this way the no-stop limit for 50 fsw was dropped from 100 minutes to 70 minutes instead of 75 minutes.

Bassett Tables

In 1985 Dr. John Knight took the no-decompression limits recommended by Bruce Bassett and modified the U.S. Navy tables. Not only were changes made to the no-decompression limits, but changes to the table rules and decompression requirements were also incorporated. A set of modified air decompression tables were provided, *"for those who accidentally exceed the no-decompression limits*."[17] The additional rules included:

- Ascent rate of 10 msw/min. (33 fsw/min.) is recommended.
- A safety stop of 3-5 minutes at 3-5 msw (10-17 fsw) is recommended after all dives deeper than 9 msw (30 fsw) whenever possible.
- The total time underwater, rather than just the bottom time, is used to calculate the Repetitive Group after a dive.

NAUI Tables

NAUI's version of the U.S. Navy tables has a few more modifications associated with it. In modifying the tables NAUI used the recommendations of many experts in the field. The resulting table has the following modifications:[18]

- The no-decompression limits have been reduced by one repetitive group for most of the table. The limit at 50 fsw was reduced by two groups, and the 40 fsw limit by three.
- A "precautionary decompression stop" of 3 minutes at 15 fsw is recommended after all dives.
- Table entries are based on total dive time. However, the time spent at the precautionary decompression stop is not added to this time because it is considered to be neutral time.
- A minimum surface interval of one hour is recommended before a repetitive dive can be performed.
- No repetitive dives deeper than 100 fsw are permitted.
- All required decompression stops are performed at a depth of 15 fsw.
- A repetitive dive is defined as a dive that occurs within 24 hours of the previous dive.

In addition, the surface interval errors discovered by the navy have been corrected.

DEEPER INTO DIVING
by John Lippmann

If you are interested in more in-depth information on decompression tables, the book *"Deeper into Diving,"* by John Lippman holds a wealth of information. This 610 page book gives detailed descriptions of many of the available tables, provides instruction on their use, and problems to work. The price of the book is $40 and it is distributed in the US by:

Aqua Quest Publications, Inc.
486 Bayville Rd.
P.O. Drawer A
Locust Valley, NY 11560-0495
(800) 933-8989

Pandora

Possibly the most altered of the modified U.S. Navy tables are the Pandora tables. These tables were designed for use during the archaeological project which was excavating the wreck of the Pandora (the ship sent to collect the Bounty mutineers who had remained on Tahiti). The modifications included:

- Shortening all table values at 30 fsw and deeper by 1 - 4 minutes. This places divers into higher repetitive groups faster.
- Altered repetitive group selection table for repetitive dives. The first dive used the same repetitive group selection as the U.S. Navy table. For subsequent dives more conservative tables are used. A dive which would place a diver in group "I" following the first dive would place them in "K" on the second dive, "L" following the third, and "M" after the fourth dive.
- A stop at 3 msw (10 fsw) for 3 minutes was required after the second dive. Six minutes and 9 minutes were required after the third and fourth dive respectively.
- The maximum ascent rate was placed at 10 msw/min. ("35" fsw/min.).

Notes on the table state that:[8]

> *The Pandora Dive Tables are based on then latest understanding of symptomatic decompression sickness and can significantly reduce your risk of decompression sickness while preserving realistic dive times. These tables have proven themselves under some of the most rigorous, controlled, field testing ever applied to a set of dive tables.*

Information on what these tests were, and where the results can be obtained, was not mentioned.

HALDANIAN MODELS & TABLES

Swiss Sport Diving Tables

In 1986 the current Swiss model was used to generate two sets of dive tables for sport divers. One set was for altitudes from 0 to 700m above sea level (0 to 2300 ft.). The other was for altitudes from 701 to 2500m (2301 to 8200 ft.). As with the full set of Swiss decompression tables, the repetitive group designators are based on the 80-minute compartment, making some repetitive dives less conservative than those allowed by the U.S. Navy tables.

German (Buhlmann/Hann) Tables

The German tables were developed by Dr. Max Hann using a derivative of the Swiss model. They consist of three set for various altitude ranges (0-250m, 201-700m, and 701-1,200m). The repetitive groups on the table are based on the 80-minute compartment. One interesting feature is that safety factors have been added to the depths on the table to take into account depth gauge inaccuracies.[17] On the two lower altitude tables, a safety factor of 2.4% has been added to the actual depth. On the highest altitude table the depth used for the calculations was actually 3% + 1 msw more than the actual depth.

Huggins Model and Tables

In 1981, this author computed a set of Repetitive Dive Tables using a model based on new no-decompression limits computed from Spencer's formula.[12] The model uses the same six

TABLE 4.6
M_o VALUES FOR HUGGINS MODEL

COMPARTMENT HALF-TIME	M_o	COMPARTMENT HALF-TIME	M_o
5 min.	102.0	40 min.	54.5
10 min.	85.0	80 min.	47.5
20 min.	67.5	120 min.	43.0

compartment half-times as the U.S. Navy model. The M_0 values for the compartments were determined by computing the maximum compartment pressures produced in the compartments following exposure to the Spencer no-decompression limits. No ΔM values were necessary since the tables were computed exclusively for "no-decompression" diving. The new M_0 values are listed in Table 4.6, along with the compartment half-times.

The tables are presented in the same format as the U.S. Navy Tables. The major computational difference is that the Repetitive Group Designators represent nitrogen levels in all six compartments instead of just the 120-minute compartment. Each repetitive group represents a 3% range of the Mo values of the compartments. For example, group "E" represents 72% to 75% of the Mo value of any of the six compartments. This type of representation allows all six compartments to be considered in repetitive dive calculations and permits certain types of multi-level diving procedures (Chapter 5) to be performed without any of the compartments exceeding their Mo values.

The Huggins Tables are presented in Appendix D. The only difference in reading the tables involves the arrows "-->" in the first table. These arrows indicate that the diver must move to the right to obtain the repetitive group designator for the dive.

These tables have **not** been officially tested. However, they are more conservative than the U.S. Navy Tables when they are used to compute no-decompression limits and repetitive no-decompression limits. These tables have been published by the Michigan Sea Grant College Program, and have gained in popularity and use. Some groups have taken to calling them the "No-Bubble" tables. This name is a misnomer since the limits the tables were calculated from would theoretically produce VGE 10 - 20% of the time.[13]

PADI Recreational Dive Planner

In the late 1980s PADI started distribution of their new tables, called the Recreational Dive Planner (RDP). The RDP was developed by Raymond Rogers, DDS and tested by DSAT (Diving Science & Technology, a corporate affilate of International PADI, Inc.). The M_0 values for the underlying model were computed from Spencer's no-stop limits, making single dive limits more conservative than the U.S. Navy. However, the repetitive group designators on the RDP are based on the 60-minute compartment of the model which allows the diver to be theoretically clear of residual nitrogen in 3 - 6 hours.

Residual nitrogen times based on a 60-minute compartment will be less than those based on a longer compartment, such as the 120-minute compartment used in the U.S. Navy table calculations. This means that less residual time needs to be added to a repetitive dive, which can result in longer repetitive dive times than those allowed by the U.S. Navy tables.

The tables have been designed for no-stop diving only, but highly recommend a safety stop of 3 minutes at 15 fsw following dives. No decompression schedules are presented. If divers execeed the no-stop limits for a certian depth, they must make an *"emergency decompression"* stop at 15 fsw. If the limit was exceeded by less than 5 minutes, the required stop time would be 8 minutes and the diver would have to remain at the surface for a minimum of 6 hours. If the limit was exceeded by more than 5 minutes the stop would be 15 minutes (*"air supply permitting"*) and no further diving could be performed for at least 24 hours.[38]

The most unique feature of the RDP is that it comes in two formats, a regular table, and "The Wheel." The Wheel is a circular calculator that runs through normal dive calculations but has been specifically designed for use in multi-level diving (Chapter 5). The Wheel allows dives to be entered to the nearest 5 fsw level, instead of the standard 10 fsw table increments, and the nearest minute. This allows for a much more flexable implementation of the model.

DSAT tested the RDP in two phases. In Phase I, up to 3 multi-level dives were performed during a single day. These dives at times exceeded the RDP limits. A total 911 person-dives were performed (518 chamber, 393 open-water) in Phase I resulting in no reported occurance of DCS;

however VGE was detected in 7.4% of the dives. The majority being low level, Grade I bubbles (Appendix F).[21]

Phase II examined multi-day dives. In Phase II the dives did not exceed the RDP limits and included the recommended safety stops. Initially Phase II(a) attempted six dives per day for six days in a row. However, the tests were suspended after one of the subjects developed DCS (in a knee which had been previously injured) at the end of the second day. The second Phase II study (b) reduced the number of dives per day to four. Twenty subjects performed 475 of the planned 480 person-dives. None of the subjects reported symptoms of DCS, and occurance of detected VGE was 8.6% (4.6% Grade I, 3.2% Grade II, 0.8% Grade III).

PSEUDO-HALDANIAN MODELS

U.S. Navy E-L Algorithm

In the early 1980s, NEDU developed a decompression model and algorithm to be programmed into an underwater decompression computer used with their constant partial pressure of oxygen, closed-circuit mixed gas system.[25,26,27] The algorithm they developed is called the E-L (or exponential-linear) Algorithm. This model assumes that nitrogen is absorbed by compartments at an Exponential rate, as in the other Haldanian models. However, nitrogen is released at a slower Linear rate. This slows the surface off-gassing rate indicating higher residual nitrogen levels for repetitive dives. Figure 4.5 compares nitrogen absorption and elimination between the E-L algorithm and a Haldanian E-E (exponential-exponential) model.

Currently there is no plan to use the E-L Algorithm to calculate a set of new U.S. Navy Air Decompression tables. The Navy believes that the current U.S. Navy tables are acceptable for their operations. Even if the E-L Algorithm was used to generate air tables, the model is, in some cases, less conservative than the present U.S. Navy model.

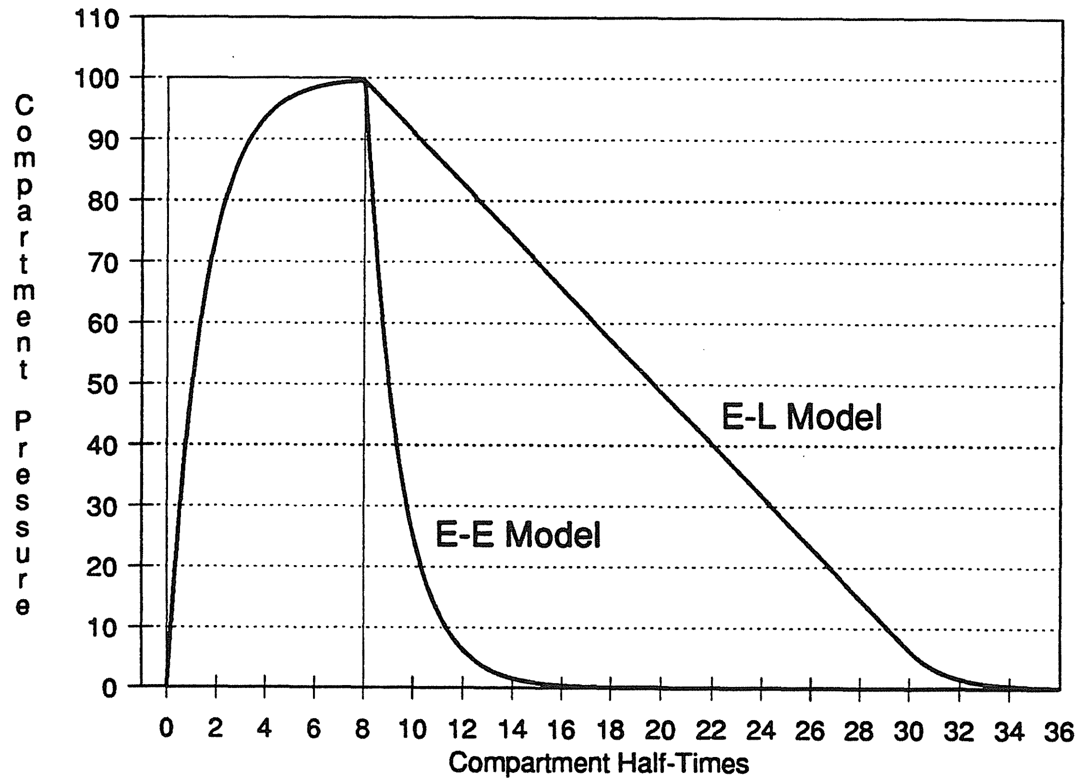

Figure 4.5. Comparison of the E-L algorithm to a Haldanian E-E model.

Reduced Gradient Bubble Model (RGBM)

The Reduced Gradient Bubble Model (RGBM) is a hybrid model developed by Dr. Bruce Wienke at Los Alamos National Laboratory. It combines concepts of bubble dynamics with a standard Haldanian model. Bubble dynamics attempt to model gas phase production resulting from a dive. The model produces a factor, ξ (xi), which is used to modify the M values of the Haldanian part of the model. Since ξ is never greater than 1.0, it can only make the model more conservative. Some of the features of ξ are as follows:[31]

- ξ equals one for a single bounce dive, and remains less than one for repetitive dives within a specific time frame
- ξ decreases with increasing exposure time (thereby further reducing the M values)
- ξ increases with increasing surface interval time
- ξ modifies faster compartments the most
- ξ decreases with the depth of a dive segment
- ξ scales deeper-than-previous dives the most

Based on these features we can see that the RGBM will restrict dive time on repetitive dives considered to be hazardous such as:

- Dives following a short surface interval
- Dives following a deep dive
- Dives following a long dive
- Dives which are deeper than the previous dive

Since this model does not lend itself easily to table format, there were plans to incorporate it into a dive computer. However, at this time, these plans seem to have been abandoned by the manufacturer.

NON-HALDANIAN MODELS

BSAC '88 Tables

In 1988 the British Sub Aqua Club released a new set of decompression tables for their members.[35] Divers had started to become frustrated with the restrictions of the earlier version of the BSAC tables which only permitted two dives a day. An interim *Third Dive Table* was developed to allow a third dive to a maximum depth of 9 msw (30 fsw). During this interim period, the '88 tables were calculated using the same RNPL data used to generate the first set of tables, which allowed more flexibility.

The tables consist of four sets of seven tables. Each set is designed to be used at different atmospheric pressures (greater than 984 millibars, 899-984 millibars, 795-899 millibars, and 701-795 millibars : 1 atmosphere = 1,013 millibars). Each table in a set represents a repetitive status. At the start of a dive series table "A" is used. Following a surface interval the table that corresponds to the diver's current repetitive status is used, without the need for any calculations.

DCIEM Sport Diving Tables

The current DCIEM sport diving tables were released in 1990.[22] These tables were calculated from the DCIEM serial model. A major difference between these tables and most of the others is the use of a repetitive factor (or multiplier). At the end of a surface interval, the table gives a repetitive factor which is to be multiplied by the actual dive time of the repetitive dive to obtain an equivalent single dive time. For example, if the repetitive factor at the start of a dive was 1.4, and the bottom time of the second dive was 20 minutes, then the decompression status at the end of the second dive would be based on an equivalent dive time of 28 minutes.

Tiny Bubble Group (Varying Permeability) Model

The Tiny Bubble Group is a group of researchers at the University of Hawaii that has developed a decompression model based on the physical properties of bubble nucleation in aqueous media. Their model, called the Varying-Permeability Model (VPM), indicates that nuclei resulting from cavitation, are thought to "seed" bubble formation, are *"spherical gas phases that are small enough to remain in solution yet strong enough to resist collapse, their stability being provided by elastic skins or membranes consisting of surface-active molecules."*[11] The ascent criteria for this model is based on the volume of bubbles that are formed upon decompression. Growth in size and number of gas bubbles is computed based on the physical properties of the "skins" and the surrounding environment. If the total volume of gas in the bubbles is less than a "critical volume", then the diver is within the safe limits of the model.

Tables based on this model have been produced, but have not been tested. The no-decompression limits for depths shallower than 140 fsw are more conservative than the U.S. Navy limits.

Maximum Likelihood Statistical Method

The Maximum Likelihood Method is a statistical approach used by the Naval Medical Research Institute (NMRI) to analyze DCS occurrence. They consider decompression sickness a probabilistic risk dependant upon a "Dose" (depth / time exposure) produced from a dive profile.[28] "Dose/Response" curves (Figure 4.6) in these statistical models are based on historical data. In this case the model is based on a database that includes over 1,700 individual exposures from various decompression studies.

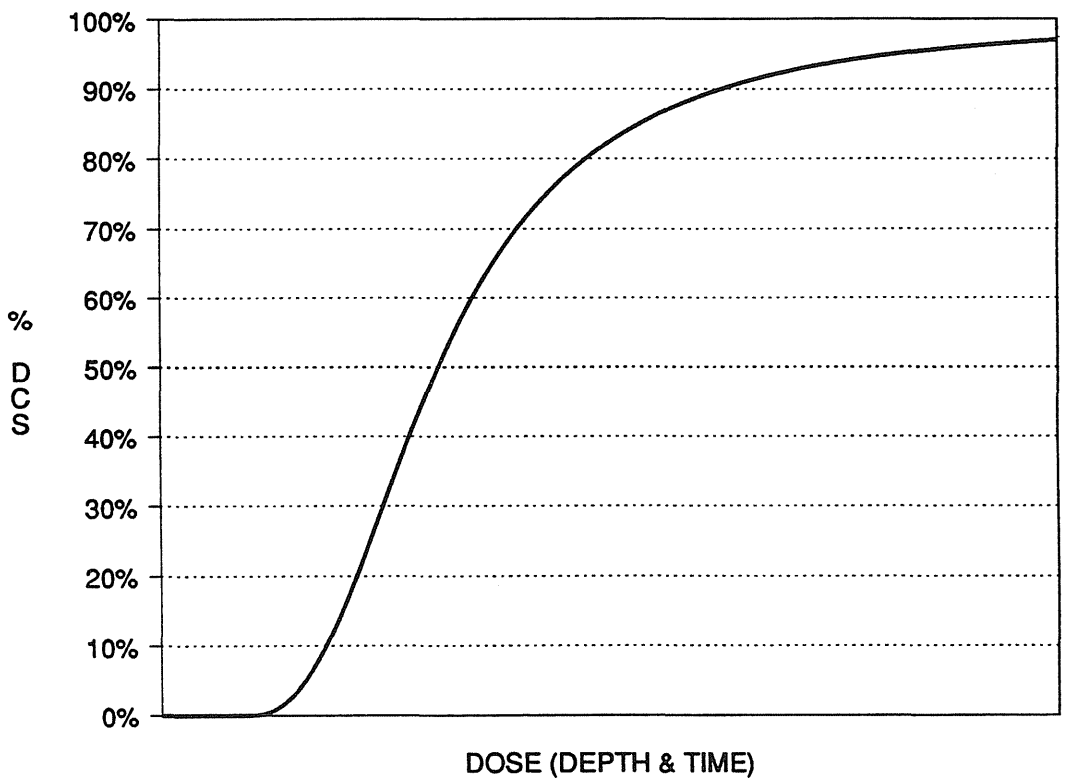

Figure 4.6. Example of a dose/response curve.

Using this statistical model, tables have been computed for DCS probabilities of 1% and 5%.[30] These tables would be used in various operations. High priority missions could use the 5% tables because of the need for greater in-water efficiency. Lower priority operations could use the 1% tables for safer operations.

Maximum likelihood and other statistical approaches are now being used with greater frequency. Various "risk" models have been developed which can compute the risk of a dive, or dive series. These models tend to predict risk well for dive profiles which fall within the range of the historical data used to generate the model. However, outside their historical data envelopes, these risk models do not do as well.

Some statistical approaches have combined maximum likelihood analysis, Haldanian models, and bubble growth models in an attempt to generate a better predictive risk model.[28]

COMPARISON OF TABLES & MODELS

TABLE 4.7
COMPARISON OF NO-STOP LIMITS

HALDANIAN TABLES

DEPTH	USN	BASSETT	JEPPESEN	NAUI	PADI	SWISS
30 fsw	inf	220	205	n/a	n/a	300
40 fsw	200	120	130	130	140	120
50 fsw	100	70	70	80	80	75
60 fsw	60	50	50	55	55	53
70 fsw	50	40	40	45	40	35
80 fsw	40	30	30	35	30	25
90 fsw	30	25	25	25	25	22
100 fsw	25	20	20	22	20	20
110 fsw	20	15	15	15	16	17
120 fsw	15	12	10	12	13	15
130 fsw	10	10	5	8	10	12

NON-HALDANIAN TABLES AND MODELS

DEPTH	DCIEM	BSAC '88	USN E-L	VPM	NMRI 1%	NMRI 5%
30 fsw	380	243	296	323	170	240
40 fsw	175	122	142	108	100	170
50 fsw	75	74	81	63	70	120
60 fsw	50	51	57	39	40	80
70 fsw	35	37	44	30	25	80
80 fsw	25	30	37	23	15	60
90 fsw	20	24	31	18	10	50
100 fsw	15	20	27	15	8	50
110 fsw	12	17	24	12	7	40
120 fsw	10	14	20	11	5	40
130 fsw	8	13	17	10	5	30

In comparing tables, to decide which one is the best for your diving requirements, one needs to look further than a simple Comparison of no-stop times for a single dive comparing the underlying models used to create the tables may also tell you very little about the way the table performs. Table 4.7 shows a comparison of no-stop limits for various tables and models previously discussed. This comparison shows that most of the no-stop limits are more conservative than those of the U.S. Navy table. Does this mean that all the dives calculated from these apparently conservative models and tables will always be more conservative than the U.S. Navy tables? No!

Figure 4.7 shows the allowed no-stop times, using various tables, for a dive to 60 fsw following a 25 minute dive to 80 fsw, and after various surface intervals. The impact of using a faster compartment to control repetitive diving is shown by the allowable times of the Swiss (80-minute control) and PADI (60-minute control) tables. Even though their underlying models are more conservative than the U.S. Navy model, the assumptions used in the creation of the tables allows them more time on the repetitive dive; creating a situation where more time is permitted on a table generated from a more conservative model. Are the assumptions used to create the U.S. Navy tables overly conservative? Are the assumptions used to create the Swiss and PADI tables not conservative enough? There is no way to tell unless a full comparative study were to be done. All that can be said is that, if the same dive is performed as the first dive, then the table which gives you the longest repetitive dive time will place you at the highest risk. Whether or not this additional risk is significant enough to be problematic, is another question altogether.

Repetitive Dive Problem

Figure 4.8 (on page 4-22) gives a three dive repetitive dive problem. Using a table of your choice, compute the answers to the questions. The answers, based on different tables, are given in Appendix E.

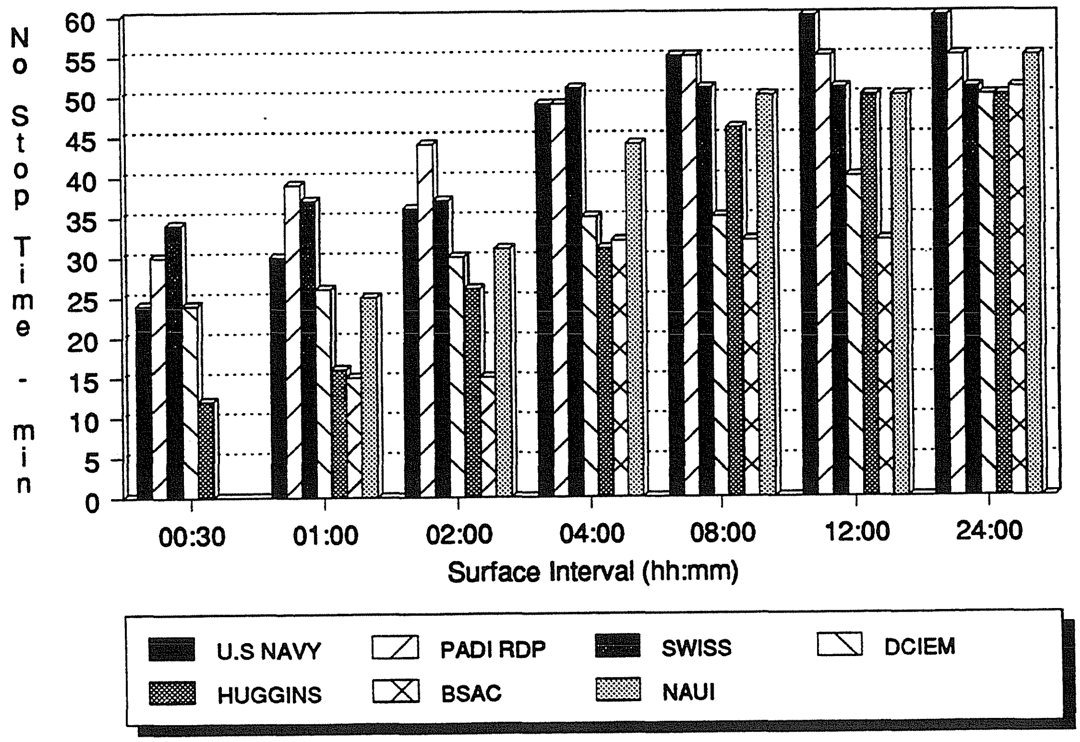

Figure 4.7. 60 fsw no-stop times following a dive to 80 fsw for 25 minutes.

SUMMARY

The basic limitation of any table, no matter which one is used, is that only a limited number of the depth/time dive combinations can be presented. Most tables present information in depth/time matrixes with normal depth increments of 10 fsw and time increments of 5 or 10 minutes. To enter these matrixes, depths and times are rounded up to the next higher table entry. For example, a 41 fsw dive for 32 minutes must be entered into the table as a 50 fsw dive for 40 minutes. This pigeon-holing of dives into a specific table entry adds conservatism by calculating decompression status based on depths and times which are greater than those actually achieved.

The other basic limitation of tables is that most are based on the assumption that the diver has performed a *"square wave"* dive profile; that is, the diver has spent the entire dive time at the maximum depth achieved. This assumption adds yet another level of conservatism, when used on dives where the maximum depth was achieved for only a fraction of the dive time. However, as will be shown in Chapter 5, techniques have been developed that bypass the square-wave assumption and allow fora diving technique called Multi-Level, or Step Diving.

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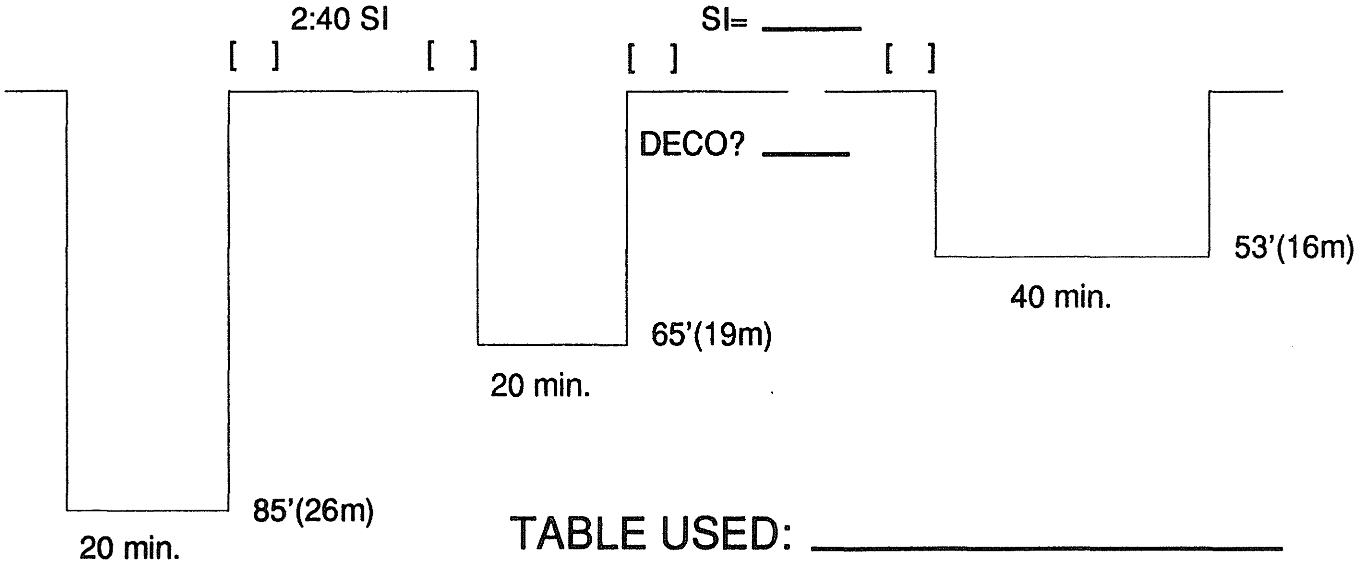

Figure 4.8. Three dive repetitive diving problem.

A. What is the No-Stop Limit for 85' (26m)?

B. What is the Repetitive Group Designator following a dive to 85' (26msw) for 20 minutes?

C. What is the Repetitive Group/Code following a Surface Interval of 2 Hours and 40 Minutes?

D. What is the No-Stop time for a second dive to 65' (19 msw)?

E. If the actual dive time of the 2nd dive was 20 min. What Required Decompression Stops if any are indicated?

F. What is the Repetitive Group Designator/Code after this 2nd dive?

G. What is the minimum Surface Interval required for a 3rd dive to 53' (16 msw) for a No-Stop time of 40 minutes?

5
MULTI-LEVEL DIVING THEORY AND TECHNIQUES

OVERVIEW

Most tables that have been generated, regardless of the model, present decompression status based upon the assumption that the diver spends the entire dive time at the deepest depth achieved. This type of *"square wave"* dive profile is not the normal dive profile performed by the average sport diver. Most dives are spent at various depths with only a small portion of the dive at the deepest depth. For this reason many divers have felt that their bottom time was being limited by these table restrictions. To circumvent the maximum depth/entire dive-time rule, various multi-level, or step diving techniques have been devised

During the 1970s sport divers performed multi-level dives with increasing frequency. Thousands of dives per year were made using multi-level techniques, even though none of these techniques had been subjected to scientific validation. The extensive number of apparently harmless multi-level dives performed over time suggests that most of the techniques were relatively "safe." However, the possibility of hidden problems, not yet fully evaluated, such as "silent bubble" formation, asymptomatic (or ignored) cases of DCS, or even the development of dysbaric osteonecrosis still exists.

MULTI-LEVEL DIVING THEORY

A multi-level dive, in its broadest sense, is a dive in which the diver does not spend the entire dive time at a specific depth. Given this definition, the majority of all sport dives could be said to be multi-level. However, the type of multi-level diving examined here depends upon how a specific dive profile compares to decompression tables or models. Normally, when the rules of the U.S. Navy and other tables are followed, the deepest depth of the dive is used to determine the allowable no-decompression time. Essentially , the diver is adding safety to the dive by not staying at the maximum depth for the entire length of the dive. This added safety may be an important factor in the "safe" use of the U.S. Navy tables over the years. The multi-level diving techniques examined here allow "no-decompression" dive times in excess of the no-decompression limit permitted at the maximum depth of the dive (according to established tables).

The basic concept behind any of these multi-level diving techniques is that nitrogen is absorbed by the body more rapidly at deeper depths than at shallower depths. If the initial depth of a dive is 100 fsw, then (according to the U.S. Navy Tables) the no-decompression limit is 25 minutes. If 10 minutes were spent at 100 fsw, the remaining no-decompression time at 100 fsw (or any depth shallower, by

MULTI-LEVEL DIVE

While collecting data for a report on knowledge possesed by divers, Mike Emmerman received the following defintion of a Multi-Level dive from an experienced dive master:

"A multi-level dive is when two or more divers of different levels of certification partisipate in the same dive."

The dive master was serious!!

the Navy Tables) would be 15 minutes. However, if the divers ascend to a shallower depth, say 50 fsw, their nitrogen absorption rate would be slower than what it was at 100 fsw. Therefore, the remaining no-decompression time at 50 fsw should be longer than 15 minutes. How much longer this no-decompression time would be is what the various multi-level diving techniques attempt to determine.

There are different methods that have been developed for calculating multi-level diving credit. Table based methods can use either established non-multi-level diving tables, such as the U.S. Navy Tables or tables specifically designed for multi-level diving. Model based multi-level diving techniques involve multi-level computations using decompression models and algorithms. Between table and model based techniques, in a class by itself, is the PADI Wheel which is, in essence, a circular calculator that can compute multi-level credit.

TABLE-BASED MULTI-LEVEL DIVING TECHNIQUES

Repetitive Group Method

Until recently, the most popular table based technique was the Repetitive Group Method or the "Graver" method, so called because it was popularized by Dennis Graver.[1,2] This technique was based on a Riser/Repet-Up Procedure used in commercial diving, which has been attributed to Workman while working for Taylor Diving and Salvage. As an example, the Oceaneering International, Inc. (a major commercial diving company) Riser/Repet-Up procedures state:[6]

> *During operations involving work on riser clamps and non-destructive testing of platforms etc., a single dive may require periods to be spent at a number of depths working up towards the surface.*
>
> *To decompress from such a dive, some procedures require that the diver is decompressed for the deepest depth achieved during the dive for the total time from leaving the surface to leaving the last and shallowest diving depth.*
>
> *This is completely unnecessary and exposes the diver to excessively long decompression. The assumption is made that the diver is absorbing inert gas from his breathing medium at a rate consistent with being at maximum depth throughout the dive. In fact, the diver has had his inert gas uptake reduced progressively throughout the dive and tissues are decompressing at the shallower working depths.*
>
> *Riser/Repet-Up Procedures provide the means whereby the inert gas (Nitrogen) uptake may be more accurately assessed and a more appropriate decompression schedule applied.*

The theory behind this method is that the repetitive groups on the U.S. Navy Tables represent a certain amount of nitrogen in the body, **no matter how that group is reached**. According to this premise divers would have the same level of excess nitrogen following a dive to 80 fsw for 30 minutes as they would have after 50 minutes at 50 fsw, since both dives place them in repetitive group G.

Using this assumption, a method of reading the U.S. Navy Tables "sideways" was developed. If, for example (as shown in Figure 5.1), divers start their dive at 110 fsw and spend 13 minutes at that depth, their repetitive group is E. At this depth, 110 fsw, they now have seven minutes of no-decompression time remaining. However, if they had reached group E at 70 fsw they would have 30 minutes of no-decompression time remaining since 20 minutes at 70 fsw would place them into group E. If the divers ascend to 70 fsw from 110 fsw, they now have, according to this procedure, 30 minutes of no-decompression time remaining. Spending 20 minutes at 70 fsw places them into group H. If they then ascend to 40 fsw, it is as if they had spent 80 minutes at 40 fsw. Now the remaining no-decompression time is 120 minutes. If they spend 40 minutes at 40 fsw and then surface, they are now in group K. They have just performed a "**no-**

decompression" dive to 110 fsw for 73 minutes! Following the U.S. Navy Table rules would have required the divers to consider the entire 73 minutes spent at 110 fsw. This would have resulted in a decompression schedule of 7 minutes at 30 fsw, 23 minutes at 20 fsw, and 57 minutes at 10 fsw, for a total of 88 minutes of decompression.

The version of this procedure that was popularized by Dennis Graver does not allow all of the No-Decompression Table to be used. The limitations are indicated by the heavy lines on the table in Figure 5.1.

On the surface (no pun intended) this technique appears theoretically sound, but discrepancies develop when dives allowed by this technique are compared to the underlying decompression model used to compute the U.S. Navy Tables.

As indicated in Chapter 3, the U.S. Navy decompression model, from which the standard air tables were computed, uses six compartments with half-times of 5, 10, 20, 40, 80, and 120 minutes. All six of these compartments were considered in the calculation of the U.S. Navy no-decompression limits. However, only the 120-minute compartment was used to compute the Repetitive Group Designator values on the no-decompression table, surface interval table, and residual nitrogen table. This method is acceptable when **single level** dives are performed using the tables, but what happens to the other five compartments when a multi-level dive is performed using this type of table technique? There is no way to obtain that information from any of the three U.S. Navy tables. This problem was recognized, hence the modified limits (bold lines) indicated on the table in Figure 5.1.

However, when 101 allowable multi-level dives were analyzed using the U.S. Navy model and formulas, it was found that many of the dive profiles built up "potentially dangerous" nitrogen levels in the other five compartments.[3] The basic reason for this build up of nitrogen pressures, primarily in the 40-minute compartment, is that the tables were not designed to be used in this

DEPTH (ft.)	NO DECOMPRESSION LIMITS (Min.)	REPETITIVE GROUPS														
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
10	–	60	120	210	300											
15	–	35	70	110	160	225	350									
20	–	25	50	75	100	135	180	240	325							
25	–	20	35	55	75	100	125	160	195	245	315					
30	–	15	30	45	60	75	95	120	145	170	205	250	310			
35	310	5	15	25	40	50	60	80	100	120	140	160	190	220	270	310
40	200	5	15	25	30	40	50	70	80	100	110	130	150	170	200	
50	100	–	10	15	25	30	40	50	60	70	80	90	100			
60	60	–	10	15	20	25	30	40	50	55	60					
70	50	–	5	10	15	20	30	35	40	45	50					
80	40	–	5	10	15	20	25	30	35	40						
90	30	–	5	10	12	15	20	25	30							
100	25	–	5	7	10	15	20	22	25							
110	20	–	–	5	10	13	15	20								
120	15	–	–	5	10	12	15									
130	10	–	–	5	8	10										
140	10	–	–	5	7	10										
150	5	–	–	5												
160	5	–	–	–	5											
170	5	–	–	–	5											
180	5	–	–	–	5											
190	5	–	–	–	5											

Figure 5.1. Sample Multi-Level Dive

TABLE 5.1
COMPARTMENT NITROGEN PRESSURES (IN FSW) PRODUCED DURING A MULTI-LEVEL DIVE PROFILE

PROFILE (Depth/Time) (fsw/min.)	COMPARTMENTS [Half-Time(M_0 Value)] 5(104)	10(88)	20(72)	40(58)	80(52)	120(51)
120/15	109.0	87.4	64.5	47.8	37.6	33.9
90/ 5	102.1	90.2	69.7	51.9	40.2	35.7
70/10	86.8	85.8	73.1	56.6	43.6	41.6
% MAP at surface	83.5%	97.5%	**101.5%**	97.6%	83.9%	81.6%

manner. Since a multi-level dive does not include the required 10 minute surface interval, the other five compartments are not permitted to off-gas to "safe" levels. An example of the compartment pressure build up in all six compartments is given in Table 5.1 (%MAP = % of the compartment's M_0 value). As shown, the 20-minute compartment's M_0 value is exceeded at the surface and the 10-minute and 40-minute compartments are very close to their limits, even though the 120-minute compartment is "safe." This shows that the Repetitive Group Method can violate the underlying decompression model. One problem with this analysis is that it assumes an instantaneous ascent between levels and produces the "worst case scenario." There is the potential that compartment pressures would decompress to "safe" levels during ascent. However, the limitations of the Hewlett-Packard HP-55 calculator used in the calculations precluded a more detailed analysis at that time.

NAUI Method

Results of a recent evaluation of the effect of compartment loading during multi-level diving with the new NAUI tables, using the "Graver" method, have been published.[8] This study, done by Bruce Wienke, utilized a CRAY supercomputer to analyze 16 million possible multi-level dive profiles, and based their calculations on descent and ascent rates of 60 fsw/min. The results of this analysis showed that, with the new no-decompression limits on NAUI tables, none of the six compartments of the U.S. Navy model ever exceeded 96% of their M_0 value. The summary of Wienke's paper stated:

> *The use of a dive computer is preferred to manual table calculations for multi-level diving applications. although manual computations may be made by those proficient in the use of the tables and knowledgeable regarding the multi-level procedures and recommendations. The purpose of this article is to show that multi-level table computations are valid when descent and ascent rates of sixty feet per minute are taken into consideration.*

DCIEM Method

The new DCIEM sport diving tables also have a multi-level diving technique designed to be used with them. It is a method that has evolved over a 5 year period and was approved for use in December 1991.[10] The rules associated with this procedure state that:

- The deepest part of the dive comes first.
- Additional steps should be at progressively shallower depths.

- Ascend at least 20 fsw (6 msw) between steps. At depths ≥ 100 fsw ascend at least 30 fsw (9 msw).
- Stay within the No-D limit at each step.
- Finish the dive in shallow water, at least 5 minutes between 10 and 20 fsw, before surfacing.
- Allow for at least a 1 hour surface interval after each dive.

The calculations are based on the repetitive groups. For example, if the first step was to 100 fsw for 10 minutes the repetitive group would be "B." If step 2 (which needs to be at least 30 fsw shallower) is at 60 fsw, the equivalent bottom time for the dive would be 20 minutes giving 30 minutes of remaining no-decompression time at 60 fsw. After spending 20 minutes at 60 fsw the repetitive group is now "E." Ascending to 40 fsw produces an equivalent bottom time of 70 minutes and a remaining no-decompression time of 80 minutes. Spending 20 minutes at 40 fsw places the diver in group "G." For the safety stop at 10 - 20 fsw the same technique is utilized to determine the end-of-dive repetitive group, using the 20 fsw table entries. A 5 minute stop at 15 fsw will then place the diver into group "H" at the completion of the dive.

U.S. Navy Multi-Level Diving Procedure

The U.S. Navy has published a report called "A Procedure For Doing Multiple-Level Dives On Air Using Repetitive Groups".[7] This report describes a somewhat complex procedure for performing multi-level dives. In this method, the water column is split into two regions: depths greater than 30 fsw and depths 30 fsw and shallower. For any dive deeper than 30 fsw the table is entered as a single-level dive to the deepest depth. The difference comes when computing the surface interval. In this procedure the diver need not surface to enter the surface interval table. The diver may consider the time spent at 30 fsw or shallower to be a surface interval. However, 30 minutes must be spent at 20 fsw (or shallower) in order to enter the surface interval table. This, according to the procedure, permits the required off-gassing that spending 10 minutes at the surface produces. Once this minimum surface interval has taken place, the diver may perform a repetitive dive in the standard fashion.

This method was designed for use with the Navy's closed-circuit mixed-gas system, to allow the Navy "Combat Swimmer" up to 12 hours of dive time without extensive decompression requirements. According to the Navy Experimental Diving Unit, this procedure has been tested and is considered safe, although, to my knowledge, no reports on the testing have been published.

Other Methods

There are many other multi-level diving techniques that have been developed and used over the years. Most of these techniques are set dive profiles that have been found safe by trial and error and have been performed by divers for years. Most are performed at dive resorts where there is a wall (sharp drop in depth) which begins in shallow water (20 to 40 fsw). In these cases, divers can spend a specified length of time on the wall at deeper depths and then are allowed to return to the shallow areas above the wall for an additional period of time. If the total time of the dive were to be compared to the no-decompression limit for the maximum depth achieved, the divers usually would have exceeded their limits. However, in many dive resorts this type of dive profile has been established. In one dive resort, over 10,000 person-dives have been performed with no ill effects, according to the resort operators.

THE WHEEL

The Wheel is a unique version of PADI's Recreational Dive Planner that can be used for calculating multi-level dives. The Wheel provides an interesting alternative to table based multi-level diving techniques. The curves on the Wheel represent nitrogen pressures in the 60-minute compartment of the PADI model. The Wheel tends to be a more continuous representation of the 60-minute compartment since depth entries are in 5 fsw increments and exact minute entries can be used.

Some restrictions to multi-level diving are in place on the Wheel. The no-stop limits are shortened for each depth if it is part of a multi-level dive. Also multi-level calculations are allowed only if an ascent has been made to a specific depth, or shallower. These restrictions attempt to eliminate the potential for the other compartments in the model to exceed their M_o values during a multi-level dive. Two problems frequently mentioned by divers I have talked to with regard to the Wheel are:

- It is too complex to learn and use.
- Different Wheels and different divers will come up with different results for the same dive profile.

Most of the testing done with the Recreational Dive Planner was done to check the validity of the multi-level profiles allowed by the Wheel. Appendix F gives a summary of these and other multi-level tests.

MODEL COMPUTATIONAL MULTI-LEVEL DIVING METHODS

The multi-level diving technique that seems to hold the most promise is the Model Computational Method. This procedure examines what is happening to all the compartments in a decompression model during a multi-level dive. This method lends itself readily to solutions using computers and microprocessors. A computer can compute the inert gas pressures in all compartments in a model, given a multi-level dive profile, at a much faster rate and with more accuracy than manual calculations. An example of this method was the technique used to compute the "safety" level of the dive profile presented in Table 5.1.

There are two ways the Model Computational Method can be used. The first is to compute a safe (according to the model) multi-level dive profile before the dive and follow that set dive profile. The other method is to compute the "safety" of the multi-level dive as it is being performed using a real-time dive computer.

Pre-Dive Evaluation of Multi-Level Dive Profiles

An example of the Pre-Dive Evaluation technique is a multi-level dive used in the testing of underwater communications equipment at NEDU during the early 1960s. The dive profile had a maximum depth of 190 fsw and a total bottom time of 45 minutes (Figure 5.2).

Using the U.S. Navy dive table procedures, this dive would have required a total of 147 minutes of decompression, and be considered exceptional exposure. However, by using the Pre-Dive Evaluation technique, the decompression requirement was reduced to only 37 minutes. Approximately 30 person-dives were completed using this profile without evidence of decompression sickness.[9] Table 5.2 shows how the multi-level profile allows the diver to ascend, following this decompression, within the "safe" confines of the U.S. Navy model.

Real Time Evaluation of Multi-Level Dive Profiles

Various dive computers have been designed over the years to perform the task of computing and displaying the decompression status of multi-level dives in real time. Early devices were mechanical analog computers with different mechanisms to simulate nitrogen absorption and elimination based on some type of decompression model. Present computers use microprocessors which have been programmed with a decompression model. Depths are read into the program through a pressure transducer and an analog-to-digital converter. These devices will be described in detail in Chapter 6 and 7.

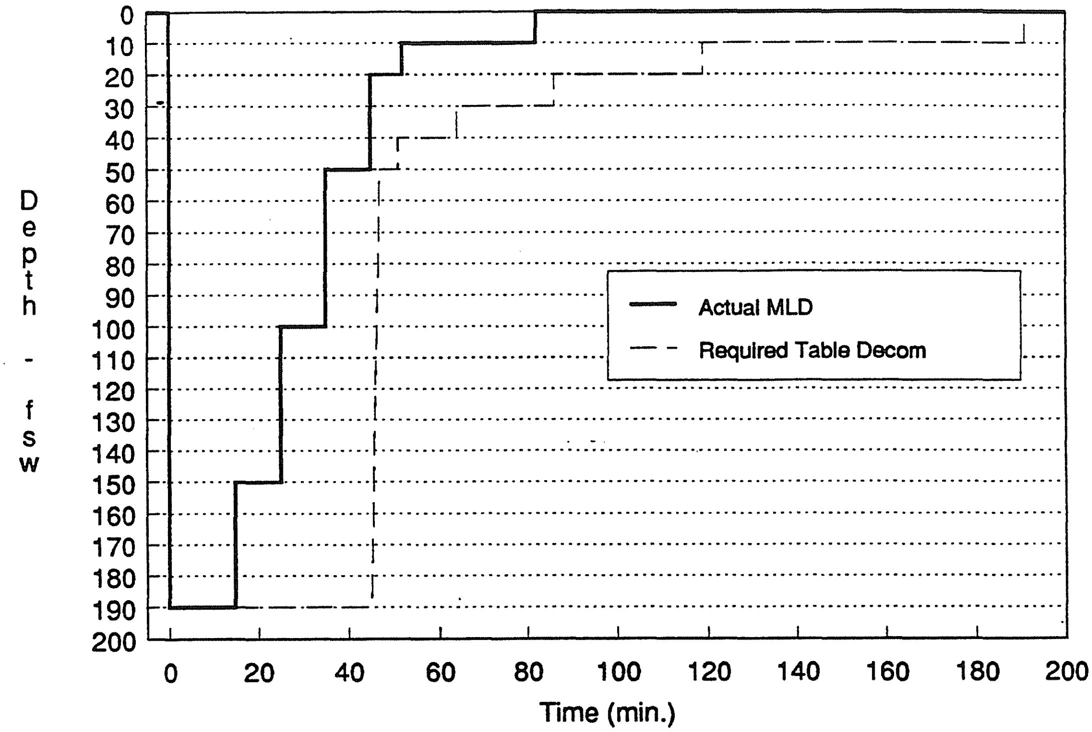

Figure 5.2. Multi-level dive profile performed while testing underwater communications equipment.

To test the safety of the decompression algorithm programmed into one of these computers (the EDGE), a series of 119 multi-level person-dive profiles were evaluated. The subjects were examined with a Doppler ultrasonic bubble detection device for the possible formation of VGE, and observed for signs of decompression sickness. The study, which extended the decompression model to its limits, resulted in only one subject developing the mildest grade of bubbles and no indication of decompression sickness.[4] A listing of the profiles tested is presented in Appendix F.

TABLE 5.2
COMPARTMENT NITROGEN PRESSURES (IN FSW) PRODUCED DURING U.S. NAVY COMMUNICATION TEST

PROFILE (Depth/Time) (fsw/min.)	COMPARTMENTS [Half-Time(M_0 Value)]					
	5(104)	10(88)	20(72)	40(58)	80(52)	120(51)
190/15	**157.41**	**123.10**	**86.92**	**60.43**	44.36	38.53
150/10	**147.78**	**133.84**	**103.81**	**73.81**	**52.68**	44.48
100/10	**115.75**	**119.45**	**104.18**	**78.79**	**57.03**	47.88
50/10	78.11	**92.51**	**92.87**	**76.68**	**57.74**	48.87
20/7	55.60	73.04	**81.88**	**72.71**	**56.80**	48.60
10/30	34.31	38.85	50.91	57.00	51.58	46.27
% MAP at surface	33.0%	44.2%	70.7%	98.3%	99.2%	90.7%

SUMMARY

It is difficult enough to study a single-level dive profile; but within that single-level profile there are an infinite number of multi-level dives that can be performed. How can all these dive profile variations be analyzed? Are there any undetectable problems associated with multi-level diving, such as asymptomatic bubble formation or development of dysbaric osteonecrosis? Or does multi-level diving reduce the probability of these complications occurring? The data are not available to answer these questions.

Currently there is insufficient evidence or data to indicate whether most of the multi-level diving techniques are "safe" or "unsafe." The techniques that have been tested seem to indicate that some types of multi-level diving can be safe, but there is still a great need for further studies in this area. Even so, with the growing popularity of dive computers, the number of divers taking advantage of multi-level diving techniques are also increasing, but there does not seem to be a proportional increase of DCS cases reported. But does field experience, by the general diving population, constitute validation of multi-level diving techniques? Some organizations seem to think so. However, unless there are accurate records of the dive profiles performed (and their outcomes) there is no way of knowing how the various techniques are being used.

The following anecdote from DCIEM illustrates the problems of relying on field or operational experience to "validate" a decompression technique. After the initial development and testing of the Kidd-Stubbs model in the 1960s, pneumatic dive computers based, on the model, were attached to hyperbaric chambers to control decompression:

> *The computer was used extensively at DCIEM for experimental diving, primarily for physiological and psychological tests, in the hyperbaric chamber to depths as great as 300 fsw. In almost all cases, the decompression was a continuous ascent following as closely as possible the safe ascent depth predicted instead of the traditional staged decompression at fixed depths. However, in 1970, Stubbs discovered that the DCIEM hyperbaric chamber operators did not trust the computer for deep dives and had been adding their own "safety factor" for these dives. The operators were staying deeper than the computed safe ascent depth by as much as 10 fsw and then surfacing when the safe ascent depth reached zero. Although this was a safe procedure, it did not verify the validity of the ascent criteria. A detailed review of dive records for the previous three years in the 200 to 300 fsw depth range showed the incidence of DCS to be only 3%. Although this figure may seem high, it was far better than could be achieved with any existing table at that time. The chamber operators were then directed to follow the safe ascent depth to within 2 feet of the ascent indicator. This resulted in the DCS incidence rising to 20 % in 76 man-dives...*[5]

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6

HISTORY OF DECOMPRESSION DEVICES AND COMPUTERS

INTRODUCTION

During World War II, the concept of deep sea diving changed with the introduction of SCUBA. Up to that time the great majority of diving operations were carried out using surface supplied air to hardhat divers, who would spend their entire dive at one depth for as long as they needed to complete a task. Decompression status computations and execution were performed by tenders at the surface.

With the advent of SCUBA came some logistical problems that had to be considered:

- Divers were now separated from surface contact and had to be responsible for their own decompression computations. This produced the need for some means to determine their decompression status underwater.
- The divers no longer had an unlimited surface supplied source of air. They had to return to the surface occasionally for a fresh tank of air. Therefore, some mechanism was needed to compute repetitive dives, an operation that had not been required often prior to the introduction of scuba.
- Divers now had three-dimensional freedom during a dive. All the previous tables assumed the divers spent their entire dive at a single depth with no 3-D movement.

The following quote, from a Navy Experimental Diving Unit (NEDU) report, indicates the need for some type of decompression device:

> *With the ever widening fields of both civilian and military free-swimming and diving using self contained breathing apparatus, and particularly when such diving is untended from the surface, there arises a very pressing need for a small portable indicating apparatus to be used to indicate proper decompression in ascent.*[17]

In the early 1950s, the U.S. Navy formed the Committee for Undersea Warfare and Underwater Swimmers to identify improvements required in diving equipment to fit scuba operations. The committee met in 1951 at Scripps Institute of Oceanography. One of the topics addressed was how to control the decompression of a non-tethered, free-swimming scuba diver. The committee report, by Groves and Monk, dealing with this problem stated:

> *In ordinary diving [hard hat] the tender aboard the ship keeps a log of the depth-time history of the dive and then computes the decompression requirements from some simple table. For a diver using self-contained equipment, three possibilities present themselves: (a) the diver keeps a log of depth and time and then computes the decompression requirement while under water (this involves a depth gauge, watch, and wits); (b) the diver follows a prearranged schedule (how dull); (c) by guess and by God. None of these alternatives is entirely satisfactory.*[9]

This report presented a preliminary design for a diver-carried decompression device. It was a pneumatic analog computer which simulated nitrogen uptake and elimination in two theoretical tissue groups. The potential benefit of such a device was summarized by the following statement:

> *The gauge automatically takes into account the depth-time history of the entire dive. The resulting continuous "optimum ascent" should be somewhat more efficient than the usual step-wise ascent, the latter being used only because of its greater simplicity of presentation in tabular form.*
>
> *There are two other situations for which the gauge is conceivably an improvement over the table. For repeated dives the gauge automatically takes into account the residual elevation of nitrogen pressure in the body from the preceding dives. (Divers are known to be more subject to bends on subsequent dives.) In the case of an emergency ascent, such as may be required by an exhaustion of breathing air, the gauge gives some indication of the desirable re-compression procedure.*

The report also included a basic design for the "Ultimate Gauge," an electrical analog computer. The envisioned device would show both decompression and air consumption status so that the diver would know if the remaining air supply would be sufficient to perform the required decompression schedule.

This report established the foundation for most of the early designs for decompression devices. Since its publication, a variety of both analog and digital decompression computers have been

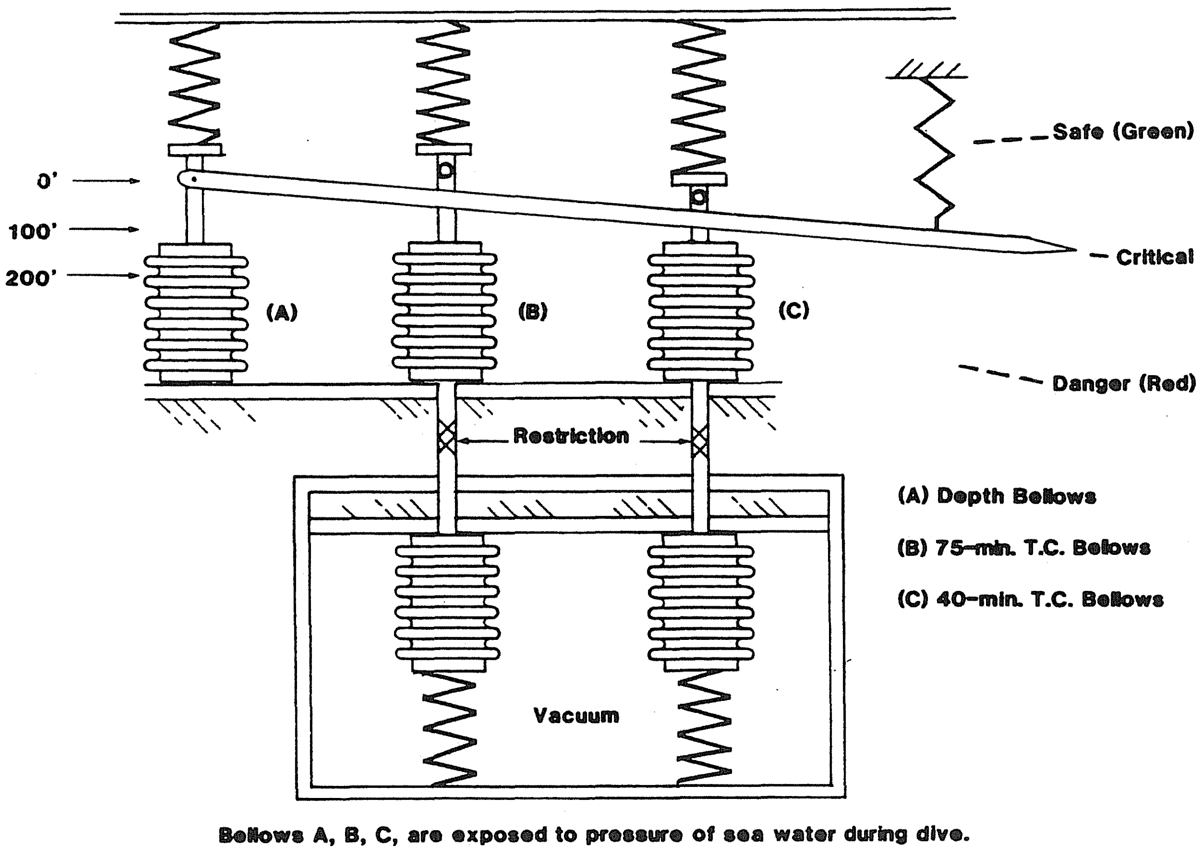

Figure 6.1. Foxboro Decomputer Mark I Schematic.

designed, built, and have met with various levels of success.

ANALOG DEVICES

Prior to the advent of microprocessor technology, mechanical and electrical analog computers were used to simulate decompression models in various decompression devices.

Foxboro Decomputer Mark I

An analog decompression computer built by the Foxboro Company in Foxboro, Massachusetts, was submitted to NEDU in October 1955. Its two compartment pneumatic design (Figure 6.1) was based on the Groves and Munk report. The two compartments to be simulated had half-times of 40 and 75 minutes and surfacing ratios (compartment nitrogen pressure to ambient pressure) of 1.75:1 for both compartments.[7] The computer used five bellows to determine decompression status.

Nitrogen absorption and elimination from the compartments was simulated by the flow of gas through porous resistors between bellows, which were exposed to the ambient pressure, and bellows sealed in a vacuum, kept under a constant pressure by a spring.

This device (Figure 6.2) was the result of communications between two brothers, Dr. Hugh Bradner (member of the Committee of Undersea Warfare) and Mead Bradner (head of Research and Development at Foxboro). The operation of the unit involved balancing the colors on a disk viewed through a window on the right side of the device. The disk was divided into three sections. One-half was white, one-quarter was red, and one-quarter was green. If the dial showed any green through the half-disk window, the diver was safe. If any red was showing, the diver had exceeded the safe ascent depth and would have to descend. Optimal decompression was achieved by keeping just the white half of the disk visible through the window.

Results of the evaluation by the NEDU stated that the device gave readings within the U.S. Navy

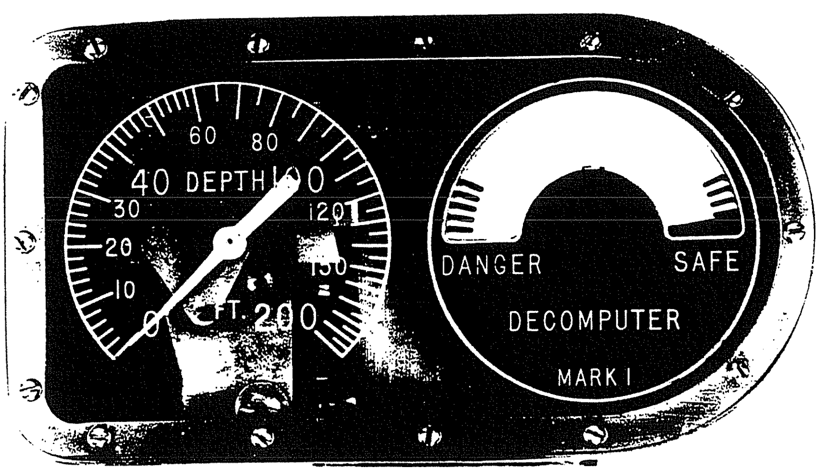

Figure 6.2. Foxboro Decomputer Mark I (photograph courtesy of Mead Bradner).

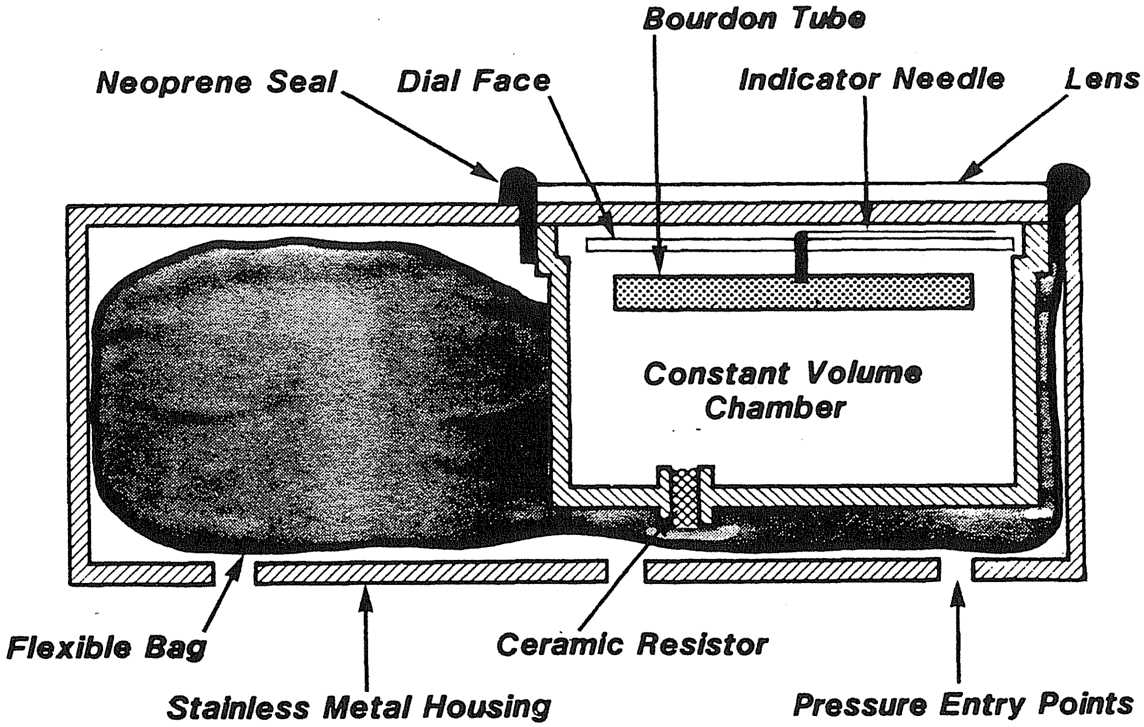

Figure 6.3. Schematic Diagram of SOS Decompression Meter.[8]

Table decompression ranges for some dives and outside the ranges for others.[17] The major reason for this was that compartment half-time values were mistaken for the time constants of the bellows. The actual compartment half-times simulated by the device were 27.7 and 52 minutes, causing deviations from tables.

The device was returned to Foxboro for re-evaluation and modification but was never resubmitted to the Navy. In 1957 the Navy published new air no-decompression/decompression tables, and repetitive dive tables. The Navy apparently rejected the idea of a decompression computer and accepted option "a" of the Groves and Monk report (i.e., depth gauge, watch, tables, and wits).

SOS Decompression Meter

Up until the 1980s the SOS decompression meter had been the most well known decompression device. It was designed in 1959 by Carlo Alinari and manufactured by an Italian firm, SOS Diving Equipment Limited.[8] The SOS Meter or DCP (Decompression Computer) is still manufactured and available. The DCP is a one-compartment, pneumatic device which "is purported to be an analog to a 'general' body tissue."[14] Due to the design of the DCP, the compartment half-time varies with the pressure differential across the ceramic resistor.

Figure 6.3 shows the construction of the DCP. As the diver descends with the device, the ambient pressure increases on the flexible bag, forcing gas through the ceramic resistor into the constant volume chamber. The role of the ceramic resistor is to simulate nitrogen uptake and elimination in the body. The pressure increase in the constant volume chamber is indicated by the bourdon tube gauge. The gauge face indicates the safe ascent depth for the diver. As the diver ascends, the gas pressure in the constant volume chamber will become greater than the external pressure and the gas flow will be reversed.

TABLE 6.1
COMPARISON OF DCP AND U.S. NAVY NO-DECOMPRESSION LIMITS

Depth	DCP Time (min:sec)	U.S. Navy Table
40 fsw	140:11	200 min.
50 fsw	72:34 - 77:57	100 min.
60 fsw	60:00	60 min.
70 fsw	47:11 - 54:07	50 min.
80 fsw	38:40 - 39:54	40 min.
90 fsw	30:15 - 32:52	30 min.
100 fsw	28:09 - 29:35	25 min.
110 fsw	25:35 - 26:43	20 min.
120 fsw	21:24 - 22:29	15 min.
130 fsw	19:18 - 21:14	10 min.
140 fsw	16:11 - 17:13	10 min.
150 fsw	14:56 - 16:05	5 min.
160 fsw	12:56 - 13:42	5 min.

A major problem with the DCP is its deviation from the U.S. Navy no-decompression limits at deeper depths. In evaluating ten DCPs Howard determined that the no-decompression limits allowed by the DCPs were more conservative than the U.S. Navy limits at depths shallower than 60 fsw (feet of seawater), but less conservative at depths deeper than 60 fsw (Table 6.1).[11]

TRACOR Electrical Analog Computer

The first electrical analog decompression device was developed in 1963 by Texas Research Associates Inc. and was known as the TRACOR computer. The device employed a 10-section ladder network of resistors in series and capacitors in parallel to simulate nitrogen diffusion within the body. Ambient pressure measurement was supplied by a depth sensor which varied the voltage supplied to the network. Two sets of batteries powered the device. Two 1/2D alkaline cells powered an oven which housed the electronics and kept them at a constant 90^{o} F. Four small mercury batteries were used as the computer network power source. The display was a micro-ammeter which was calibrated in fsw. The meter would display how many fsw the diver could safely ascend. To obtain the most efficient decompression the diver would ascend at a rate which kept the meter reading zero throughout decompression.

An evaluation of the computer by NEDU found:

> *The decompression meter predicted minimal decompression requirements adequately for schedules throughout the depth range tested from 40 through 190 feet for ascent rates of 20 and 60 fpm. Longer and deeper exposures were not provided adequate depth and total decompression time at stops compared to the present U.S. Navy air decompression tables. Continuous ascent decompression predicted by the instrument was inadequate both in depth and duration of total decompression time. Temperature dependency of the instrument was excessive, particularly for cold exposures, and resulted in widely varying decompression requirements for the same dive schedule.*[22]

Workman further suggested that a mechanical analog computer could be used to avoid the instability and breakdowns which occurred in the electrical circuitry.

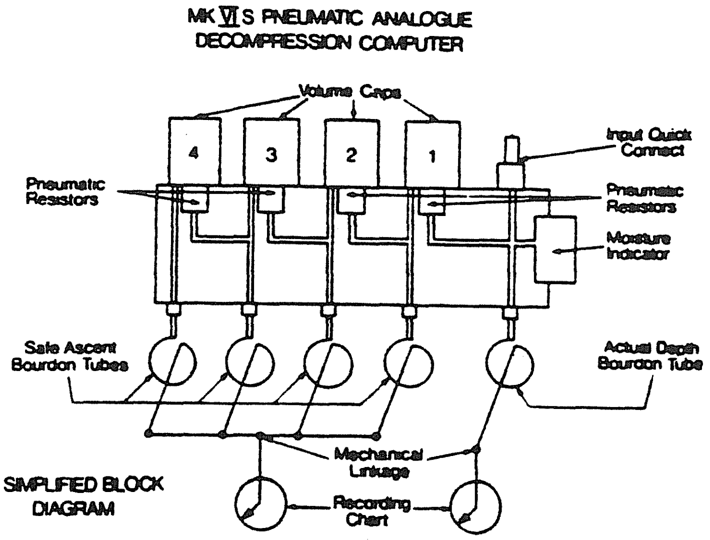

Figure 6.4. Schematic of the Mark VS & VIS Pneumatic Analog Decompression Computers.

DCIEM Analog Computer Series

In 1962, the Defense and Civil Institute of Environmental Medicine (DCIEM) began to develop a series of pneumatic analog decompression computers under the direction of D. J. Kidd and R.A. Stubbs. The device had four compartments to simulate the nitrogen absorption and elimination in the diver. Initial versions arranged the compartments in parallel. The final design arranged the compartments in series, resulting in the Kidd-Stubbs decompression model.[13] Table 6.2 shows test results for the various versions of the device.[5]

The MARK VS was the first thoroughly tested, successful decompression computer. The four compartments in series gave effective half-times of 5 minutes to over 300 minutes.[16] The display

TABLE 6.2
INCIDENCE OF DCS PRODUCED WITH VARIOUS VERSIONS OF THE DCIEM PNEUMATIC ANALOG DECOMPRESSION COMPUTER

	DECOMPRESSION COMPUTER		
	MARK II P	MARK III P	MARK V S
CONFIGURATION	PARALLEL	PARALLEL	SERIAL
HALF-TIMES (min)	10 20 40 80	20 40 80 160	21 common
SUPERSATURATION RATIO (PTN2/PA)	2.65, 2.15 1.85, 1.65	1.6 common	1.44 common
NUMBER OF DIVES	526	478	3775
DCS INCIDENCE	5.0%	1.5%	0.6%

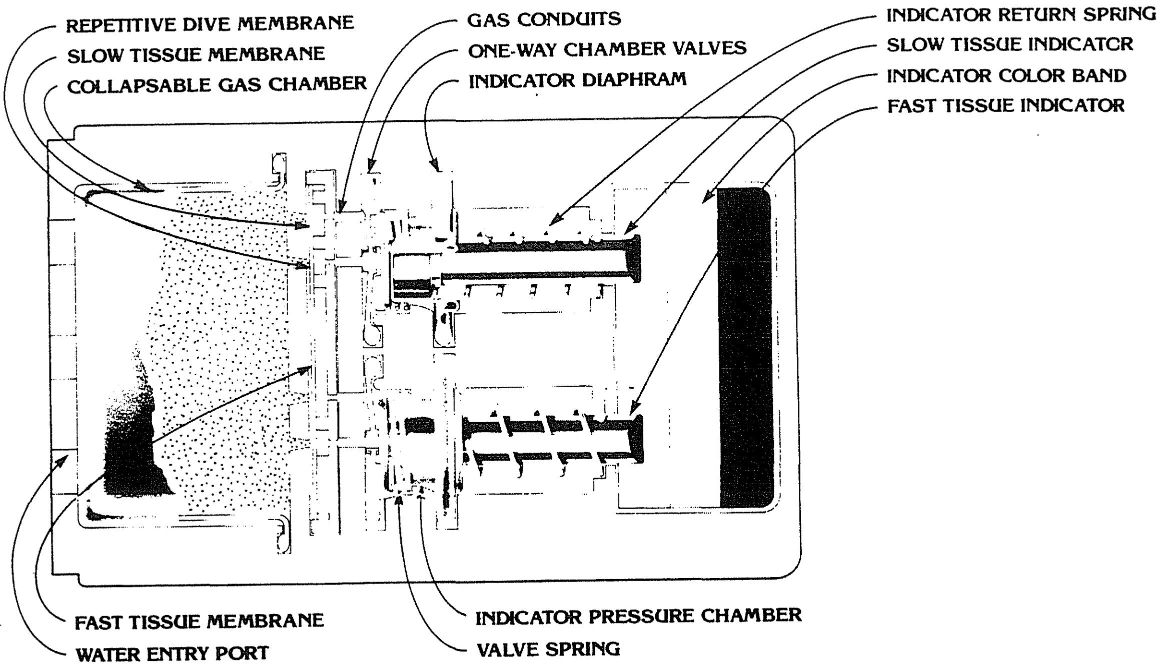

Figure 6.5. Farallon Decomputer.[24]

consisted of a depth gauge face with two needles: one to indicate the diver's present depth, and the other to indicate the depth to which the diver could safely ascend.

The unit was small enough to fit into a housing 9 cm in diameter and 18 cm long, which could be easily carried by a scuba diver. Another version of the device, called the MARK VIS, was designed utilizing the same algorithm for hyperbaric chamber use. Figure 6.4 gives the schematic diagram for both the MARK VS & VIS.

The MARK VS was produced by Spar Aerospace in the late 1960s for sale to industrial and military agencies with operational depth limits to 200 fsw. In 1970, Spar developed a smaller and lighter version operational to 300 fsw. Due to the complexity of construction, high manufacturing costs, and extensive maintenance and calibration requirements, the MARK VS computer was not a commercially viable product for sport divers.

GE Decompression Meter

General Electric designed a decompression meter in 1973 which utilized semipermeable silicon membranes to simulate nitrogen diffusion.[4] These membranes operate better than porous resistors since the simulated half-time of a compartment does not vary with depth (as in the SOS meter). A four-chamber device was built to simulate the U.S. Navy air decompression tables using compartment half-times of 24, 39, 90, and 144 minutes. Initial evaluations by GE showed that the membrane-based decompression meter concept was sound. The size of the unit could be reduced and temperature dependence was "well within satisfactory limits." However, no information on any subsequent development and testing is available.

Farallon Decomputer

As scuba diving entered the mid 1970s the only commercially viable decompression computer available was still the SOS Meter. All other attempts to develop a reliable and safe decompression meter did not succeed or resulted in a product too expensive for the average sport diver. In 1975, Farallon Industries in California released a device called the Decomputer. The device was a pneumatic analog computer which used semipermeable membrane technology. It had four membranes which simulated two theoretical tissue groups. Two of the membranes were used for gas uptake and the other two for elimination. Figure 6.5 shows the schematic of this device.

Air from the collapsible gas chamber flows through the "fast tissue" (large) and "slow tissue" (small) membranes when exposed to elevated pressures. The increased pressure within the mechanism causes the pistons to move along the display. The display, color-coded green, yellow, and red, indicates the diver's decompression status. The object was to never surface with the pistons in the red, or upper yellow, portion of the display. When the ambient pressure is reduced to less than the pressure inside the tissue simulator, the air flows out through the "repetitive dive membrane". Both compartments had off-gassing membranes which simulated a slow off-gassing rate.

Testing at Scripps Institute of Oceanography indicated that the device failed to "approximate" the U.S. Navy air decompression limits and tables.[12] Some allowable no-decompression limits were: 60 fsw for 75.5 minutes; 80 fsw for 51 minutes; 150 fsw for 12.5 minutes, and; 190 fsw for 7 minutes. Tests using the device for repetitive dives proved even less acceptable. The Royal Australian Navy also evaluated the Decomputer, and found that it was too permissive and it developed too much mechanical deterioration with use.[5]

DIGITAL DEVICES

By the mid-1970s the microprocessor revolution was well underway. Now it was possible to construct a small digital computer dedicated to the specific task of decompression computation. Digital computers are more accurate than mechanical analog computers and have fewer calibration problems than electronic analog computers. However, a major drawback with these early digital computers was the lack of an adequate power supply.

DCIEM XDC Digital Decompression Computer Series

DCIEM began work on the XDC Digital Decompression Computer Series in the mid-1970s. Due to their previous success with pneumatic decompression computers, they elected to use the Kidd-Stubbs decompression model with their digital computers.

DCIEM's first computer, the XDC-1, was a desk-top model. It was used to analyze dive profiles or plan upcoming dive operations by accepting dive profile information through the keyboard. It can also be used in a real-time mode where the diver's depth information is supplied via a pressure transducer and an A/D converter. The decompression status is determined by computing the nitrogen pressure accumulated in the four compartments of the Kidd-Stubbs model.

During the dive, the operator could extrapolate the dive profile and determine required decompression debt based on numerous dive options.[15,25,26] The XDC-1 was manufactured by Canadian Thin Films Systems Inc. in British Columbia and successfully used in laboratory hyperbaric facilities. However, the design was not practical for open water diving situations.

To handle the rigors of diving operations, DCIEM designed the XDC-2. This computer is a dedicated real-time decompression computer used with surface supplied diving operations. The unit can be connected to a pressure transducer carried by the diver or connected to the pneumo hose on the diver's umbilical. The decompression model in the XDC-2 was the same Kidd-Stubbs model used in the XDC-1. The output information of the XDC-2 consists of four large LED displays and two arrays of LED indicator lamps. The main information supplied by the four large LED displays is:

- Depth.
- Elapsed Dive Time.

- Safe Depth (depth to which the diver can ascend safely without violating the model).
- No-Decompression Time/Ascent Time Display. When the diver is within the no-decompression limits this display will show the no-decompression time remaining if the diver stays at that depth (a negative number). If the diver goes into a decompression dive this display will give the optimum ascent/ decompression time (a positive number).

One array of LED lamps presents a bar graph showing the safe ascent depth and the other array is composed of warning lights that indicate the system's status. The unit runs off a standard 110V AC line and has internal rechargeable NiCd batteries that power the unit for two hours if the AC power fails.[27] The unit can also run off an external 12V DC power supply. The XDC-2 is still used in the Canadian Navy, with slight modifications to the Kidd-Stubbs decompression model software. The main limitation with the XDC-2 is that it requires the diver to be tended from the surface because the computer cannot be carried by the diver.

To accommodate the free-swimming scuba diver, the XDC-3, or Cyberdiver, was developed. The Cyberdiver was the first diver-carried microprocessor-based underwater decompression computer.[23]

This device, which attached to the diver's tank, and its small hand-held display presented the same information as the XDC-2. The unit was powered by four 9V batteries with a lifetime of about four hours. The batteries could be replaced without losing the existing decompression information. To conserve power, since the display LEDs had a large current drain, the display was equipped with an inertial switch that would turn the LEDs on for six seconds for reading. The XDC-3 met with limited success because of its high power requirements. DCIEM was just a few years ahead of its time, since low power CMOS microchip technology was not readily available at the time of the Cyberdiver's development.

DACOR Dive Computer The most effective way to use microprocessor technology in decompression computers is to program the decompression model into the microprocessor software program, as in the XDC series. Another less efficient way to utilize microprocessors is to store established tables in the memory, and design the software to read those tables. In this configuration, any advantage obtained by integrating the decompression status over the entire dive is lost.

The Dacor Corporation was interested in designing and producing an underwater decompression computer during the late 1970s. They decided, due to liability reasons, to design a diver-carried computer which would read the U.S. Navy air decompression tables for the diver.[6] In the first section of this chapter, choice "a" in the Groves and Monk report stated that a diver would need a table, depth gauge, watch, and wits. Dacor's solution combined the first three items and eliminated the diver's need for wits.

Dacor was prepared to market the unit, but the power consumption in the device was so high that it required a special battery to allow it to continuously run for at least twelve hours. This, and the high demand for microchips in the toy industry, finally caused the project to be shelved.

Cyberdiver II

Kybertec (now Newtec) in British Columbia which worked with DCIEM on the XDC-3, or Cyberdiver, entered the sport diving market with Cyberdiver II in 1980. Like the Dacor computer, it read the U.S. Navy air decompression tables. It also connected to the high pressure hose of the regulator and displayed the diver's tank pressure. Its power supply was one 9V battery which provided six-to-twelve hours of continuous operation, depending on water temperature. However, there was a way to save previous dive information if the battery was changed. The unit had an audio warning system to indicate hazardous decompression situations.

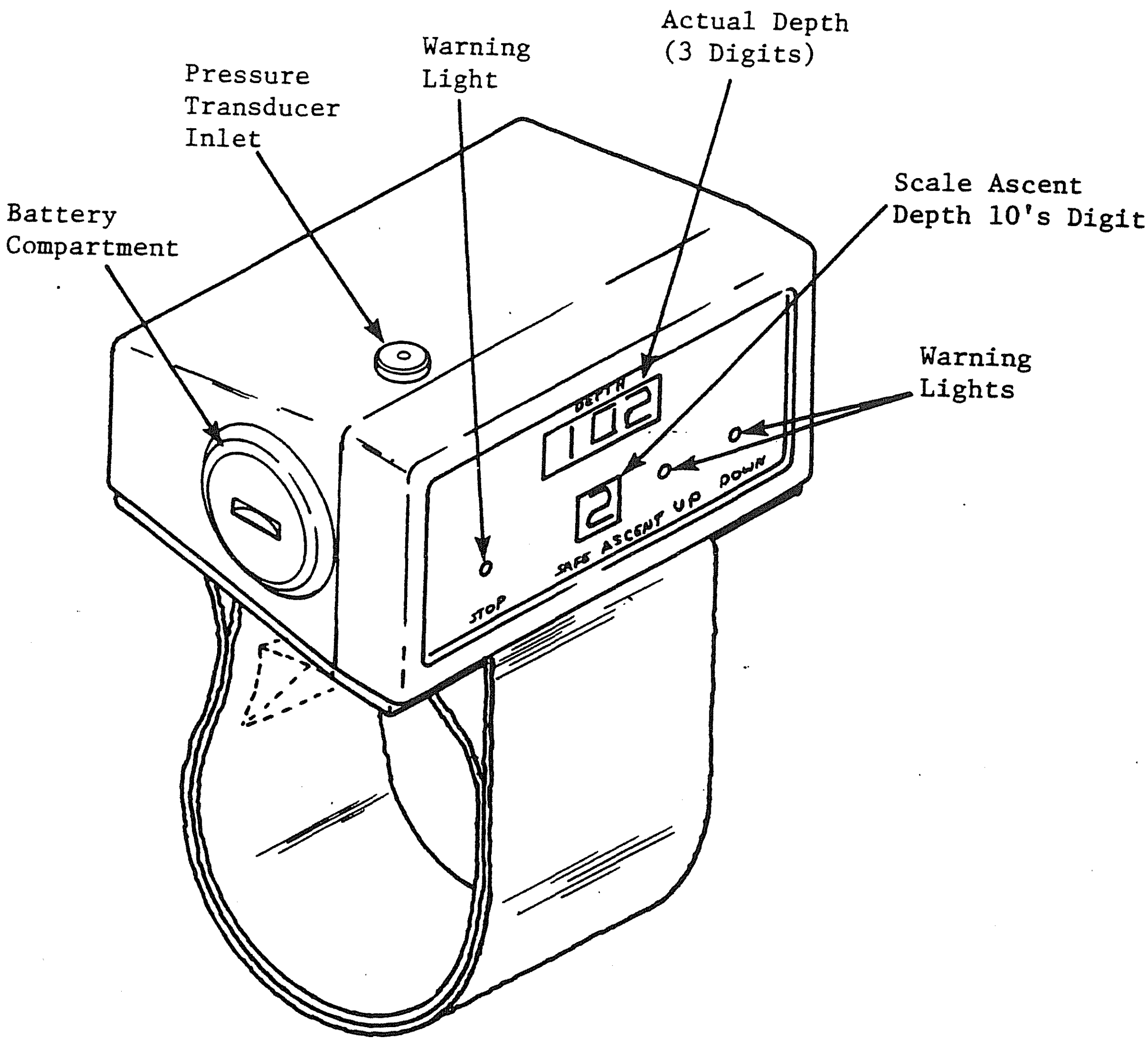

Figure 6.6. Prototype of U.S. Navy Underwater Decompression Computer.

The Cyberdiver II met with some marketing success, but the primary complaints were that it was too bulky and the calibration system was too complex.

Cyberdiver III

In 1981 Newtec returned to a decompression model instead of a table to determine decompression status with the development of the Cyberdiver III. The Cyberdiver III uses the Kidd-Stubbs model, like the original Cyberdiver. The decompression status is displayed in graphical form using five LEDs which indicate the diver's safe ascent depth and safe ascent altitude for flying after diving. Like the Cyberdiver II, the Cyberdiver III attaches to the high-pressure hose of the regulator, and the size of the two units is almost identical. The Cyberdiver III was slightly more successful than the Cyberdiver II, but it did manage to start to get divers interested in model based, digital dive computers.

U.S. Navy UDC

Since 1980 NEDU has been developing a decompression model and algorithm to program into an UDC to be used with their constant partial pressure of oxygen closed-circuit mixed gas system.[19,20,21] Initial plans called for the use of the "E-L Algorithm" to be used to calculate decompression status. However, at this time it is unclear what the final algorithm will be.

Figure 6.6 shows a preliminary design for the U.S. Navy UDC. This initial design incorporated only the "essential readouts for safely informing the diver of his decompression status." The display would show the present depth, a safe ascent depth (SAD), and three warning lights. The SAD display would present the first decompression stop depth as 10 fsw multiple. The "UP" light would indicate when the diver was deeper than the SAD, the "DOWN" light would illuminate when the diver was shallower than the SAD, and the "STOP" light would turn on when the diver reached the SAD. Decompression would be performed by moving up to the first decompression stop and waiting until the SAD decreases and the "UP" light comes on. At present, the specifications for the unit has been modified such that the display now includes total dive time, total ascent time (total decompression time required from present depth to surface), time required at decompression stop until it is safe to move to the next decompression stop, and a battery level indicator.[18] Prototypes from Divetronics, Orca Industries, and Tekna have been submitted to NEDU and preliminary evaluations performed. However, at this writing it is not clear if the U.S. Navy has an operational UDC.

Decobrain I

The Decobrain I was introduced to the U.S. in 1983. It was a table-based decompression device. The tables it used were the five sets of Swiss tables that were available at the time of its design. Each table could be used in a different altitude ranges from 0 to 3500 meters above sea level. Manufactured by a company in Liechtenstein called Divetronic, the unit, worn on the wrist, would display the diver's depth, bottom time, ascent time, and initial decompression stop. When the diver got within two minutes of the no-decompression limit, two zeros would blink in the decompression stop display. If a diver entered a decompression dive, the decompression stop display would present the first decompression stop depth and time. When the diver came within 5 fsw of the stop depth, the decompression time counted down to zero and the next decompression stop would be displayed. At the surface, the Decobrain displayed the maximum depth and bottom time of the previous dive, the surface interval, and the desaturation time (time required to eliminate all residual nitrogen). The power source was a rechargeable NiCd pack which allowed 80 hours of operation on a full charge.[10] The Decobrain was somewhat bulky and was designed to be worn only on the divers wrist.

When the unit was turned on it read the ambient air pressure and determined which of the five sets of tables to use. The decompression information for subsequent dives was based on the table range that covered the ambient pressure sensed at initialization.

A unique aspect of the Decobrain I was that, even though it was table-based, it allowed multi-level dives. This was done by having the computer perform multi-level computations using the table's repetitive group designators. The problem with this repetitive group technique is that only one tissue group in the model is considered. In this case it is the 80-minute half-time compartment. None of the other compartments are considered in the computation of the Swiss table repetitive groups.

Dr. Bruce Bassett and this author separately performed tests on this device and found that the unit could easily be put into an "out of range" situation, rendering the unit useless as a decompression device. Also, "*The technical information and operating instructions supplied with the product are sorely lacking in the details needed to adequately use and interpret the device.*"[2]

Decobrain II

In 1984 Divetronic decided to forgo their table reading program and utilize the actual Swiss model to determine decompression status in the Decobrain. This new Decobrain II outwardly looked exactly like the original Decobrain. In fact a Decobrain I could be upgraded to become a

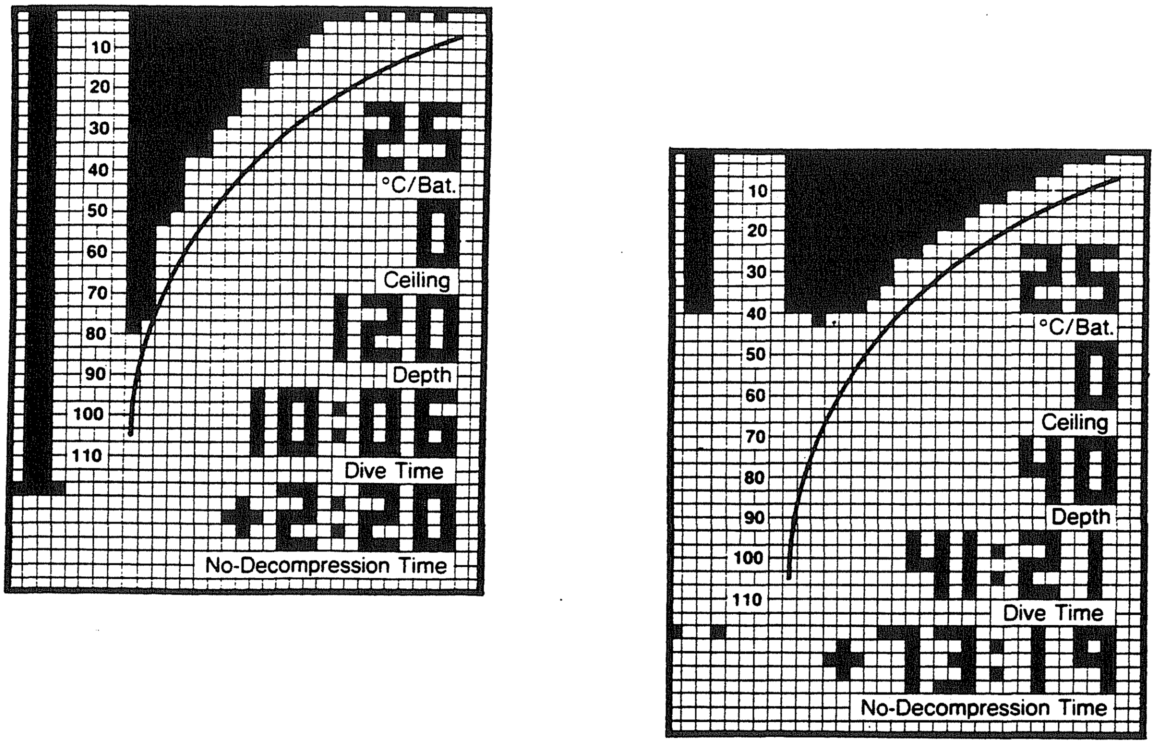

Figure 6.7. The EDGE No-Decompression/Decompression Computer display.

Decobrain II. This software modification eliminated many of the problems associated with the original unit.

Since decompression diving does not hold the same stigma for European divers as it does for U.S. based diving organizations, the Decobrains allowed for deep decompression diving. This fact, plus the software fix, helped to establish the Decobrain II as the computer of choice for many hard core deep decompression divers (eg. cave and wreck divers) worldwide.

The EDGE:

The Edge was manufactured and distributed by Orca Industries from 1983 to 1991. It was the first commercially viable model based dive computer, and over the years has attracted a loyal band of followers. Bruce Bassett, in a review, stated that the introduction of the EDGE, *"brings an innovation to sport divers equal to the original introduction of scuba."*[3] The model it uses is a twelve compartment Haldanian model based on Spencer's Doppler research.[29] The compartment half-times range from 5 to 480-minutes. Every three seconds the "nitrogen pressure" in the compartments are updated based on the new pressure that is read in through the pressure transducer. The EDGE's case was made out of aluminium making it one of the most rugged dive computers ever produced. There are stories of the EDGE being used as a hammer and as a club to ward off sharks.

The display on the EDGE (Figure 6.7) is divided into graphical and digital information. The display is split into the two sections by a curve (limit-line) which represents the maximum pressure allowed in the twelve compartments (their Mo values). The display area above and to the left of the curve, gives a bar graph representation of the pressures in the twelve compartments against a depth scale (running vertically down the left side of the display). As long as all the compartment bars are above the limit-line, the model is indicating a no-decompression dive and the diver can ascend directly to the surface. To the left of the depth scale is the depth bar, which represents the divers actual depth and a maximum depth indicator. All the compartment bars will try to equilibrate to the same level as the depth bar. If any of the compartment bars have crossed the limit-line, two "ears" start to move down the depth bar, indicating the ceiling, or minimum depth, the diver can ascend to without violating the model. To decompress the compartments that have exceeded their Mo values, the diver must ascend to a depth shallower than the value of the Mo value of the violated compartment in order for the required off-gassing to occur.[1]

The graphical display is the feature that seems to have endeared the EDGE to many divers. When ORCA Industries filed for bankruptcy at the end of 1991, and before its resurrection as ORCA a Division of EIT, there was a "panic" from many EDGE owners who were concerned about being able to maintain their EDGE.

SUMMARY

In the years since the introduction of the EDGE and Decobrain, there has been a virtual explosion of dive computers available to divers. At the start of 1991 there were 23 dive computers to choose from.[28] Description and evaluations of the available dive computers can be found in the book, "Dive Computers - A Consumer's Guide to History, Theory, and Performance" from Watersport Books (See sidebar).

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7
HOW DIVE COMPUTERS WORK

WHAT IS A DIVE COMPUTER?

What is a dive computer? A dive computer is just that, a computer. It does not monitor the amount of nitrogen in a divers body. All a dive computer does is automatically compute the divers' theoretical decompression status. This is done by reading in the depth and time and then by using either a table or model, (which is programmed into the dive computer), the decompression status is determined by reading the tables or running calculations against the model. This decompression status information is then displayed to the diver, who can use it as an **additional source of information** in the execution of a dive.[3,4,5]

Dive computers are relatively simple electronic devices. All, in some form or the other, have a structure like the one shown in Figure 7.1. The primary components of the dive computer are:

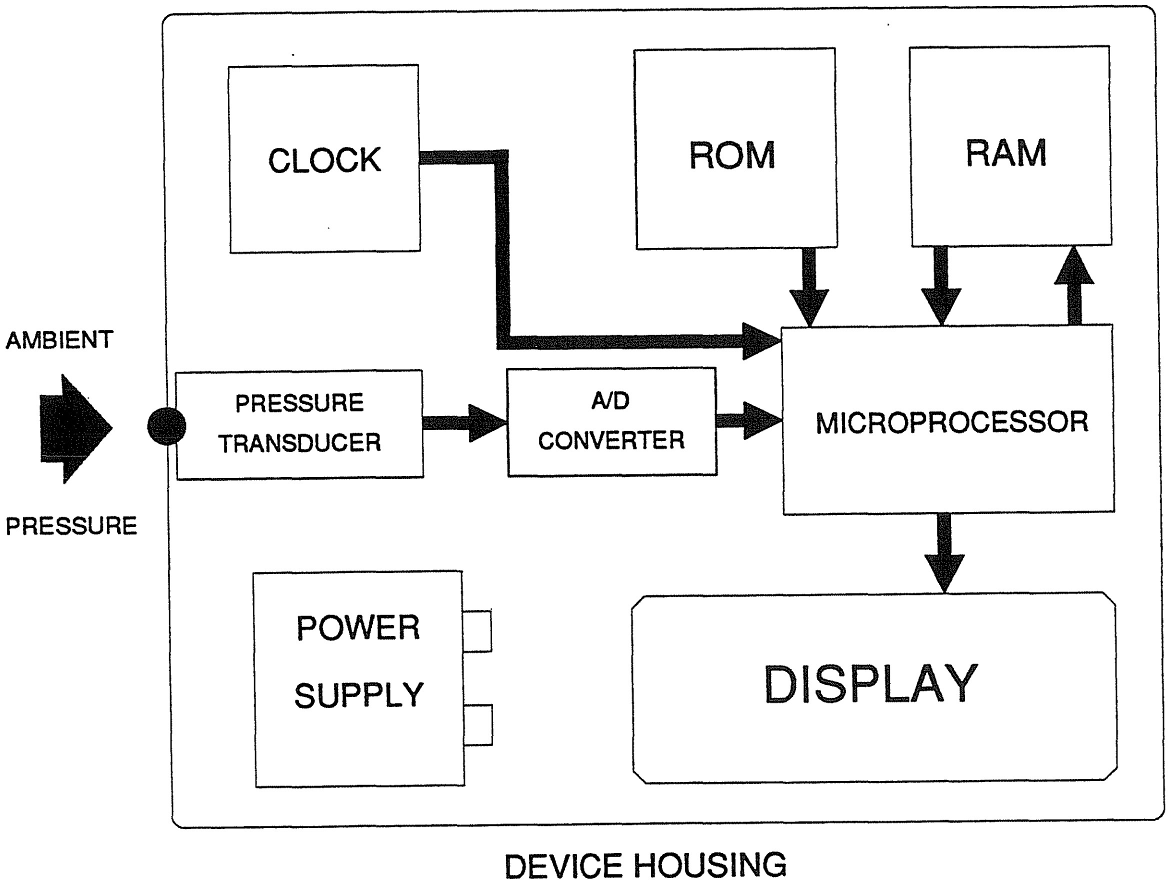

Figure 7.1. Generic Dive Computer Schematic.

- **Pressure Transducer**; The pressure transducer converts ambient pressure to a signal (generally a voltage level) that is fed into the analog to digital converter.
- **A/D (Analog to Digital) Converter**; The A/D converter takes the analog signal from the pressure transducer and converts it into a binary word that the microprocessor can manipulate.
- **Clock**; The clock is used in the timing of the computational steps and provides the time input for the calculations.
- **ROM**; Read only memory contains permanent information that the computer will always need, such as the decompression program and model constants.
- **RAM**; Random access memory is used to store the results of calculations during the dive. In some computers storage is set aside to store profile information. This memory can either be volatile (lost if the computer goes off or loses power) or nonvolatile (maintains information even if the computer is turned off).
- **Microprocessor**; The microprocessor is the "brain" of the system. It takes and executes the program steps that are stored in ROM and performs the calculations and sends the resulting information to RAM or the display.
- **Display**; The display is the interface between the computer and the user. It condenses all the calculations done by the system into a, hopefully, easy to read format that the diver can use to help in the decision making process of dive planning.
- **Battery**; The power source that runs the system. The size of the system, its current drain, and the size of the battery all play a part in determining how long the battery power will last.
- **Housing**; The housing protects the electronics from the aquatic environment. Early devices needed a rugged water tight housing that allowed the pressure transducer access to the outside pressure, but kept the innards dry. More recent dive computers are being "potted," or embedded in a slab of rubbery material. The potting protects the electronics from the water; plus the pressure transducer can now be placed directly on the circuit board since the outside pressure is transmitted through the potting material to the transducer. The housing is only needed to protect the display and to keep sharp objects from poking through the potting material and damaging the circuitry.

Many divers believe that dive computers just read established dive tables. This is not true. Only two of the dive computers that have been developed since 1982 have been table readers and both of these (Decobrain I and Suunto SME-USN) are no longer being distributed. The dive computers of today use a decompression model (algorithm) to **compute** the diver's decompression status.

Figure 7.2 shows a generic diagram of how a dive computer calculates decompression status. The dive computer uses the Initial Compartment Pressures [P_i(1-n)], the new ambient pressure the dive computer senses, the compartment half-times, and the update interval (1-5 seconds) to compute the New Compartment Pressures [P_t(1-n)]. Based on the new compartment pressures, the current ambient pressure, the compartment half-times, and the compartment M_o values [M(1-n)] the No-Decompression (or Decompression) times for each compartment is calculated [T(1-n)]. The shortest no-decompression (or longest decompression) time is then displayed to the diver as the Decompression Status. The Initial Compartment Pressures [P_i(1-n)] are then replaced with the New Compartment Pressures [P_t(1-n)] before the next update occurs and then the process starts over again.

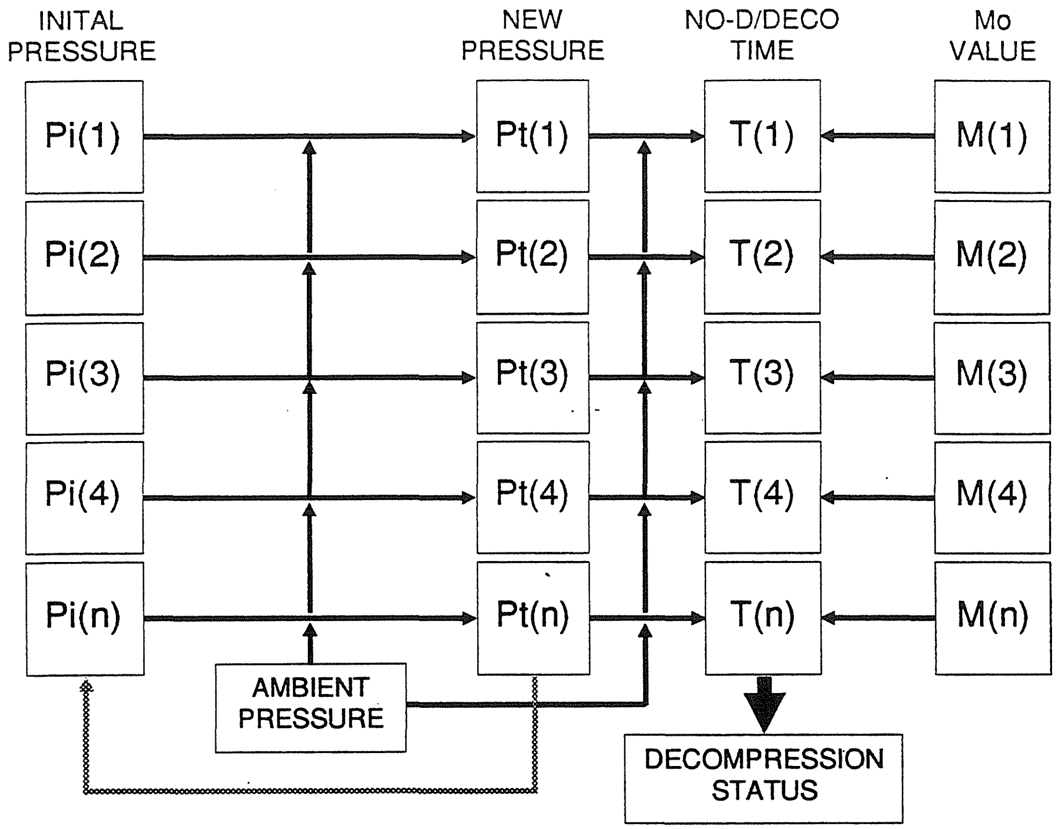

Figure 7.2. Generic Dive Computer Calculation Flow.

DIVE COMPUTERS VS. DECOMPRESSION TABLES

The algorithms used in dive computers are just mathematical formulas, which use depth and time as variables. They are much more flexible than tables. A pure mathematical model affords an infinite number of depth/time solutions. Dive tables are a finite, stagnant, listing of solutions, produced at certain depth and time increments, from a mathematical model. The implementation of a decompression model in a dive computer is not "pure." As with tables, the dive computer still deals with depth and time increments, only on a much smaller scale. These increments are based on the update interval of the computer (how often it recalculates the divers decompression status) and the resolution of the pressure transducer circuitry (the smallest change in depth it can detect).

The U.S. Navy no-decompression table has only 135 depth/time combinations for depths between 0 and 140 fsw. However, a dive computer that updates its calculations every 3 seconds and has a depth resolution of 0.5 fsw can distinguish 400 possible "square-wave" depth/time combinations in a one minute period over a 10 fsw depth range. This shows that even though dive computers work with discrete depth and time increments the number of possible depth/time combinations that a dive computer can resolve is magnitudes above a set of tables.

Tables also base decompression status on various assumptions. One assumption is that the entire dive was spent at the maximum depth. Another is that diver must assume that they were at the next greatest depth and/or time entry. Most recreational divers spend only a portion of their dive time at the deepest depth achieved during the dive. This means that during most of dive the diver is taking on less nitrogen than assumed by the tables. Model based dive computers that update the divers status every few seconds will compensate for the changes in depth. This allows the diver to be presented with decompression status calculations based on the actual dive that was performed. The advantages of computing decompression status in this manner includes:

- Profile Integration (no maximum depth - entire dive assumption).
- Takes shallow portions of dive into account.
- Actual Depth used in Calculation (eg. 51 fsw not 60 fsw).
- The entire model is taken into account when performing Multi-Level Dives.

However, many of these advantages produce potential safety disadvantages of dive computers verses tables:

- If the device is pushed to its limit the model is pushed to its limit.
- There are no safety factors programmed into the units, except for the conservative nature of the models themselves.
- In using tables, the maximum depth - entire dive rule adds a safety factor if the diver is at shallower depths during most of the dives.
- Rounding up to a depth or time value greater than the actual depth and time of the dive adds a safety factor.

Other disadvantages present themselves. A diver needs to read the device, understand the information that is being presented, and act upon that information. There is also the possibility that the dive computer will become a crutch. Some divers might use it as an excuse to not teach, learn, or use tables (just like BC's are being used by some to circumvent the teaching of proper weighting and buoyancy control). The major disadvantage, shared by tables and dive computers alike, is the fact that the dive computer or table only knows about depth and time.

COMPARING DIVE COMPUTERS TO DECOMPRESSION TABLES

Comparing dive computers to decompression tables is difficult. They are two different entities that may or may not have a common origin. A dive computer programmed with a model can respond quite differently from a set of decompression tables developed from the same model.

As we saw in Chapter 3, many assumptions were made in the development of the U.S. Navy Repetitive Dive tables. These assumptions took the original six compartment model and, in essence, created a new model. If the U.S. Navy decompression model was utilized in a dive computer, its results would start to diverge from the results of the tables. The following shows the perception of a U.S. Navy model based dive computer and the U.S. Navy Repetitive Dive tables to a dive series:

Prior to the First Dive to 120 fsw:

Table

According to the table the no-decompression time at 120 fsw is 15 minutes. This time is from the start of the dive to the beginning of a direct ascent to the surface at 60 fsw/min.

Computer

The dive computer is initialized at sea level and senses a total ambient pressure of 33 fswa. The ambient nitrogen pressure is 26.07 fswa. The six compartment pressures are initialized at a pressure of 26.07 fsw nitrogen pressure. In surface mode the computer calculates the time it will take the compartments to reach their M_0 values at various depths. In determining this time for 120 fsw the lowest of the six "no-decompression" times is 12.45 minutes, which is shown as a 12 minute limit for 120 fsw.

Ambient Pressure		Cmptment Pressure	NoD/D Time	M_o Value
26.07	C_5	26.07	* **12.45**	104.00
	C_{10}	26.07	15.28	88.00
120 fsw	C_{20}	26.07	19.12	72.00
Depth	C_{40}	26.07	23.70	58.00
12 min.	C_{80}	26.07	36.88	52.00
Deco Status	C_{120}	26.07	52.83	51.00
TIME: 0 min.		MODE:	SURFACE	

After Descent to 120 fsw in 2 minutes:

Table

According to the table, 2 minutes of bottom time have elapsed, leaving 13 minutes of no-decompression time remaining.

Computer

Ambient Pressure		Cmptment Pressure	NoD/D Time	M_o Value
120.87	C_5	38.36	* **11.45**	104.00
	C_{10}	32.50	14.27	88.00
120 fsw	C_{20}	29.36	18.10	72.00
Depth	C_{40}	27.73	22.68	58.00
11 min.	C_{80}	26.91	35.86	52.00
Deco Status	C_{120}	26.63	51.80	51.00
TIME: 2 min.		MODE:	DIVE	

During the 2 minute descent the six compartments have started to build up pressure. Based on these pressures and the current ambient pressure, the shortest time it will take a compartment to reach its M_o value is 11.45 minutes (5-min. compartment) resulting in the dive computer displaying no-decompression time remaining of 11 minutes.

If the remaining time of 11 minutes is added to the descent time of 2 minutes, the total allowable bottom time becomes 13 minutes, as opposed to the 12 minutes which was shown at the surface. Where did this additional minute come from? In the surface calculations the dive computer made the assumption of an instantaneous descent to 120 fsw. Since it took 2 minutes to descend to 120 fsw the compartments did not build up as much pressure as they would have if the 2 minutes were spent at 120 fsw.

After 15 minutes Bottom Time at 120 fsw:

Table

The no-decompression limit has been reached. The diver must start to ascend to the surface at a rate of 60 fsw/minute to avoid mandatory decompression.

Computer

Oops! We have stayed 2 minutes past the end of our remaining no-decompression time. The 5-minute compartment pressure now exceeds its M_o value. Decompression is required before being able to surface. All the other five compartments are below their M_o values, but the 10-minute compartment only has 1.27 minutes before it also exceeds its M_o value. The decompression status now indicates a ceiling (safe ascent depth) of 2 fsw.

Ambient Pressure		Cmptment Pressure	NoD/D Time	M_o Value
120.87	C_5	107.26	*** over**	104.00
	C_{10}	84.98	1.27	88.00
120 fsw	C_{20}	62.55	5.10	72.00
Depth	C_{40}	46.52	9.68	58.00
2 fsw	C_{80}	36.92	22.86	52.00
Deco Status	C_{120}	33.45	38.80	51.00
TIME: 15 min.		MODE: DIVE		

At 39 fsw During Ascent to the Surface at 60 fsw/min.

Ambient Pressure		Cmptment Pressure	NoD/D Time	M_o Value
56.88	C_5	103.75	inf.	104.00
	C_{10}	85.18	inf.	88.00
39 fsw	C_{20}	63.69	inf.	72.00
Depth	C_{40}	47.47	inf.	58.00
159 min.	C_{80}	37.51	*** 159.13**	52.00
Deco Status	C_{120}	33.87	236.22	51.00
TIME: 16 min.		MODE: DIVE		

Table

One minute and 21 seconds into the ascent. Surface will be reached in 39 more seconds.

Computer

Off gassing in the 5-minute compartment that has occurred during ascent drops the pressure below its M_o value. The required decompression obligation has been met. At 39 fsw the ambient nitrogen pressure is 56.88 and only the 80- or 120-minute compartments would be able to reach their M_o values at this depth. The one taking the shortest time is the 80-minute compartment, which would reach its limit in 159.13 minutes, resulting in a remaining no-decompression time of 159 minutes displayed (inf. = infinite amount of time allowed).

Upon Reaching the Surface:

Table

Diver is now in Repetitive Group "F" and will not be able to enter the Surface Interval table to calculate a repetitive dive until a 10 minute surface interval has elapsed. Group "F" indicates that a nitrogen pressure of 33.97 - 35.55 fsw was built up in the 120-minute compartment during the previous dive.

Computer

Ambient Pressure		Cmptment Pressure	NoD/D Time	M_o Value
26.07	C_5	98.77	inf.	104.00
	C_{10}	83.39	22.10	88.00
80 fsw	C_{20}	63.23	*** 11.85**	72.00
Depth	C_{40}	47.43	16.84	58.00
11 min.	C_{80}	37.53	37.87	52.00
Deco Status	C_{120}	33.89	63.97	51.00
TIME: 17 min.		MODE:	SURFACE	

Upon surfacing all the compartment pressures are below their M_o values. If our repetitive dive will be to a depth of 80 fsw then, according to the computer, the no-decompression time upon surfacing is 11 minutes. Physiologically, would it be wise to throw on another tank and do an immediate second dive to 80 fsw for 11 minutes? I think not! The consensus opinion is that this type of diving is "dangerous." However, the decompression model would not be violated by this dive.

Another point of interest is that the table Repetitive Group of "F" indicates a nitrogen pressure in the 120-minute compartment of 33.97 - 35.55 fsw while the dive computer shows a pressure of 33.89 fsw. This is because the table calculations assume an instantaneous descent to 120 fsw and the ascent to be 2 minutes spent at 60 fsw (midpoint between 120 fsw and the surface). These assumptions produce a pressure in the 120-minute compartment of 34.39 fsw which falls within the "F" range.

Following a 60 minute Surface Interval and Planning a Dive to 80 fsw:

Table

All the table "remembers" from the previous dive is the Repetitive Group "F." Following the surface interval, the Repetitive Group drops to an "E" representing a nitrogen pressure in the 120-minute compartment of 32.39 - 33.97 fsw. The table *asks*, "If the 120-minute compartment starts "clear" of residual nitrogen, how long would it take at 80 fsw for it to reach a nitrogen pressure of 33.97 fsw?" The answer, 23.12 minutes. This 23 minutes is the Residual Nitrogen time. The no-decompression time for a non-repetitive dive to 80 fsw is 40 minutes, but the 120-minute compartment has 23 minutes, at 80 fsw, worth of nitrogen pressure in it, leaving only 17 minutes of allowed no-decompression time for this second dive.

Computer

Ambient Pressure		Cmptment Pressure	NoD/D Time	M_o Value
26.07	C_5	26.09	inf.	104.00
	C_{10}	26.97	56.16	88.00
80 fsw	C_{20}	30.72	35.23	72.00
Depth	C_{40}	33.61	*** 33.27**	58.00
33 min.	C_{80}	32.88	47.79	52.00
Deco Status	C_{120}	31.60	70.99	51.00
TIME: 60 min.		MODE: SURFACE		

The computer's "memory" of the first dive is the nitrogen pressure in the six compartments. The 5- and 10-minute compartments are almost back to their "clear" starting pressures since twelve 5-minute and six 10-minute half-times have elapsed. To calculate the allowed no-decompression time at 80 fsw the computer determines how long it will take, at 80 fsw, for each compartment to get from their current nitrogen pressure to their M_o value. In this case the 40-minute compartment will take the shortest time, producing a no-decompression time of 33 minutes. Notice that it was the 20-minute compartment that controlled the no-decompression time of 11 minutes upon surfacing from the previous dive.

Why does the computer allow almost twice the no-decompression time as the tables do? The process of basing repetitive dives upon the 120-minute compartment adds conservatism to the model. The "clean" no-decompression time of 40 minutes for 80 fsw is controlled by the 20-minute compartment. By using a Residual Nitrogen time generated from the slow 120-minute compartment and subtracting it from a no-decompression time determined by the relatively fast 20-minute compartment, a level of conservatism is obtained.

After Descent to 80 fsw in 1.33 minutes:

Table

The diver has an Equivalent Single Dive Time of 24.33 minutes. Only 15.67 minutes of no-decompression time remain for this dive.

Computer

Ambient Pressure		Cmptment Pressure	NoD/D Time	M_o Value
89.27	C_5	31.91	inf.	104.00
	C_{10}	29.89	55.47	88.00
80 fsw	C_{20}	32.03	34.58	72.00
Depth	C_{40}	34.21	*** 32.65**	58.00
32 min.	C_{80}	33.19	47.16	52.00
Deco Status	C_{120}	31.82	70.34	51.00
TIME: 1 min.		MODE: DIVE		

The compartments have picked up additional pressure on the descent and now the remaining no-decompression time is based on these new pressures. If at this point we looked only at the 120-minute compartment, we would have 70 minutes of no-decompression time. However, 70 minutes would place the other five compartments into required decompression status.

After 17 minutes of Bottom Time:

Table

The no-decompression limit has been reached. In order to avoid required decompression, an ascent to the surface at 60 fsw/min. should be initiated.

Computer

Ambient Pressure		Cmptment Pressure	NoD/D Time	M_o Value
89.27	C_5	82.74	inf.	104.00
	C_{10}	69.23	39.80	88.00
80 fsw	C_{20}	56.02	18.91	72.00
Depth	C_{40}	47.30	*** 16.98**	58.00
16 min.	C_{80}	40.31	31.49	52.00
Deco Status	C_{120}	36.79	54.67	51.00
TIME: 17 min.		MODE: DIVE		

All the compartments are below their M_o values. According to the model, another 16 minutes can be spent at this depth without decompression being required. If ascent was initiated at this time the compartment closest to its M_o value would be the 20-minute compartment, which is only at 82% of its M_o value .

Now it starts to get real complex in attempting to compare tables to computers. The table has two options open to it. Surface, staying in no-decompression mode, or extend the bottom time out past the no-decompression limit and perform the required decompression. The computer has a multitude of options available to it. If the dive time at 80 fsw is extended to 20 minutes, the model in the dive computer is still within its limits; but the table would indicate 10 minutes of required decompression at 10 fsw.

If, after those 20 minutes at 80 fsw, an ascent is made to 50 fsw the table would still indicate the 10 minute decompression obligation, but the computer would show a remaining no-decompression time of 39 minutes.

Ambient Pressure		Cmptment Pressure	NoD/D Time	M_o Value
65.57	C_5	85.04	inf.	104.00
	C_{10}	74.48	inf.	88.00
50 fsw	C_{20}	60.92	inf.	72.00
Depth	C_{40}	50.56	*** 39.51**	58.00
39 min.	C_{80}	42.26	62.45	52.00
Deco Status	C_{120}	38.20	109.13	51.00
TIME: 20 min.		MODE: DIVE		

Spending an additional 20 minutes at 50 fsw still keeps the model within its limits. However, the decompression debt incurred on the tables is now 23 minutes at 10 fsw.

This example shows the difficulty in comparing dive computers to decompression tables, even though they may be based on the same underlying model. Imagine trying to find some degree of agreement between a decompression table and a computer which is based on a different model than the one used to create the tables.

The complexities of this type of comparison have not deterred people from making wide sweeping statements on the safety of dive computers with respect to U.S. Navy Decompression tables. These statements come both from promoters of dive computers and dive computer skeptics.[1,6]

Some supporters tend only to focus on the fact that the models in dive computers are more conservative than the U.S. Navy model and will allow less no-decompression time for a single square-wave dive profile, making computers "safer" than the U.S. Navy tables. Furthermore, they laud the dive computer's ability to allow more bottom time, due to multi-level dive calculation capabilities, without exceeding the model's limits (which, of course, are more conservative than the U.S. Navy model's). The general slogan is "Dive Longer - Safer" even though the dive computer model may permit profiles that are questionable from some peoples perspectives.

The harshest critics focus only on the fact that single no-decompression dive times are allowed that exceed the U.S. Navy no-decompression limits, even though these dives are multi-level. There is also concern that dive computers may allow repetitive square-wave dive times in excess of allowed U.S. Navy repetitive no-decompression times. From their perspective, devices which allow dive times in excess of what the U.S. Navy tables permit are unsafe and dangerous.

As with most issues, the "truth" (if it does exist) falls somewhere between the two beliefs. Depending on the type, depth, and sequence of a dive, and the model in the dive computer, there are three possible outcomes:

- The dive computer will allow more time than the U.S. Navy tables.
- The dive computer will allow the same time as the U.S. Navy tables.
- The dive computer will allow less time than the U.S. Navy tables.

All that can be concluded, if multi-level dives are not considered in the comparison, is that if the dive computer allows more time for a dive then the risk of that dive will be higher than the allowed table dive. If the times are the same then the risks should be the same. Finally, if the table permits more time than the computer, then the risk associated with diving the table to the limit will be greater than taking the computer to its limit. Just because the risk may be greater using one technique verses the other does not mean that one is "dangerous" and the other is "safe." The times allowed by both table and computer may produce a negligible risk of DCS for an individual diver on that day. Conversely, both times may produce a risk level which places the diver at a great risk of DCS that day.

When multi-level dives are thrown into the formula the risk comparisons get even muddier. Which would have a higher risk? A no-decompression dive to the limit of the U.S. Navy table (say 100 fsw for 25 minutes) followed by a direct ascent to the surface, or a multi-level dive to 100 fsw for 20 minutes followed by an additional 20 minutes at 50 fsw before ascending? No one knows for certain. Hypotheses have been formulated which theorize that multi-level dives hold less risk than square-wave dives, to the same maximum depth, with less bottom time. Some newer bubble dynamic models predict this.[2] However, there are not sufficient data collected at this time to confirm or reject these theories.

DECOMPRESSION MODELS VS. REALITY

What the dive computer understands and calculates, and what is actually occurring within the diver are two vastly different worlds. Decompression models do not actually represent what is happening in the body. All models do is attempt to produce depth/time combinations that are safe for most divers most of the time. Nearly all decompression models to date use only two variables, depth and time. These are the variables the dive computers use to compute the decompression status displayed to the diver.

There are many other factors that change the divers susceptibility to DCS. These include depth, time, breathing mixture, ascent rate, physical exertion, water temperature, physical condition, hydration level, blood alcohol, age, gender, etc. If two divers perform the exact same depth/time dive profile, one being a low exertion dive by a young, healthy diver in a warm Caribbean environment and the other, performed in cold water by an older, out of shape diver, who was working heavily, then the same decompression status will be computed by a dive computer (if the same dive computer model was used).

All the dive computer knows is depth and time. **A mathematical equation does not a body make!** Divers must be aware that they need to add safety factors based on their own physiological state and the diving environment, just like they have been taught to do in the use of the tables.

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8

USES AND ABUSES OF DIVE COMPUTERS

INTRODUCTION

Ever since the introduction of dive computers, divers have been developing imaginative, albeit somewhat misguided, ways of using them. This chapter looks at how dive computers are being used and abused. Cases in which dive computers have been used successfully will be presented along with cases in which problems have developed. Recommendations for diving safety from American Academy of Underwater Sciences (AAUS) workshops, will be presented, as well as suggestions for adding conservatism to dive computer use.

GENERAL MISUSES OF DIVE COMPUTERS

There seems to be some general techniques that have been developed by "clever" divers to squeeze every second of dive time that they can out of a dive computer. The reasons behind these abuses can be somewhat narrowed down to the following categories:

- Ignorance
- Laziness and/or Worship
- Arrogance
- Stupidity

These categories are represented by various activities. What follows are some of the practices, within these catagories, that are being performed by divers with dive computers.

Ignorance:

- **Regularly pushing unit to limits:** Many divers run their dive computers down to zero no-decompression time, ascend to a shallower depth, and then run the time back down to zero, pushing the decompression model in the unit to its limit.
- **Using outside operating range:** Some of the dive computers on the market are designed to be used only at sea level, or the first few thousand feet of altitude. However, some divers have used sea level dive computers "as is" at altitudes outside the model's operating realm. Another activity in this category is diving to depths that exceed the maximum depth range of the dive computer. What purpose is there in having a dive computer if it is being used on dives where it will not be able to calculate properly or be placed in an ERROR mode?
- **Diving outside of the "tested" envelope:** Many divers routinely dive to depths which exceed the depths used to test the dive computer's decompression algorithm, and perform may more dives a day then were ever tested. In this type of activity divers are basically performing uncontrolled human subject tests of the decompression algorithm.

Pushing the dive computer to its limit essentially indicates the diver's ignorance of individual variation in susceptibility to DCS. If they were aware that there is no real "line," but a grey zone, they might have second thoughts before pushing a dive computer to the limit.

Even if these divers were unaware of individual susceptibility, many manuals suggest that divers should not push the dive computer to its limit (if an attempt had been made to read the manual). Reading the manual also provides the operational limitations for the dive computer, which should eliminate the practice of using the dive computer outside of its operating realm.

From my perspective, another problem is that many divers have no urge to seek additional information on their dive computer. They make the assumption that their device is "safe" and dive with it, not knowing the background or validity of its decompression model. They do not know the amount of testing done on the model (types of dives, depth/time ranges, number of dives a day, etc.). Without this information they can easily dive outside the tested envelope of the dive computer model, making themselves uncontrolled human guinea pigs.

Even if divers do seek additional information, many times that information is not available. Dive computer decompression algorithms are considered by most manufacturers to be "proprietary" information and therefore are not always available for public scrutiny. Human subject testing done on actual dive computer algorithms is virtually non-existent. Most of the algorithms have been "validated" by extrapolating tests of other tables or models. When asked at an AAUS workshop, "How do you 'validate' your decompression models?", only one dive computer manufacturer indicated that they had performed any type of controlled human subject testing of their decompression algorithm. All the responses to this question are presented in Chapter 10.

Laziness/Worship

- **Blind trust in numbers:** Many divers think that because a dive computer is showing them exact numbers, that these numbers are **true**. As pointed out at the AAUS dive computer workshop, "They are like a small television, and people believe what they see on television."
- **Turn thinking over to a machine:** Some divers do not want to worry, or think about their decompression status, so they let a little box made out of silicon, metal, and plastic take over their thinking requirements.
- **Ritualistic dances praising dive computers:** Although this sound extremely silly there is a video tape of a group of divers at Truk Lagoon performing a ritualistic dance on the fantail of a dive boat with their EDGE dive computers. Even though this group's outlandish activity was "all in fun," there are many divers who have a personal attachment to their dive computers and they will not dive without them.

The problem I see in these situations is that the divers are unwilling to use the dive computers as tools. Instead they are allowing themselves to be lead by the dive computer. As we have seen in the previous chapter, all the dive computer can do is present a diver with the results of simple mathematical calculations based on a depth/time profile. Since the results of these simple calculations are so precise, and are sometimes presented to the nearest second, many divers *believe* that these numbers are right and have *faith* that the results apply to them personally. There is a hesitation or reluctance in this group of divers to ask why the dive computer is showing this information or how it came up with this information.

The numbers produced by the dive computer are only a guide to a diver's decompression status. The diver **must** be aware of the other factors that may influence susceptibility to DCS and add their own safety factors. The dive computer's information is not the gospel! Divers need to be able to think for themselves and understand the risks they are taking.

Arrogance:

- **Not reading, or ignoring, information:** Some divers will just ignore the information provided by a dive computer if they don't like the information displayed.
- **Ignoring ascent rate warnings:** Most of the dive computers assume ascent rates slower than the 60 fsw/min. U.S. Navy standard. However, some divers do not want to follow these suggested ascent rates even though it may place them outside the tested limits of the model.
- **Violate decompression requirements:** Some divers do not want to follow the suggested decompression requirements. They will surface before the dive computer indicates that it is "safe" to surface, based on its calculations.
- **Abusing safety features:** Some of the dive computers have safety features that allow a diver to "get out of" situations outside of its model or electrical limitations. Case in point, the EDGE dive computer has a maximum depth resolution of approximately 165 fsw. At that depth the ambient pressure register is storing the largest number it can resolve. If the diver were to descend further, the dive computer would not be able recognize the fact that the diver was at a deeper depth. In the EDGE a safety feature was added that assumes that the diver is at approximately 200 fsw any time the maximum depth has been exceeded. This assumption was designed to handle an accidental violation of the depth limit for only a moment or so. The diver upon noticing the faux pas could return to a shallower depth without having the unit stop its calculations. It was **not** designed, or tested, to allow divers to dive to 200 fsw. However, there are divers who pervert this feature to make dives to 200 fsw with the EDGE. Some even use it to depths deeper than 200 fsw. Why? In some cases another diver has told them they could do it, while in other cases they have misinterpreted information presented in the manual.

Why do these divers bother spending hundreds of dollars on a dive computer if they only ignore it when it suits their purpose? I don't know. Some responses given for these activities include, "I'm not a normal diver.", "I don't want to go up that slow.", and "I've gotten away with this before." This group is at the opposite end of the spectrum from the previous group (lazy worshipers). They will only use the dive computer information when it suits their purpose. However, if it starts to restrict their activity, they will choose to ignore it.

In the case of safety feature abuse, divers try to rationalize their behavior by redefining the dive computer's normal operating realm to include the dives they want to perform. Once they do this, they can then justify their diving by stating, "My dive computer said it was ok." Most of the time these divers don't understand how the dive computer works, even though they think they do. They will probably believe what they want to believe, and continue to dive the way they want to dive, until they no longer get away with it.

Stupidity:

- **Turning off unit to clear residual nitrogen:** Some divers, who do not like the repetitive dive information being shown by their dive computer, will actually turn it off to clear the residual nitrogen from the computer's registers, giving them more time on the repetitive dive. Clearing the residual nitrogen memory from the dive computer does not clear it from the diver's body!

- **Continuing to dive with a dive computer that did not initialize before the first dive:** There are cases where a dive computer did not initialize prior to the first dive. Upon surfacing the dive computer concluded its initialization process and considered itself at the start of a new dive series, having no memory of the first dive. Some divers have actually continued to dive the computer to its limit on subsequent dives even though they were fully aware that the computer was not operational during their first dive.
- **Hanging the dive computer:** One of the most ludicrous techniques observed. Some divers who violate the dive computer's ascent rate or have surfaced while the dive computer still indicates required decompression will tie a rope to the dive computer and hang it over the side of a boat to clear the warnings and prevent the dive computer from going into ERROR mode. If the ceiling is shallow enough (1 - 2 fsw) some divers "decompress" their computers in a camera wash bucket on the boat. What can one say? The computer understands depth and time. It has no idea if it is attached to the diver or not.

Why?!!!

Who knows.

HOW DIVE COMPUTERS ARE BEING USED

How are divers using dive computers in actual diving situations? In general, information on the actual dives being performed is hard to come by. Records of maximum depth and bottom time

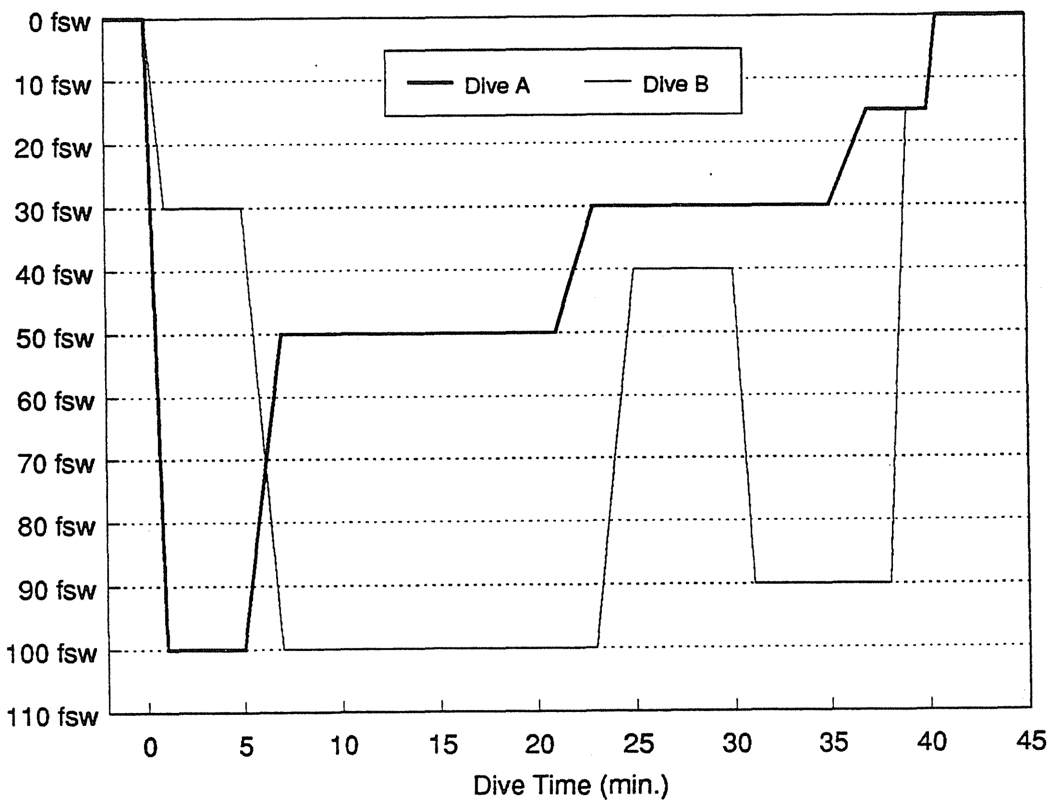


Figure 8.1. Dive A and Dive B have the same maximum depth and bottom time.

> **DISCLAIMER**
>
> Some of the profiles presented here are quite extreme. They are only reported as activities that have occurred. The author does not condone their practice!
>
> **NO ATTEMPT SHOULD BE MADE TO DUPLICATE THEM!**

are virtually useless when you consider the computer's ability to handle multi-level dives. Two dives with the same maximum depth and bottom time can quite easily be vastly different dives (Figure 8.1). Data currently is being collected in an attempt to understand the type of diving that occurs in the real world. The Diver's Alert Network (DAN) Doppler trips utilize dive profile recorders, and to date have collected over 500 dive profiles. In addition the Delphi, and Suunto's SME-ML and Solution dive computers store dive profile information which, hopefully, will be made available to researchers.

This section deals with some of the actual profiles and dive histories that have been collected regarding the use of dive computers in the field.

Some of the dives performed in the real world are so extreme that it is a wonder that these divers survive, in spite of themselves.

Galapagos Trip:

In 1987 a group ten sport divers were monitored during a 14 day dive trip to the Galapagos Islands. All the divers, except one, used a dive computer. Following 76 of the dives the divers

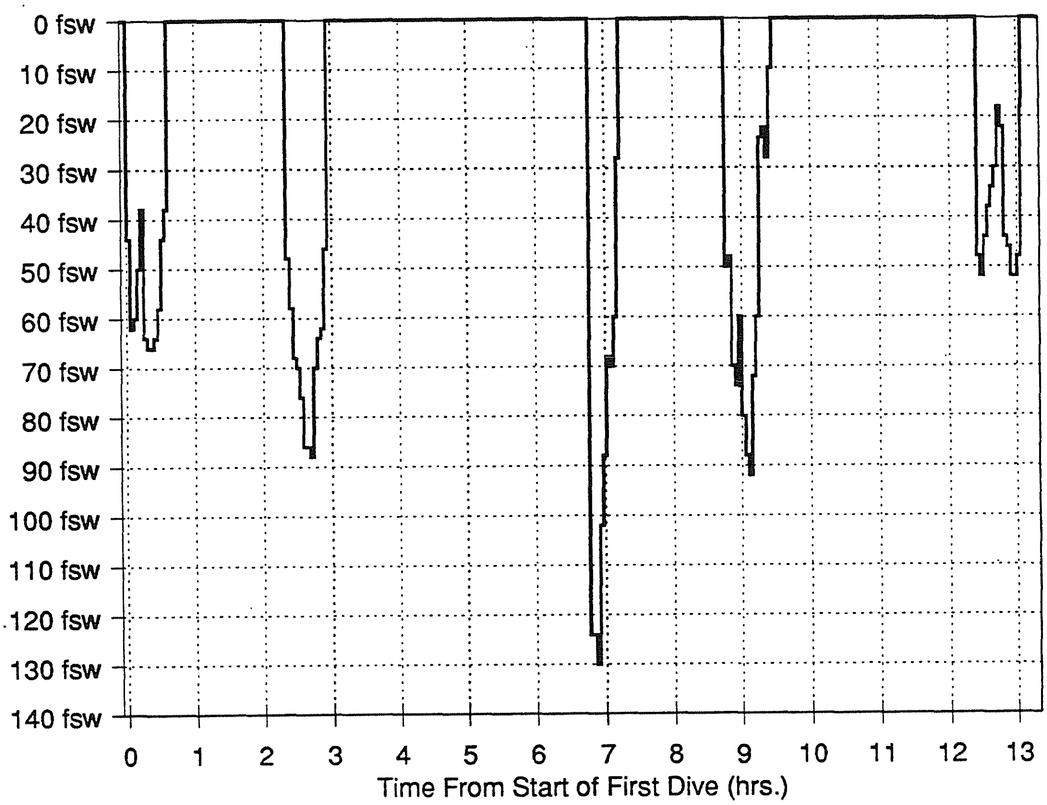


Figure 8.2. Day of diving in the Galapagos Islands.

were monitored using a Doppler ultrasonic bubble detector to check for "silent bubbles." On 65 dives the actual dive profile was recorded (maximum depth every 3 minutes).

When compared to the U.S. Navy tables, 52 of the dives indicated omitted decompression. The maximum omitted decompression time for a single dive was 71 minutes. The average was 23.0 minutes. For an entire day, the maximum omitted decompression was 145 minutes and the average was 46.2 minutes. The maximum time extended past the U.S. Navy No-Decompression limits was 55 minutes on a single dive (average of 23.8 minutes).

The profile data indicate that:

- 48.5% of the dive time was spent at depths which were between 75-100% of the maximum depth of the dive.
- 26.2% of the dive time was spent in the range of 50-75% of maximum depth.
- 16.3% of the time was in the 25-50% range.
- Only 9.0% was spent in the shallowest quarter of the dive.

This shows that, for this group of divers, the dive computers were not being used to make a short excursion to a deep depth, followed by the remainder of the dive in shallower water. Instead the computers were being used to extend dive time at the deeper depths.

Figure 8.2 shows the five dives performed by one of the divers in a single day. It is evident that the diver was not concerned about making the first dive of the day the deepest nor was there any indication of an attempt to perform the deepest part of the dive first and then work shallower. The diver was using the dive computer with no additional rules applied.

Little Cayman:

One of the more frightening series of dives, obtained from a DAN trip, involves a diver upon a live-aboard boat off of Little Cayman. Figure 8.3 shows a series of three dives to 190 fsw within a period of six hours! The first of the three dives looks as if it is a straight forward decompression dive with all of the decompression requirements taken at 30 fsw. The second dive, however, is a different story. What motivates a diver to repeat such a deep dive after so short a surface interval? Also, why does the diver proceed back down to 105 fsw after reaching 30 fsw? These are questions only the diver can answer. But then to follow these two dives with another 190 fsw dive just boggles my mind. I am certain that it would be very difficult to try to get a profile like this approved for human testing.

What was the outcome of this dive series? The diver did not report any signs or symptoms of DCS and Doppler monitoring showed only the mildest grade of bubbles following the last two dives.

Bonaire Dives:

Another series involves a diver in Bonaire who performed three dives in excess of 130 fsw in a period of about six hours (Figure 8.4). The difference between this diver and the one from Little Cayman is that this diver tended to do a deep bounce and then spend the remainder of the dive in shallow water without returning to deeper depths. The only time where there tends to be a deeper return is on the third dive where there was a quick excursion from 45 to 70 fsw. This diver is at least attempting to add a bit of safety to the use of the computer by spending lots of time at the end of the dive in shallower waters.

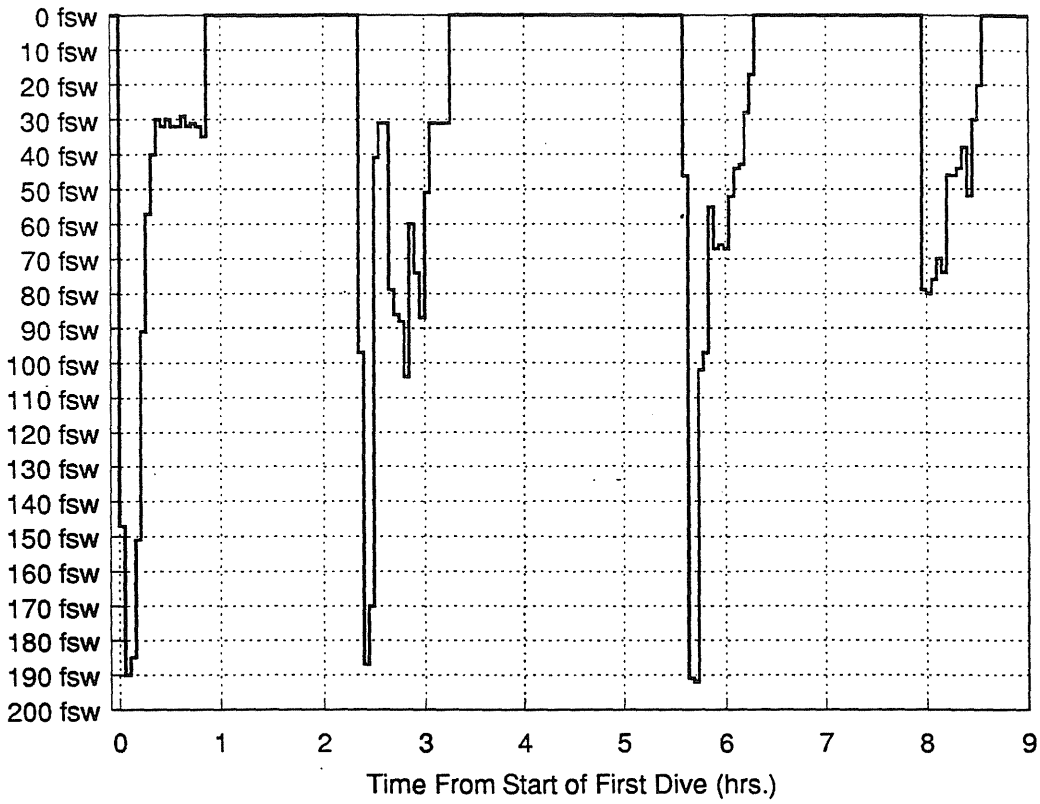


Figure 8.3. Day of diving off Little Cayman.

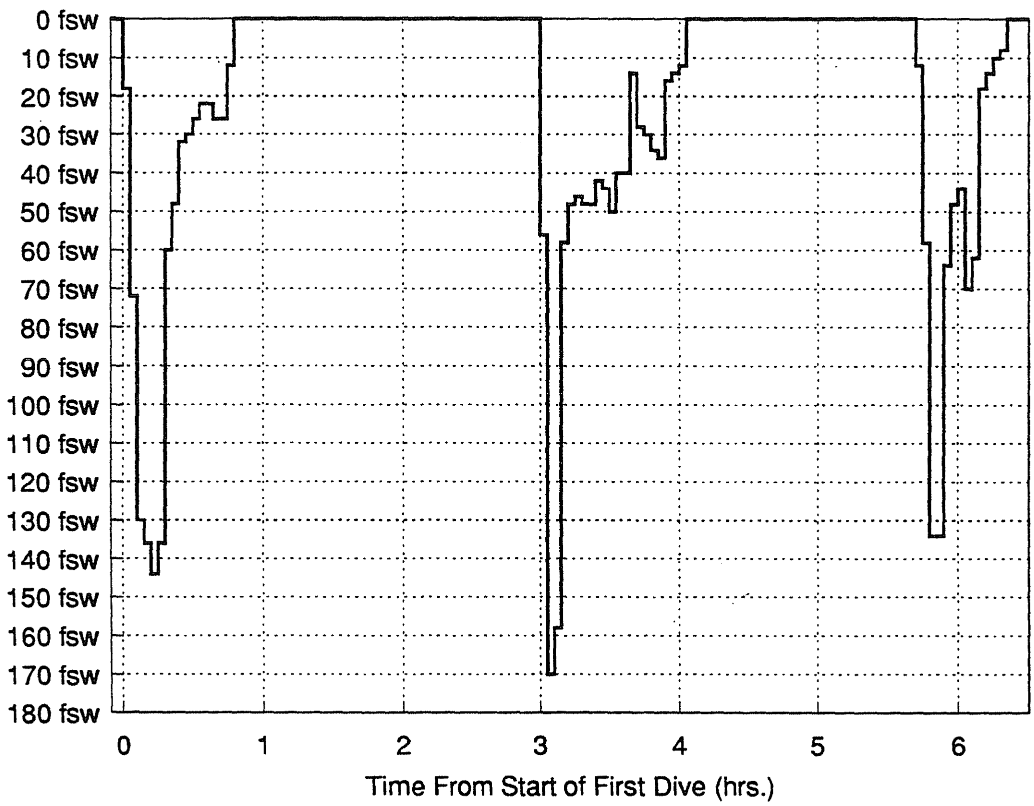


Figure 8.4. Day of diving in Bonaire.

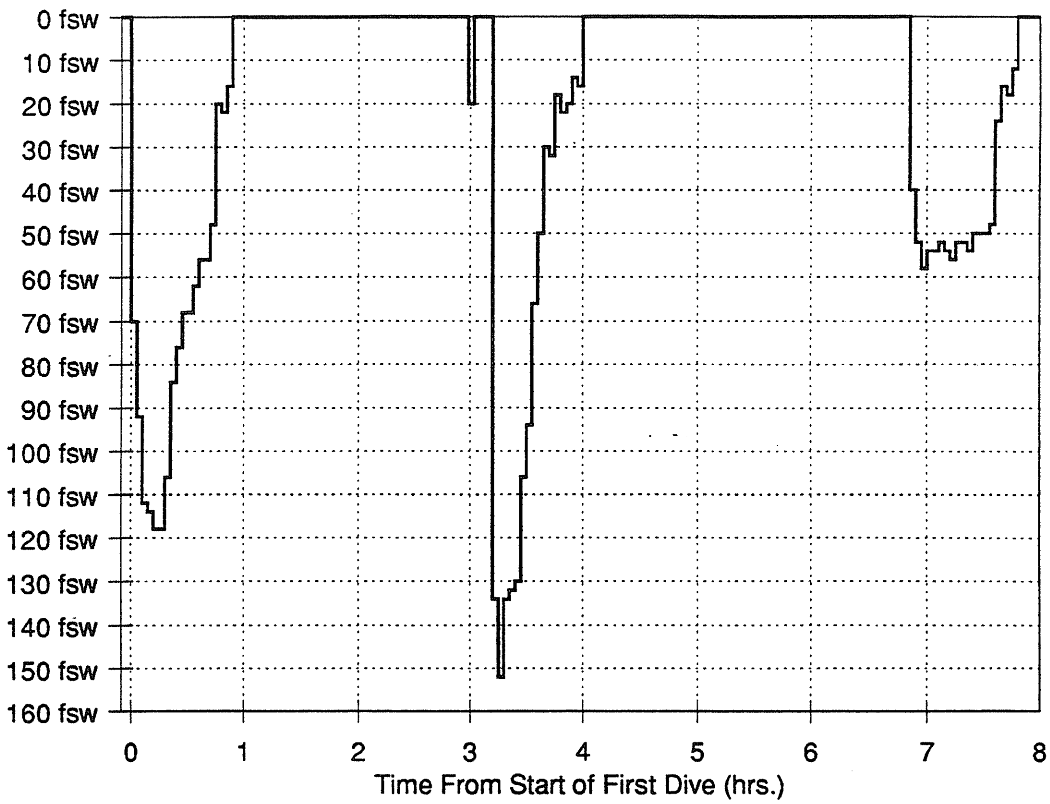


Figure 8.5. Day of diving off Papua New Guinea.

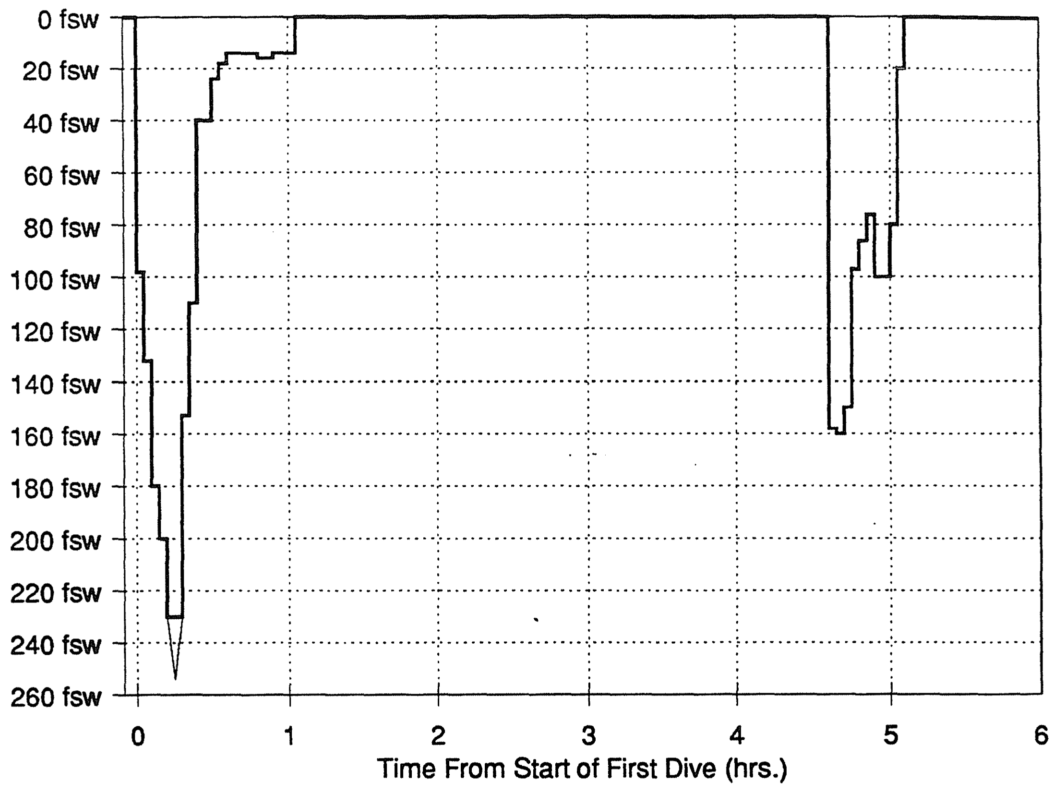
Papua New Guinea:

Following a trip to Papua New Guinea, John Lewis noted that the divers had added a few rules to their diving.[1] These rules were, that there should be at least a two hour surface interval between dives, and divers should surface with as little air in their tanks as possible. The reason for the second rule was that the divers were encouraged to "burn off" their tanks at shallow depths (30 fsw and shallower) as a safety stop before surfacing. Figure 8.5 shows a three dive day from this trip.

Some divers push their dive computers past their operational limits and end up in trouble:

Andrea Doria:

Mike Emmerman reported dive profiles that were being used on the Andrea Doria.[2] What he observed was frightening. Divers were doing 210 fsw dives, waiting 4 to 6 hours, and then performing the same dive over again. Some would do two dives a day and others did three! This was done three days in a row. Over 50% of the divers used dive computers. Some used dive computers that had maximum depth ranges that were shallower than the depths of the dives. Of the 16 divers on the trip six of them presented definite signs and symptoms of DCS! These six divers did express some concern for their condition, but at that time none of them sought treatment.



Courtesy of Dr. Tom Neuman, UC San Diego

Figure 8.6. Series of dives off of San Diego resulting in DCS.

San Diego:

Dr. Tom Neuman at the University of California - San Diego related a case of DCS where a diver and his buddy had been diving with dive computers.[3] The dive profiles indicated by the diver, during the interview, was a first dive to 254 fsw followed by a dive to 160 fsw 3-1/2 hours later. This profile was hard to believe until it was discovered that the computer the diver wore also recorded the dive profile. The profile was recalled (Figure 8.6) and it confirmed the dives, except that it showed a maximum depth on the first dive of 230 fsw. This was due to the fact that the maximum depth limit for the computer was 230 fsw. However, when the dive log information was retrieved from the buddy's dive computer (one that has a depth limit of 330 fsw) the maximum depth of 254 fsw was confirmed.

Other divers stay within the limits of the dive computer, but still push those limits with painful results:

Caribbean Vacation:

Another case involves a 26 year old male diver on vacation in the Caribbean using a dive computer. On the day the problem developed, the first dive was a no-decompression multi-level dive to 140 fsw for a total dive time of 56 minutes. Four hours later a second dive was performed to 160 fsw for 47 minutes. Both dives were within the limits of the dive computer. The diver noticed an onset of fatigue two hours following the second dive, however he decided to perform a third dive following a three hour surface interval. This third dive was a night dive to 47 fsw for 67 minutes. That night he had a restless sleep, cold sweats, and minor pain in the elbow.

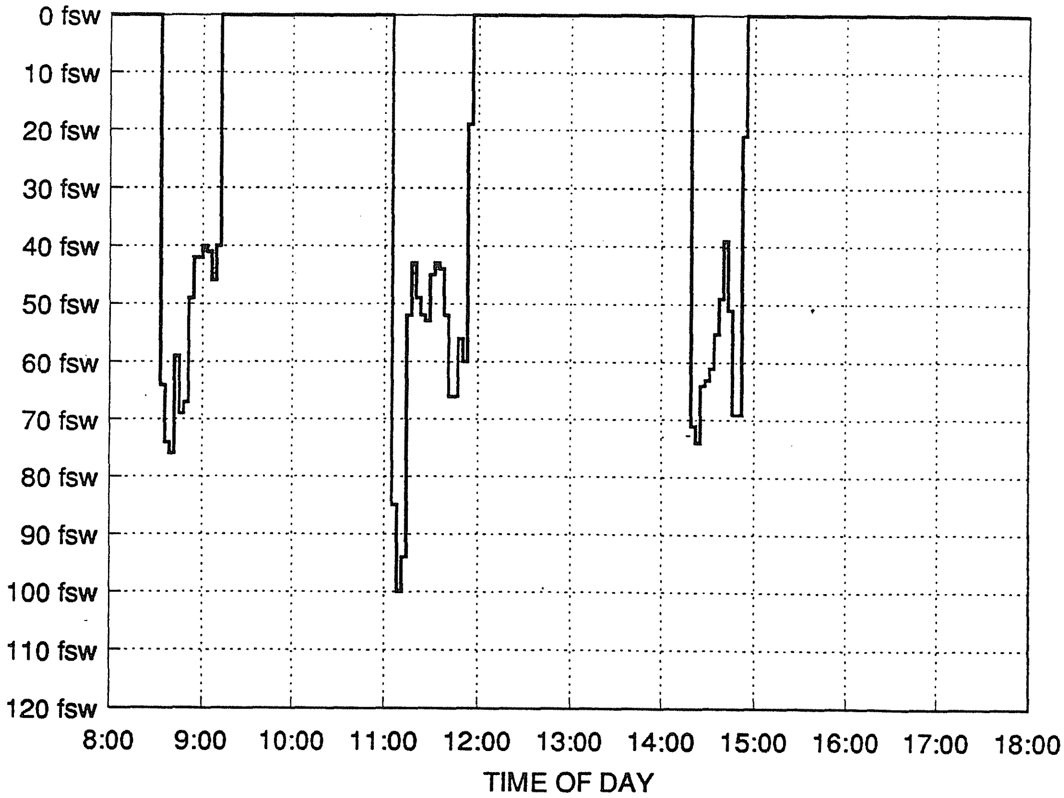


Figure 8.7. Truk Lagoon dives - Day 1

In the morning, the fatigue and pain remained, yet he proceeded to perform another dive. The dive was to 65 fsw for 40 minutes and during the dive he had relief from the pain. It was at this point that he concluded that he was probably bent. The morning after his revelation, the pain and fatigue remained along with a headache. He flew back to the states that day and sought treatment; four days after the dive series that produced the problem. After being treated on a treatment table 6, the diver showed no residual problems.

Truk Lagoon:

One of the more fascinating case histories involves a diver on a DAN trip to Truk Lagoon. The reason that it is so interesting is that all of the dives, over a period of two days, leading up to a case of DCS were recorded, and Doppler scores were obtained for all the dives on the first day and after the diver complained of DCS at the end of the second day. Figures 8.7 and 8.8 show the dive profiles over the two days. Notice that the dives do not seem to be as severe as some of the previous profiles shown where the divers evidently "got away" with their dives. Of additional interest is the end of the final dive where the diver returns to 15 fsw for a few minutes after surfacing. The reason given for this action was that the dive computer was very close to its limit and the diver wanted to perform some additional decompression. Evidently this additional time did not help prevent the onslaught of DCS, and the diver had to be evacuated to Guam for recompression.

Finally there are those divers who do not push the dive computer to the limit, but still end up with problems:

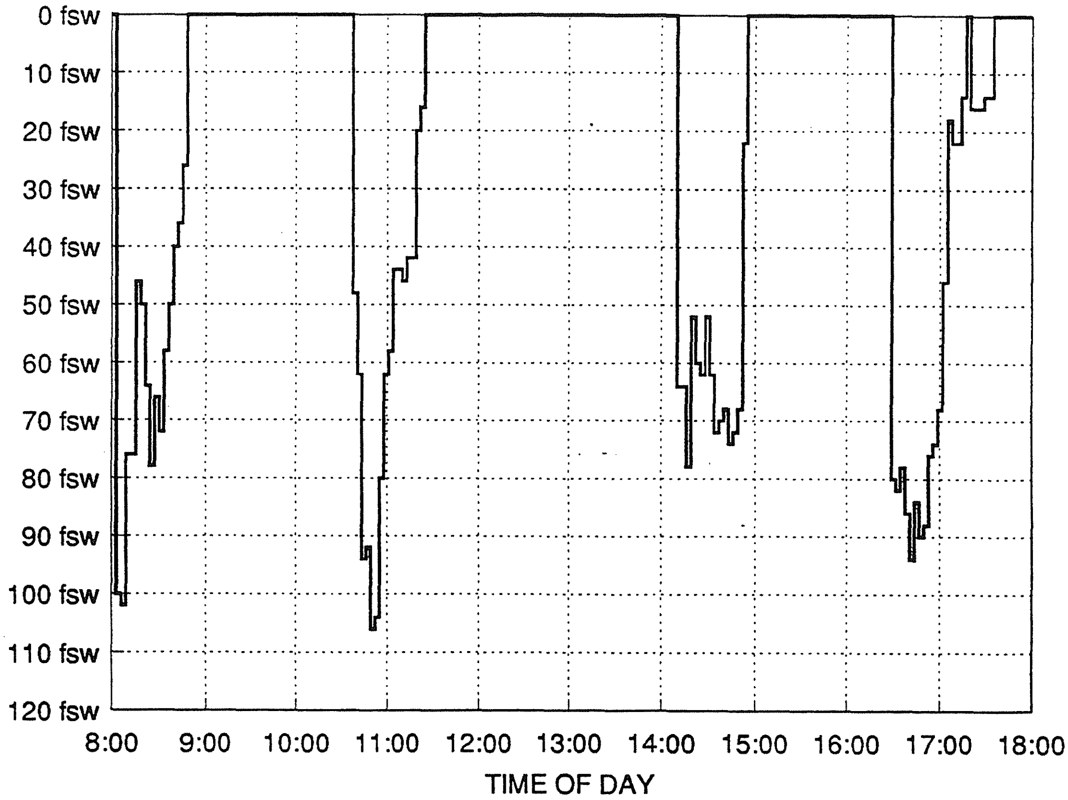


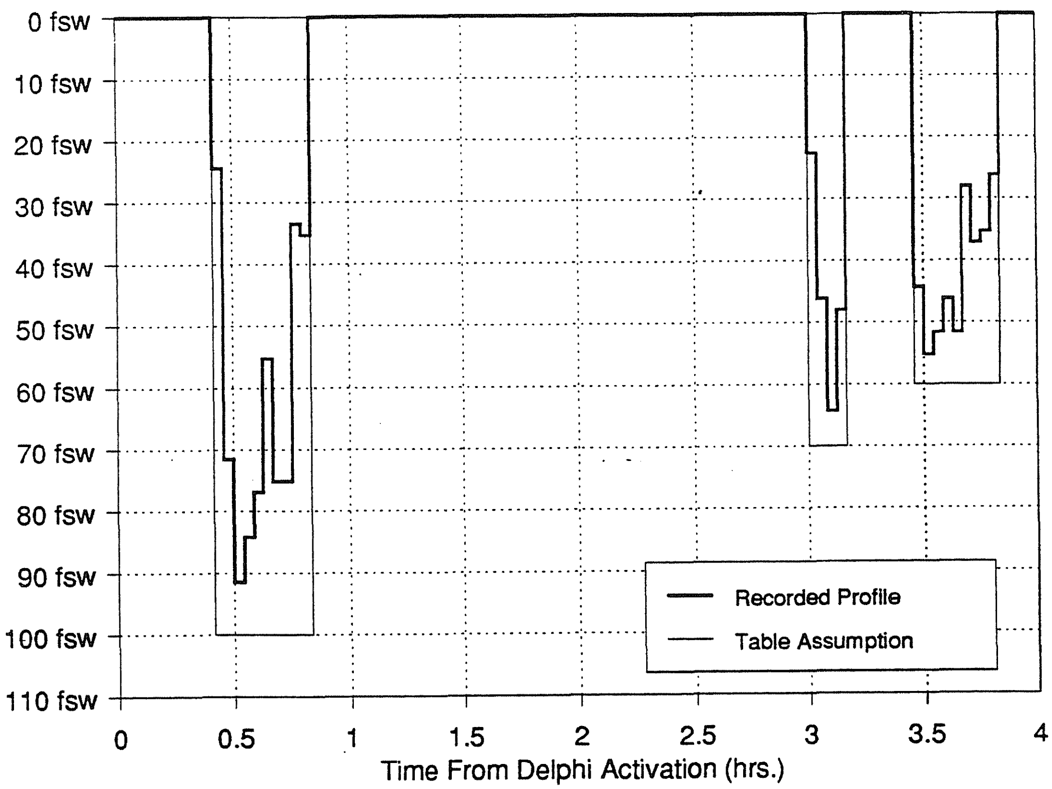
Figure 8.8. Truk Lagoon dives - Day 2.

Wreck of the Regina:

This case involves a 53 year old experienced female diver in excellent physical condition diving on the wreck of the Regina in the Great Lakes. She performed three dives to depths of 70 - 80 fsw using a dive computer. At no time was there less than 5 minutes of no-decompression time remaining on the dive computer. However, on the second dive the sleeve to her dry suit ripped exposing her arm to very cold water. Following the dive she had pain in her arm, but attributed it to the exposure to cold water. The suit was fixed and she performed the third dive. Later that evening, the pain in her arm became so severe that she could not tolerate it and she sought treatment. A major extenuating factor, besides exposure of the arm to very cold water, was that she had no hydration during the day (when she finally passed urine it was dark brown). There was no way for the dive computer to know that the dry suit had ripped or that the diver was dehydrated.

Northridge Chamber Treatment:

This final case involves a diver who was treated for a "minor" bends case at the Northridge Hospital chamber.[4] The diver suffered from elbow pain following a series of three dives. The dive computer the diver was wearing recorded the dive series which consisted of an initial dive to 92 fsw followed a couple of hours later by two dives, to 64 fsw and 56 fsw, in rapid succession (Figure 8.9). When these dives are run through the U.S. Navy tables, a decompression requirement of 7 minutes at 10 fsw is obtained at the end of the third dive. The U.S. Navy table calculations assume that the diver spent the entire dive at the maximum/rounded-up depth for the entire dive time. As it can be seen in Figure 8.9 the actual dive profile is multi-level and the diver only went beyond 90 fsw for a brief time during the first dive. If the U.S. Navy table



Courtesy of Orca Industries

Figure 8.9. Dives leading up to Northridge treatment.

calculations were done using 90 fsw for the depth of the first dive, none of the dives would have required decompression.

What does all of this tell us? Not much. No additional background information on the diver or the dive was communicated. The physiological and environmental factors of this dive "dealt" this diver a diagnosed case of DSC for this dive series. A series which was well within the "safe" envelope of depth/time calculations done by the dive computer.

THE DIVER'S RESPONSIBILITY

Divers need to realize that they have to take responsibility for their actions. They must acknowledge the fact that every time they dive there is risk involved. One of these risks is the possibility of developing DCS. A diver needs to make a risk-benefit assessment of the dive that is being planned. The goal of such an assessment is to maximize the benefit while minimizing the risk.

The operations and limitations of the dive computers being used need to be understood. The more the diver understands about the equipment being used, the more educated the decisions will become.

Don't push dive computers to their limits! Divers should add safety factors to the use of computers, just as safety factors are added to table use. Remember, all a dive computer knows about is depth and time. Dive computers are not anti-DCS talismen. They will not ward off bubble formation. Most of all, a diver needs to employ **common sense** in all phases of diving.

AAUS RECOMMENDATIONS

The AAUS has held workshops dealing with diving safety and dive computer use. The following are recommendations for general diving practices compiled from three of their workshops:

- Each diver relying on a dive computer to plan dives and indicate or determine decompression status must have their own unit.[5]
- On any given dive, both divers in the buddy pair must follow the most conservative dive computer.[5]
- If the dive computer fails at any time during the dive, the dive must be terminated and appropriate surfacing procedures should be initiated immediately.[5]
- A diver should not dive for 24 hours before activating a dive computer to use it to control his/her diving.[5]
- Once a dive computer is in use, it must not be switched off until it indicates complete outgassing has occurred, 24 hours have elapsed (whichever comes first), or if no more dive are planned over the next few days.[5]
- Non-emergency ascents are to be at the rate(s) specified for the table, or make and model of dive computer being used.[5,6]
- Ascent rates shall not exceed 60 fsw per minute.[6]
- A stop in the 10-30 fsw zone for 3-5 minutes is recommended on every dive.[6]
- Repetitive and multi-level diving procedures should start the dive, or the series of dives, at the maximum planned depth, followed by subsequent dives of shallower exposures.[5]
- Multiple deep dives should be avoided.[5]
- Breathing 100% oxygen above water is preferred to in-water air procedures for omitted decompression.[6]
- It is recommended that the attention of divers be directed, with emphasis on the ancillary factors, to decompression risk such as fitness to dive, adequate rest, hydration, body weight, age, and especially rate of ascent which should not be more than 60 fsw/min.[7]
- Divers are encouraged to learn and remember the signs and symptoms of decompression illness and report them promptly, so as to receive effective treatment as rapidly as possible to prevent residual injury.[7]
- The use of oxygen breathing on the surface, whenever possible via a demand regulator mask system, to insure the highest percentage of oxygen to the patient, is recommended while awaiting treatment if decompression illness is thought to be present. The use of 100% oxygen in the water while awaiting treatment is not recommended for recreational diving.[7]

ADDING SAFETY FACTORS

Much has been said about divers adding safety factors while diving. But just how is this done with dive computers? Some divers utilize the practice of allowing no less than 5 - 10 minutes of no-decompression time to be displayed on their dive computer. This method insures that the algorithm is not pushed to its limit. However, this does not provide the same safety margin for every depth. If the no-decompression time, displayed by a dive computer, for 130 fsw is 10 minutes then a 5 minute safety margin will give a 50% safety margin. While at 30 fsw, where the

TABLE 8.1
NEW TIME LIMITS FOR HYPOTHETICAL DIVE COMPUTER

DEPTH	NO-D LIMIT	PERCENT SAFETY MARGIN 0%	10%	25%	30%	50%
30 fsw	220 min.	0 min.	22 min.	55 min.	66 min.	110 min.
40 fsw	120 min.	0 min.	12 min.	30 min.	36 min.	60 min.
50 fsw	70 min.	0 min.	7 min.	18 min.	21 min.	35 min.
60 fsw	50 min.	0 min.	5 min.	13 min.	15 min.	25 min.
70 fsw	40 min.	0 min.	4 min.	10 min.	12 min.	20 min.
80 fsw	30 min.	0 min.	3 min.	8 min.	9 min.	15 min.
90 fsw	25 min.	0 min.	3 min.	7 min.	8 min.	13 min.
100 fsw	20 min.	0 min.	2 min.	5 min.	6 min.	10 min.
110 fsw	15 min.	0 min.	2 min.	4 min.	5 min.	8 min.
120 fsw	12 min.	0 min.	2 min.	3 min.	4 min.	6 min.
130 fsw	10 min.	0 min.	1 min.	3 min.	3 min.	5 min.

no-decompression limit is 220 minutes, the same 5 minute margin will only provide a 2.3% safety margin. In other words, the 5 minute margin will allow the model to be pushed to 50% of its limit at 130 fsw and to 97.7% of its limit at 30 fsw.

A method of maintaining a constant safety margin has been proposed by Paul Heinmiller of ORCA. It involves multiplying the no-decompression limits at each depth by the safety factor that is desired. If a 10% safety margin is wanted then all of the no-decompression times scrolled by the dive computer need to be multiplied by 0.10. This will give the shortest time permitted at each depth in order to maintain this margin. Using the previous example, the 130 fsw limit would be 1 minute while the 30 fsw limit would be 22 minutes. Diving until the no-decompression time equals 0 places the diver at the actual limits of the model. Diving up to these new limits will push the model to 90% of its limits. Table 8.1 shows the no-decompression limits of a hypothetical dive computer and the remaining time limits required to reach various levels of the model's limits.

Once the limits have been calculated for the specific dive computer and safety level, they can be transferred to a slate and taken on the dive. The diver then makes sure that the remaining no-decompression time at any specific depth does not fall below the new time limit.

CONCLUSIONS

It should be remembered that the advent of reliable dive computers should not give the "train em fast and easy" people in diving an excuse not to teach tables, and lazy divers an excuse not to learn tables or practice using the tables. I have talked to instructors who would have no qualms about having their students strap on a little black box that "tells" them their "decompression status" so that they would not have to teach dive tables. There are also cases where Basic students show up to their first pool sessions wearing dive computers. What incentive do they have for learning the concepts and use of dive tables?

No dive table or computer is 100% effective! Divers need to understand how and where the numbers are coming from, be it with tables or computers. They need to realize that the only variables these devices understand are depth and time applied to a mathematical model programmed into it. All they do is produce a depth/time envelope that hopefully is safe for most of the people.... most of the time.

Common sense and understanding must be part of the equation. Dive computers are tools, and as such can be used to enhance the diving experience, but they are only tools, not demigods to be worshiped and followed religiously. You do not want to end up like the diver being treated for DCS who, when asked, "What type of dive computer were you using?", answered,

"It was YELLOW."[2]

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THE DEPTH AND GAS DILEMMA
by: Lee H. Somers, PhD

INTRODUCTION

During the last decade, the recreational diving community demonstrated a renewed interest in deep scuba diving. In spite of instructional agency decree, increasing numbers of divers are answering the call of the deep. Mixtures of helium, nitrogen, and oxygen were used to extend scuba diving depth beyond 800 feet. This paper explores individual motivations, physiological responses, and diver responsibility associated with diving to depths beyond 130 feet. Human nature inspires individuals to explore the unknown and achieve the impossible. The diver has the right to confront the environmental, physiological, and psychological limits of depth. Unfortunately, today's educational programs do not address the true nature and limiting factors of breathing gases at high pressures. Although most recreational divers learn of nitrogen narcosis during deep diving specialty training, the potential problems associated with carbon dioxide and oxygen are seldom addressed. The roles of nitrogen-carbon dioxide synergism and elevated partial pressure of oxygen pose potential risks in deep air diving. Today, we stand on the threshold of modern high-technology diving with mixed gases and closed-circuit mixed-gas scuba. New technologies and improved training can, and will soon, enable recreational divers to venture to depths far beyond those recognized today. Individuals who choose to challenge the depths of our aquatic environment and extend beyond conventional limits must recognize their responsibilities to families, friends, and themselves. Diver education organizations must be prepared to meet the challenges of high-technology diving.

HISTORICAL REVIEW

In the late 1940s and early 1950s, a few recreational scuba divers breathed oxygen from closed-circuit scuba. However, by the mid-50s, Cousteau's compressed air Aqua Lung emerged as the dominate form of recreational scuba, and compressed air was the breathing gas of choice. Breathing gases such as 100% oxygen and mixtures of nitrogen-oxygen (nitrox), helium-oxygen (heliox), helium-nitrogen-oxygen (trimix), hydrogen-oxygen (hydrox), and hydrogen-helium-oxygen (hydreliox) were reserved for military and commercial divers.

Depth has been an allurement since humans first ventured into the underwater world. Soon after development of the first modern Aqua Lung, Frederic Dumas in 1943, dived to 203 feet breathing compressed air. In 1947, Cousteau's team (formed in 1943) made experimental compressed air scuba dives to 297 feet.[12]

In recent years, Andrea Doria dives have become popular. As I recall, it was July of 1956, when Peter Gimbel and Dumas made the first dive to the sunken luxury liner. Two weeks later, Ramsey Parks (LA County Lifeguard), Earl Murray (a Scripps geologist), Bob Dill (geologist at the Naval Electronics Laboratory in San Diego), and Peter Gimbel filmed the sunken vessel for Life Magazine. These pioneer scuba divers used compressed air scuba at a depth of about 240 feet for these dives.

In 1967, Hal Watts (personal communication) made a record compressed air scuba dive to 390 fsw, and in 1968, Neil Watson reached 437 feet. More recently (1989), Brent Gilliam completed a series of air dives in excess of 300 feet with an unofficial record dive to 452 feet (personal communication). In Lake Superior, 19 divers have dived to a particular shipwreck at a depth of approximately 250 feet. Apparently, two have died while diving on that wreck and two of the others while diving on other deep shipwrecks. The popular appeal and machismo associated with such deep dives tends to lure unsuspecting novice divers to depths beyond the capacity of their equipment, knowledge, skill, and physiology.

Today, recreational diving instructional agencies recognize 130 fsw as the maximum depth of compressed air scuba diving, and some recommend a limit of 100 fsw. In reality, recreational scuba divers, especially shipwreck and cave divers, often exceed these limits. Deep air diving has become quite fashionable in the recreational diving community. Published and unpublished accounts of recreational dives using compressed air scuba to depths of 200 to 300 fsw are not uncommon. Many recreational divers, including prominent certification agency instructor trainers, openly exceed the limits specified for recreational scuba diving. Unfortunately, they also get hurt. For example, during a five-day period in August of 1989, three Great Lakes shipwreck divers experienced decompression sickness, one experienced severe air embolism and decompression sickness, and one diver died. All were using compressed air scuba at depths of 190 to 250 feet.

In 1937, Max Gene Nohl dived to 420 feet in Lake Michigan using a self-contained helmet diving system and a mixture of helium and oxygen under the direction of Dr. Edgar End of Marquette University. The U.S. Navy conducted experimental dives to 500 feet in a chamber at the Experimental Diving Unit in Washington, D.C. The U.S. Navy conducted the first deep, operational heliox dives to a depth of 240 feet in 1938, during the rescue and salvage of the *Squalus*. Bollard of the Royal Navy completed a helmet dive to a depth of 540 feet breathing helium-oxygen in 1948. In 1954, Jean Clarke-Samazan made a 350 foot helium-oxygen scuba dive.[12]

By the late 1950s, heliox had caught the attention of an expanding commercial diving industry.[24] In 1962, Dan Wilson dived to 420 feet, and in 1967 Nic Zinkowski made a record dive in the Gulf of Mexico to 600 feet. The first commercial saturation diving job in the United States was conducted in the summer of 1965 (Smith Mountain Dam), and heliox saturation diving soon emerged as the dominate mode of deep diving. As commercial divers pushed beyond depths of 1,000 feet, they encountered new physiological problems -- high-pressure nervous syndrome (HPNS) and articular joint pain. In the mid-1980s Comex divers (French) successfully used hydrox during chamber dives to 520 meters to overcome HPNS and breathing resistance problems. In 1988 Comex divers saturated at 500 meters on hydreliox, and dove to 531 meters (1742 feet) for 4-hour works shifts in the open sea.[9]

The use of nitrogen-oxygen breathing mixtures[18] (other than compressed air) was recognized as early as 1943 and was used by the U.S. Navy with semi-closed circuit scuba beginning in the later 1950s. Nitrox diving was introduced to the scientific diving community in the early 1970s and is currently used for operational diving by several research groups. Nitrox was introduced to the recreational diving community in the mid-1980s and is currently gaining popularity. However, to my knowledge, only one major recreational diving training agency has embraced the concept. Nitrox is advantageous in extending no-decompression dive time in the depth range of 40 to 130 feet, however, it is not intended as a deep diving gas mixture.

Mixtures of helium-nitrogen-oxygen (trimix) have been used to varying degrees in commercial diving since the 1960s. However, it wasn't until the 1980s that adventurous recreational divers began serious experimentation with trimix. Deeper diving with gases other than compressed air has always been limited by the volume of gas that a self-contained diver can carry, facilities for lengthy decompression, and the availability of safe dive tables. The gas volume problem has been addressed by over-pressurizing scuba cylinders, multiple-cylinder scuba, staging techniques, and oxygen supplied from the surface for decompression. Bill Hamilton pioneered an effort to design special trimix dive tables for the recreational diving community. In 1988 Sheck Exley used staging techniques and Hamilton's trimix tables in his record dive to 780 feet.[11]

The cave and wreck diving communities have always maintained the "cutting edge" of advancement in recreational diving technique and technology. While the major recreational diving training agencies have been terrified and manipulated by the Great American Lawsuit Society, the cave and wreck diving communities have established their own standards. The national training agencies currently advocate no-decompression diving only, air diving only, open-circuit scuba only, and a depth limit of 130 feet (more ideally 100 feet). The recreational diving equipment manufacturers promote color coordinated diving equipment, high-performance regulators, and dive computers (some designed for air dives to 300 feet or deeper). The cave and wreck diving communities have embraced compressed air diving depths commonly exceeding 200 feet, trimix diving to approximately 800 feet, decompression diving, closed-circuit scuba, and a host of other advances in diving technology and techniques.

Today, we stand on the threshold of modern, deep, high-technology recreational diving. The commercial diving community was there in the early 1960s. Using diving bells, deck chambers, umbilical-supplied recirculating breathing equipment, active thermal protection, mixed-gases, and millions of dollars; they have extended their in-water diver working capability to nearly 2,000 feet. However, as they extended their depth, they recognized major logistical, economical, and physiological limitations. Today, almost 30 years later, atmospheric diving systems (ADS) and remotely-operated vehicles (ROVs) with force-feedback manipulators enable commercial divers to perform safe and productive work at great depths. Where will the recreational diving community be in 2020 AD?

DEEP DIVING PHYSIOLOGY: A BRIEF REVIEW

To remain underwater, humans must don a breathing apparatus and carry a supply of the atmosphere to depth with them. The air is fed to the diver through a series of valves and tubes which offer some resistance to air flow. As the diver descends deeper into the water column, the air, which must be breathed at ambient pressure, becomes denser. The diver must now work harder to breathe; and as a result, increased quantities of carbon dioxide are produced and retained by the body.

As the diver descends deeper and deeper, the gases -- nitrogen and oxygen -- begin to affect the central nervous system. Soon the nitrogen becomes intoxicating and at greater depths the oxygen -- so essential to sustaining life -- becomes toxic.

The brief review of diving physiology given below addresses only those conditions specific to breathing gases (primarily compressed air) at deep depths, and is not intended as a comprehensive discussion. Physiological conditions such as barotrauma, breathing gas contamination, and thermal stress are not addressed.

Inert Gas Narcosis

Among the major factors most likely to cause performance impairment in divers at increased ambient pressures is inert gas narcosis. Although the most common inert gas (nitrogen) associated with diving is physiologically inert under normal conditions, it has distinct anesthetic properties when the partial pressure is sufficiently high. The problem of compressed air *intoxication* has long been recognized by divers and researchers. Early researchers' inference was based on the hypothesis that narcotic potency is related to the affinity of an anesthetic for lipid, or fat, or the Meyer-Overton hypothesis.[5]

In fact, the narcotic potency of inert gases may be related to many physical constants including molecular weight, absorption coefficients, thermodynamic activity, Van der Waal's constant, and the formation of clathrates. Lipid solubility appears to give the best correlation, although polarization and molar volume are also important to the mechanism of narcosis which involves interaction of the molecule with the neuronal membrane. Consequently, the molecule size and the degree of electrical charge upon it are important considerations.[6]

Many theories of compressed air intoxication were advanced by various early investigators. Damant attributed part of the intoxicating effects to the increased oxygen pressure.[10] Bean, a University of Michigan physiologist, expressed doubt that nitrogen was the responsible agent. He contended that the sole causative factor is a rise in body CO_2 tension brought about by raised gas density.[2] Manifestations of anxiety and claustrophobia, a combination of all of the aforementioned factors, or the pressure itself have also been suggested as causes.[13] However, encephalographic studies by Bennett and Glass leave little doubt that high nitrogen pressure constitutes an important causative factor of compressed air narcosis.[5] Associated causes may include the density and oxygen partial pressure of the respired mixture which in turn, may cause an increased carbon dioxide tension that synergistically potentiates the narcosis.[3]

Several predisposing factors may advance the onset of symptoms and ameliorating factors may help to increase the tolerance to nitrogen narcosis. Alcohol, marijuana, and social drugs taken prior to diving greatly enhance the nitrogen effect. Alcohol and nitrogen become almost additive. Rapid compression will also facilitate the onset of narcosis. Hard work and fatigue will increase susceptibility as will any circumstance causing retention of carbon dioxide.

Acclimatization may also play a role in nitrogen tolerance.[13] Studies have shown that the mean additional time to solve mathematical problems at elevated pressures is reduced by 5 to 10 percent in acclimatized divers compared to non-acclimatized divers. Acclimatization is accomplished by frequent and progressive exposures to higher pressures. Unfortunately, the acclimatization effect probably diminishes in about a week.

Oxygen Toxicity

The toxic effects of excess oxygen breathing are of considerable importance in diving and hyperbaric treatment. The administration of 100% oxygen to humans continuously for long periods (generally exceeding 24 hours) at normal atmospheric pressure causes pulmonary manifestations. Under pressures slightly above 1.0 atmosphere for a sufficiently long time or at sufficiently high pressures (2.5 ata), humans develop central nervous system oxygen toxicity which can eventually lead to grand mal seizures.

Oxygen toxicity is a function of pressure and duration. The safe period of oxygen inhalation is further reduced by immersion, exercise, and carbon dioxide inhalation and retention. High pressure oxygen poisoning affecting the brain and causing convulsions can definitely occur at pO_2 of 2.0 ata and sometimes even lower. Central nervous system oxygen toxicity has been identified as the causative factor in an incident in which a diver convulsed at a depth of about 225 feet while breathing compressed air (D. Rutkowski, personal communication). This has led some individuals to suggest that the limit for compressed air dives of any type should be less than 218 feet (1.6 ata pO_2). Some physiologists consider oxygen toxicity to be a greater threat to compressed air divers at depths exceeding 200 feet than nitrogen narcosis.

Pure oxygen has been breathed during decompression since the 1950s to either shorten decompression or reduce decompression sickness risk. There are "stories" of divers developing symptoms of oxygen toxicity during decompression using scuba and apparently, at least one death has occurred. Oxygen decompression appears to be increasing in popularity among cave and wreck divers. There is certainly some potential risk of oxygen toxicity, especially at deeper stops, in oxygen sensitive individuals, and in individuals who have experienced exceptionally high doses of oxygen during extended exposures at depth.

Oxygen tolerance varies with individual divers and may also vary from day to day. Exercise while breathing oxygen increases susceptibility to oxygen toxicity. The Navy administers an oxygen tolerance test which requires breathing pure oxygen for 30 min. at 60 ft in a dry chamber. The US Navy recommends a 25-ft (1.6 ata) depth limit for a duration not exceeding 75 minutes.[22] Scientific divers breathing mixtures of nitrogen and oxygen currently use a 1.6 ata/30 minute limit.[18]

Carbon Dioxide Retention

Conditions which enhance the retention of CO_2 in the body include unusual exertion, inadequate ventilation, high oxygen tensions, increased density of breathing medium, and inadequate gas supply to ventilate the breathing system and remove carbon dioxide; this is extremely important under conditions of heavy exertion. Increased alveolar oxygen pressure affects the carbon dioxide response. Increased breathing resistance, due to apparatus design or gas density favors CO_2 retention and, therefore, decreases sensitivity to CO_2. Increased breathing resistance causes pCO_2 and exertion levels to rise in parallel, whereas ventilation response remains constant or even decreases.

If divers do not ventilate their lungs sufficiently to eliminate as much CO_2 as is produced, self-poisoning can occur. A number of accidents in which the diver has lost consciousness for no apparent reason have been explained on this basis. Deliberate reduction in breathing rate to conserve air in the use of open-circuit scuba is an extremely dangerous practice. Most authorities consider it better to breathe normally and consume more air than to practice periods of breath-holding between inspirations and risk the lethal consequences of CO_2 buildup.

Alteration of breathing pattern and reduction in breathing rate is somewhat normal for experienced divers at low exertion levels. It has become quite fashionable to breath lightly and conserve air. Many instructors and guides encourage air conservation techniques. In addition, deep divers use air conservation breathing techniques to increase dive time at depth with a limited air supply.

Some divers use a technique called *skip-breathing*. The diver draws a full breath and simply holds that breath for 20 to 30 seconds or more, exhales, draws another breath, and repeats the process. This pattern of breathing can lead to significant carbon dioxide retention. *If the process is carried to extremes, the diver can lose consciousness without prior respiratory warning from carbon dioxide poisoning*. The term "shallow water blackout" has also been used to identify this condition. Needless to say, skip-breathing is discouraged.Unfortunately, there is a fine line between acceptable air conservation techniques and skip-breathing. I certainly endorse techniques for efficient use of air supply; however, I discourage competitiveness and peer pressure techniques used to promote air supply conservation. Some individuals are more physiologically efficient and others will tolerate a slightly higher level of carbon dioxide without adversity.

Breathing Resistance

Resistance to turbulent flow of air or other gas mixtures within the bronchopulmonary system is proportional to the square root of the gas density. At great depth, work capacity is more directly determined by the effectiveness of pulmonary ventilation. The factor tending to limit complete ventilation at depth is that the density of the breathing gas mixture causes increased resistance to gas movement. One advantage of substituting helium and hydrogen for nitrogen is reduction in gas density. For example, the density of a helium-oxygen breathing mixture at 1,000 feet is about 4.3 times that of air at the surface, or about the same as breathing air at a depth of 110 feet.

Early studies demonstrated that divers equipped with scuba and breathing nitrogen-oxygen during exercise were impaired by a reduced ventilatory response. Divers whose pulmonary ventilation in response to exercise is inadequate for carbon dioxide elimination are more susceptible to carbon dioxide poisoning and oxygen toxicity. Furthermore, divers in poor physical condition produce significantly more carbon dioxide than divers in good physical condition.

Nitrogen-Carbon Dioxide Synergism

Nitrogen-carbon dioxide synergism is seldom addressed in the discussion of nitrogen narcosis; however, in recreational diving it may be an important factor. Synergism involves the combined action of two separate agents having a greater total effect than the sum of their individual effects if used separately. Recreational scuba divers encounter several factors that may influence carbon dioxide retention. First, some divers are less than physically fit. Poorly conditioned individuals produce and retain more carbon dioxide than highly conditioned individuals. Recreational scuba divers carry a limited amount of air and thus practice controlled breathing techniques. Improper breathing can result in carbon dioxide retention. The density of air increases significantly with depth. Normal breathing resistance afforded by the scuba, as well as potentially less than adequate pulmonary ventilation caused by higher density air, can lead to increased carbon dioxide retention. Finally, increased oxygen partial pressure also apparently enhances carbon dioxide retention.

Depth Blackout

Cave diving researchers have documented cases of depth blackout.[13] The victims simply appear to fall asleep with their eyes open and do not move except for breathing. For unknown reasons the sleeping victim apparently retains the scuba mouthpiece and continues to breath, lying inert on the bottom until their air supply is exhausted. Cases of 15 survivors (rescued by other divers) were analyzed. In all cases, the incident of blackout occurred on the individual's deepest dive up to that time, and the shallowest occurrence involved heavy exertion prior to blackout. Victims do not recall any symptoms prior to blackout. Authorities suspect that this condition results from a cumulative and combined effect of nitrogen, oxygen, and carbon dioxide.

Decompression Sickness

The term *decompression sickness* refers to the signs, symptoms, and basic underlying pathological processes caused by rapid reduction in ambient pressure (i.e., ascending from a dive). The basic underlying pathological process in decompression sickness is the local formation of bubbles in body tissue, both intravascular and extravascular. The resulting symptoms vary widely in nature and intensity depending on the location and magnitude of bubble formation. When the diver is breathing air, the primary constituent of these bubbles is nitrogen with a small fraction of carbon dioxide.

To understand the basic causes of the bubble formation phenomenon, it is necessary to examine what happens to air when breathed under increased ambient pressure. In accordance with the laws of physics that govern gas absorption, the amount of a given gas that will dissolve in a given liquid is determined by the percentage of that gas in the total mixture, the ambient pressure, and the solubility coefficient of the given gas. When the pressure of the gas mixture is increased, a pressure gradient exists between the tensions of the dissolved and undissolved phases of the gas. This gradient drives each gas into solution in proportion to its partial pressure until an equilibrium is established between the dissolved and undissolved phases of the gas. If the ambient pressure is then decreased, the tension of the gas in the dissolved phase exceeds that of the gas phase, and the pressure gradient is reversed. The factor of time for equilibrium to be established in either direction is a principal factor in the discussion of decompression sickness.

Nitrogen is the only principal component of air that is inert; it therefore is unaltered in the respiratory process and, for all practical purposes, quantitatively obeys purely physical laws. Consequently, at gaseous equilibrium, the partial pressure values of nitrogen in the alveolar air, venous and arterial blood, and body tissues are identical. Oxygen and carbon dioxide are actively functional in the metabolic processes and under ordinary diving circumstances, the metabolic cushion renders the tissue tensions of these two gases of little significance in the mechanism of bubble formation.

Nitrogen will not dissolve in all body tissue at the same rate or in the same amount. This is because nitrogen is transported from the alveoli to the tissue in solution by the blood. Consequently, tissues rich in blood supply will equilibrate at a faster rate than those having more limited circulation. Nitrogen is approximately five times more soluble in fat than in water; tissues high in lipid content (e.g., spinal cord, bone marrow, and fat deposits) must take up a proportionately greater amount of nitrogen before saturation (equilibrium) is reached. When the pressure gradient is reversed, the slowest tissues to release all extra nitrogen will again be those with limited circulation or high lipid content.

From the diver's point of view, the degree of tissue saturation and, consequently, the amount of time required for tissue desaturation (subsequent decompression time) is dependent upon the depth or pressure of the dive and the amount of time at depth. Unfortunately, individual physiological variables also influence tissue saturation and desaturation.

Bubbles tend to form in any tissues that are saturated with nitrogen whenever the ambient pressure is reduced to a point where a *steep* pressure gradient is driving the gas out of solution. Haldane first postulated that when the tissue partial pressure of nitrogen is more than twice that of the ambient partial pressure of nitrogen, symptom-producing bubble formation will occur.[14] Once this 2:1 threshold pressure gradient is exceeded, the number and size of symptom-producing bubbles formed will be directly proportional to the magnitude of the disparity between these two partial pressures. Under these conditions the rate of diffusion of gas from the tissues into the expired air, via the blood and alveolar membrane is too slow to cope with the nitrogen pressure. Hence, the nitrogen comes out of a solution locally in the tissue in the form of bubbles.

Spencer demonstrated that bubbles can be detected in the venous circulation using the Doppler bubble detector without giving rise to symptomatic manifestations of decompression sickness.[20] Bateman had previously suggested that some degree of bubble formation probably occurs whenever the tissue partial pressure of nitrogen even moderately exceeds that of the surrounding atmosphere.[1]

The above discussion would lead one to believe that internal gas bubbles is the principal factor in decompression sickness. These tiny bubbles are just one factor, possibly the initiating one, in the development of decompression sickness. Numerous changes in blood, including clumping of red cells, rouleau formation, shunting of blood in small vessels, and decreased platelet count, have been noted following decompression. Hemoconcentrations or fluid shifts and blood chemistry changes also occur. Numerous biologically active substances associated with *stress* have been observed in the blood of decompression sickness victims.

Obesity, physiological aging, excessive physical exertion during the dive, pre-dive physical condition, alcohol consumption, dehydration, and poor general physical condition are factors that may predispose an individual diver to decompression sickness . As previously pointed out, fatty tissues constitute a large nitrogen reservoir due to the 5:1 oil-water solubility ratio. During a deep or lengthy dive a considerable amount of nitrogen is dissolved in the body tissues. If the diver is obese, then during ascent the blood -- essentially a watery tissue -- will not be capable of transporting in solution the increased volume of gas evolved from the excess fatty tissues. Consequently, the blood will supersaturate and lead to intravascular bubble formation on the capillary level. This will result in subsequent supersaturation and extravascular bubble formation in *blocked* tissue. Aging introduces an increasing proportion of tissue with sluggish circulation and, therefore, the increased possibility of local bubble formation.

Excessive physical exertion increases the respiration rate and the rate of circulation of the total blood volume. Consequently, during excess exertion under pressure, larger amounts of nitrogen are transported to the tissue per unit of time than normally. Consider the circumstances where a diver is working hard underwater, e.g., moving heavy objects, swimming against a strong current, etc. This diver's tissues may absorb excessive nitrogen equivalent to 10-20 min. of extra diving time under normal conditions, and even if the diver is on a no-decompression dive schedule, he/she may suffer decompression sickness when surfacing without decompression stops. Poor physical condition is a direct extension of the above situation.

It has also been demonstrated that forceful movement of muscles and joints under increased ambient pressure results in an increase in bubble formation at those sites during decompression. Excessive carbon dioxide buildup in tissue has also been empirically and experimentally observed to lower the threshold for bubble formation during ascent. Scuba divers commonly use various methods (e.g., skip-breathing or controlled breathing) to lower air utilization and increase dive time. These practices can result in excessive carbon dioxide retention in tissue and could possibly be a factor predisposing a diver to decompression sickness.

Negative pressure breathing (as when using scuba), the effect of immersion, and trigeminal stimulation all trigger diuresis. This loss of fluid from the body via diuresis, combined with fluid loss associated with breathing dry air, causes a degree of dehydration which may well reduce the efficiency of the circulatory system. Reduced circulatory efficiency may in turn modify the normal nitrogen absorption/elimination functions and contribute to the formation of extravascular bubbles (i.e., decompression sickness). Consequently, it is possible that drinking large quantities of liquid (such as fruit juice and water) prior to and between dives could be significant in avoiding decompression sickness.

Most divers do not realize how important it is to avoid drinking alcoholic beverages before and between dives. The immediate apparent effects such as mental disorientation, impaired physical coordination, vertigo, poor judgment, and general physical weakness are serious enough in themselves to disqualify the diver. However, it is also an established medical fact that alcohol produces a diuretic effect thereby causing a dehydration of the body. This results in blood thickening and reduced circulatory efficiency which could contribute to the onset of decompression sickness. It is recommended that the diver refrain from alcohol before and, in the opinion of some physiologist, for a reasonable period of time after diving.

Although specific time periods between alcohol consumption and diving are not clearly defined in the literature, some authorities suggest that the diver should refrain for 12 to 24 hours prior to the dive. Consumption of small quantities such as wine or beer with dinner the evening prior to diving is a matter of individual discretion. However, those consuming large quantities of alcohol and exhibiting signs of intoxication are at a much greater risk of decompression sickness and should refrain from diving for *at least 24 hours*. Persons exhibiting signs of after effects of intoxication (hangovers) should not be permitted to dive.

Needless to say, these *modifying factors* cannot be overlooked in operational diving. If all of these factors were accounted for in standard dive tables, the tables would be impractical for normal diving and divers. Consequently, the discretion of the diving supervisor and the individual diver must be relied upon to take these factors into account when planning the dive schedule.

Dysbaric Osteonecrosis

Dysbaric osteonecrosis (aseptic bone necrosis or avascular necrosis) refers to destructive sclerotic and cystic changes in bone which are not infectious in origin. It may occur in association with a variety of conditions such as chronic alcoholism, pancreatitis, sickle cell anemia, and ailments stemming from pressurization and depressurization. Historically, dysbaric osteonecrosis has been known as caisson disease of the bone because it was diagnosed early in this century among compressed air tunnel workers. The condition was first described in a diver in 1941.[3]

Dysbaric osteonecrosis is characterized by lesions in long bones such as the femur or humerus. As long as the lesions are confined to the shaft, they appear to be of limited consequence.[16] However, if the lesions develop in sites adjacent to the joint surfaces of the hip or shoulder (juxta-articular lesions), the consequences can be very serious. Areas of dead bone and marrow (infarct) in these sites can result in buckling of the cartilage around the area infarcted or loss of the subchondral plate over the area of infarct. In the latter case, fragments of bone grind into the cartilage during movements of the point. Continued fragmentation or crumbling of the bone can grind away large portions of the joint. Eventually, the weight bearing joint fractures and collapses. Disruption of the bearing surface or collapse of the dead bone can lead to secondary conditions of incapacitating arthritis. Other types of bone lesions are also associated with dysbaric osteonecrosis.[3]

The exact etiology of dysbaric osteonecrosis (bone necrosis) remains to be unequivocally demonstrated. There is general agreement that dead bone and marrow are the result of gas absorption and release from tissue. However, there is no agreement about how gas absorption or release results in dead bone and marrow. Beckett summarized the major hypothesis.[3] Various investigators have suggested that gas bubbles from anywhere in the body can lead to obstruction of the small blood vessels of bone tissue. Others state that these gas bubbles can damage the lining of small blood vessels and cause chemical alterations that produce clots in the vessels of the bone. An alternate hypothesis is that fat cells which break apart upon release of gas anywhere in the body can lead to fat emboli in the small blood vessels in the bone. Some researchers suggest that expanding gas within the cells expands the fat cells to the point where circulation is inhibited.

It has also been suggested that complications may arise from excessive compression rates rather than decompression. The compression phase causes an increase in the osmotic pressure of the blood. In response to a pressure gradient between blood and bone tissue, plasma water is shifted from the blood vessels into the spaces of the bone, thus restricting the bone blood flow. Some investigators feel that there is a correlation between dysbaric osteonecrosis and the number of compression and decompression phases while others have related it to elevated oxygen pressure.[15] None of the above hypotheses appears to be entirely satisfactory.

Dysbaric osteonecrosis has apparently resulted from as little as a single decompression exposure. In tunnel workers, the lowest pressure associated with the disease is 17 psig or equivalent of 39 fsw.[16] Survey radiographic examination is the primary method of detecting dysbaric osteonecrosis.[3]

Published data from approximately 3,800 professional divers throughout the world show that about 800 had radiological evidence of significant skeletal lesions. Navy divers using standard tables appear to exhibit the lowest incidence of lesions (2.3%). Commercial divers have reported incidence in the range of 3 to 33%. Divers in Japan using traditional techniques have incidence of osteonecrosis reportedly as high as 40 to 75%.[3] There appears to be no survey data available on the recreational diving population.

Until the etiology of dysbaric osteonecrosis is clearly defined, it is difficult to establish preventive measures. At present, the population of divers at risk appears to include all those diving to a depth in excess of 33 fsw. The apparent predisposing factors include obesity, age, prior decompression sickness, and the number, depth, and duration of dives. In other words, a higher element of risk appears to exist for those participating in large numbers of dives, to greater depths, for longer durations. The incidence is probably greatest among saturation divers. Until this condition is better understood, divers must also assume that there is a relationship between osteonecrosis and inadequate decompression and/or decompression sickness.

Dysbaric osteonecrosis has, to my knowledge, not been described in recreational divers and the topic is seldom mentioned in a recreational diving training program. However, as recreational divers become more aggressive -- diving deeper and longer and bending more frequently -- they are predisposing themselves to this condition. Furthermore, as the number of aging deep divers increases, the likelihood of bone necrosis appearing in this population increases. Scientific saturation divers are also at higher risk of bone necrosis. I feel that every diver should be aware of the potential risks that they are taking -- even the minor risks.

Treatment of dysbaric osteonecrosis is an important consideration in commercial diving and saturation diving. As recreational divers extend their depth and dive durations to near saturation levels and experiment with new dive tables, dysbaric osteonecrosis may also appear in that population. For additional information, the reader is encouraged to consult the medical and references list at the end of this discussion.[3,4,6,9,10,16]

Other Physiological Considerations

As recreational divers venture to deeper and deeper depths, they will invariably encounter problems associated with thermal stress. The high thermal conductivity of helium (approximately 6 times that of air) draws heat away from the diver at a great rate. At 600 feet, a diver may lose more heat through *respiratory heat loss* than the body can generate even with exercise and active thermal protection. With a cold breathing gas (approximately equal to ambient water temperature), the diver can suffer from respiratory distress in the form of incapacitating shivering, chest pain, nasal and tracheo-bronchial secretions, and difficult and labored breathing.

As divers exceed 1,000 feet breathing heilox or trimix, they may experience *articular pain* during descent or after arrival at depth. This is frequently associated with rapid compression (descent). *High-pressure nervous syndrome* (HPNS) can seriously impair a heliox diver beyond 1,500 foot depths. Muscular tremors, dizziness, decreased alertness, a desire to sleep, and electroencephalograph (EEG) changes have been noted. The onset of HPNS has been reduced or eliminated by slowing compression rates and breathing hydrogen-helium-oxygen. Reports of recreational divers having experienced significant temporary physical and mental impairment when switching from air to trimix have also been noted.

HIGH-TECHNOLOGY EQUIPMENT

Recreational diving is no longer just multi-colored wet suits and new T-shirt designs. Today, we have entered the era of *"hi-tec"* (high-technology) diving. Only within the last 5 years have dive computers emerged as a dominate instrumentality for recreational divers. Many authorities suggest that the majority of recreational divers will be using dive computers by 1995.

Although deep diving has been practiced with conventional recreational diving scuba/compressed air for decades, authorities have recognized the overwhelming limits of open-circuit scuba/air as a deep diving tool and gas. Physiologically, deep air divers have pushed the capability of the apparatus and gas to ultimate limits, exceeding what is considered reasonable and prudent by diving authorities. Recreational training agencies have, for many reasons (including economics and fear of liability), stood firm by imposing "limits" that may or may not be realistic -- 130 feet, air, no-decompression.

We now stand on the threshold of recreational "hi-tec" diving! Compact, efficient, and safe *closed-circuit mixed-gas scuba* is currently being tested and used by select recreational and scientific divers. More than a year ago one of my colleagues completed a 310 feet dive for 30 minutes using in-water oxygen decompression techniques. The scuba performed flawlessly and the diver indicated that he felt better physically and emotionally at than depth that he ever had at 160 feet on scuba/air.

Current closed-circuit mixed-gas scuba is an electronically controlled unit that mixes the breathing gas during the dive. The breathing gas used in closed-circuit mixed-gas scuba may be oxygen, air, or mixtures of nitrogen-oxygen, helium-oxygen, or helium-nitrogen-oxygen depending upon the type of scuba used and operational requirements. Actually, the two gases, oxygen and a diluent gas, are contained in separate cylinders and mixed in the apparatus during the dive. The partial pressure of oxygen is preset and continuously measured by a series of oxygen sensors. Oxygen is automatically added as needed to maintain the preset partial pressure. Diluent gas is generally added to the system only at the beginning of the dive and during descent to compensate for increased ambient pressure. Carbon dioxide and moisture is removed by chemical absorption and trapping. All gas is recirculated and there is no intentional discharge of gas from the system except during ascent to shallower depths. Current closed-circuit mixed-gas scuba systems capable of supplying a diver with up to 6 hours of breathing gas at depths in excess of 1000 feet are available. However, the units are more frequently used by combat swimmers for clandestine operations (limited bubble discharge) and long duration dives (gas supply availability).

Keep in mind that closed-circuit mixed gas scuba has been available to military and commercial divers for several decades. However, it was expensive ($35,000 per unit) and required extensive training and maintenance. Within the next 6 to 18 months (present date: March 1991) one or more manufacturers will probably release several models of computerized closed-circuit mixed gas scuba with depth capabilities up to 1000 feet and several hours of gas supply for use by recreational and scientific divers. Some units will provide complete self-sufficiency through total redundancy in life-support subsystems. These units will have significant refinements and technologically far exceed the current military units. Special training programs will be available (and required) and unit cost will probably not much exceed that of a sophisticated recreational diver video and still underwater photography system.

The one remaining physiological barrier for the deep scuba diver is *thermal stress*. To date, and to my knowledge, we still lack an effective self-contained diver suit heating system. In order to safely endure the lengthy in-water decompression associated with deep mixed-gas dives, an effective and feasible suit heater must be developed. By 1993, technologically, only the possible lack of a self-contained heating system will stand as a barrier to swimming the decks of the *Fitzgerald* (Lake Superior, 500+ fsw, 38°F.

THE RIGHT TO DIvE!

Where do we go from here? Do recreational divers have the right to dive as deep as they wish? If so, why is there so much dialogue on this topic? Why do some authorities in diving stand so firmly opposed to deep diving? Why do major recreational diving training agencies recommend that all recreational scuba diving be limited to depths of 130 feet? Are deep recreational divers breaking the law? Do we endorse or condemn deep diving? Do we take measures to protect divers from themselves through legislation?

In America, we believe in individual rights. A criminal is assumed to be innocent until proven guilty. For the most part, we are a society of self-determination. In essence, an American citizen has the right to do almost anything that he/she wishes as long as it does not transcend the laws and legislative acts addressing the common good of society.

To my knowledge, there are no laws that govern the depth of recreational diving. There is a commonly accepted *standard of the community* that is recognized by major recreational diving training agencies. A review of literature distributed by recreational diver training agencies leaves little or no doubt regarding their position. *On the other hand, recreational divers do knowingly and wantonly exceed a depth of 130 feet every day of the year in waters ranging from the warm, clear Caribbean to the dark, cold Great Lakes.*

It is my opinion, that in America, recreational divers have the legalright to dive as deep as they wish. Participants in other recreational activities such as rock climbing, skiing, and mountaineering appear to have the right to extend the limits of their sport to and beyond those considered prudent by most of society. Their accomplishments are deemed spectacular to say the least. In 1980, Reinhold Messner ascended to the summit of Mt. Everest *without* using supplemental oxygen and *alone*. Did he break a law? No! Did he violate a standard of the climbing community? Some might say "yes," others would say "no!" In mountaineering, the standard of the community is often viewed as, "to challenge the limits of human endurance and capability!"

In the diving community, we tend to ridicule a recreational diver who dives to 250 feet using compressed air scuba. This exceeds both the physiological and technical limits that most authorities regard proper for compressed air scuba diving. Therefore, the recreational diver is insane, brain-dead, or stupid.

Mountain climbers die each year in an attempt to defy nature and extend their personal limits. In fact, the death rate in mountain climbing (per 100,000 participants) is *200 times* that of recreational scuba diving. Their deaths are mourned by family and fellow mountaineers. To some, they are heros. Monuments are erected on mountain sides to their memories. I doubt that a monument has ever been placed on a seashore to commemorate a recreational diver who lost his life during a deep dive.

For the past three decades, wreck diver-film makers have devoted their attention to exploits that are beyond the scope of the recreational diver's training and community standards. They have filmed diving excursions to great depths -- over 250 feet -- and commonly beyond 160 feet. These films have both taunted and lured divers. The concept of a virgin (or near-virgin) wreck or cave exploration is extremely appealing to divers. The concept of going where no human has gone before becomes a compulsion -- a driving force. The film accomplishments have been deemed as spectacular, feats of expertise, daring, and talented. They have been viewed as outstanding accomplishments by some and reckless abandonment by others. The film makers have been both worshiped and ridiculed.

Recreational divers have the right of self-determination and are not subject to the standards and regulations that regulate commercial divers. It is a well-established fact that recreational deep divers knowingly and wantonly exceed the currently published standards of recreational, military, and commercial diving.

Regardless of the opinions of educators, physiologists, physicians, and other authorities, the recreational diver must be allowed to retain his/her right of self-determination and freedom to pursue his/her recreational activity to its fullest extent, as long as they do not endanger the health and well-being of other individuals. Only when the act of deep diving can be defined as an illegal activity such as attempting suicide, or knowingly and wantonly endangering the lives and well-being of others, can the rights of the individual be superseded.

However, by the same token, the rights and well-being of any and all agencies, businesses, and individuals who provided services or goods to this diver, as well as individuals and agencies that may be called on to provide services in the event that said diver is lost or injured, must also be provided with the fullest protection of the law. It must be clearly established that any recreational diver participating in deep diving shall accept sole, full, and complete responsibility for his/her actions and well-being. There must be clear and complete acknowledgment and assumption of risk. No recreational diver who knowingly and wantonly participates in deep diving or his/her heirs, executors, administrators, or assigns shall prosecute or present any claim for personal injury, property damage, or wrongful death against any dive charter operator, diving instructor, diving companion, dive travel business, diving equipment manufacturer, diving equipment retailer, physician, or any of their said agents, servants, or employees for any cause of action.

It is difficult, if not impossible, to address recreational diver responsibility through legislative avenues; nor should they be. The recreational diver by virtue of citizenship has certain rights of self-determination. Along with these rights, one must assume responsibility to society and family. The recreational diver who elects to exceed the standard of the diving community with regard to diving techniques, procedures, and depth must, at a minimum, accept the following responsibilities:

- The individual diver must be completely aware of the risks associated with extended deep diving and breathing various gas mixtures and, more importantly, accept these risks.

- The diver shall be responsible for fully and completely informing spouse, family, and loved ones of the risks, both short term and long term, associated with their chosen diving activity and to make said parties fully and completely aware of the fact that they have elected to exceed the standard of the recreational diving community.
- The spouse, family, and loved ones shall be prepared to accept the potential consequences of injury associated with diving including both short term and lifelong disability, loss of sexual partnership, and death.
- The diver shall acquire and maintain adequate medical insurance to cover any and all costs of treatment and hospitalization that might result from injury sustained during or as a result of diving.
- The diver shall maintain full and complete disability insurance that will cover the cost of long term disability and loss of earnings to the family.
- The diver shall maintain appropriate life insurance or other financial means to assure full and complete support of spouse and children until the children are 21 years of age and/or have completed college education.

DIVING COMMUNITY RESPONSIBILITY

An even more difficult issue to address is the question of responsibility of the recreational diving community to the deep diver. The recreational diving industry has, at least to date, refused to officially recognize or endorse the exploits of the deep recreational diver. The community is divided. The recreational diver training agencies stand firm on *no-decompression diving with a depth limit of 130 feet.*

On the other hand, other segments of the recreational diving community (i.e., cave divers and shipwreck divers) openly defy this rather limited standard and routinely dive to considerably deeper depths on dives requiring extensive decompression. Furthermore, with some exception, these divers are primarily *self-taught* deep divers. The deep diving specialty courses supported by the major training agencies are, to many deep diving enthusiasts, *a joke*. Only the National Association of Cave Divers and the Professional Scuba Association (PSA of Orlando, Florida) appear to provide training in deep and/or decompression diving at this time. The Professional Scuba Association will train individuals for compressed air scuba diving to depths of 300 feet.

Unfortunately, the beginning diver receives many mixed signals with regard to dive depth and decompression. The major training agencies stand firm -- 130 feet and no-decompression. Books, manuals, promotional materials, and course standards are all directed at maintaining this standard. The largest recreational diver training agency in the world has developed and promotes dive tables that are strictly for no-decompression diving. Exceeding the limits of these tables is considered to be an emergency situation. Based on modern trends in diver education (guided by marketing concepts rather than sound educational concepts), the "anyone can dive" philosophy, the more diverse population of divers (physically and mentally) attracted by this philosophy, and public attitudes regarding diving safety, these limits seem somewhat realistic, maybe even to liberal.

Yet, recreational diving businesses actively promote deep diving activities such as excursions to the Andrea Doria. Shipwreck diving filmmakers produce films of recreational divers exploring at depths exceeding 200 feet. Magazine articles praise deep diving exploits.

An even more difficult item for the beginning diver to comprehend is the fact that many recreational diving instructors aggressively maintain the party line of the training agencies in their course lectures -- 130 feet and no-decompression. Yet, the same instructor boasts of dives to great depths and proudly displays the special equipment of the deep diver. *Is there a double standard?* Everyone knows the rules or standards of the recreational diving community. Also, even the most novice diver has difficulty imagining that there are significant physiological differences between them and their instructor. However, these rules or standards simply do not appear to apply to many recreational diving instructors. Although the physiological difference may be slight, the psychological differences appear to be significant.

The recreational diving community has an obligation to beginning divers to sort out the deep diving issue. In the meantime, I encourage deep divers and recreational diving instructors to refrain from boasting of their exploits. Most recreational divers are *followers*. They often follow -- often blindly and without questioning -- the lead of their instructor and idols. Some of the followers will be lured into deep diving even though they lack the training, experience, equipment, and knowledge of risks.

I further recommend that the recreational diver training agencies *stop burying their heads in the sand* and face the real issues of the day. Many recreational divers exceed the recommended limits for compressed air diving daily. *Let's not promote one thing and do another!* It is time to re-examine depth limits, diver training, and community responsibility.

I predict that, during the decade of the 90s, increasing numbers of recreational divers will dive deeper than ever before in history. Dive computers have opened a new door to the depths. Yet more and more recreational divers will challenge the depths with only very limited knowledge of the risks. Home study dive courses, three lesson dive courses, take home video lectures, weekend certification courses, and the like, will increase the numbers of divers significantly over the next decade. The concept of continuing education is sound. However, subjectively I feel that only a very small percentage of the divers who are exposing themselves to deep dives on their Caribbean vacation, have the advantages of continuing education courses, or even understand the risk of their exposure.

Deep diving is here to stay! Obviously, diving to great depths should be limited to properly trained, physically fit, and experienced divers. Entry level training courses should provide students with a realistic view of physiology, diving, and risks factors. Deep air diving courses must include detailed physiological and risk information with comprehensive coverage of all related topics and equipment. Trainees must have considerable prior diving experience -- far exceeding 100 dives. *Furthermore, this type of deep diver training should not be entered into as a means of collecting another plastic card and cannot be promoted by dive shops and instructors as "a high-volume/high-profit everyone can deep dive course."* In all probability the recommended depth limit for recreational compressed air scuba diving could be extended into the range of 150 to 190 feet, if the topic was dealt with in a responsible manner. Diving to depths in excess of 190 feet, breathing compressed air, will probably no longer be recommended in the near future; even within the deep diving sub-community, on the basis that more appropriate mixed-gases and high-tec scuba will become readily available to recreational divers, probably my mid-decade.

The above may seem somewhat extreme to some individuals. *Keep in mind that I am not an advocate of deep recreational diving and unnecessary risk-taking*. However, I am a realist. Freedom of self-determination is fundamental to the American way of life. Divers have the right to challenge limits of technology and human capability. On the other hand, each and every individual has a responsibility to society and their loved ones. It is time that individuals who demand these freedoms also accept full and complete responsibility for their actions. It is time for diving leaders to address the needs of our community in a responsible manner. God willing, both the individual and society will emerge unscathed.

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10
VALIDATION OF DECOMPRESSION MODELS, ALGORITHMS, AND TABLES

INTRODUCTION

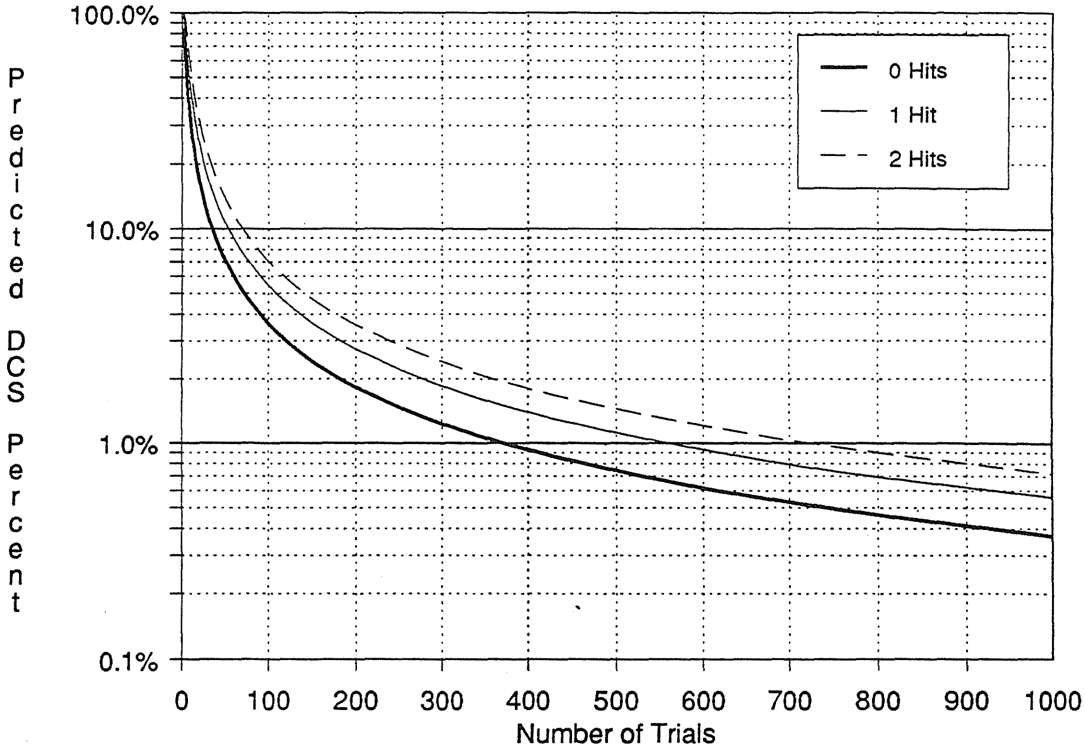
How much testing does it take to be able to say that a decompression model, algorithm, or table has been validated and can be considered "safe?" This chapter takes a brief look at some of the problems associated with validating decompression models, algorithms, and tables. Before any conclusion of statistical significance can be made, a large number of trials are required. Therefore, there are few models or tables in the field which can claim to have been tested to statistical significance. Financial, personnel, and resource limitations are a few of the forces that limit the number of trials that can be performed. However, various statistically based protocols have been proposed to reduce the number of trials required to approve or reject decompression schedules. In addition, a methodology has been recommended by a UHMS workshop on table validation, to facilitate the evaluation and distribution of new models or tables. Ultimately it must be realized that no matter how much testing has been done there is always the possibility of developing DCS, and that it is the responsibility of divers to do all they can to add safety to their diving practices.

NUMBER OF TRIALS

How many trials does it take in order to say a decompression protocol is "safe?" It depends on what is considered "safe." A DCS risk of 5% may be acceptable for some military operations, while a 1% occurrence of DCS would generally be considered unacceptable for the recreational diving community.

The major obstacle in testing a protocol to a reasonable level of statistical significance, is the number of trials required. If a decompression schedule was tested 20 times without producing any DCS, you might feel relatively comfortable about it, but perhaps you shouldn't be. Based on a binomial distribution table, 20 trials with no DCS cases allows you to say, with 95% confidence, that the occurrence of DCS with this schedule is between 0.00% and 16.84%. This range (0.00% - 16.84%) is called the 95% confidence interval. If you want to be 95% certain that the upper limit of the confidence interval is less than 1%, then over 350 DCS free trials need to be performed. If one case of DCS is encountered in the trails, then approximately 200 additional DCS free trials are needed. Figure 10.1 shows the upper limit of the 95% confidence interval from the binomial distribution table for a DCS free trial and a trials with one and two occurrences of DSC.[1] If a higher confidence level is desired, then the number of required trials increases. If you want to be 99% confident that the upper limit of the confidence interval is less than 1%, then over 500 DSC free trials need to be performed.

In addition to binomial distributions, other statistical techniques have been used to determine the number of trials required to reach a certain level of confidence in a decompression schedule. Some of these alternate values are presented in Table 10.1. These numbers are slightly lower



From Binomial Distribution Chart

Figure 10.1. Maximum percent of DCS predicted with a 95% confidence vs. number of trials.

than the previous numbers, but still represent large numbers of person-dives to be statistically significant.[2]

If the lower number of trials is picked from these two approaches it will still take approximately 300 DCS free trials to be able to say, with 95% confidence, that the risk of DCS from a **single decompression schedule** falls between 0% and 1%. What if we want to validate a whole set of decompression tables, or a dive computer decompression algorithm which can generate an infinite number of decompression schedules, to this level of certainty? To validate just five decompression schedules, approximately 1,500 person-dives would be required. In most circumstances the cost of performing such a test series would be prohibitive.

TABLE 10.1
TRIALS REQUIRED TO REACH 95% OR 99% CONFIDENCE
IN A 1% DCS INCIDENCE FOR A DECOMPRESSION PROCEDURE

Number of Trials Required for Confidence in a 1% DCS Incidence		Confidence Level 95%	99%
Number of DCS Incidents	0	298	458
	1	448	645

Some model/table developers and testers make the assumption that the risk of DCS is constant throughout the range of the table or model. A series of schedules are selected and then tested enough so that the total number of combined trials is large enough have statistical significance. Is this a reasonable assumption? In some cases it may be, but in others it may not. If the operational depth and time ranges are narrow then this type of assumption may be valid. However, if the model is supposedly operational across the entire pressure spectrum, and time ranges from 5 minutes to saturation, then this assumption is not reasonable.

ACCEPT AND REJECTION CRITERIA

The design of decompression model/table validation trials has been looked at by many groups. The U.S. Navy has worked in the area of probabilistic models, and has developed their 1% and 5% maximum likelihood risk tables (Chapter 4).. They have also used statistical analysis to evaluate the validation processes. The following presents some of their views on problems in designing validation trials:[3]

> *If we were to make a wish list for the testing phase, we would put the following three items on our list:*
>
> 1) *We would like to conduct a minimum number of test dives;*
> 2) *We would like to encounter a minimum number of cases of DCS; and*
> 3) *We would like to have clear answers at the end of our dive trial.*

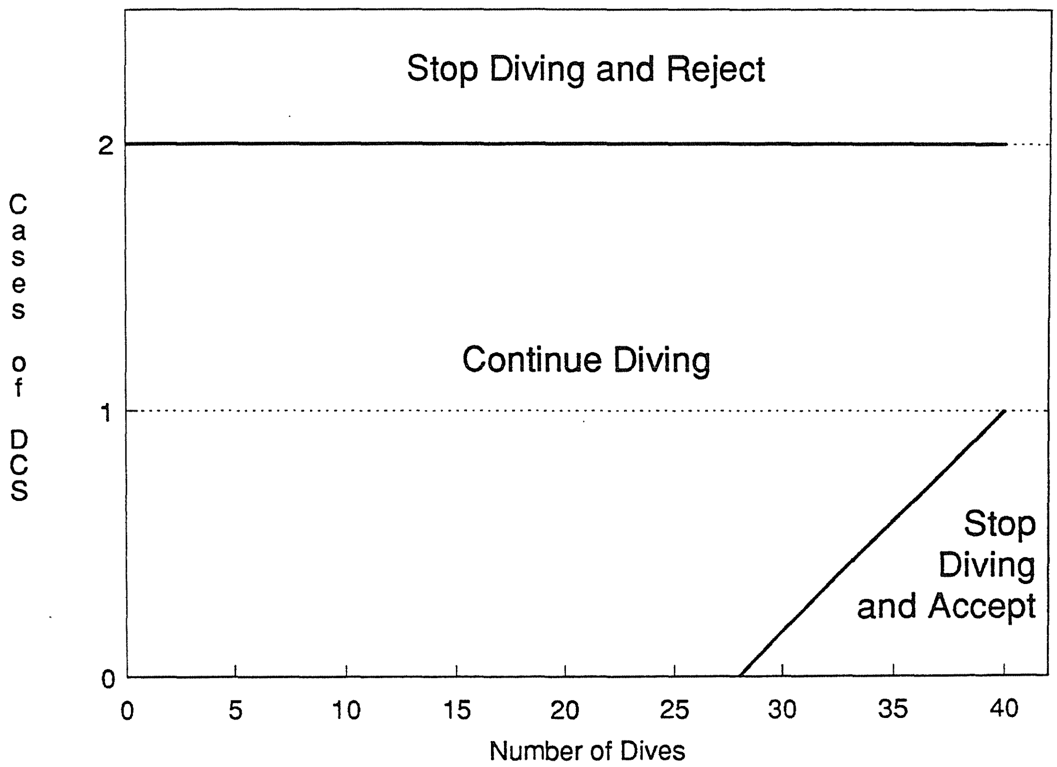


Figure 10.2. Sequential dive trial (2/40).

Unfortunately, we get to pick at the most two items out of the three. For instance, if we want to keep the dive trial size and cases of DCS to a minimum, we may not get very clear answers. Or, if we want clear answers and want to keep cases of DCS to a minimum, we may have to conduct a rather large dive trial.

NMRI looked at what was required in order to minimize the probability of accepting an "unsafe" protocol as "safe," or rejecting a "safe" protocol as "unsafe." One of the trials they developed was a Sequential Dive Trial, which involved a maximum of 40 dives (Figure 10.2). If 28 DCS free trials were performed then the schedule would be accepted. If one case of DCS developed then all 40 dives would be performed, unless a second case of DCS was encountered. If no additional cases of DCS developed the schedule would also be accepted. However, if a second case of DCS was encountered the schedule would be rejected and the trial would stop.

If we go back to the binomial distribution chart and look at the 95% confidence interval for 0 cases of DCS in 28 trials, and 1 case in 40 trials we find the following:

0 / 28	(0.00% - 12.34%)	Midpoint = 6.17%
1 / 40	(0.06% - 13.16%)	Midpoint = 6.61%

According to these values, the midpoint of these two ranges indicate an incidence of DCS slightly higher than 6%. However, NMRI's calculations show that the probability of accepting a schedule with a 6% incidence of DCS, using this test design, is about 35%. If the true incidence was 12%, then there would only be about a 5% chance of accepting the schedule, according to their figures. On the other end of the spectrum, if the true incidence of DCS is 1%, then the probability of accepting the schedule is over 90%, or conversely the probability of rejecting the schedule is less than 10%. This achieves the goal that was set forth, to reduce the possibility of accepting an "unsafe" schedule as well as rejecting a "safe" one.

DECOMPRESSION TABLE/MODEL DEVELOPMENT AND VALIDATION PROCESS

Validation of decompression tables was the topic of discussion at a 1987 UHMS workshop. The proceedings from this workshop present methods of validation used by military and commercial diving organizations.[4] The outcome of this workshop was a consensus on a technique for the evaluation and distribution of new decompression models and tables. Presented as a flowchart (Figure 10.3), this technique is divided into two realms, Laboratory Research and Operations.

In the Laboratory Research realm the new model is developed based on historical data, knowledge of known problems, and/or new advances and ideas. From the model a set of tables can then be calculated. If the model is to be tested then the table calculation step can be skipped. A testing protocol is then developed which *"confirms to the prevailing standards for human research of the institution conducting the tests. This would imply conformance with the principles of the Declaration of Helsinki."*[5] The protocol is then submitted to an Institutional Review Board (IRB) which will evaluate the proposal for compliance to ethical principles. The Laboratory Testing phase is not limited to chamber tests, but can also include openwater evaluations. The primary consideration in this phase is that the tests are **research** and as such are carried out **under medical supervision**.

The testing phase may be terminated at any point if problems develop. Changes will then be made either to the tables or to the underlying model. Then a new testing protocol needs to be developed and approved by the IRB. How many trials are performed in the Laboratory Testing phase? It will depend. If the model is based on a model or technique that has a good history, then only a minimum number of dives may be warranted to assure against any catastrophic failure in

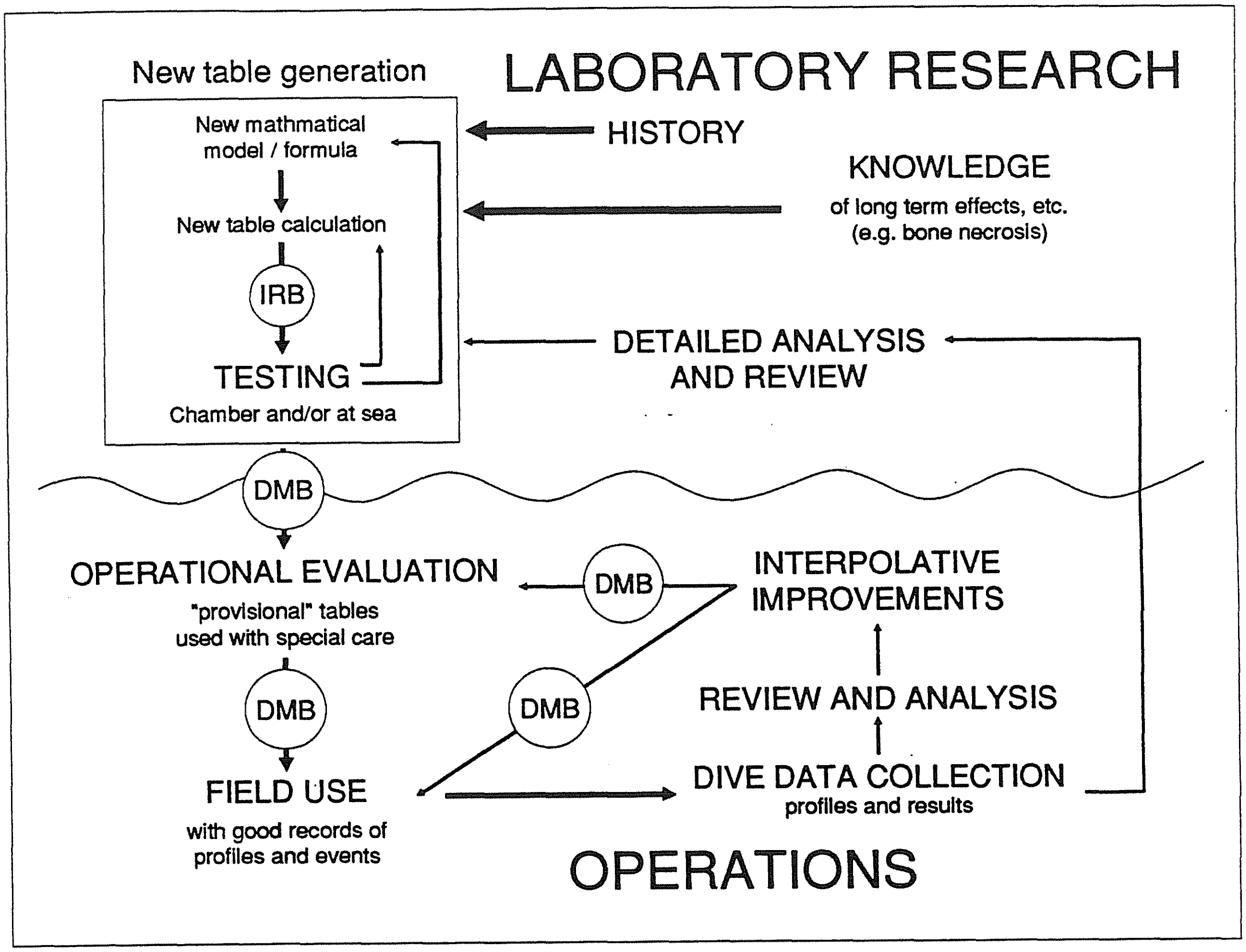


Figure 10.3. Flow diagram of the decompression table development and validation process.

the model. If the model is based on new ideas and techniques, then the number of required trials will need to be greater to develop confidence before going operational.

In order to approve the movement from Laboratory to Operations, the technique recommends the development of a Decompression Monitoring Board (DMB). *"The makeup of the DMB is up to the organization, but, as an example, it might consist of the safety officer, the medical director, a member of top operational management, and the decompression specialist."* In the Operational Evaluation, the tables or procedures are used in the same manner as in Field Use, only under closer scrutiny than normal (proper training and supervision, good medical coverage, extremely accurate record keeping, profile recordings, etc.).

If no problems are evident in the Operational Evaluation phase, the DMB can approve the move to actual Field Use. However, the process does not end there. In field use, good records of profiles and events (problems or advantages) are kept and periodically reviewed and analyzed by the DMB. If improvements in the procedures are warranted, the DMB may either choose to move them directly into Field Use or place them under Operational Evaluation again. If, during Field Use, the procedures "fall apart," then the process may need to start from the beginning with the Operations data contributing to the history and knowledge information base.

This process is being used in one form or another by various military, commercial, and recreational diving groups. If you are considering using a new set of tables, or model, that supposedly has gone through this validation process, I suggest you ask for the data from the laboratory testing and operational evaluation, as well as reports from the DMB, presenting their reasoning for moving from testing to operational evaluation to field use.

VALIDATION OF DIVE COMPUTER MODELS

Now that we have discussed some of the criteria for testing decompression models and tables, it is interesting to review what type of validation process the dive computer models have gone through. At the 1991 AAUS workshop on Repetitive Diving, one of the questions asked of various dive computer manufacturers was, "How do you *validate* your decompression models?"[6] The following are the responses to that question:

> **DACOR:** *The reduction of the 16 compartments of the Buhlmann System ZHL-12 to an equivalent compartment model was accomplished by Prof. Dr. Buhlmann and Dr. Max Hahn in 1986, and was updated to the latest research standards by Dr. Max Hahn in 1987. Latest tests and evaluations of research results from pressure chamber tests by D.K.L.Z. (Zurich), B.L.F.S. (Berlin), and Navy Experimental Diving Unit (Panama City, FL) motivated Dr. Hahn in 1988 to revise the model again for safer decompression. Both manned and unmanned tests were performed during the validation employing chamber and wet exposures.*

> **OCEANIC:** *We believe that all theoretical decompression algorithms require carefully controlled and documented human testing, and we have based our algorithms on the extensive Doppler monitored NoD multilevel repetitive test data of Dr. Michael Powell of DSAT. The experiments of Dr. Merrill Spencer provide additional validation of our selection of NoD limits, and the experiments of Karl Huggins adds to our confidence of the validity of multilevel diving. Our decompression model is more conservative than either Buhlmann or the U.S. Navy, often requiring deeper stops than either of these tested tables. However, we do not believe that repetitive multilevel decompression diving has a proper experimental basis, and we strongly recommend to out users that they avoid such diving practices.*

> **ORCA:** *The ORCA method of decompression calculation was verified by Huggins in 199 [Note: actually 119] man dives designed to load each compartment to its theoretical maximum value. Testing was conducted on 12 individuals, representing the wide spectrum of recreational diving physiology, and consisted of 10 dives for each diver over a period of 4 days. Doppler evaluation of the subjects revealed one incident of Grade 1 bubbles (Spencer grading), and no substantive DCS symptoms were noted. As the algorithm has remained largely unchanged since its release in 1983, no further manned testing has been conducted by the company.*

> **SUUNTO:** *Because the model or algorithm used is commonly accepted through research to obtain the Navy tables and in other dive computers, it is believed to be reliable.*

> **TEKNA (OCEAN EDGE):** *Extensive computer simulation testing of the algorithm versus Dr. Hahn's model and equations have been performed. It would be much more appropriate for Dr. Hahn to answer any further questions concerning validation of the decompression model itself.*

In addition to the ORCA dives, a series of test dives using one version of Buhlmann's model is also presented in Appendix F.[7] Aside from these two trials, I am not aware of any testing performed specifically to evaluate dive computer decompression algorithms.

In attempts to collect information on field use of dive computers, both Suunto and Orca have included dive profile recorders in some of their devices. Both the Suunto Solution and the ORCA Phoenix (the new Delphi) are able to download profile data directly to personal computers. The older Suunto SME-USN, SME-ML, and SME-ML R1 dive computers allowed profile information to be displayed on the dive computer's display so it could be written down. What is needed, is a central depository for collection and analysis of all this data. Currently plans are underway to establish such a database at DAN.

DECOMPRESSION MODEL/TABLE LIMITATIONS

Although stated before, it should be remembered that no dive computer or decompression table is 100% effective. All that they do is present divers with depth and time envelopes that hopefully will keep most of the people safe most of the time. There is always the possibility that DCS will develop even while diving well within this envelope. Conversely there are divers who routinely dive outside the envelope who "get away with it." This is not a good group to follow, for moving outside the envelope only increases your risk for developing DCS.

Make informed choices on your decompression options. Ask at dive shops how a dive computer decompression model was validated. Ask for information from manufacturers. Let the diving industry know that you want to be informed divers. Let them know that you are concerned about what they have programmed into their little black boxes or printed on pieces of plastic. Send a message that you want information from them and will not blindly trust their tables or computers. Make sure that you are comfortable with whatever technique you decide upon, and then add safety factors.

Safe Diving

(If you decide to go back after all of this!)

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APPENDIX A
1937 U.S. NAVY DECOMPRESSION TABLES

The Old Navy Standard Decompression Table (Using Compressed Air)

Ascent Rate
25 ft. Per Minute

Depth of dive (feet)	Time on bottom (minutes)	Stops (feet and minutes)									Sum of times at various stops (minutes)	Approximate total decompression time (minutes)
		Feet 90	Feet 80	Feet 70	Feet 60	Feet 50	Feet 40	Feet 30	Feet 20	Feet 10		
40	120									0	0	2
40	180									2	2	4
40	Opt.* 240									4	4	6
40	300									6	6	8
50	78									0	0	2
50	120									2	2	5
50	150									5	5	8
50	Opt.* 190									9	9	12
50	300									12	12	15
60	55									0	0	3
60	75									2	2	5
60	110									13	13	16
60	Opt.* 150								5	15	20	24
60	180								7	16	23	27
60	210								8	18	26	30
70	43									0	0	3
70	60									4	4	8
70	75									13	13	17
70	90								4	16	20	24
70	Opt.* 120								13	16	29	33
70	150								18	21	39	43
70	180								21	32	53	57
80	35									0	0	3
80	50									6	6	10
80	70								6	16	22	27
80	100								20	16	36	41
80	Opt.* 115								22	26	48	53
80	150								28	29	57	62
90	30									0	0	4
90	45									6	6	10
90	60								9	16	25	30
90	75								18	14	32	37
90	Opt.* 95							2	27	21	50	56
90	130							9	27	29	65	71
100	25									0	0	4
100	40									12	12	17
100	60								18	16	34	39
100	75								27	21	48	53
100	Opt.* 85							6	28	21	55	61
100	90							8	27	24	59	65
100	120							17	28	48	93	99
110	20									0	0	5
110	35									12	12	17
110	55								22	21	43	49
110	Opt.* 75							14	27	37	78	84
110	105						2	22	29	50	103	110
120	18									0	0	5

*These are the optimum exposure times for each depth which represent the best balance between length of work period and amount of useful work for the average diver. Exposure beyond these times is permitted only under special conditions.

The Old Navy Standard Decompression Table Cont. (Using Compressed Air)

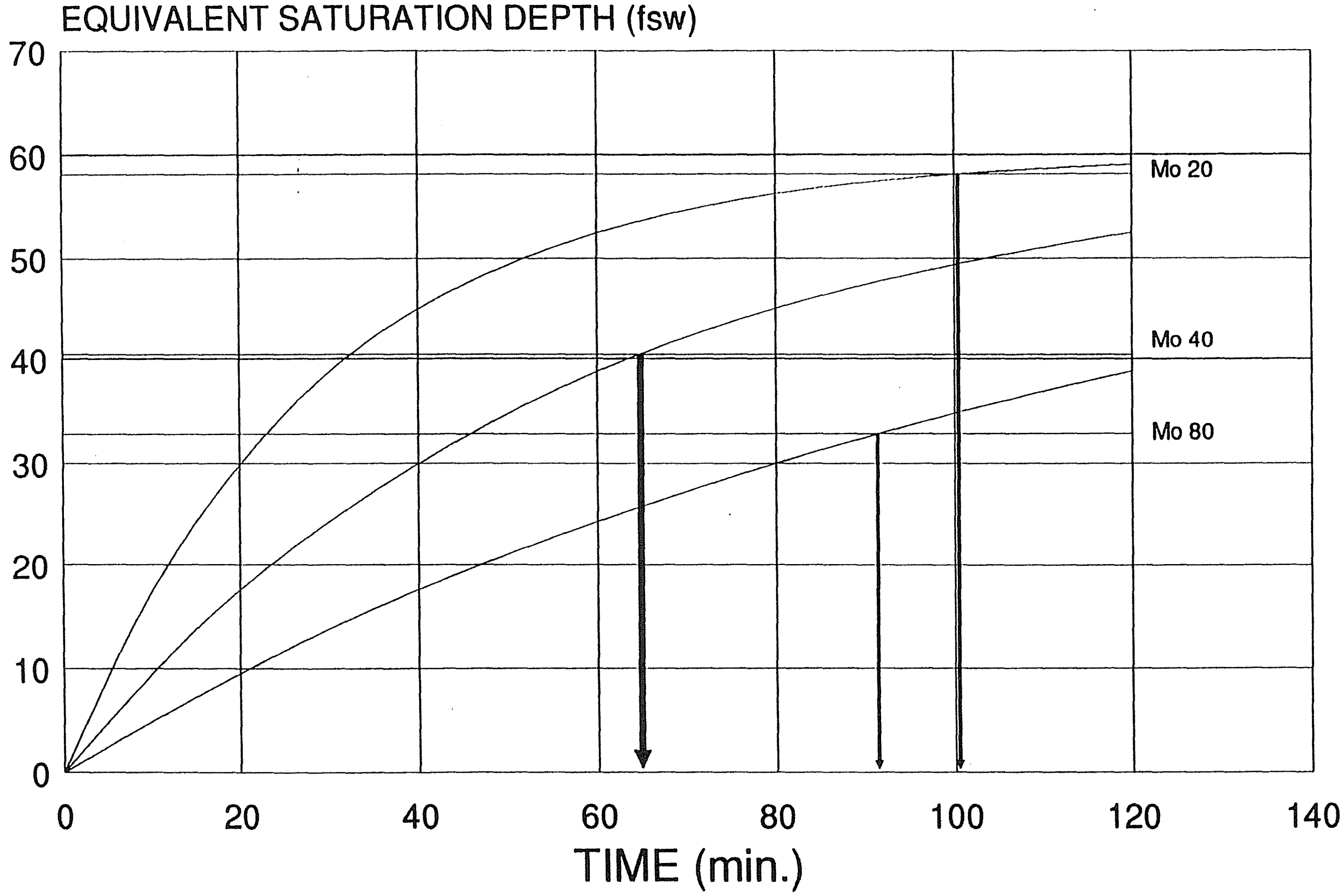
Ascent Rate
25 ft. Per Minute

Depth of dive (feet)	Time on bottom (minutes)	Stops (feet and minutes)									Sum of times at various stops (minutes)	Approximate total decompression time (minutes)
		Feet 90	Feet 80	Feet 70	Feet 60	Feet 50	Feet 40	Feet 30	Feet 20	Feet 10		
120	30									11	11	17
120	45								18	21	39	45
120	Opt.* 65							13	28	32	73	80
120	100						5	22	27	69	123	130
130	15									0	0	5
130	35								11	15	26	32
130	52							6	28	28	62	69
130	Opt.* 60							13	28	28	69	76
130	90						9	22	28	69	128	136
140	15									4	4	10
140	30								8	21	29	36
140	45							5	27	27	59	67
140	Opt.* 55							15	28	32	75	82
140	85						14	22	32	69	137	145
150	15									7	7	14
150	30								13	21	34	41
150	38								28	30	58	65
150	Opt.* 50							16	28	32	76	84
150	80						18	23	32	69	141	150
160	15									9	9	16
160	34								27	28	55	63
160	Opt.* 45							17	28	43	88	96
160	75					3	19	23	34	68	147	156
170	15									11	11	18
170	30								24	27	51	59
170	Opt.* 40							19	28	46	93	102
170	75					9	19	23	38	68	157	167
185	15									25	25	33
185	26								24	37	61	70
185	Opt.* 35							19	28	46	93	102
185	65				18	18	23	37	65	51	212	223
200	15									32	32	41
200	23								23	37	60	69
200	Opt.* 35							22	28	46	96	106
200	60			5	18	18	23	37	65	51	217	229
210	15									35	35	44
210	Opt.* 30						5	16	28	40	89	100
210	55			6	18	18	23	37	65	51	218	231
225	15								6	35	41	51
225	Opt.* 27						22	26	35	48	131	143
225	60			13	18	18	23	47	65	83	267	280
250	15								17	37	54	66
250	Opt.* 25					2	23	26	35	51	137	150
250	50		12	14	17	19	29	49	65	83	288	303
300	12								20	37	57	70
300	Opt.* 20					9	23	26	35	51	144	159
300	45	6	14	15	17	18	31	49	65	83	298	315

*These are the optimum exposure times for each depth which represent the best balance between length of work period and amount of useful work for the average diver. Exposure beyond these times is permitted only under special conditions.

APPENDIX B
60 FSW NO-DECOMPRESSION LIMIT DETERMINATION

DETERMINATION OF NO-DECOMPRESSION LIMIT FOR 60 FSW USING U.S. NAVY MODEL



APPENDIX C

U.S. NAVY DECOMPRESSION TABLES (Rev. 1958)

DEPTH (ft.)	NO DECOM-PRESSION LIMITS (Min.)	REPETITIVE GROUPS														
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
10	–	60	120	210	300											
15	–	35	70	110	160	225	350									
20	–	25	50	75	100	135	180	240	325							
25	–	20	35	55	75	100	125	160	195	245	315					
30	–	15	30	45	60	75	95	120	145	170	205	250	310			
35	310	5	15	25	40	50	60	80	100	120	140	160	190	220	270	310
40	200	5	15	25	30	40	50	70	80	100	110	130	150	170	200	
50	100	–	10	15	25	30	40	50	60	70	80	90	100			
60	60	–	10	15	20	25	30	40	50	55	60					
70	50	–	5	10	15	20	30	35	40	45	50					
80	40	–	5	10	15	20	25	30	35	40						
90	30	–	5	10	12	15	20	25	30							
100	25	–	5	7	10	15	20	22	25							
110	20	–	–	5	10	13	15	20								
120	15	–	–	5	10	12	15									
130	10	–	–	5	8	10										
140	10	–	–	5	7	10										
150	5	–	–	5												
160	5	–	–	–	5											
170	5	–	–	–	5											
180	5	–	–	–	5											
190	5	–	–	–	5											

(Rev. 1958)

INSTRUCTIONS FOR USE

I. "No decompression" limits

This column shows at various depths greater than 30 feet the allowable diving times (in minutes) which permit surfacing directly at 60 ft. a minute with no decompression stops. Longer exposure times require the use of the Standard Air Decompression Table.

II. Repetitive group designation table

The tabulated exposure times (or bottom times) are in minutes. The times at the various depths in each vertical column are the maximum exposures during which a diver will remain within the group listed at the head of the column.

To find the repetitive group designation at surfacing for dives involving exposures up to and including the "no decompression limits": Enter the table on the exact or next greater depth than that to which exposed and select the listed exposure time exact or next greater than the actual exposure time. The repetitive group designation is indicated by the letter at the head of the vertical column where the selected exposure time is listed.

For example: A dive was to 32 feet for 45 minutes. Enter the table along the 35 ft. depth line since it is next greater than 32 ft. The table shows that since group "D" is left after 40 minutes exposure and group "E" after 50 minutes, group "E" (at the head of the column where the 50 min. exposure is listed) is the proper selection.

Exposure times for depths less than 40 ft. are listed only up to approximately five hours since this is considered to be beyond field requirements for this table.

REPETITIVE GROUP AT THE END OF THE SURFACE INTERVAL																
	Z	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A
Z	0:10-0:22	0:34	0:48	1:02	1:18	1:36	1:55	2:17	2:42	3:10	3:45	4:29	5:27	6:56	10:05	12:00*
O		0:10-0:23	0:36	0:51	1:07	1:24	1:43	2:04	2:29	2:59	3:33	4:17	5:16	6:44	9:54	12:00*
N			0:10-0:24	0:39	0:54	1:11	1:30	1:53	2:18	2:47	3:22	4:04	5:03	6:32	9:43	12:00*
M				0:10-0:25	0:42	0:59	1:18	1:39	2:05	2:34	3:08	3:52	4:49	6:18	9:28	12:00*
L					0:10-0:26	0:45	1:04	1:25	1:49	2:19	2:53	3:36	4:35	6:02	9:12	12:00*
K						0:10-0:28	0:49	1:11	1:35	2:03	2:38	3:21	4:19	5:48	8:58	12:00*
J							0:10-0:31	0:54	1:19	1:47	2:20	3:04	4:02	5:40	8:40	12:00*
I								0:10-0:33	0:59	1:29	2:02	2:44	3:43	5:12	8:21	12:00*
H									0:10-0:36	1:06	1:41	2:23	3:20	4:49	7:59	12:00*
G										0:10-0:40	1:15	1:59	2:58	4:25	7:35	12:00*
F											0:10-0:45	1:29	2:28	3:57	7:05	12:00*
E												0:10-0:54	1:57	3:22	6:32	12:00*
D													0:10-1:09	2:38	5:48	12:00*
C														0:10-1:39	2:49	12:00*
B															0:10-2:10	12:00*
A																0:10-12:00*

REPETITIVE GROUP AT THE BEGINNING OF SURFACE INTERVAL (FROM PREVIOUS DIVE)

(Rev. 1958)

INSTRUCTIONS FOR USE

Surface interval time in the table is in hours and minutes ("7:59" means 7 hours and 59 minutes). The surface interval must be at least 10 minutes.

Find the repetitive group designation letter (from the previous dive schedule) on the diagonal slope. Enter the table horizontally to select the listed surface interval time that is exactly or next greater than the actual surface interval time. The repetitive group designation for the end of the surface interval is at the head of the vertical column where the selected surface interval time is listed. For example – a previous dive was to 110 ft. for 30 minutes. The diver remains on the surface 1 hour and 30 minutes and wishes to find the new repetitive group designation: The repetitive group from the last column of the 110/30 schedule in the Standard Air Decompression Tables is "J". Enter the surface interval credit table along the horizontal line labeled "J". The 1 hour and 47 min. listed surface interval time is next greater than the actual 1 hour and 30 minutes surface interval time. Therefore, the diver has lost sufficient inert gas to place him in group "G" (at the head of the vertical column selected).

*NOTE: Dives following surface intervals of more than 12 hours are not considered repetitive dives. Actual bottom times in the Standard Air Decompression Tables may be used in computing decompression for such dives.

REPET. GROUPS	REPETITIVE DIVE DEPTH (Ft.)															
	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190
A	7	6	5	4	4	3	3	3	3	3	2	2	2	2	2	2
B	17	13	11	9	8	7	7	6	6	6	5	5	4	4	4	4
C	25	21	17	15	13	11	10	10	9	8	7	7	6	6	6	6
D	37	29	24	20	18	16	14	13	12	11	10	9	9	8	8	8
E	49	38	30	26	23	20	18	16	15	13	12	12	11	10	10	10
F	61	47	36	31	28	24	22	20	18	16	15	14	13	13	12	11
G	73	56	44	37	32	29	26	24	21	19	18	17	16	15	14	13
H	87	66	52	43	38	33	30	27	25	22	20	19	18	17	16	15
I	101	76	61	50	43	38	34	31	28	25	23	22	20	19	18	17
J	116	87	70	57	48	43	38	34	32	28	26	24	23	22	20	19
K	138	99	79	64	54	47	43	38	35	31	29	27	26	24	22	21
L	161	111	88	72	61	53	48	42	39	35	32	30	28	26	25	24
M	187	124	97	80	68	58	52	47	43	38	35	32	31	29	27	26
N	213	142	107	87	73	64	57	51	46	40	38	35	33	31	29	28
O	241	160	117	96	80	70	62	55	50	44	40	38	36	34	31	30
Z	257	169	122	100	84	73	64	57	52	46	42	40	37	35	32	31

(Rev. 1958)

INSTRUCTIONS FOR USE

The bottom times listed in this table are called "residual nitrogen times" and are the times a diver is to consider he has already spent on bottom when he starts a repetitive dive to a specific depth. They are in minutes.

Enter the table horizontally with the repetitive group designation from the Surface Interval Credit Table. The time in each vertical column is the number of minutes that would be required (at the depth listed at the head of the column) to saturate to the particular group.

For example – the final group designation from the Surface Interval Credit Table, on the basis of a previous dive and surface interval, is "H". To plan a dive to 110 feet, determine the "residual nitrogen time" for this depth required by the repetitive group designation: Enter this table along the horizontal line labeled "H". The table shows that one must start a dive to 110 feet as though he had already been on the bottom for 27 minutes. This information can then be applied to the Standard Air Decompression table or "No Decompression" Table in a number of ways:

(1) Assuming a diver is going to finish a job and take whatever decompression is required, he must add 27 minutes to his actual bottom time and be prepared to take decompression according to the 110 foot schedules for the sum or equivalent single dive time.

(2) Assuming one wishes to make a quick inspection dive for the minimum decompression, he will decompress according to the 110/30 schedule for a dive of 3 minutes or less (27 + 3 = 30). For a dive of over 3 minutes but less than 13, he will decompress according to the 110/40 schedule (27 + 13 = 40).

(3) Assuming that one does not want to exceed the 110/50 schedule and the amount of decompression it requires, he will have to start ascent before 23 minutes of actual bottom time (50 - 27 = 23).

(4) Assuming that a diver has air for approximately 45 minutes bottom time and decompression stops, the possible dives can be computed: A dive of 13 minutes will require 23 minutes of decompression (110/40 schedule), for a total submerged time of 36 minutes. A dive of 13 to 23 minutes will require 34 minutes of decompression (110/50 schedule), for a total submerged time of 47 to 57 minutes. Therefore, to be safe, the diver will have to start ascent before 13 minutes or a standby air source will have to be provided.

DEPTH (ft)	BOTTOM TIME (mins)	TIME TO FIRST STOP	DECOMPRESSION STOPS 50	40	30	20	10	TOTAL ASCENT TIME	REPET. GROUP
40	200						0	0.7	•
	210	0.5					2	2.5	N
	230	0.5					7	7.5	N
	250	0.5					11	11.5	O
	270	0.5					15	15.5	O
	300	0.5					19	19.5	Z
50	100						0	0.8	•
	110	0.7					3	3.7	L
	120	0.7					5	5.7	M
	140	0.7					10	10.7	M
	160	0.7					21	21.7	N
	180	0.7					29	29.7	O
	200	0.7					35	35.7	O
	220	0.7					40	40,7	Z
	240	0.7					47	47.7	Z
60	60						0	1.0	•
	70	0.8					2	2.8	K
	80	0.8					7	7.8	L
	100	0.8					14	14.8	M
	120	0.8					26	26.8	N
	140	0.8					39	39.8	O
	160	0.8					48	48.8	Z
	180	0.8					56	56.8	Z
	200	0.6				1	69	70.6	Z
70	50						0	1.2	•
	60	1.0					8	9.0	K
	70	1.0					14	15.0	L
	80	1.0					18	19.0	M
	90	1.0					23	24.0	N
	100	1.0					33	34.0	N
	110	0.8				2	41	43.8	O
	120	0.8				4	47	51.8	O
	130	0.8				6	52	58.8	O
	140	0.8				8	56	64.8	Z
	150	0.8				9	61	70.8	Z
	160	0.8				13	72	85.8	Z
	170	0.8				19	79	98.8	Z
80	40						0	1.3	•
	50	1.2					10	11.2	K
	60	1.2					17	18.2	L
	70	1.2					23	24.2	M
	80	1.0				2	31	34.0	N
	90	1.0				7	39	47.0	N
	100	1.0				11	46	58.0	O
	110	1.0				13	53	67.0	O
	120	1.0				17	56	74.0	Z
	130	1.0				19	63	83.0	Z
	140	1.0				26	69	96.0	Z
	150	1.0				32	77	110.0	Z
90	30						0	1.5	•
	40	1.3					7	8.3	J
	50	1.3					18	19.3	L
	60	1.3					25	26.3	M
	70	1.2				7	30	38.2	N
	80	1.2				13	40	54.2	N
	90	1.2				18	48	67.2	O
	100	1.2				21	54	76.2	Z
	110	1.2				24	61	86.2	Z
	120	1.2				32	68	101.2	Z
	130	1.0			5	36	74	116.0	Z
100	25						0	1.7	•
	30	1.5					3	4.5	I
	40	1.5					15	16.5	K
	50	1.3				2	24	27.3	L
	60	1.3				9	28	38.3	N
	70	1.3				17	39	57.3	O
	80	1.3				23	48	72.3	O
	90	1.2			3	23	57	84.2	Z
	100	1.2			7	23	66	97.2	Z
	110	1.2			10	34	72	117.2	Z
	120	1.2			12	41	78	132.2	Z
110	20						0	1.8	•
	25	1.7					3	4.7	H
	30	1.7					7	8.7	J
	40	1.5				2	21	24.5	L
	50	1.5				8	26	35.5	M
	60	1.5				18	36	55.5	N
	70	1.3			1	23	48	73.3	O
	80	1.3			7	23	57	88.3	Z
	90	1.3			12	30	64	107.3	Z
	100	1.3			15	37	72	125.3	Z

DEPTH (ft)	BOTTOM TIME (mins)	TIME TO FIRST STOP	DECOMPRESSION STOPS 50	40	30	20	10	TOTAL ASCENT TIME	REPET. GROUP
120	15						0	2.0	•
	20	1.8					2	3.8	H
	25	1.8					6	7.8	I
	30	1.8					14	15.8	J
	40	1.7				5	25	31.7	L
	50	1.7				15	31	47.7	N
	60	1.5			2	22	45	70.5	O
	70	1.5			9	23	55	88.5	O
	80	1.5			15	27	63	106.5	Z
	90	1.5			19	37	74	131.5	Z
	100	1.5			23	45	80	149.5	Z
130	10						0	2.2	•
	15	2.0					1	3.0	F
	20	2.0					4	6.0	H
	25	2.0					10	12.0	J
	30	1.8				3	18	22.8	M
	40	1.8				10	25	36.8	N
	50	1.7			3	21	37	62.7	O
	60	1.7			9	23	52	85.7	Z
	70	1.7			16	24	61	102.7	Z
	80	1.5		3	19	35	72	130.5	Z
	90	1.5		8	19	45	80	153.5	Z
140	10						0	2.3	•
	15	2.2					2	4.2	G
	20	2.2					6	8.2	I
	25	2.0				2	14	18.0	J
	30	2.0				5	21	28.0	K
	40	1.8			2	16	26	45.8	N
	50	1.8			6	24	44	75.8	O
	60	1.8			16	23	56	96.8	Z
	70	1.7		4	19	32	68	124.7	Z
	80	1.7		10	23	41	79	154.7	Z
150	5						0	2.5	C
	10	2.3					1	3.3	E
	15	2.3					3	5.3	G
	20	2.2				2	7	11.2	H
	25	2.2				4	17	23.2	K
	30	2.2				8	24	34.2	L
	40	2.0			5	19	33	59.0	N
	50	2.0			12	23	51	88.0	O
	60	1.8		3	19	26	62	111.8	Z
	70	1.8		11	19	39	75	145.8	Z
	80	1.7	1	17	19	50	84	172.7	Z
160	5						0	2.7	D
	10	2.5					1	3.5	F
	15	2.3				1	4	7.3	H
	20	2.3				3	11	16.3	J
	25	2.3				7	20	29.3	K
	30	2.2			2	11	25	40.2	M
	40	2.2			7	23	39	71.2	N
	50	2.0		2	16	23	55	98.0	Z
	60	2.0		9	19	33	69	132.0	Z
	70	1.8	1	17	22	44	80	165.8	Z
170	5						0	2.8	D
	10	2.7					2	4.7	F
	15	2.5				2	5	9.5	H
	20	2.5				4	15	21.5	J
	25	2.3			2	7	23	34.3	L
	30	2.3			4	13	26	45.3	M
	40	2.2		1	10	23	45	81.2	O
	50	2.2		5	18	23	61	109.2	Z
	60	2.0	2	15	22	37	74	152.0	Z
	70	2.0	8	17	19	51	86	183.0	Z
180	5						0	3.0	D
	10	2.8					3	5.8	F
	15	2.7				3	6	11.7	I
	20	2.5			1	5	17	25.5	K
	25	2.5			3	10	24	39.5	L
	30	2.5			6	17	27	52.5	N
	40	2.3		3	14	23	50	92.3	O
	50	2.2	2	9	19	30	65	127.2	Z
	60	2.2	5	16	19	44	81	167.2	Z
190	5						0	3.2	D
	10	2.8				1	3	6.8	G
	15	2.8				4	7	13.8	I
	20	2.7			2	6	20	30.7	K
	25	2.7			5	11	25	43.7	M
	30	2.5		1	8	19	32	62.5	N
	40	2.5		8	14	23	55	102.5	O
	50	2.3	4	13	22	33	72	146.3	Z
	60	2.3	10	17	19	50	84	182.3	Z

APPENDIX D
HUGGINS / MICHIGAN SEA GRANT TABLES

HUGI

University of Michigan Sea Grant Dive Tables

Developed by Karl E. Huggins & Jeff Bozanic

DANGER– READ WARNINGS!!

These tables have been developed mathematically and have not been subjected to testing to validate them. This table is more conservative than the United States Navy tables. If this table is used in the same manner as the USN tables you will have less allowed bottom time. The maximum recommended ascent rate is 40 fpm when you are between 130 and 20 fsw, and 20 fpm between 20 fsw and the surface. You should make a safety stop at 10-30 fsw for 3-5 minutes when the depth of your dive is greater than 60 fsw. If you are within the no-decompression time limits of this table when reaching the safety stop, and the 3-5 minutes causes you to exceed the no-decompression limit, you will be a group "N" diver. You should wait 24 hours after your last dive before ascending over 2,000 feet in altitude.

If these or any other dive tables are used incorrectly, it is possible to develop decompression sickness which may result in severe injury or death. Although statistically less likely, it is also possible to develop decompression sickness even if these or any other dive tables are used correctly. The use of these tables to conduct multi-level dives is discouraged. In the case of a diving accident or illness, call the Divers Alert Network (DAN) at the 24-hour emergency line (919) 684-8111.

Production of these tables was made possible by the National Association of Underwater Instructors (NAUI), P.O. Box 14650, Montclair, CA 91763-1150; (909) 621-5801. Distributed by the Wrigley Marine Science Center, P.O. Box 398, Two Harbors, CA 90704-0398; (213) 743-6792. Revised July 4, 1993.

Table 1 - End-of-Dive Letter Group

Total Time Underwater (in minutes)

Depth in fsw														
20	10	25	40	60	85	110	135	170	215	275	325	569	999	
30	5	15	25	40	50	65	75	95	110	130	150	175	205	225
35	5	15	20	30	40	50	60	70	85	100	120	135	155	165
40	5	10	20	25	35	40	45	55	60	70	85	100	120	135
50	-	10	15	20	25	30	35	37	40	50	55	60	70	75
60	-	5	10	15	20	23	25	27	30	35	40	45	47	50
70	-	5	10	13	15	17	20	23	25	27	30	33	35	40
80	-	5	7	☞	10	13	15	17	20	☞	25	27	☞	30
90	-	-	5	7	☞	10	☞	13	15	17	☞	20	23	25
100	-	-	-	5	7	☞	☞	10	☞	☞	13	15	17	20
110	-	-	-	-	5	☞	7	☞	☞	10	☞	☞	13	15
120	-	-	-	-	-	5	☞	☞	7	☞	☞	10	☟	☟
130	-	-	-	-	-	5	☟	☟	☟	☟	☟	☟	☟	☟
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
	☟	☟	☟	☟	☟	☟	☟	☟	☟	☟	☟	☟	☟	☟

Table 2 - Surface Interval Time (hours:minutes)

New Group	A	B	C	D	E	F	G	H	I	J	K	L	M	N
N													☜	0:10 0:17
M	☜	☜		☜		☜		☜		☜		☜	0:10 0:23	0:18 0:32
L											☜	0:10 0:23	0:24 0:39	0:33 0:48
K	☜	☜		☜		☜		☜		☜	0:10 0:25	0:24 0:41	0:40 0:57	0:49 1:06
J									☜	0:10 0:28	0:26 0:44	0:42 1:00	0:58 1:16	1:07 1:25
I	☜	☜		☜		☜		☜	0:10 0:29	0:29 0:50	0:45 1:06	1:01 1:21	1:17 1:38	1:26 1:47
H							☜	0:10 0:33	0:30 0:53	0:51 1:14	1:07 1:30	1:22 1:45	1:39 2:02	1:48 2:11
G	☜	☜		☜		☜	0:10 0:33	0:34 1:01	0:54 1:21	1:15 1:42	1:31 1:58	1:46 2:13	2:03 2:30	2:12 2:39
F					☜	0:10 0:42	0:34 1:06	1:02 1:34	1:22 1:54	1:43 2:15	1:59 2:31	2:14 2:46	2:31 3:03	2:40 3:12
E	☜	☜		☜	0:10 0:49	0:43 1:23	1:07 1:47	1:35 2:15	1:55 2:35	2:16 2:56	2:32 3:12	2:47 3:27	3:04 3:44	3:13 3:53
D			☜	0:10 1:03	0:50 1:43	1:24 2:17	1:48 2:41	2:16 3:09	2:36 3:29	2:57 3:50	3:13 4:06	3:28 4:21	3:45 4:38	3:54 4:47
C	☜	☜	0:10 1:19	1:04 2:20	1:44 3:00	2:18 3:34	2:42 3:58	3:10 4:26	3:30 4:46	3:51 5:07	4:07 5:23	4:22 5:38	4:39 5:55	4:48 6:04
B		0:10 2:30	1:20 3:41	2:21 4:42	3:01 5:22	3:35 5:56	3:59 6:20	4:27 6:48	4:47 7:08	5:08 7:29	5:24 7:45	5:39 8:00	5:58 8:17	6:05 8:26
A	0:10 12:00	2:31 12:00	3:42 12:00	4:43 12:00	5:23 12:00	5:57 12:40	6:21 13:10	6:49 13:30	7:09 14:00	7:30 14:20	7:46 14:40	8:01 14:50	8:18 15:10	8:27 15:30

Depth of Repetitive Dive (fsw)

	20	30	35	40	50	60	70	80	90	100	110	120	130
N	-- 999	225 --	165 --	135 --	75 --	53 --	41 --	31 --	26 --	21 --	16 --	13 --	11 --
M	-- 999	207 18	158 7	128 7	71 4	52 --	40 --	30 --	25 --	20 --	15 --	12 --	10 --
L	569 999	178 47	139 26	109 26	64 11	47 3	37 3	28 2	23 2	18 2	13 2	11 --	9 --
K	369 999	154 71	122 43	92 43	57 18	43 7	33 7	26 4	21 4	16 4	12 3	10 --	8 --
J	279 999	132 93	103 62	75 60	51 24	38 12	29 11	23 7	18 7	13 7	11 4	9 1	8 --
I	219 999	113 112	86 79	65 70	45 38	34 16	26 14	21 9	16 9	12 8	10 5	8 2	7 --
H	175 999	96 129	73 92	57 78	40 35	30 20	24 16	19 11	14 11	11 9	9 6	8 2	7 --
G	140 999	80 145	62 103	49 86	36 39	27 23	22 18	17 13	12 13	10 10	8 7	7 3	6 --
F	111 999	66 159	53 112	43 92	32 43	24 26	19 21	14 16	11 14	9 11	7 8	6 4	6 --
E	86 999	53 172	44 121	37 98	28 47	22 28	17 23	12 18	9 16	8 12	7 8	6 4	5 --
D	65 999	41 184	34 131	30 105	23 52	19 31	15 25	10 20	8 17	7 13	6 9	5 5	5 --
C	45 999	29 196	24 141	21 114	17 58	14 36	12 28	9 21	8 17	6 14	6 9	5 5	5 --
B	28 999	18 207	16 149	14 121	11 64	9 41	8 32	7 23	6 19	6 14	5 10	5 5	4 1
A	12 999	8 217	7 158	6 129	5 70	4 46	4 36	3 27	3 22	3 17	3 12	2 8	2 3

Table 3 - Residual Nitrogen Time (min.)

00 Light face numbers are Residual Nitrogen Times (RNT)

00 Bold face numbers are Adjusted No-Decompression Limits (ANDL)--Actual bottom time should not exceed this number.

APPENDIX E

ANSWERS TO THE THREE DIVE REPETITIVE DIVE PROBLEM

DIVE TABLE COMPARISON
THREE DIVE REPETITIVE PROBLEM
ANSWERS

Table	A. 85 fsw (26 msw) No-S Limit	B. 85 fsw (26 msw) for 20 min RGD	C. RGD after SI of 2 Hr. 40 Min.	D. 65 fsw (19 msw) No-S Limit	E. 65 fsw 20 min Deco Stop if Needed	F. 65 fsw (19 msw) for 20 min RGD	G. Surface Interval needed for 40 min @ 53 fsw
U.S. Navy	30 min	F	C	35 min	none	G	2:59
Jeppesen	25 min	F	C	25 min	none	G	7:36
NAUI DTC	25 min	F	C	30 min	none	G	4:26
Pandora	27 min	G	D	28 min	none	J	4:03
HUGI	25 min	L	F	21 min	none	N	6:05
German	21 min	D	N/A	28 min	none	F	0:45
PADI Table	25 min	M	A	35 min	none	L	1:00
PADI Wheel	27 min	L	A	40 min	none	K	0:24
DCIEM	20 min	D	1.3	21 min	none	E	9:00
BSAC	24 min	E	C	10 min	1 min @ 6 msw	G	16:00

APPENDIX F
MULTI-LEVEL / MULTI-DAY DIVING STUDIES

ORCA DIVE SERIES - FOUR DAYS - DAYS 1 & 2

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
O1	Descend to	130 fsw	in	2.0 min.	2.0 min.	
	Hold at	130 fsw	for	6.0 min.	8.0 min.	
	Ascend to	70 fsw	in	3.0 min.	11.0 min.	
	Hold at	70 fsw	for	16.0 min.	27.0 min.	
	Ascend to	40 fsw	in	2.0 min.	29.0 min.	
	Hold at	40 fsw	for	18.0 min.	47.0 min.	
	Ascend to	0 fsw	in	1.0 min.	48.0 min.	(0 / 12)
	Hold at	0 fsw	for	45.0 min.	93.0 min.	
O2	Descend to	25 fsw	in	1.0 min.	94.0 min.	
	Hold at	25 fsw	for	58.0 min.	152.0 min.	
	Ascend to	0 fsw	in	1.0 min.	153.0 min.	(0 / 12)
	Hold at	0 fsw	for	180.0 min.	333.0 min.	
O3	Descend to	60 fsw	in	1.0 min.	334.0 min.	
	Hold at	60 fsw	for	14.0 min.	348.0 min.	
	Descend to	100 fsw	in	2.0 min.	350.0 min.	
	Hold at	100 fsw	for	10.0 min.	360.0 min.	
	Ascend to	60 fsw	in	1.0 min.	361.0 min.	
	Hold at	60 fsw	for	6.0 min.	367.0 min.	
	Ascend to	40 fsw	in	0.5 min.	367.5 min.	
	Hold at	40 fsw	for	4.0 min.	371.5 min.	
	Ascend to	0 fsw	in	1.0 min.	372.5 min.	(0 / 12)
	Hold at	0 fsw	for	1067.0 min.	1439.5 min.	
O4	Descend to	90 fsw	in	1.0 min.	1440.5 min.	
	Hold at	90 fsw	for	11.0 min.	1451.5 min.	
	Descend to	130 fsw	in	1.0 min.	1452.5 min.	
	Hold at	130 fsw	for	2.0 min.	1454.5 min.	
	Ascend to	50 fsw	in	2.0 min.	1456.5 min.	
	Hold at	50 fsw	for	30.0 min.	1486.5 min.	
	Ascend to	0 fsw	in	2.0 min.	1488.5 min.	(0 / 12)
	Hold at	0 fsw	for	60.0 min.	1548.5 min.	
O5	Descend to	25 fsw	in	1.0 min.	1549.5 min.	
	Hold at	25 fsw	for	14.0 min.	1563.5 min.	
	Descend to	60 fsw	in	5.0 min.	1568.5 min.	
	Hold at	60 fsw	for	15.0 min.	1583.5 min.	
	Ascend to	25 fsw	in	5.0 min.	1588.5 min.	
	Hold at	25 fsw	for	19.0 min.	1607.5 min.	
	Ascend to	0 fsw	in	1.0 min.	1608.5 min.	(0 / 12)
	Hold at	0 fsw	for	371.0 min.	1979.5 min.	
O6	Descend to	60 fsw	in	1.0 min.	1980.5 min.	
	Hold at	60 fsw	for	9.0 min.	1989.5 min.	
	Descend to	110 fsw	in	2.0 min.	1991.5 min.	
	Hold at	110 fsw	for	5.0 min.	1996.5 min.	
	Ascend to	50 fsw	in	3.0 min.	1999.5 min.	
	Hold at	50 fsw	for	20.0 min.	2019.5 min.	
	Ascend to	0 fsw	in	1.0 min.	2020.5 min.	(0 / 12)
	Hold at	0 fsw	for	859.0 min.	2879.5 min.	

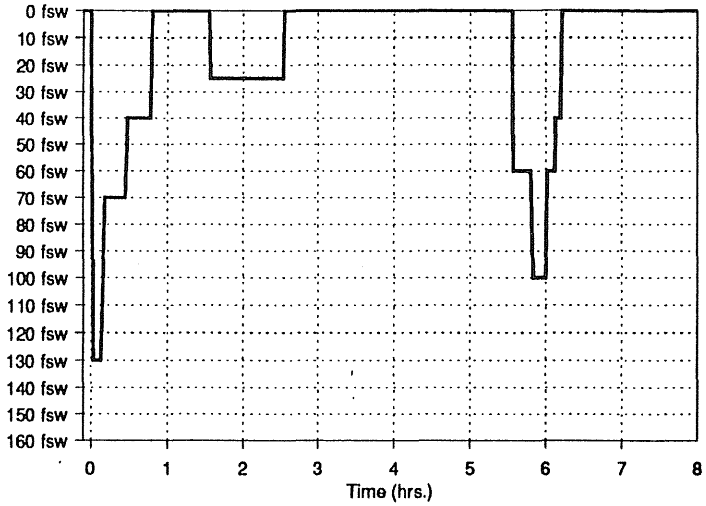
ORCA DIVE SERIES - FOUR DAYS - DAYS 3 & 4

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
O7	Descend to	130 fsw	in	2.0 min.	2881.5 min.	
	Hold at	130 fsw	for	3.0 min.	2884.5 min.	
	Ascend to	50 fsw	in	2.0 min.	2886.5 min.	
	Hold at	50 fsw	for	20.0 min.	2906.5 min.	
	Descend to	130 fsw	in	2.0 min.	2908.5 min.	
	Hold at	130 fsw	for	3.0 min.	2911.5 min.	
	Ascend to	30 fsw	in	2.0 min.	2913.5 min.	
	Hold at	30 fsw	for	10.0 min.	2923.5 min.	
	Ascend to	0 fsw	in	1.0 min.	2924.5 min.	(0 / 12)
	Hold at	0 fsw	for	51.0 min.	2975.5 min.	
O8	Descend to	40 fsw	in	1.0 min.	2976.5 min.	
	Hold at	40 fsw	for	24.0 min.	3000.5 min.	
	Ascend to	25 fsw	in	2.0 min.	3002.5 min.	
	Hold at	25 fsw	for	40.0 min.	3042.5 min.	
	Ascend to	0 fsw	in	1.0 min.	3043.5 min.	(0 / 12)
	Hold at	0 fsw	for	166.0 min.	3209.5 min.	
O9	Descend to	70 fsw	in	1.0 min.	3210.5 min.	
	Hold at	70 fsw	for	14.0 min.	3224.5 min.	
	Ascend to	40 fsw	in	2.0 min.	3226.5 min.	
	Hold at	40 fsw	for	7.0 min.	3233.5 min.	
	Ascend to	0 fsw	in	1.0 min.	3234.5 min.	(0 / 12)
	Hold at	0 fsw	for	1445.0 min.	4679.5 min.	
O10	Descend to	125 fsw	in	1.0 min.	4680.5 min.	
	Hold at	125 fsw	for	19.0 min.	4699.5 min.	
	Ascend to	30 fsw	in	2.0 min.	4701.5 min.	
	Hold at	30 fsw	for	12.0 min.	4713.5 min.	
	Ascend to	0 fsw	in	1.0 min.	4714.5 min.	(0 / 11)

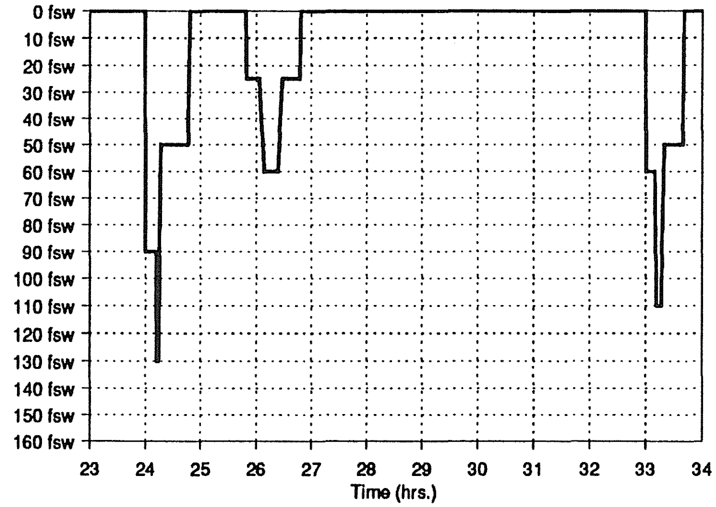
ORCA DIVE SERIES - DOPPLER BUBBLE SCORES

Dive #	Person Dives	Spencer Doppler Grade 0	1	2	3	4
O1	12	12	0	0	0	0
O2	12	12	0	0	0	0
O3	12	12	0	0	0	0
O4	12	12	0	0	0	0
O5	12	12	0	0	0	0
O6	12	12	0	0	0	0
O7	12	12	0	0	0	0
O8	12	12	0	0	0	0
O9	12	12	0	0	0	0
O10	11	10	1	0	0	0
TOTAL	119	118	1	0	0	0

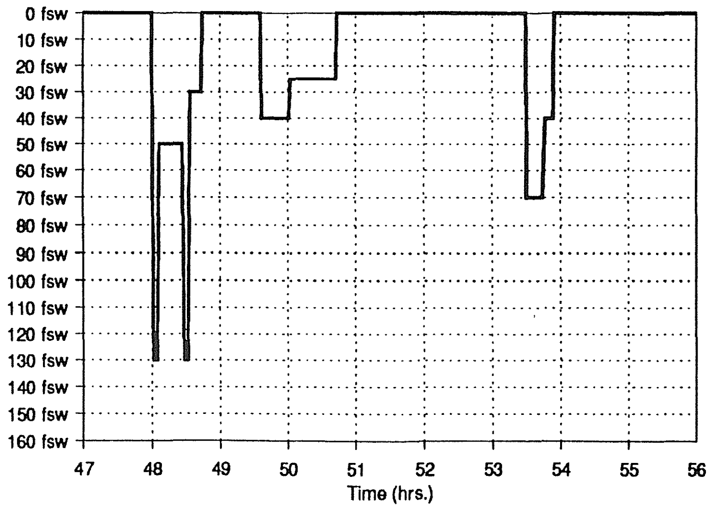
ORCA TEST DIVES - DAY 1
(O1 - O3)



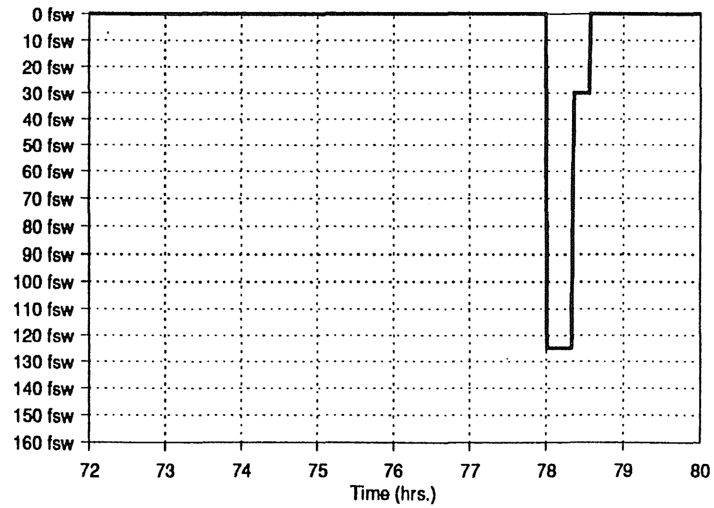
ORCA TEST DIVES - DAY 2
(O4 - O6)



ORCA TEST DIVES - DAY 3
(O7 - O9)



ORCA TEST DIVES - DAY 4
(O10)



PADI/DSAT DIVE SERIES I - MULTI-LEVEL / REPETITIVE DIVES

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
I1a	Descend to	130 fsw	in	2.2 min.	2.2 min.	
	Hold at	130 fsw	for	9.8 min.	12.0 min.	
	Ascend to	0 fsw	in	2.2 min.	14.2 min.	(0 / 25)
	Hold at	0 fsw	for	43.0 min.	57.2 min.	
I1b	Descend to	45 fsw	in	0.8 min.	58.0 min.	
	Hold at	45 fsw	for	83.0 min.	141.0 min.	
	Ascend to	0 fsw	in	0.8 min.	141.8 min.	(0 / 25)
I2a	Descend to	55 fsw	in	0.9 min.	0.9 min.	
	Hold at	55 fsw	for	64.1 min.	65.0 min.	
	Ascend to	0 fsw	in	0.9 min.	65.9 min.	(0 / 18)
	Hold at	0 fsw	for	57.0 min.	122.9 min.	
I2b	Descend to	55 fsw	in	0.9 min.	123.8 min.	
	Hold at	55 fsw	for	43.0 min.	166.8 min.	
	Ascend to	9 fsw	in	0.9 min.	167.7 min.	(0 / 18)
I3a	Descend to	85 fsw	in	1.4 min.	1.4 min.	
	Hold at	85 fsw	for	25.6 min.	27.0 min.	
	Ascend to	0 fsw	in	1.4 min.	28.4 min.	(0 / 20)
	Hold at	0 fsw	for	43.0 min.	71.4 min.	
I3b	Descend to	45 fsw	in	0.8 min.	72.2 min.	
	Hold at	45 fsw	for	71.2 min.	143.4 min.	
	Ascend to	0 fsw	in	0.8 min.	144.2 min.	(0 / 20)
I4a	Descend to	45 fsw	in	0.8 min.	0.8 min.	
	Hold at	45 fsw	for	99.2 min.	100.0 min.	
	Ascend to	0 fsw	in	0.8 min.	100.8 min.	(0 / 5)
	Hold at	0 fsw	for	75 min.	175.8 min.	
I4b	Descend to	85 fsw	in	1.4 min.	177.2 min.	
	Hold at	85 fsw	for	18.6 min.	195.8 min.	
	Ascend to	0 fsw	in	1.4 min.	197.2 min.	(0 / 5)
I5	Descend to	120 fsw	in	2.0 min.	2.0 min.	
	Hold at	120 fsw	for	12.0 min.	14.0 min.	
	Ascend to	55 fsw	in	1.1 min.	15.1 min.	
	Hold at	55 fsw	for	27.0 min.	42.1 min.	
	Ascend to	0 fsw	in	0.9 min.	43.0 min.	(0 / 32)
I6	Descend to	100 fsw	in	1.7 min.	1.7 min.	
	Hold at	100 fsw	for	18.3 min.	20.0 min.	
	Ascend to	50 fsw	in	0.8 min.	20.8 min.	
	Hold at	50 fsw	for	29.0 min.	49.8 min.	
	Ascend to	0 fsw	in	0.9 min.	50.7 min.	(0 / 18)
I7	Descend to	80 fsw	in	1.3 min.	1.3 min.	
	Hold at	80 fsw	for	28.7 min.	30.0 min.	
	Ascend to	45 fsw	in	0.6 min.	30.6 min.	
	Hold at	45 fsw	for	32.0 min.	62.6 min.	
	Ascend to	0 fsw	in	0.7 min.	63.3 min.	(0 / 15)

PADI/DSAT DIVE SERIES I - MULTI-LEVEL / REPETITIVE DIVES

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
I8	Descend to	60 fsw	in	1.0 min.	1.0 min.	
	Hold at	60 fsw	for	54.0 min.	55.0 min.	
	Ascend to	40 fsw	in	0.3 min.	55.3 min.	
	Hold at	40 fsw	for	25.0 min.	80.3 min.	
	Ascend to	0 fsw	in	0.7 min.	81.0 min.	(0 / 24)
I9a	Descend to	120 fsw	in	2.0 min.	2.0 min.	
	Hold at	120 fsw	for	12.0 min.	14.0 min.	
	Ascend to	0 fsw	in	2.0 min.	16.0 min.	(0 / 27)
	Hold at	0 fsw	for	40.0 min.	56.0 min.	
I9b	Descend to	55 fsw	in	0.9 min.	56.9 min.	
	Hold at	55 fsw	for	48.1 min.	105.0 min.	
	Ascend to	0 fsw	in	0.9 min.	105.9 min.	(0 / 27)
I10a	Descend to	75 fsw	in	1.3 min.	1.3 min.	
	Hold at	75 fsw	for	33.7 min.	35.0 min.	
	Ascend to	0 fsw	in	1.3 min.	36.3 min.	(0 / 6)
	Hold at	0 fsw	for	57.0 min.	93.3 min.	
I10b	Descend to	55 fsw	in	0.9 min.	94.2 min.	
	Hold at	55 fsw	for	46.1 min.	140.3 min.	
	Ascend to	0 fsw	in	0.9 min.	141.2 min.	(0 / 6)
I11a	Descend to	100 fsw	in	1.7 min.	1.7 min.	
	Hold at	100 fsw	for	18.3 min.	20.0 min.	
	Ascend to	0 fsw	in	1.7 min.	21.7 min.	(0 / 15)
	Hold at	0 fsw	for	77.0 min.	98.7 min.	
I11b	Descend to	75 fsw	in	1.3 min.	100.0 min.	
	Hold at	75 fsw	for	27.7 min.	127.7 min.	
	Ascend to	0 fsw	in	1.3 min.	129.0 min.	(0 / 15)
I12	Descend to	130 fsw	in	2.2 min.	2.2 min.	
	Hold at	130 fsw	for	9.8 min.	12.0 min.	
	Ascend to	70 fsw	in	0.9 min.	12.9 min.	
	Hold at	70 fsw	for	13 min.	25.9 min.	
	Ascend to	45 fsw	in	0.5 min.	26.4 min.	
	Hold at	45 fsw	for	29.0 min.	55.4 min.	
	Ascend to	0 fsw	in	0.8 min.	56.2 min.	(0 / 19)
I13a	Descend to	110 fsw	in	1.8 min.	1.8 min.	
	Hold at	110 fsw	for	15.2 min.	17.0 min.	
	Ascend to	0 fsw	in	1.8 min.	18.8 min.	(0 / 2)
	Hold at	0 fsw	for	37.0 min.	55.8 min.	
I13b	Descend to	65 fsw	in	1.1 min.	56.9 min.	
	Hold at	65 fsw	for	29.9 min.	86.8 min.	
	Ascend to	0 fsw	in	1.1 min.	87.9 min.	(0 / 2)
	Hold at	0 fsw	for	23.0 min.	110.9 min.	
I13c	Descend to	45 fsw	in	0.8 min.	111.7 min.	
	Hold at	45 fsw	for	50.2 min.	161.9 min.	
	Ascend to	0 fsw	in	0.8 min.	162.7 min.	0 / 2)

PADI/DSAT DIVE SERIES I - MULTI-LEVEL / REPETITIVE DIVES

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
I14	Descend to	130 fsw	in	2.2 min.	2.2 min.	
	Hold at	130 fsw	for	9.8 min.	12.0 min.	
	Ascend to	60 fsw	in	1.2 min.	13.2 min.	
	Hold at	60 fsw	for	19.0 min.	32.2 min.	
	Ascend to	45 fsw	in	0.3 min.	32.5 min.	
	Hold at	45 fsw	for	21.0 min.	53.5 min.	
	Ascend to	35 fsw	in	0.1 min.	53.6 min.	
	Hold at	35 fsw	for	35.0 min.	88.6 min.	
	Ascend to	0 fsw	in	0.6 min.	89.2 min.	(0 / 15)
I15a	Descend to	130 fsw	in	2.2 min.	2.2 min.	
	Hold at	130 fsw	for	9.8 min.	12.0 min.	
	Ascend to	0 fsw	in	2.2 min.	14.2 min.	(0 / 5)
	Hold at	0 fsw	for	43.0 min.	57.2 min.	
I15b	Descend to	90 fsw	in	1.5 min.	58.7 min.	
	Hold at	90 fsw	for	14.5 min.	72.2 min.	
	Ascend to	0 fsw	in	1.5 min.	73.7 min.	(0 / 4)
	Hold at	0 fsw	for	37.0 min.	110.7 min.	
I15c	Descend to	60 fsw	in	1.0 min.	111.7 min.	
	Hold at	60 fsw	for	31.0 min.	142.7 min.	
	Ascend to	0 fsw	in	1.0 min.	143.7 min.	(0 / 4)
	Hold at	0 fsw	for	21.0 min.	164.7 min.	
I15d	Descend to	40 fsw	in	0.7 min.	165.4 min.	
	Hold at	40 fsw	for	70.3 min.	235.7 min.	
	Ascend to	0 fsw	in	0.7 min.	236.4 min.	(0 / 4)
I16a	Descend to	90 fsw	in	1.5 min.	1.5 min.	
	Hold at	90 fsw	for	23.5 min.	25.0 min.	
	Ascend to	45 fsw	in	0.7 min.	25.7 min.	
	Hold at	45 fsw	for	34.0 min.	59.7 min.	
	Ascend to	0 fsw	in	0.8 min.	60.5 min.	(0 / 2)
	Hold at	0 fsw	for	49.0 min.	109.5 min.	
I16b	Descend to	60 fsw	in	1.0 min.	110.5 min.	
	Hold at	60 fsw	for	38.0 min.	148.5 min.	
	Ascend to	0 fsw	in	1.0 min.	149.5 min.	(0 / 2)
I17a	Descend to	55 fsw	in	0.9 min.	0.9 min.	
	Hold at	55 fsw	for	64.1 min.	65.0 min.	
	Ascend to	0 fsw	in	0.9 min.	65.9 min.	(0 / 4)
	Hold at	0 fsw	for	24.0 min.	89.9 min.	
I17b	Descend to	55 fsw	in	0.9 min.	90.8 min.	
	Hold at	55 fsw	for	26.1 min.	116.9 min.	
	Ascend to	40 fsw	in	0.2 min.	117.1 min.	
	Hold at	40 fsw	for	20.0 min.	137.1 min.	
	Ascend to	0 fsw	in	0.7 min.	137.8 min.	(0 / 4)

PADI/DSAT DIVE SERIES I - MULTI-LEVEL / REPETITIVE DIVES

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
I18a	Descend to	130 fsw	in	2.2 min.	2.2 min.	
	Hold at	130 fsw	for	9.8 min.	12.0 min.	
	Ascend to	50 fsw	in	1.3 min.	13.2 min.	
	Hold at	50 fsw	for	41.0 min.	54.2 min.	
	Ascend to	0 fsw	in	0.9 min.	55.1 min.	(0 / 15)
	Hold at	0 fsw	for	84.0 min.	139.1 min.	
I18b	Descend to	80 fsw	in	1.3 min.	140.4 min.	
	Hold at	80 fsw	for	19.7 min.	160.1 min.	
	Ascend to	45 fsw	in	0.6 min.	160.7 min.	
	Hold at	45 fsw	for	33.0 min.	193.7 min.	
	Ascend to	0 fsw	in	0.7 min.	194.4 min.	(0 / 15)
I19a	Descend to	110 fsw	in	1.8 min.	1.8 min.	
	Hold at	110 fsw	for	15.2 min.	17.0 min.	
	Ascend to	65 fsw	in	0.7 min.	17.8 min.	
	Hold at	65 fsw	for	11.0 min.	28.8 min.	
	Ascend to	0 fsw	in	1.1 min.	29.1 min.	(0 / 17)
	Hold at	0 fsw	for	33.0 min.	62.1 min.	
I19b	Descend to	50 fsw	in	0.8 min.	62.9 min.	
	Hold at	50 fsw	for	46.2 min.	109.1 min.	
	Ascend to	35 fsw	in	0.2 min.	109.3 min.	
	Hold at	35 fsw	for	37.0 min.	146.3 min.	
	Ascend to	0 fsw	in	0.6 min.	146.9 min.	(0 / 17)
	Hold at	0 fsw	for	32.0 min.	178.9 min.	
I19c	Descend to	60 fsw	in	1.0 min.	179.9 min.	
	Hold at	60 fsw	for	16.0 min.	195.9 min.	
	Ascend to	40 fsw	in	0.3 min.	196.2 min.	
	Hold at	40 fsw	for	29.0 min.	225.2 min.	
	Ascend to	0 fsw	in	0.7 min.	225.9 min.	(0 / 17)
I20a	Descend to	120 fsw	in	2.0 min.	2.0 min.	
	Hold at	120 fsw	for	12.0 min.	14.0 min.	
	Ascend to	60 fsw	in	1.0 min.	15.0 min.	
	Hold at	60 fsw	for	19.0 min.	34.0 min.	
	Ascend to	45 fsw	in	0.3 min.	34.3 min.	
	Hold at	45 fsw	for	22.0 min.	56.3 min.	
	Ascend to	0 fsw	in	0.7 min.	57.0 min.	(0 / 17)
	Hold at	0 fsw	for	23.0 min.	80.0 min.	
I20b	Descend to	40 fsw	in	0.7 min.	80.7 min.	
	Hold at	40 fsw	for	66.3 min.	147.0 min.	
	Ascend to	0 fsw	in	0.7 min.	147.7 min.	(0 / 17)

PADI/DSAT DIVE SERIES I - MULTI-LEVEL / REPETITIVE DIVES

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
I21a	Descend to	65 fsw	in	1.1 min.	1.1 min.	
	Hold at	65 fsw	for	43.9 min.	45.0 min.	
	Ascend to	0 fsw	in	1.1 min.	46.1 min.	(0 / 3)
	Hold at	0 fsw	for	37.0 min.	83.1 min.	
I21b	Descend to	65 fsw	in	1.1 min.	84.2 min.	
	Hold at	65 fsw	for	15.9 min.	100.1 min.	
	Ascend to	45 fsw	in	0.3 min.	100.4 min.	
	Hold at	45 fsw	for	26.0 min.	126.4 min.	
	Ascend to	35 fsw	in	0.2 min.	126.6 min.	
	Hold at	35 fsw	for	36.0 min.	162.6 min.	
	Ascend to	0 fsw	in	0.6 min.	163.2 min.	(0 / 3)
I22a	Descend to	95 fsw	in	1.6 min.	1.6 min.	
	Hold at	95 fsw	for	20.4 min.	22.0 min.	
	Ascend to	0 fsw	in	1.6 min.	23.6 min.	(0 / 2)
	Hold at	0 fsw	for	39.0 min.	62.6 min.	
I22b	Descend to	55 fsw	in	0.9 min.	63.5 min.	
	Hold at	55 fsw	for	34.1 min.	97.6 min.	
	Ascend to	40 fsw	in	0.2 min.	97.8 min.	
	Hold at	40 fsw	for	34.0 min.	131.8 min.	
	Ascend to	35 fsw	in	0.2 min.	132.0 min.	
	Hold at	35 fsw	for	17.0 min.	149.0 min.	
	Ascend to	0 fsw	in	0.5 min.	149.5 min.	(0 / 2)
I51a	Descend to	100 fsw	in	1.7 min.	1.7 min.	
	Hold at	100 fsw	for	16.3 min.	18.0 min.	
	Ascend to	0 fsw	in	1.7 min.	19.7 min.	(0 / 48)
	Hold at	0 fsw	for	33.0 min.	52.7 min.	
I51b	Descend to	65 fsw	in	1.1 min.	53.8 min.	
	Hold at	65 fsw	for	24.9 min.	78.7 min.	
	Ascend to	0 fsw	in	1.1 min.	79.8 min.	(0 / 48)
	Hold at	0 fsw	for	30.0 min.	109.8 min.	
I51c	Descend to	50 fsw	in	0.8 min.	110.6 min.	
	Hold at	50 fsw	for	38.2 min.	148.8 min.	
	Ascend to	0 fsw	in	0.8 min.	149.6 min.	(0 / 48)
I52a	Descend to	80 fsw	in	1.3 min.	1.3 min.	
	Hold at	80 fsw	for	19.7 min.	21.0 min.	
	Ascend to	0 fsw	in	1.3 min.	22.3 min.	(0 / 40)
	Hold at	0 fsw	for	30.0 min.	52.3 min.	
I52b	Descend to	60 fsw	in	1.0 min.	53.3 min.	
	Hold at	60 fsw	for	32.0 min.	85.3 min.	
	Ascend to	0 fsw	in	1.0 min.	86.3 min.	(0 / 40)
	Hold at	0 fsw	for	30.0 min.	116.3 min.	
I52c	Descend to	55 fsw	in	0.9 min.	117.2 min.	
	Hold at	55 fsw	for	27.1 min.	144.3 min.	
	Ascend to	0 fsw	in	0.9 min.	145.2 min.	(0 / 40)

PADI/DSAT DIVE SERIES I - MULTI-LEVEL / REPETITIVE DIVES

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
I53a	Descend to	65 fsw	in	1.1 min.	1.1 min.	
	Hold at	65 fsw	for	33.9 min.	35.0 min.	
	Ascend to	0 fsw	in	1.1 min.	36.1 min.	(0 / 43)
	Hold at	0 fsw	for	28.0 min.	64.1 min.	
I53b	Descend to	55 fsw	in	0.9 min.	65.0 min.	
	Hold at	55 fsw	for	31.1 min.	96.1 min.	
	Ascend to	0 fsw	in	0.9 min.	97.0 min.	(0 / 43)
	Hold at	0 fsw	for	25.0 min.	122.0 min.	
I53c	Descend to	50 fsw	in	0.8 min.	122.8 min.	
	Hold at	50 fsw	for	32.2 min.	155.0 min.	
	Ascend to	0 fsw	in	0.8 min.	155.8 min.	(0 / 43)

PADI/DSAT DIVE SERIES I - DOPPLER BUBBLE SCORES

Dive #	Person Dives	Rest/ Move	Spencer Doppler Grade 0	1	2	3	4
I1a	25	Rest	25	0	0	0	0
		Move	25	0	0	0	0
I1b	25	Rest	25	0	0	0	0
		Move	23	1	1	0	0
I2a	18	Rest	17	1	0	0	0
		Move	14	4	0	0	0
I2b	18	Rest	17	1	0	0	0
		Move	13	5	0	0	0
I3a	20	Rest	20	0	0	0	0
		Move	20	0	0	0	0
I3b	20	Rest	20	0	0	0	0
		Move	20	0	0	0	0
I4a	5	Rest	5	0	0	0	0
		Move	5	0	0	0	0
I4b	5	Rest	5	0	0	0	0
		Move	5	0	0	0	0
I5	32	Rest	32	0	0	0	0
		Move	28	4	0	0	0
I6	18	Rest	17	1	0	0	0
		Move	16	2	0	0	0
I7	15	Rest	15	0	0	0	0
		Move	11	4	0	0	0
I8	24	Rest	21	0	3	0	0
		Move	18	3	0	3	0
I9a	27	Rest	26	1	0	0	0
		Move	25	1	1	0	0
I9b	27	Rest	27	0	0	0	0
		Move	24	2	1	0	0
I10a	6	Rest	6	0	0	0	0
		Move	5	1	0	0	0
I10b	6	Rest	6	0	0	0	0
		Move	4	2	0	0	0

PADI/DSAT DIVE SERIES I - DOPPLER BUBBLE SCORES

Dive #	Person Dives	Rest/ Move	Spencer Doppler Grade 0	1	2	3	4
I11a	15	Rest	15	0	0	0	0
		Move	14	0	0	0	0
I11b	15	Rest	15	0	0	0	0
		Move	14	1	0	0	0
I12a	19	Rest	19	0	0	0	0
		Move	17	2	0	0	0
I13a	2	Rest	2	0	0	0	0
		Move	2	0	0	0	0
I13b	2	Rest	2	0	0	0	0
		Move	2	0	0	0	0
I13c	2	Rest	2	0	0	0	0
		Move	2	0	0	0	0
I14	15	Rest	15	0	0	0	0
		Move	15	0	0	0	0
I15a	5	Rest	5	0	0	0	0
		Move	4	1	0	0	0
I15b	4	Rest	4	0	0	0	0
		Move	3	1	0	0	0
I15c	4	Rest	4	0	0	0	0
		Move	3	1	0	0	0
I15d	4	Rest	3	1	0	0	0
		Move	3	1	0	0	0
I16a	2	Rest	2	0	0	0	0
		Move	1	1	0	0	0
I16b	2	Rest	2	0	0	0	0
		Move	1	1	0	0	0
I17a	4	Rest	4	0	0	0	0
		Move	4	0	0	0	0
I17b	4	Rest	4	0	0	0	0
		Move	4	0	0	0	0
I18a	15	Rest	15	0	0	0	0
		Move	15	0	0	0	0
I18b	15	Rest	15	0	0	0	0
		Move	15	0	0	0	0
I19a	17	Rest	17	0	0	0	0
		Move	16	1	0	0	0
I19b	17	Rest	16	0	0	0	0
		Move	17	0	0	0	0
I19c	17	Rest	17	0	0	0	0
		Move	16	1	0	0	0
I20a	17	Rest	16	1	0	0	0
		Move	16	0	1	0	0
I20b	17	Rest	17	0	0	0	0
		Move	14	3	0	0	0
I21a	3	Rest	3	0	0	0	0
		Move	3	0	0	0	0
I21b	3	Rest	3	0	0	0	0
		Move	3	0	0	0	0

PADI/DSAT DIVE SERIES I - DOPPLER BUBBLE SCORES

Dive #	Person Dives	Rest/ Move	Spencer Doppler Grade 0	1	2	3	4
I22a	2	Rest	2	0	0	0	0
		Move	2	0	0	0	0
I22b	2	Rest	2	0	0	0	0
		Move	2	0	0	0	0
I51a	48	Rest	47	1	0	0	0
		Move	46	2	0	0	0
I51b	48	Rest	45	1	2	0	0
		Move	43	1	1	2	0
I51c	48	Rest	46	2	0	0	0
		Move	42	5	1	0	0
I52a	40	Rest	40	0	0	0	0
		Move	40	0	0	0	0
I52b	40	Rest	40	0	0	0	0
		Move	38	2	0	0	0
I52c	40	Rest	40	0	0	0	0
		Move	39	1	0	0	0
I53a	43	Rest	42	1	0	0	0
		Move	42	0	1	0	0
I53b	43	Rest	43	0	0	0	0
		Move	42	1	0	0	0
I53c	43	Rest	43	0	0	0	0
		Move	40	3	0	0	0
TOTAL	908	Rest	890	11	5	0	0
		Move	837	58	7	5	0

***** NO GRAPHS PREPARED FOR PADI/DSAT DIVE SERIES I *****

PADI/DSAT DIVE SERIES IIa - SIX DIVES A DAY - SIX DAYS - DAY 1

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
IIa1	Descend to	95 fsw	in	1.6 min.	1.6 min.	
	Hold at	95 fsw	for	20.4 min.	22.0 min.	
	Ascend to	15 fsw	in	1.3 min.	23.3 min.	
	Hold at	15 fsw	for	3.0 min.	26.3 min.	
	Ascend to	0 fsw	in	0.3 min.	26.6 min.	(0 / 4)
	Hold at	0 fsw	for	60 min.	86.6 min.	
IIa2	Descend to	65 fsw	in	1.1 min.	87.7 min.	
	Hold at	65 fsw	for	28.9 min.	116.6 min.	
	Ascend to	15 fsw	in	0.8 min.	117.4 min.	
	Hold at	15 fsw	for	3.0 min.	120.4 min.	
	Ascend to	0 fsw	in	0.3 min.	120.7 min.	(0 / 4)
	Hold at	0 fsw	for	63.0 min.	183.7 min.	
IIa3	Descend to	45 fsw	in	0.8 min.	184.5 min.	
	Hold at	45 fsw	for	60.2 min.	244.7 min.	
	Ascend to	15 fsw	in	0.5 min.	245.2 min.	
	Hold at	15 fsw	for	3.0 min.	248.2 min.	
	Ascend to	0 fsw	in	0.3 min.	248.5 min.	(0 / 4)
	Hold at	0 fsw	for	130.0 min.	378.5 min.	
IIa4	Descend to	55 fsw	in	0.9 min.	379.4 min.	
	Hold at	55 fsw	for	53.1 min.	432.5 min.	
	Ascend to	15 fsw	in	0.7 min.	433.2 min.	
	Hold at	15 fsw	for	3.0 min.	436.2 min.	
	Ascend to	0 fsw	in	0.3 min.	436.5 min.	(0 / 4)
	Hold at	0 fsw	for	60.0 min.	496.5 min.	
IIa5	Descend to	90 fsw	in	1.5 min.	498.0 min.	
	Hold at	90 fsw	for	8.5 min.	506.5 min.	
	Ascend to	60 fsw	in	0.5 min.	507.0 min.	
	Hold at	60 fsw	for	9.0 min.	516.0 min.	
	Ascend to	35 fsw	in	0.4 min.	516.4 min.	
	Hold at	35 fsw	for	57.0 min.	573.4 min.	
	Ascend to	15 fsw	in	0.3 min.	573.7 min.	
	Hold at	15 fsw	for	3.0 min.	576.7 min.	
	Ascend to	0 fsw	in	0.3 min.	577.0 min.	(0 / 4)
	Hold at	0 fsw	for	95.0 min.	672.0 min.	
IIa6	Descend to	120 fsw	in	2.0 min.	674.0 min.	
	Hold at	120 fsw	for	4.0 min.	678.0 min.	
	Ascend to	80 fsw	in	0.7 min.	678.7 min.	
	Hold at	80 fsw	for	8.0 min.	686.7 min.	
	Ascend to	50 fsw	in	0.5 min.	687.2 min.	
	Hold at	50 fsw	for	17.0 min.	704.2 min.	
	Ascend to	35 fsw	in	0.3 min.	704.5 min.	
	Hold at	35 fsw	for	42.0 min.	746.5 min.	
	Ascend to	15 fsw	in	0.3 min.	746.8 min.	
	Hold at	15 fsw	for	3.0 min.	749.8 min.	
	Ascend to	0 fsw	in	0.3 min.	750.1 min.	(0 / 4)
	Hold at	0 fsw	for	689.9 min.	1440.0 min.	

PADI/DSAT DIVE SERIES IIa - SIX DIVES A DAY - SIX DAYS - DAY 2

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
IIa7	Descend to	60 fsw	in	1.0 min.	1441.0 min.	
	Hold at	60 fsw	for	54.0 min.	1495.0 min.	
	Ascend to	15 fsw	in	0.7 min.	1495.7 min.	
	Hold at	15 fsw	for	3.0 min.	1498.7 min.	
	Ascend to	0 fsw	in	0.3 min.	1499.0 min.	(0 / 4)
	Hold at	0 fsw	for	75.0 min.	1574.0 min.	
IIa8	Descend to	45 fsw	in	0.8 min.	1574.8 min.	
	Hold at	45 fsw	for	64.2 min.	1639.0 min.	
	Ascend to	15 fsw	in	0.5 min.	1639.5 min.	
	Hold at	15 fsw	for	3.0 min.	1642.5 min.	
	Ascend to	0 fsw	in	0.3 min.	1642.8 min.	(0 / 4)
	Hold at	0 fsw	for	130.0 min.	1772.8 min.	
IIa9	Descend to	85 fsw	in	1.4 min.	1774.2 min.	
	Hold at	85 fsw	for	18.6 min.	1792.8 min.	
	Ascend to	45 fsw	in	0.7 min.	1793.5 min.	
	Hold at	45 fsw	for	26.0 min.	1819.5 min.	
	Ascend to	15 fsw	in	0.5 min.	1820.0 min.	
	Hold at	15 fsw	for	3.0 min.	1823.0 min.	
	Ascend to	0 fsw	in	0.3 min.	1823.3 min.	(0 / 4)
	Hold at	0 fsw	for	60.0 min.	1883.3 min.	
IIa10	Descend to	75 fsw	in	1.3 min.	1884.6 min.	
	Hold at	75 fsw	for	14.7 min.	1899.3 min.	
	Ascend to	40 fsw	in	0.6 min.	1899.9 min.	
	Hold at	40 fsw	for	34.0 min.	1933.9 min.	
	Ascend to	15 fsw	in	0.4 min.	1934.3 min.	
	Hold at	15 fsw	for	3.0 min.	1937.3 min.	
	Ascend to	0 fsw	in	0.3 min.	1937.6 min.	(0 / 4)
	Hold at	0 fsw	for	60.0 min.	1997.6 min.	
IIa11	Descend to	80 fsw	in	1.3 min.	1998.9 min.	
	Hold at	80 fsw	for	10.7 min.	2009.6 min.	
	Ascend to	40 fsw	in	0.7 min.	2010.3 min.	
	Hold at	40 fsw	for	34.0 min.	2044.3 min.	
	Ascend to	15 fsw	in	0.4 min.	2044.7 min.	
	Hold at	15 fsw	for	3.0 min.	2047.7 min.	
	Ascend to	0 fsw	in	0.3 min.	2048.0 min.	(0 / 4)
	Hold at	0 fsw	for	87.0 min.	2135.0 min.	
IIa12	Descend to	110 fsw	in	1.8 min.	2136.8 min.	
	Hold at	110 fsw	for	5.2 min.	2142.0 min.	
	Ascend to	65 fsw	in	0.8 min.	2142.8 min.	
	Hold at	65 fsw	for	10.0 min.	2152.8 min.	
	Ascend to	50 fsw	in	0.3 min.	2153.1 min.	
	Hold at	50 fsw	for	11.0 min.	2164.1 min.	
	Ascend to	40 fsw	in	0.2 min.	2164.3 min.	
	Hold at	40 fsw	for	19.0 min.	2183.3 min.	
	Ascend to	15 fsw	in	0.4 min.	2183.7 min.	
	Hold at	15 fsw	for	3.0 min.	2186.7 min.	
	Ascend to	0 fsw	in	0.3 min.	2187.0 min.	(1 / 4)
	Hold at	0 fsw	for	693.0 min.	2880.0 min.	

PADI/DSAT DIVE SERIES IIa - SIX DIVES A DAY - SIX DAYS - DAY 3

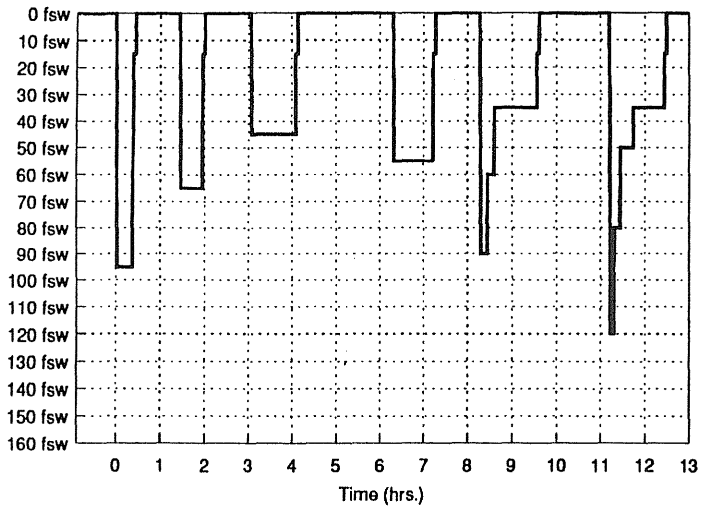
	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
IIa13	Descend to	110 fsw	in	1.8 min.	2881.8 min.	
	Hold at	110 fsw	for	14.2 min.	2896.0 min.	
	Ascend to	15 fsw	in	1.6 min.	2897.6 min.	
	Hold at	15 fsw	for	3.0 min.	2900.6 min.	
	Ascend to	0 fsw	in	0.3 min.	2900.9 min.	(0 / 3)

*** TEST TERMINATED ***

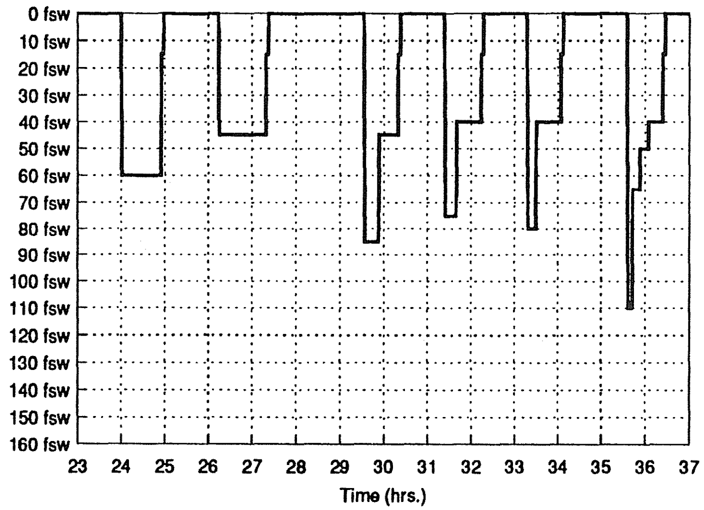
PADI/DSAT DIVE SERIES IIa - DOPPLER BUBBLE SCORES

Dive #	Person Dives	Rest/ Move	Spencer Doppler Grade 0	1	2	3	4
IIa1	4	Rest	4	0	0	0	0
		Move	4	0	0	0	0
IIa2	4	Rest	4	0	0	0	0
		Move	4	0	0	0	0
IIa3	4	Rest	4	0	0	0	0
		Move	0	3	0	1	0
IIa4	4	Rest	4	0	0	0	0
		Move	2	0	1	1	0
IIa5	4	Rest	3	0	1	0	0
		Move	3	0	0	1	0
IIa6	4	Rest	4	0	0	0	0
		Move	3	0	0	1	0
IIa7	4	Rest	4	0	0	0	0
		Move	3	1	0	0	0
IIa8	4	Rest	3	1	0	0	0
		Move	2	2	0	0	0
IIa9	4	Rest	4	0	0	0	0
		Move	3	0	1	0	0
IIa10	4	Rest	4	0	0	0	0
		Move	4	0	0	0	0
IIa11	4	Rest	4	0	0	0	0
		Move	3	0	1	0	0
IIa12	4	Rest	3	1	0	0	0
		Move	2	1	0	1	0
IIa13	3	Rest	3	0	0	0	0
		Move	1	2	0	0	0
TOTAL	51	Rest	48	2	1	0	0
		Move	34	9	3	5	0

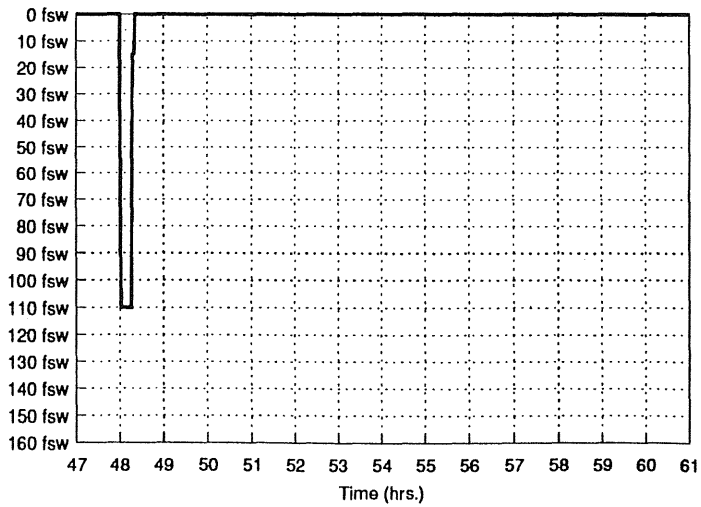
PADI/DSAT DIVE SERIES IIa - DAY 1
(IIa1 - IIa6)



PADI/DSAT DIVE SERIES IIa - DAY 2
(IIa7 - IIa12)



PADI/DSAT DIVE SERIES IIa - DAY 3
(IIa13)



PADI/DSAT DIVE SERIES IIb - FOUR DIVES A DAY - SIX DAYS - DAY 1

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
IIb1	Descend to	120 fsw	in	2.0 min.	2.0 min.	
	Hold at	120 fsw	for	11.0 min.	13.0 min.	
	Ascend to	70 fsw	in	0.8 min.	13.8 min.	
	Hold at	70 fsw	for	11.0 min.	24.8 min.	
	Ascend to	50 fsw	in	0.3 min.	25.1 min.	
	Hold at	50 fsw	for	14.0 min.	39.1 min.	
	Ascend to	35 fsw	in	0.3 min.	39.4 min.	
	Hold at	35 fsw	for	13.0 min.	52.4 min.	
	Ascend to	15 fsw	in	0.3 min.	52.7 min.	
	Hold at	15 fsw	for	3.0 min.	55.7 min.	
	Ascend to	0 fsw	in	0.3 min.	56.0 min.	(0 / 17)
	Hold at	0 fsw	for	80.0 min.	136.0 min.	
IIb2	Descend to	80 fsw	in	1.3 min.	137.3 min.	
	Hold at	80 fsw	for	14.7 min.	152.0 min.	
	Ascend to	50 fsw	in	0.5 min.	152.5 min.	
	Hold at	50 fsw	for	13.0 min.	165.5 min.	
	Ascend to	40 fsw	in	0.2 min.	165.7 min.	
	Hold at	40 fsw	for	25.0 min.	190.7 min.	
	Ascend to	15 fsw	in	0.4 min.	191.1 min.	
	Hold at	15 fsw	for	3.0 min.	194.1 min.	
	Ascend to	0 fsw	in	0.2 min.	194.3 min.	(0 / 18)
	Hold at	0 fsw	for	180.0 min.	374.3 min.	
IIb3	Descend to	60 fsw	in	1.0 min.	375.3 min.	
	Hold at	60 fsw	for	47.0 min.	422.3 min.	
	Ascend to	35 fsw	in	0.5 min.	422.8 min.	
	Hold at	35 fsw	for	54.0 min.	476.8 min.	
	Ascend to	15 fsw	in	0.3 min.	477.1 min.	
	Hold at	15 fsw	for	3.0 min.	480.1 min.	
	Ascend to	0 fsw	in	0.2 min.	480.3 min.	(0 / 19)
	Hold at	0 fsw	for	180.0 min.	660.3 min.	
IIb4	Descend to	40 fsw	in	0.7 min.	661.0 min.	
	Hold at	40 fsw	for	89.3 min.	750.3 min.	
	Ascend to	15 fsw	in	0.4 min.	750.7 min.	
	Hold at	15 fsw	for	3.0 min.	753.7 min.	
	Ascend to	0 fsw	in	0.3 min.	754.0 min.	(0 / 19)
	Hold at	0 fsw	for	686.0 min.	1440.0 min.	

PADI/DSAT DIVE SERIES IIb - FOUR DIVES A DAY - SIX DAYS - DAY 2

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
IIb5	Descend to	95 fsw	in	1.6 min.	1441.6 min.	
	Hold at	95 fsw	for	20.4 min.	1462.0 min.	
	Ascend to	65 fsw	in	0.5 min.	1462.5 min.	
	Hold at	65 fsw	for	5.0 min.	1467.5 min.	
	Ascend to	50 fsw	in	0.2 min.	1467.7 min.	
	Hold at	50 fsw	for	13 min.	1480.7 min.	
	Ascend to	35 fsw	in	0.3 min.	1481.0 min.	
	Hold at	35 fsw	for	26.0 min.	1507.0 min.	
	Ascend to	15 fsw	in	0.4 min.	1507.4 min.	
	Hold at	15 fsw	for	3.0 min.	1510.4 min.	
	Ascend to	0 fsw	in	0.2 min.	1510.6 min.	(0 / 20)
	Hold at	0 fsw	for	71.0 min.	1581.6 min.	
IIb6	Descend to	70 fsw	in	1.2 min.	1582.8 min.	
	Hold at	70 fsw	for	20.8 min.	1603.6 min.	
	Ascend to	40 fsw	in	0.5 min.	1604.1 min.	
	Hold at	40 fsw	for	37.0 min.	1641.1 min.	
	Ascend to	15 fsw	in	0.4 min.	1641.5 min.	
	Hold at	15 fsw	for	3.0 min.	1644.5 min.	
	Ascend to	0 fsw	in	0.3 min.	1644.8 min.	(0 / 20)
	Hold at	0 fsw	for	180.0 min.	1824.8 min.	
IIb7	Descend to	55 fsw	in	0.9 min.	1825.7 min.	
	Hold at	55 fsw	for	58.1 min.	1883.8 min.	
	Ascend to	15 fsw	in	0.7 min.	1884.5 min.	
	Hold at	15 fsw	for	3.0 min.	1887.5 min.	
	Ascend to	0 fsw	in	0.2 min.	1887.7 min.	(0 / 20)
	Hold at	0 fsw	for	180.0 min.	2067.7 min.	
IIb8	Descend to	45 fsw	in	0.8 min.	2068.5 min.	
	Hold at	45 fsw	for	91.2 min.	2159.7 min.	
	Ascend to	15 fsw	in	0.5 min.	2160.2 min.	
	Hold at	15 fsw	for	3.0 min.	2163.2 min.	
	Ascend to	0 fsw	in	0.3 min.	2163.5 min.	
	Hold at	0 fsw	for	716.0 min.	2879.5 min.	

PADI/DSAT DIVE SERIES IIb - FOUR DIVES A DAY - SIX DAYS - DAY 3

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
IIb9	Descend to	90 fsw	in	1.5 min.	2881.0 min.	
	Hold at	90 fsw	for	23.5 min.	2904.5 min.	
	Ascend to	55 fsw	in	0.6 min.	2905.1 min.	
	Hold at	55 fsw	for	9.0 min.	2914.1 min.	
	Ascend to	35 fsw	in	0.3 min.	2914.4 min.	
	Hold at	35 fsw	for	40.0 min.	2954.4 min.	
	Ascend to	15 fsw	in	0.3 min.	2954.7 min.	
	Hold at	15 fsw	for	3.0 min.	2957.7 min.	
	Ascend to	0 fsw	in	0.3 min.	2958.0 min.	(0 / 20)
	Hold at	0 fsw	for	87.0 min.	3045.0 min.	
IIb10	Descend to	60 fsw	in	1.0 min.	3046.0 min.	
	Hold at	60 fsw	for	37.0 min.	3083.0 min.	
	Ascend to	15 fsw	in	0.7 min.	3083.7 min.	
	Hold at	15 fsw	for	3.0 min.	3086.7 min.	
	Ascend to	0 fsw	in	0.3 min.	3087.0 min.	(0 / 20)
	Hold at	0 fsw	for	92.0 min.	3179.0 min.	
IIb11	Descend to	50 fsw	in	0.8 min.	3179.8 min.	
	Hold at	50 fsw	for	60.2 min.	3240.0 min.	
	Ascend to	15 fsw	in	0.6 min.	3240.6 min.	
	Hold at	15 fsw	for	3.0 min.	3243.6 min.	
	Ascend to	0 fsw	in	0.2 min.	3243.8 min.	(0 / 20)
	Hold at	0 fsw	for	180.0 min.	3423.8 min.	
IIb12	Descend to	40 fsw	in	0.7 min.	3424.5 min.	
	Hold at	40 fsw	for	89.3 min.	3513.8 min.	
	Ascend to	15 fsw	in	0.4 min.	3514.2 min.	
	Hold at	15 fsw	for	3.0 min.	3517.2 min.	
	Ascend to	0 fsw	in	0.3 min.	3517.5 min.	(0 / 20)
	Hold at	0 fsw	for	802.0 min.	4319.5 min.	

PADI/DSAT DIVE SERIES IIb - FOUR DIVES A DAY - SIX DAYS - DAY 4

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
IIb13	Descend to	110 fsw	in	1.8 min.	4321.3 min.	
	Hold at	110 fsw	for	14.9 min.	4336.2 min.	
	Ascend to	70 fsw	in	0.7 min.	4336.9 min.	
	Hold at	70 fsw	for	8.0 min.	4344.9 min.	
	Ascend to	50 fsw	in	0.3 min.	4345.2 min.	
	Hold at	50 fsw	for	13.0 min.	4358.2 min.	
	Ascend to	40 fsw	in	0.2 min.	4358.4 min.	
	Hold at	40 fsw	for	15.0 min.	4373.4 min.	
	Ascend to	15 fsw	in	0.4 min.	4373.8 min.	
	Hold at	15 fsw	for	3.0 min.	4376.8 min.	
	Ascend to	0 fsw	in	0.2 min.	4377.0 min.	(0 / 20)
	Hold at	0 fsw	for	66.0 min.	4443.0 min.	
IIb14	Descend to	75 fsw	in	1.3 min.	4444.3 min.	
	Hold at	75 fsw	for	15.7 min.	4460.0 min.	
	Ascend to	50 fsw	in	0.4 min.	4460.4 min.	
	Hold at	50 fsw	for	11.0 min.	4471.4 min.	
	Ascend to	35 fsw	in	0.3 min.	4471.7 min.	
	Hold at	35 fsw	for	55.0 min.	4526.7 min.	
	Ascend to	15 fsw	in	0.3 min.	4527.0 min.	
	Hold at	15 fsw	for	3.0 min.	4530.0 min.	
	Ascend to	0 fsw	in	0.3 min.	4530.3 min.	(0 / 20)
	Hold at	0 fsw	for	180.0 min.	4710.3 min.	
IIb15	Descend to	60 fsw	in	1.0 min.	4711.3 min.	
	Hold at	60 fsw	for	48.0 min.	4759.3 min.	
	Ascend to	35 fsw	in	0.4 min.	4759.7 min.	
	Hold at	35 fsw	for	41.0 min.	4800.7 min.	
	Ascend to	15 fsw	in	0.3 min.	4801.0 min.	
	Hold at	15 fsw	for	3.0 min.	4804.0 min.	
	Ascend to	0 fsw	in	0.3 min.	4804.3 min.	(0 / 20)
	Hold at	0 fsw	for	180.0 min.	4984.3 min.	
IIb16	Descend to	40 fsw	in	0.7 min.	4985.0 min.	
	Hold at	40 fsw	for	89.3 min.	5074.3 min.	
	Ascend to	15 fsw	in	0.4 min.	5074.7 min.	
	Hold at	15 fsw	for	3.0 min.	5077.7 min.	
	Ascend to	0 fsw	in	0.3 min.	5078.0 min.	(0 / 19)
	Hold at	0 fsw	for	682.0 min.	5760.0 min.	

PADI/DSAT DIVE SERIES IIb - FOUR DIVES A DAY - SIX DAYS - DAY 5

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
IIb17	Descend to	100 fsw	in	1.7 min.	5761.7 min.	
	Hold at	100 fsw	for	18.3 min.	5780.0 min.	
	Ascend to	65 fsw	in	0.6 min.	5780.6 min.	
	Hold at	65 fsw	for	6.0 min.	5786.6 min.	
	Ascend to	50 fsw	in	0.2 min.	5786.8 min.	
	Hold at	50 fsw	for	13.0 min.	5799.8 min.	
	Ascend to	35 fsw	in	0.2 min.	5800.0 min.	
	Hold at	35 fsw	for	26.0 min.	5826.0 min.	
	Ascend to	15 fsw	in	0.4 min.	5826.4 min.	
	Hold at	15 fsw	for	3.0 min.	5829.4 min.	
	Ascend to	0 fsw	in	0.3 min.	5829.7 min.	(0 / 20)
	Hold at	0 fsw	for	80.0 min.	5909.7 min.	
IIb18	Descend to	70 fsw	in	1.2 min.	5910.9 min.	
	Hold at	70 fsw	for	22.8 min.	5933.7 min.	
	Ascend to	40 fsw	in	0.5 min.	5934.2 min.	
	Hold at	40 fsw	for	49.0 min.	5983.2 min.	
	Ascend to	15 fsw	in	0.4 min.	5983.6 min.	
	Hold at	15 fsw	for	3.0 min.	5986.6 min.	
	Ascend to	0 fsw	in	0.3 min.	5986.9 min.	
	Hold at	0 fsw	for	180.0 min.	6166.9 min.	
IIb19	Descend to	50 fsw	in	0.8 min.	6167.7 min.	
	Hold at	50 fsw	for	72.2 min.	6239.9 min.	
	Ascend to	15 fsw	in	0.6 min.	6240.5 min.	
	Hold at	15 fsw	for	3.0 min.	6243.5 min.	
	Ascend to	0 fsw	in	0.2 min.	6243.7 min.	(0 / 20)
	Hold at	0 fsw	for	180.0 min.	6423.7 min.	
IIb20	Descend to	45 fsw	in	0.8 min.	6424.5 min.	
	Hold at	45 fsw	for	91.2 min.	6515.7 min.	
	Ascend to	15 fsw	in	0.5 min.	6516.2 min.	
	Hold at	15 fsw	for	3.0 min.	6519.2 min.	
	Ascend to	0 fsw	in	0.3 min.	6519.5 min.	(0 / 20)
	Hold at	0 fsw	for	680.0 min.	7199.5 min.	

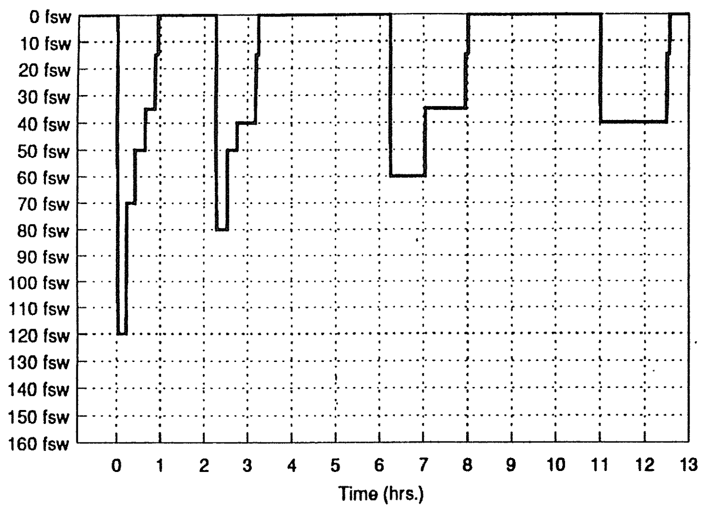
PADI/DSAT DIVE SERIES IIb - FOUR DIVES A DAY - SIX DAYS - DAY 6

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
IIb21	Descend to	85 fsw	in	1.4 min.	7200.9 min.	
	Hold at	85 fsw	for	25.6 min.	7226.5 min.	
	Ascend to	50 fsw	in	0.6 min.	7227.1 min.	
	Hold at	50 fsw	for	17.0 min.	7244.1 min.	
	Ascend to	35 fsw	in	0.2 min.	7244.3 min.	
	Hold at	35 fsw	for	26.0 min.	7270.3 min.	
	Ascend to	15 fsw	in	0.3 min.	7270.6 min.	
	Hold at	15 fsw	for	3.0 min.	7273.6 min.	
	Ascend to	0 fsw	in	0.3 min.	7273.9 min.	(0 / 20)
	Hold at	0 fsw	for	95.0 min.	7368.9 min.	
IIb22	Descend to	65 fsw	in	1.1 min.	7370.0 min.	
	Hold at	65 fsw	for	29.9 min.	7399.9 min.	
	Ascend to	15 fsw	in	0.8 min.	7400.7 min.	
	Hold at	15 fsw	for	3.0 min.	7403.7 min.	
	Ascend to	0 fsw	in	0.3 min.	7404.0 min.	(0 / 20)
	Hold at	0 fsw	for	117.0 min.	7521.0 min.	
IIb23	Descend to	55 fsw	in	0.9 min.	7521.9 min.	
	Hold at	55 fsw	for	52.1 min.	7574.0 min.	
	Ascend to	15 fsw	in	0.7 min.	7574.7 min.	
	Hold at	15 fsw	for	3.0 min.	7577.7 min.	
	Ascend to	0 fsw	in	0.2 min.	7577.9 min.	(0 / 20)
	Hold at	0 fsw	for	60.0 min.	7637.9 min.	
IIb24	Descend to	40 fsw	in	0.7 min.	7638.6 min.	
	Hold at	40 fsw	for	99.3 min.	7737.9 min.	
	Ascend to	15 fsw	in	0.4 min.	7738.3 min.	
	Hold at	15 fsw	for	3.0 min.	7741.3 min.	
	Ascend to	0 fsw	in	0.3 min.	7741.6 min.	(0 / 20)

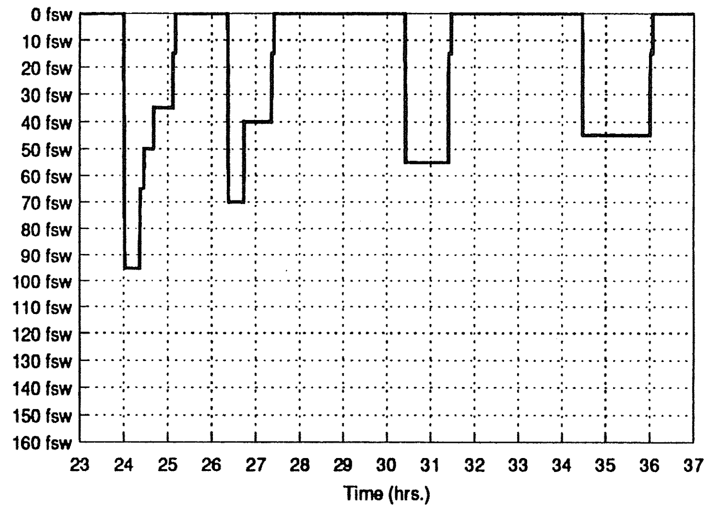
PADI/DSAT DIVE SERIES IIb - DOPPLER BUBBLE SCORES

Dive #	Person Dives	Rest/ Move	Spencer Doppler Grade 0	1	2	3	4
IIb1	17	Rest	17	0	0	0	0
		Move	17	0	0	0	0
IIb2	18	Rest	18	0	0	0	0
		Move	18	0	0	0	0
IIb3	18	Rest	18	0	0	0	0
		Move	16	1	1	0	0
IIb4	19	Rest	19	0	0	0	0
		Move	19	0	0	0	0
IIb5	20	Rest	20	0	0	0	0
		Move	20	0	0	0	0
IIb6	20	Rest	18	2	0	0	0
		Move	18	1	1	0	0
IIb7	20	Rest	19	1	0	0	0
		Move	17	2	0	1	0
IIb8	20	Rest	19	0	1	0	0
		Move	17	1	1	1	0
IIb9	20	Rest	20	0	0	0	0
		Move	20	0	0	0	0
IIb10	20	Rest	20	0	0	0	0
		Move	18	2	0	0	0
IIb11	20	Rest	18	2	0	0	0
		Move	15	3	1	1	0
IIb12	20	Rest	19	1	0	0	0
		Move	18	1	1	0	0
IIb13	20	Rest	20	0	0	0	0
		Move	19	1	0	0	0
IIb14	20	Rest	19	1	0	0	0
		Move	19	0	1	0	0
IIb15	20	Rest	19	1	0	0	0
		Move	19	0	1	0	0
IIb16	19	Rest	19	0	0	0	0
		Move	19	0	0	0	0
IIb17	20	Rest	18	2	0	0	0
		Move	19	0	1	0	0
IIb18	20	Rest	20	0	0	0	0
		Move	20	0	0	0	0
IIb19	20	Rest	18	1	1	0	0
		Move	17	0	3	0	0
IIb20	20	Rest	18	2	0	0	0
		Move	18	0	2	0	0
IIb21	20	Rest	20	0	0	0	0
		Move	18	2	0	0	0
IIb22	20	Rest	20	0	0	0	0
		Move	20	0	0	0	0
IIb23	20	Rest	19	1	0	0	0
		Move	15	2	3	0	0
IIb24	20	Rest	16	4	0	0	0
		Move	12	4	3	1	0
TOTAL	471	Rest	451	18	2	0	0
		Move	428	20	19	4	0

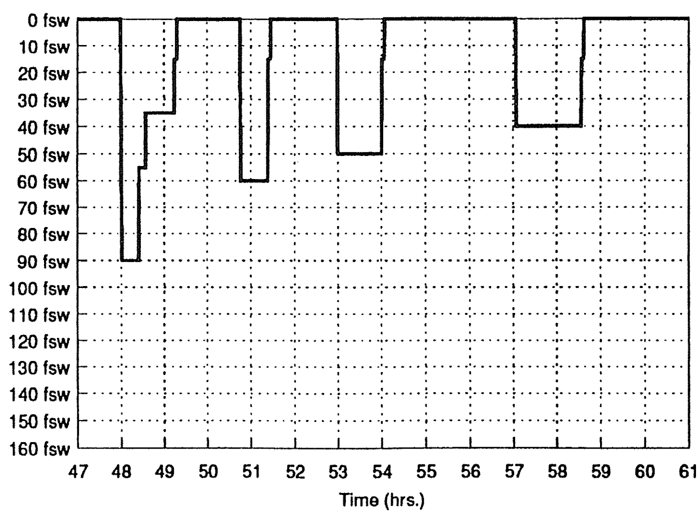
PADI/DSAT DIVE SERIES IIb - DAY 1
(IIb1 - IIb4)



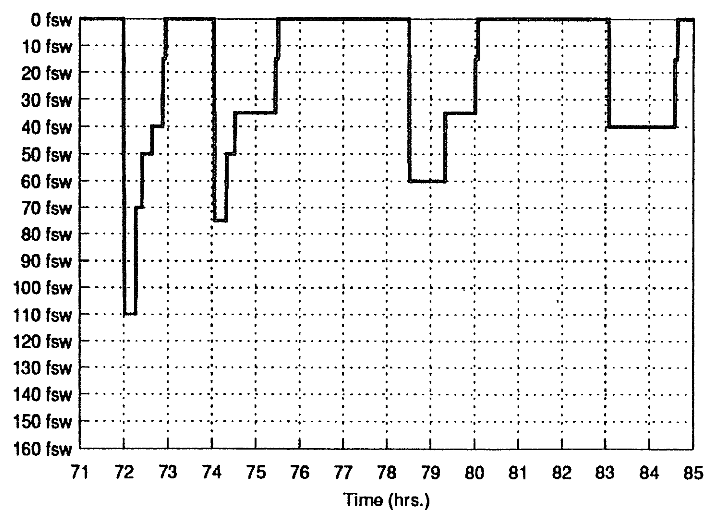
PADI/DSAT DIVE SERIES IIb - DAY 2
(IIb5 - IIb8)



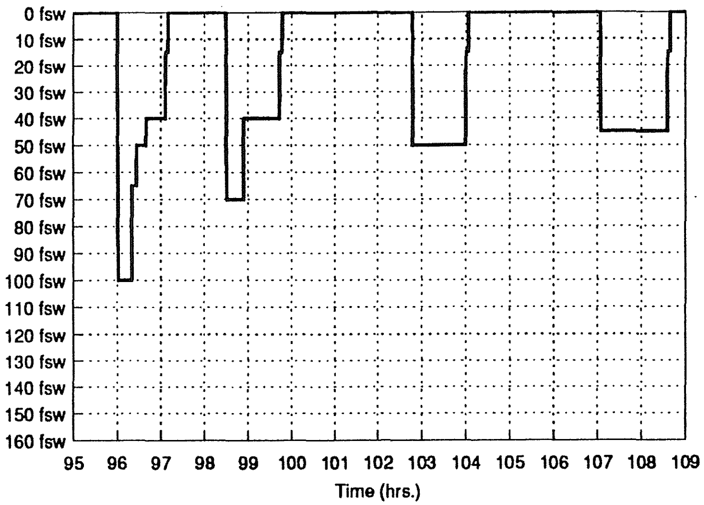
PADI/DSAT DIVE SERIES IIb - DAY 3
(IIb9 - IIb12)



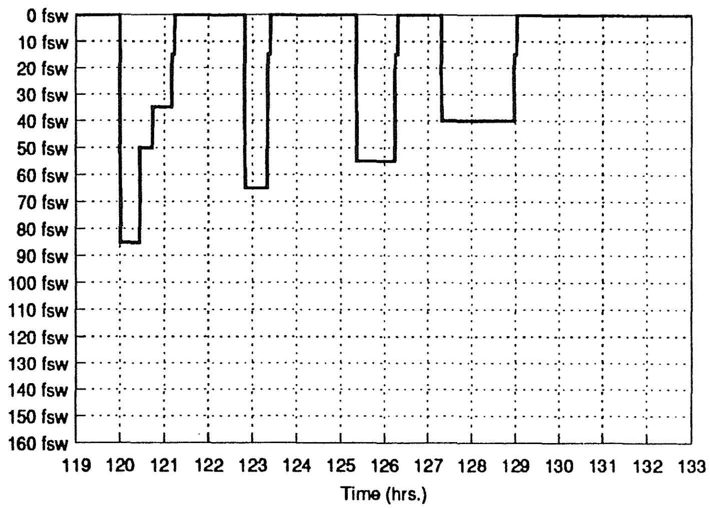
PADI/DSAT DIVE SERIES IIb - DAY 4
(IIb13 - IIb16)



PADI/DSAT DIVE SERIES IIb - DAY 5
(IIb17 - IIb20)



PADI/DSAT DIVE SERIES IIb - DAY 6
(IIb21 - IIb24)



HANN DIVE SERIES A(1-3) - ONE DAY

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
A1	Descend to	40 msw	in	2.0 min.	2.0 min.	
	Descend to	48 msw	in	0.1 min.	2.1 min.	
	Hold at	48 msw	for	9.8 min.	11.9 min.	
	Ascend to	40 msw	in	0.1 min.	12.0 min.	
	Ascend to	3 msw	in	4.5 min.	16.5 min.	
	Hold at	3 msw	for	4.0 min.	20.5 min.	
	Ascend to	0 msw	in	0.3 min.	20.8 min.	(0 / 3)
	Hold at	0 msw	for	10.0 min.	30.8 min.	
A2	Descend to	40 msw	in	2.0 min.	32.8 min.	
	Descend to	48 msw	in	0.1 min.	32.9 min.	
	Hold at	48 msw	for	9.8 min.	42.7 min.	
	Ascend to	40 msw	in	0.1 min.	42.8 min.	
	Ascend to	6 msw	in	4.2 min.	47.0 min.	
	Hold at	6 msw	for	4.0 min.	51.0 min.	
	Ascend to	3 msw	in	0.3 min.	51.3 min.	
	Hold at	3 msw	for	12.0 min.	63.3 min.	
	Ascend to	0 msw	in	0.3 min.	63.6 min.	(0 / 3)
	Hold at	0 msw	for	10.0 min.	73.6 min.	
A3	Descend to	40 msw	in	2.0 min.	75.6 min.	
	Descend to	48 msw	in	0.1 min.	75.7 min.	
	Hold at	48 msw	for	9.8 min.	85.5 min.	
	Ascend to	40 msw	in	0.1 min.	85.6 min.	
	Ascend to	6 msw	in	4.2 min.	89.8 min.	
	Hold at	6 msw	for	4.0 min.	93.8 min.	
	Ascend to	3 msw	in	0.3 min.	94.1 min.	
	Hold at	3 msw	for	27.0 min.	121.1 min.	
	Ascend to	0 msw	in	0.3 min.	121.4 min.	(0 / 3)

HANN DIVE SERIES B(1-9) - THREE DAYS - DAY 1

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
B1	Descend to	40 msw	in	2.0 min.	2.0 min.	
	Hold at	40 msw	for	6.0 min.	8.0 min.	
	Descend to	48 msw	in	0.1 min.	8.1 min.	
	Hold at	48 msw	for	12.0 min.	20.1 min.	
	Ascend to	40 msw	in	0.1 min.	20.2 min.	
	Hold at	40 msw	for	5.8 min.	26.0 min.	
	Ascend to	12 msw	in	3.0 min.	29.0 min.	
	Hold at	12 msw	for	1.0 min.	30.0 min.	
	Ascend to	9 msw	in	1.0 min.	31.0 min.	
	Hold at	9 msw	for	3.5 min.	34.5 min.	
	Ascend to	6 msw	in	0.3 min.	34.8 min.	
	Hold at	6 msw	for	5.7 min.	40.5 min.	
	Ascend to	3 msw	in	1.0 min.	41.5 min.	
	Hold at	3 msw	for	16.0 min.	57.5 min.	
	Ascend to	0 msw	in	1.0 min.	58.5 min.	(0 / 5)
	Hold at	0 msw	for	63.0 min.	121.5 min.	
B2	Descend to	40 msw	in	2.0 min.	123.5 min.	
	Hold at	40 msw	for	6.0 min.	129.5 min.	
	Descend to	48 msw	in	0.1 min.	129.6 min.	
	Hold at	48 msw	for	12.0 min.	141.6 min.	
	Ascend to	40 msw	in	0.1 min.	141.7 min.	
	Hold at	40 msw	for	5.8 min.	147.5 min.	
	Ascend to	12 msw	in	3.0 min.	150.5 min.	
	Hold at	12 msw	for	1.0 min.	151.5 min.	
	Ascend to	9 msw	in	1.0 min.	152.5 min.	
	Hold at	9 msw	for	3.0 min.	155.5 min.	
	Ascend to	6 msw	in	1.0 min.	156.5 min.	
	Hold at	6 msw	for	13.0 min.	169.5 min.	
	Ascend to	3 msw	in	1.0 min.	170.5 min.	
	Hold at	3 msw	for	31.0 min.	201.5 min.	
	Ascend to	0 msw	in	1.0 min.	202.5 min.	(1 / 5)
	Hold at	0 msw	for	152.0 min.	354.5 min.	
B3	Descend to	40 msw	in	2.0 min.	356.5 min.	
	Hold at	40 msw	for	6.0 min.	362.5 min.	
	Descend to	48 msw	in	0.1 min.	362.6 min.	
	Hold at	48 msw	for	12.0 min.	374.6 min.	
	Ascend to	40 msw	in	0.1 min.	374.7 min.	
	Hold at	40 msw	for	5.8 min.	380.5 min.	
	Ascend to	12 msw	in	3.0 min.	383.5 min.	
	Hold at	12 msw	for	1.0 min.	384.5 min.	
	Ascend to	9 msw	in	1.0 min.	385.5 min.	
	Hold at	9 msw	for	3.0 min.	388.5 min.	
	Ascend to	6 msw	in	1.0 min.	389.5 min.	
	Hold at	6 msw	for	5.0 min.	394.5 min.	
	Ascend to	3 msw	in	0.5 min.	395.0 min.	
	Hold at	3 msw	for	25.0 min.	420.0 min.	
	Ascend to	0 msw	in	0.5 min.	420.5 min.	(1 / 4)
	Hold at	0 msw	for	1016.0 min.	1436.5 min.	

HANN DIVE SERIES B(1-9) - THREE DAYS - DAY 2

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
B4	Descend to	30 msw	in	2.0 min.	1438.5 min.	
	Hold At	30 msw	for	6.0 min.	1444.5 min.	
	Descend to	38 msw	in	0.1 min.	1444.6 min.	
	Hold At	38 msw	for	12.0 min.	1456.6 min.	
	Ascend to	30 msw	in	0.1 min.	1456.7 min.	
	Hold At	30 msw	for	5.8 min.	1462.5 min.	
	Ascend to	6 msw	in	3.0 min.	1465.5 min.	
	Hold At	6 msw	for	2.0 min.	1467.5 min.	
	Ascend to	3 msw	in	1.0 min.	1468.5 min.	
	Hold At	3 msw	for	3.0 min.	1471.5 min.	
	Ascend to	0 msw	in	1.0 min.	1472.5 min.	(0 / 3)
	Hold At	0 msw	for	80.0 min.	1552.5 min.	
B5	Descend to	30 msw	in	2.0 min.	1554.5 min.	
	Hold At	30 msw	for	6.0 min.	1560.5 min.	
	Descend to	38 msw	in	0.1 min.	1560.6 min.	
	Hold At	38 msw	for	12.0 min.	1572.6 min.	
	Ascend to	30 msw	in	0.1 min.	1572.7 min.	
	Hold At	30 msw	for	5.8 min.	1578.5 min.	
	Ascend to	6 msw	in	3.0 min.	1581.5 min.	
	Hold At	6 msw	for	3.0 min.	1584.5 min.	
	Ascend to	3 msw	in	0.5 min.	1585.0 min.	
	Hold At	3 msw	for	13.0 min.	1598.0 min.	
	Ascend to	1 msw	in	0.5 min.	1598.5 min.	
	Hold At	1 msw	for	8.5 min.	1607.0 min.	
	Ascend to	.8 msw	in	0.1 min.	1607.1 min.	
	Hold At	.8 msw	for	9.7 min.	1616.8 min.	
	Ascend to	.5 msw	in	0.1 min.	1616.9 min.	
	Hold At	.5 msw	for	10.0 min.	1626.9 min.	
	Ascend to	0 msw	in	0.5 min.	1627.4 min.	(0 / 3)
	Hold At	0 msw	for	166.0 min.	1793.4 min.	
B6	Descend to	30 msw	in	2.0 min.	1795.4 min.	
	Hold At	30 msw	for	6.0 min.	1801.4 min.	
	Descend to	38 msw	in	0.1 min.	1801.5 min.	
	Hold At	38 msw	for	12.0 min.	1813.5 min.	
	Ascend to	30 msw	in	0.1 min.	1813.6 min.	
	Hold At	30 msw	for	5.8 min.	1819.4 min.	
	Ascend to	6 msw	in	3.0 min.	1822.4 min.	
	Hold At	6 msw	for	2.0 min.	1824.4 min.	
	Ascend to	3 msw	in	0.5 min.	1824.9 min.	
	Hold At	3 msw	for	1.0 min.	1825.9 min.	
	Ascend to	2 msw	in	0.5 min.	1826.4 min.	
	Hold at	2 msw	for	4.0 min.	1830.4 min.	
	Ascend to	1.5 msw	in	0.5 min.	1830.9 min.	
	Hold at	1.5 msw	for	7.5 min.	1838.4 min.	
	Ascend to	1 msw	in	0.5 min.	1838.9 min.	
	Hold at	1 msw	for	9.5 min.	1848.4 min.	
	Ascend to	.5 msw	in	0.5 min.	1848.9 min.	
	Hold at	.5 msw	for	9.0 min.	1857.9 min.	
	Ascend to	0 msw	in	0.5 min.	1858.4 min.	(0 / 3)
	Hold at	0 msw	for	1015.0 min.	2873.4 min.	

HANN DIVE SERIES B(1-9) - THREE DAYS - DAY 3

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
B7	Descend to	35 msw	in	2.0 min.	2875.4 min.	
	Hold at	35 msw	for	6.0 min.	2881.4 min.	
	Descend to	43 msw	in	0.1 min.	2881.5 min.	
	Hold at	43 msw	for	12 min.	2893.5 min.	
	Ascend to	35 msw	in	0.1 min.	2893.6 min.	
	Hold at	35 msw	for	5.8 min.	2899.4 min.	
	Ascend to	9 msw	in	3.0 min.	2902.4 min.	
	Hold at	9 msw	for	2.0 min.	2904.4 min.	
	Ascend to	6 msw	in	0.3 min.	2904.7 min.	
	Hold at	6 msw	for	5.7 min.	2910.4 min.	
	Ascend to	3 msw	in	0.3 min.	2910.7 min.	
	Hold at	3 msw	for	8.7 min.	2919.4 min.	
	Ascend to	1 msw	in	1.0 min.	2920.4 min.	
	Hold at	1 msw	for	2.5 min.	2922.9 min.	
	Ascend to	0 msw	in	0.5 min.	2923.4 min.	(0 / 3)
	Hold at	0 msw	for	69.0 min.	2992.4 min.	
B8	Descend to	30 msw	in	2.0 min.	2994.4 min.	
	Hold at	30 msw	for	6.0 min.	3000.4 min.	
	Descend to	38 msw	in	0.1 min.	3000.5 min.	
	Hold at	38 msw	for	12.0 min.	3012.5 min.	
	Ascend to	30 msw	in	0.1 min.	3012.6 min.	
	Hold at	30 msw	for	5.8 min.	3018.4 min.	
	Ascend to	6 msw	in	3.0 min.	3021.4 min.	
	Hold at	6 msw	for	2.0 min.	3023.4 min.	
	Ascend to	3 msw	in	1.0 min.	3024.4 min.	
	Hold at	3 msw	for	13.0 min.	3037.4 min.	
	Ascend to	2 msw	in	1.0 min.	3038.4 min.	
	Hold at	2 msw	for	7.0 min.	3045.4 min.	
	Ascend to	1 msw	in	0.3 min.	3045.7 min.	
	Hold at	1 msw	for	2.7 min.	3048.4 min.	
	Ascend to	.5 msw	in	0.3 min.	3048.7 min.	
	Hold at	.5 msw	for	15.0 min.	3063.7 min.	
	Ascend to	0 msw	in	0.2 min.	3063.9 min.	(0 / 3)
	Hold at	0 msw	for	169.0 min.	3232.9 min.	
B9	Descend to	30 msw	in	2.0 min.	3234.9 min.	
	Hold at	30 msw	for	6.0 min.	3240.9 min.	
	Descend to	38 msw	in	0.1 min.	3241.0 min.	
	Hold at	38 msw	for	12.0 min.	3253.0 min.	
	Ascend to	30 msw	in	0.1 min.	3253.1 min.	
	Hold at	30 msw	for	5.8 min.	3258.9 min.	
	Ascend to	6 msw	in	3.0 min.	3261.9 min.	
	Hold at	6 msw	for	1.5 min.	3263.4 min.	
	Ascend to	3 msw	in	0.5 min.	3263.9 min.	
	Hold at	3 msw	for	4.0 min.	3267.9 min.	
	Ascend to	1 msw	in	0.5 min.	3268.4 min.	
	Hold at	1 msw	for	21.0 min.	3289.4 min.	
	Ascend to	.7 msw	in	0.3 min.	3289.7 min.	
	Hold at	.7 msw	for	7.7 min.	3297.4 min.	
	Ascend to	.5 msw	in	0.3 min.	3297.7 min.	
	Hold at	.5 msw	for	6.4 min.	3304.1 min.	
	Ascend to	0 msw	in	0.3 min.	3304.4 min.	(0 / 3)

HANN DIVE SERIES C(1-6) - TWO DAYS - DAY 1

	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
C1	Descend to	40 msw	in	2.0 min.	2.0 min.	
	Hold at	40 msw	for	2.0 min.	4.0 min.	
	Descend to	48 msw	in	0.1 min.	4.1 min.	
	Hold at	48 msw	for	11.8 min.	15.9 min.	
	Ascend to	40 msw	in	0.1 min.	16.0 min.	
	Hold at	40 msw	for	10.0 min.	26.0 min.	
	Ascend to	9 msw	in	3.1 min.	29.1 min.	
	Hold at	9 msw	for	4.0 min.	33.1 min.	
	Ascend to	6 msw	in	0.3 min.	33.4 min.	
	Hold at	6 msw	for	5.0 min.	38.4 min.	
	Ascend to	3 msw	in	0.3 min.	38.7 min.	
	Hold at	3 msw	for	16.0 min.	54.7 min.	
	Ascend to	0 msw	in	0.3 min.	55.0 min.	(0 / 6)
	Hold at	0 msw	for	65.0 min.	120.0 min.	
C2	Descend to	40 msw	in	2.0 min.	122.0 min.	
	Hold at	40 msw	for	8.0 min.	130.0 min.	
	Descend to	48 msw	in	0.1 min.	130.1 min.	
	Hold at	48 msw	for	7.8 min.	137.9 min.	
	Ascend to	40 msw	in	0.1 min.	138.0 min.	
	Hold at	40 msw	for	8.9 min.	146.9 min.	
	Ascend to	9 msw	in	3.1 min.	150.0 min.	
	Hold at	9 msw	for	4.0 min.	154.0 min.	
	Ascend to	6 msw	in	0.3 min.	154.3 min.	
	Hold at	6 msw	for	20.0 min.	174.3 min.	
	Ascend to	3 msw	in	0.3 min.	174.6 min.	
	Hold at	3 msw	for	38.0 min.	212.6 min.	
	Ascend to	0 msw	in	0.3 min.	212.9 min.	(1 / 6)
	Hold at	0 msw	for	148.0 min.	360.9 min.	
C3	Descend to	40 msw	in	2.0 min.	362.9 min.	
	Hold at	40 msw	for	8.0 min.	370.9 min.	
	Descend to	48 msw	in	0.1 min.	371.0 min.	
	Hold at	48 msw	for	7.8 min.	378.8 min.	
	Ascend to	40 msw	in	0.1 min.	378.9 min.	
	Hold at	40 msw	for	8.9 min.	387.8 min.	
	Ascend to	9 msw	in	3.1 min.	390.9 min.	
	Hold at	9 msw	for	4.0 min.	394.9 min.	
	Ascend to	6 msw	in	0.3 min.	395.2 min.	
	Hold at	6 msw	for	9.0 min.	404.2 min.	
	Ascend to	3 msw	in	0.3 min.	404.5 min.	
	Hold at	3 msw	for	44.0 min.	448.5 min.	
	Ascend to	0 msw	in	0.3 min.	448.8 min.	(0 / 5)
	Hold at	0 msw	for	933.0 min.	1381.8 min.	

HANN DIVE SERIES C(1-6) - TWO DAYS - DAY 2

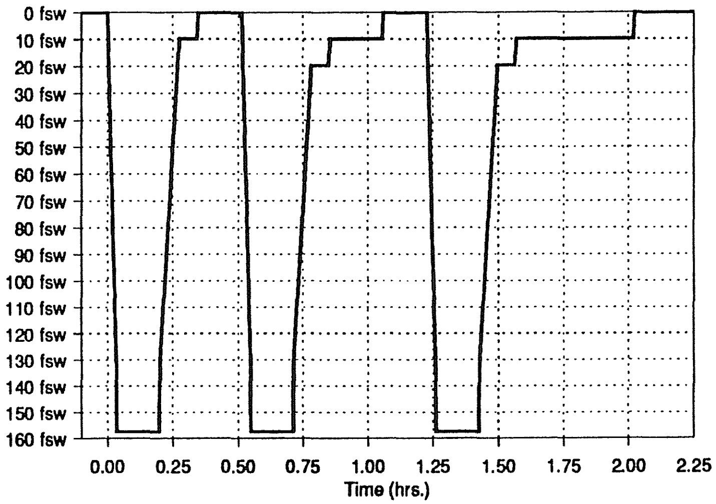
	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
C4	Descend to	40 msw	in	2.0 min.	1383.8 min.	
	Hold at	40 msw	for	2.0 min.	1385.8 min.	
	Descend to	48 msw	in	0.1 min.	1385.9 min.	
	Hold at	48 msw	for	11.8 min.	1397.7 min.	
	Ascend to	40 msw	in	0.1 min.	1397.8 min.	
	Hold at	40 msw	for	10.0 min.	1407.8 min.	
	Ascend to	9 msw	in	3.1 min.	1410.9 min.	
	Hold at	9 msw	for	4.0 min.	1414.9 min.	
	Ascend to	6 msw	in	0.3 min.	1415.2 min.	
	Hold at	6 msw	for	5.0 min.	1420.2 min.	
	Ascend to	3 msw	in	0.3 min.	1420.5 min.	
	Hold at	3 msw	for	16.0 min.	1436.5 min.	
	Ascend to	0 msw	in	0.3 min.	1436.8 min.	(0 / 5)
	Hold at	0 msw	for	65.0 min.	1501.8 min.	
C5	Descend to	40 msw	in	2.0 min.	1503.8 min.	
	Hold at	40 msw	for	8.0 min.	1511.8 min.	
	Descend to	48 msw	in	0.1 min.	1511.9 min.	
	Hold at	48 msw	for	7.8 min.	1519.7 min.	
	Ascend to	40 msw	in	0.1 min.	1519.8 min.	
	Hold at	40 msw	for	8.9 min.	1528.7 min.	
	Ascend to	9 msw	in	3.1 min.	1531.8 min.	
	Hold at	9 msw	for	4.0 min.	1535.8 min.	
	Ascend to	6 msw	in	0.3 min.	1536.1 min.	
	Hold at	6 msw	for	20.0 min.	1556.1 min.	
	Ascend to	3 msw	in	0.3 min.	1556.4 min.	
	Hold at	3 msw	for	38.0 min.	1594.4 min.	
	Ascend to	0 msw	in	0.3 min.	1594.7 min.	(0 / 5)
	Hold at	0 msw	for	148.0 min.	1742.7 min.	
C6	Descend to	40 msw	in	2.0 min.	1744.7 min.	
	Hold at	40 msw	for	8.0 min.	1752.7 min.	
	Descend to	48 msw	in	0.1 min.	1752.8 min.	
	Hold at	48 msw	for	7.8 min.	1760.6 min.	
	Ascend to	40 msw	in	0.1 min.	1760.7 min.	
	Hold at	40 msw	for	8.9 min.	1769.6 min.	
	Ascend to	9 msw	in	3.1 min.	1772.7 min.	
	Hold at	9 msw	for	4.0 min.	1776.7 min.	
	Ascend to	6 msw	in	0.3 min.	1777.0 min.	
	Hold at	6 msw	for	9.0 min.	1786.0 min.	
	Ascend to	3 msw	in	0.3 min.	1786.3 min.	
	Hold at	3 msw	for	44.0 min.	1830.3 min.	
	Ascend to	0 msw	in	0.3 min.	1830.6 min.	(0 / 5)

HANN DIVE SERIES D - ONE DIVE

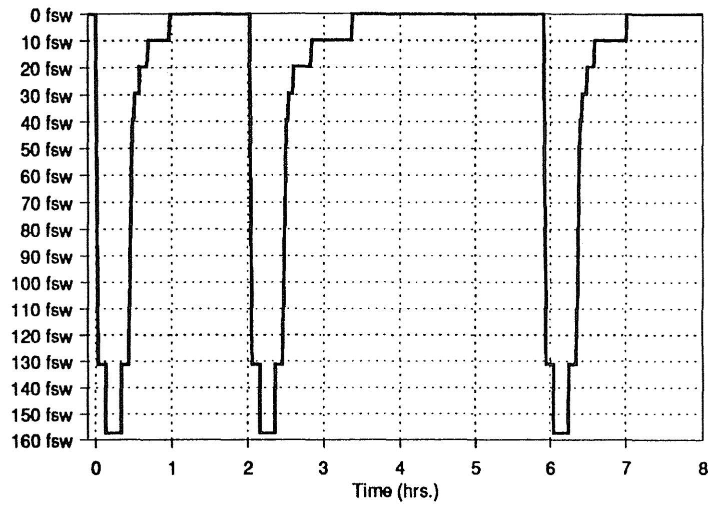
	Activity	Depth		Activity Time	Elapsed Time	(DCS/ Trials)
D	Descend to	40 msw	in	2.0 min.	2.0 min.	
	Hold at	40 msw	for	4.0 min.	6.0 min.	
	Descend to	48 msw	in	0.1 min.	6.1 min.	
	Ascend to	42 msw	in	14.8 min.	20.9 min.	
	Ascend to	34 msw	in	0.1 min.	21.0 min.	
	Hold at	34 msw	for	20.0 min.	41.0 min.	
	Ascend to	9 msw	in	2.5 min.	43.5 min.	
	Hold at	9 msw	for	3.0 min.	46.5 min.	
	Ascend to	6 msw	in	0.3 min.	46.8 min.	
	Hold at	6 msw	for	14.0 min.	60.8 min.	
	Ascend to	3 msw	in	0.3 min.	61.1 min.	
	Hold at	3 msw	for	28.0 min.	89.1 min.	
	Ascend to	0 msw	in	0.3 min.	89.4 min.	(0 / 20)

*** NO DOPPLER SCORES AVAILABLE FOR HANN DIVES ***

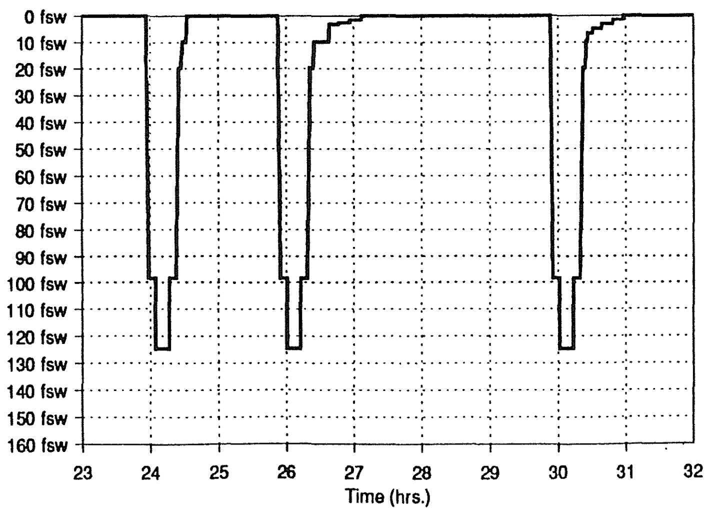
HANN DIVE SERIES
(A1 - A3)



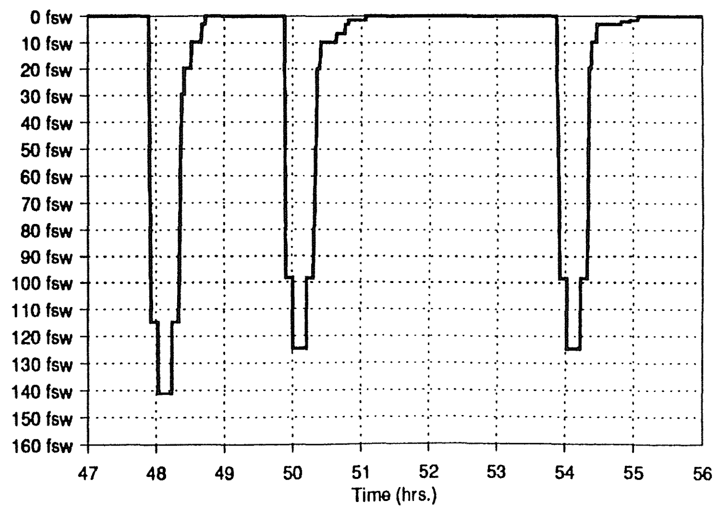
HANN DIVE SERIES B - DAY 1
(B1 - B3)



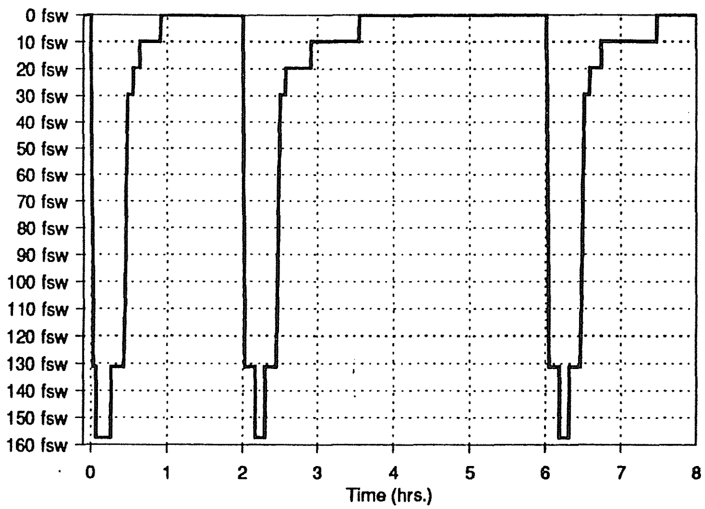
HANN DIVE SERIES B - DAY 2
(B4 - B6)



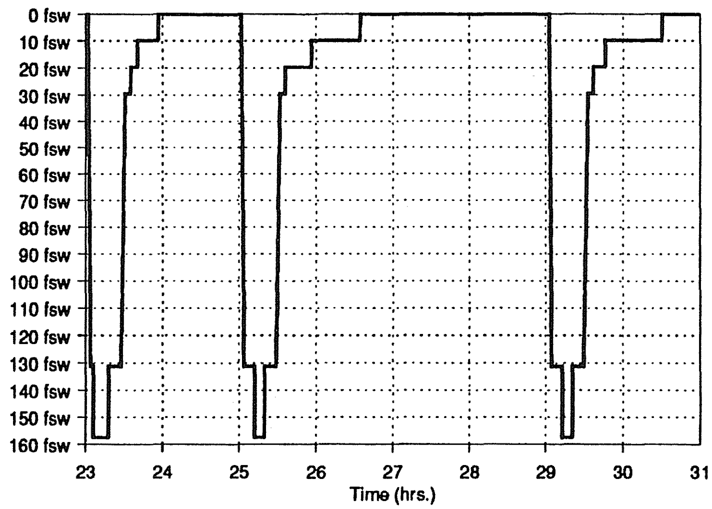
HANN DIVE SERIES B - DAY 3
(B7 - B9)



HANN DIVE SERIES C - DAY 1
(C1 - C3)



HANN DIVE SERIES C - DAY 2
(C4 - C6)



HANN DIVE SERIES D