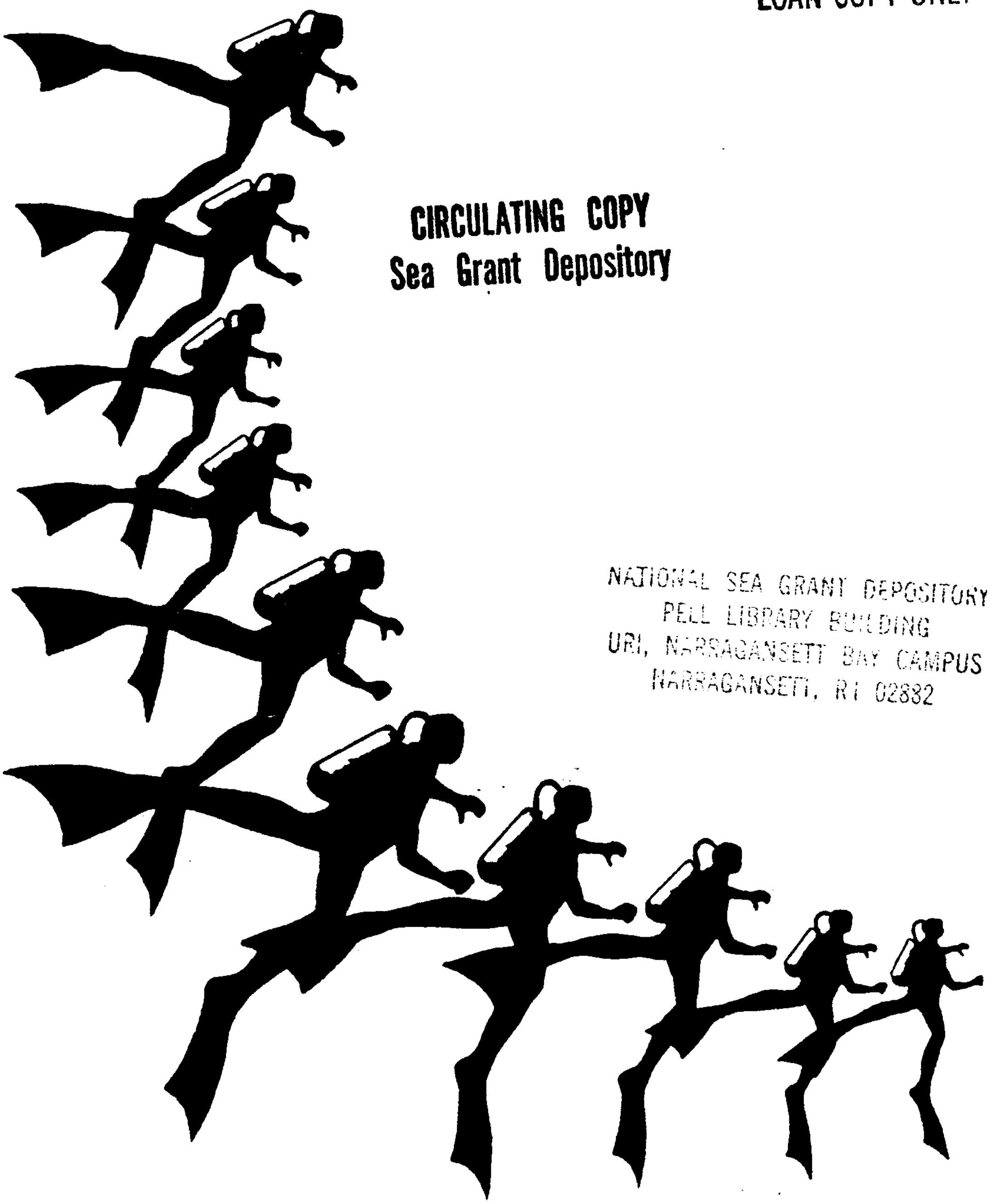
Microprocessor Applications to Multi-Level Air Decompression Problems

Karl E. Huggins



Michigan Sea Grant College Program
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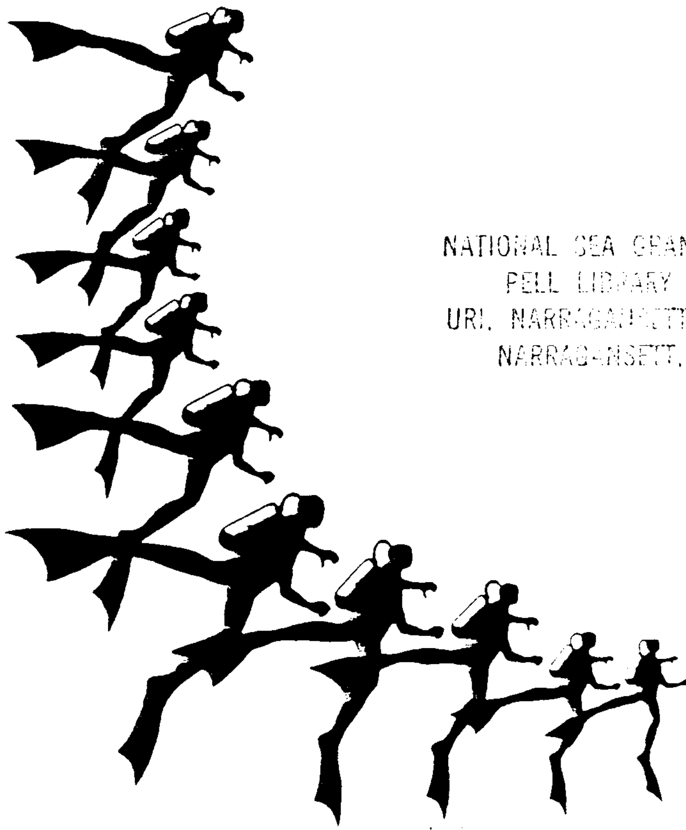

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ABSTRACT

Multi-level decompression problems are ones in which a person is exposed to a variable pressure profile as opposed to a single step pressure change (*square-wave* profile). The use of microprocessors for solving air decompression problems associated with multi-level diving exposures is growing in many areas of the diving community.

A background of decompression problems, theories, and tables is presented. Tables commonly used for decompression problem solving are described. Techniques using these tables and other practices which permit multi-level profiles to be performed are then examined and their limitations discussed. It is suggested that the most effective way to solve multi-level decompression problems is to use a decompression device that continuously tracks the pressure profile and computes decompression status based on an integration of the actual profile in real time.

The history of decompression devices from 1955 to present is reviewed, focusing on the advantages and disadvantages of the various designs. The development and testing of a specific decompression computer, the EDGE (Electronic Dive GuidE), is described. A summary of a follow-up survey given to EDGE owners regarding in-field operation indicates that most users are satisfied with the way the device handles multi-level diving computations. Some complain about the conservative nature of the EDGE's decompression algorithm.

All indications point to microprocessor-based devices being successfully used in computing decompression status for multi-level pressure profiles. These decompression computers will play an increasing role in solving multi-level decompression problems. They can be applied to problems in most areas of diving as well as to other situations requiring pressure reductions, such as shuttle and space station EVA procedures.

However, any passive decompression device can only inform the diver of his or her decompression status. How that information is used is the responsibility of the diver. There is much room for further improvements to present decompression devices. These improvements will stem from new studies that will develop new decompression models that include additional variables in addition to depth and time, or that monitor the diver's decompression stress.

Microprocessor-based decompression devices, after a slow start, are finally becoming established, trusted pieces of equipment. They have the capability to solve problems related to multi-level decompression situations which can not be solved using standard table practices.

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INTRODUCTION

The problem of preventing decompression sickness in man, primarily following exposures to increased pressures, began in the 1800s with the advent of construction caissons and hardhat diving systems. Since that time, many decompression theories, tables, and devices have been developed. Most recently advances in electronics and microprocessor technology have been used to solve air decompression problems.

Chapter I presents background information on the problem of decompression sickness, decompression theories, and decompression tables (which have been the primary tools for the solution of decompression problems since the early 1900s). Because of the inflexibility of the tables various multi-level diving techniques have been developed to adapt and use existing tables in a way which conforms more to actual diving practices. Chapter II presents these non-standard (multi-level) techniques and some of the problems associated with them.

Numerous decompression devices have been developed over the past thirty years. Designed to eliminate the rigidity of a set of tables these "decompression computers" integrate a dive profile so that the displayed decompression status is based on the actual dive and not a table entry. Chapter III looks at the history of these decompression devices which have been in existence since the introduction of scuba in the 1950s.

Chapter IV presents the development of the no-decompression/decompression computer called The EDGE. The protocol for testing the safety of the decompression algorithm and the results of the tests are covered along with a summary of a survey of EDGE owners.

Chapter V examines the possible future of microprocessor-based decompression devices in diving and their potential in space operations. The author concludes that there is still much work to be done in the field of decompression research, especially in the area of multi-level diving. Nevertheless, microprocessor-based decompression devices have become established and are here to stay.

CHAPTER I

DEVELOPMENT OF DECOMPRESSION TABLES

DECOMPRESSION SICKNESS

The problem of decompression sickness (DCS), also known as "the bends" or caisson disease, has plagued man ever since he first subjected himself to hyperbaric (elevated pressure) environments. During a hyperbaric exposure the increased gas pressures cause more gas molecules to be transported through the lungs and become dissolved in the body tissues. Inert gas pressures (such as that of nitrogen [N_2] when air is being breathed) in the body gradually increase until they equal their ambient partial pressures. DCS is the result of the release of excess inert gas from solution in the body tissues when there is a rapid decrease in the surrounding pressure, just as carbon dioxide bubbles are released from solution when a carbonated beverage is opened. This gas bubble release within the blood and tissues can produce a wide range of physiological problems. Pain and neurological detriment are the most common symptoms associated with DCS.

DCS is normally separated into two types, Type I and Type II. The primary symptoms of Type I and II DCS are listed below:

TYPE I (Pain Only)

* Limb and/or Joint Pain
* Itching (more prevalent in hyperbaric chamber than in water exposures)
* Skin Rash

TYPE II (Serious)

* Central Nervous System Detriment
* Lung Involvement (Chokes)

Type I DCS usually causes pain to the joints and is probably the result of gas formation in the connecting tissues of the joints and other regions of relatively low blood flow. TYPE II DCS primarily involves neurological detriment and is considered to be much more serious than TYPE I DCS. Most often the victim of TYPE II DCS will have bilateral detriment below lesions in the spinal column, caused by the disruption of the spinal cord nerve tissue by inert gas bubbles. Chokes are believed to be produced by gas bubbles in returning venous blood that become trapped in the pulmonary capillaries. If approximately 10% or more of the pulmonary vascular bed is blocked by these gas bubbles the respiratory process is greatly impaired.

The primary treatment of DCS involves repressurization and oxygen breathing. 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.

This paper will examine the various models, tables, and techniques used to **prevent** the development of DCS. The role that the recent microprocessor revolution can play in this area will also be examined.

DECOMPRESSION 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 juyces* [sic] *and soft parts of the body*" (Edmonds, 1981).

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 (Strauss, 1976).

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. J.S. Haldane, an English physiologist, was commissioned by the British Admiralty to examine these problems. Haldane exposed goats to various pressures for three hours in order to saturate (equalize the nitrogen pressure in all the goats' tissues to the ambient nitrogen pressure) them at the new pressure. Following the exposure he would rapidly decompress the goats back to normal surface pressure and examine them for signs of DCS.

Haldane found that if the goats had been exposed to a pressure equivalent to 33 feet of sea water (fsw) or less, they would show no signs of DCS. He concluded that the goats could withstand an overpressure ratio or "supersaturation ratio" of 2:1 (Surface pressure = 1 atmosphere [1 ATA] = 33 fsw; Pressure at 33 fsw = 33 fsw [surface pressure] + 33 fsw [water pressure] = 66 fsw total pressure = 2 ATA).

Haldane then saturated goats at a pressure equivalent to 99 fsw, or 4 ATA absolute and then decompressed them to 33 fsw (2 ATA), a 2:1 pressure reduction. He again found that none of the goats showed symptoms of DCS. Following saturation (3 hours) at 33 fsw the goats were decompressed to surface pressure with no ill effects. These results indicated that safe decompression would occur if the diver or caisson worker was decompressed to one-half the pressure they were working at and allowed to saturate at this new pressure. This procedure would be repeated until they reached surface pressure. However, if this technique was to be used, no matter the length of the initial exposure, it would be inefficient in terms of time and worker utilization. Haldane stated that he felt man reached saturation after five hours as opposed to the three hours needed for goats. Therefore, exposure to any pressure between 33 fsw and 99 fsw, regardless of the exposure time, would require 5 hours of decompression.

DECOMPRESSION MODEL

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

A. Tissues in the body absorb and eliminate the inert gas nitrogen at an exponential rate, with the driving force being the pressure differential between the ambient nitrogen pressure and the pressure of the nitrogen dissolved in the tissue.

B. There is a continuous spectrum of tissue groups within the body with various rates of absorption and elimination.

C. A specific tissue group absorbs and eliminates nitrogen at the same rate.

D. The spectrum of tissue groups can be approximated by selecting a finite number of tissue groups from within the spectrum.

Haldane designated the selected tissue groups by their "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. According to the half-time model a tissue group would never reach a point of equilibrium with the ambient nitrogen pressure since the exponential function would only permit saturation to occur following an infinite time at a given pressure. However, the tissue pressures are close enough to the ambient pressure after six half-times that they are considered to be saturated.

Haldane selected five tissue groups 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 95% saturated after five hours, which he considered to be the time it would take to equilibrate a man to a new ambient pressure. The following summarizes the model that Haldane used to create his tables.

A. The body can be represented by five tissue groups with half-times of 5, 10, 20, 40, and 75 minutes.

B. Each of the tissue groups can withstand a pressure reduction ratio of 2:1.

DECOMPRESSION TABLES

Using the above model Haldane computed a set of decompression tables. Figure 1.1 illustrates the steps taken to compute a decompression schedule. It shows an exposure to 168 fsw for 15 minutes and decompression stops at 10 fsw increments. The following is the method of computation:

A. The tissue pressures for the five tissue groups are computed for the exposure to 168 fsw for 15 minutes.

B. The highest pressure produced is in the 5-minute tissue group and corresponds to the tissue being saturated at a depth of 130 fsw.

C. The absolute pressure of the 5-minute tissue is 163 fsw (130 + surface pressure of 33 fsw).

D. Using the 2:1 ratio the 5-minute tissue group could withstand a pressure drop to 81.5 fsw absolute (163 fsw / 2). This corresponds to a depth of 48.5 fsw (81.5 - 33 fsw). Since the decompression stops are in 10 fsw increments the first stop in the decompression will be at 50 fsw.

E. The diver then spends enough time at 50 fsw to allow the tissue pressures to drop to a level which will allow an ascent to 40 fsw. This pressure is equivalent to a saturation depth of 113 fsw (40 + 33 = 73 fsw; 73 fsw * 2 = 146 fsw; 146 - 33 = 113 fsw).

F. All five tissue groups pressures are computed for each decompression stop. Their pressures must not exceed the 2:1 ratio set forth in the model.

Steps E and F are repeated until the diver is allowed to surface. In the first two decompression stops the time at the stop is controlled by the 5-minute tissue group. The third stop is controlled by the 10-minute group, the fourth by the 20-minute group, and the last stop by the 40-minute tissue group.

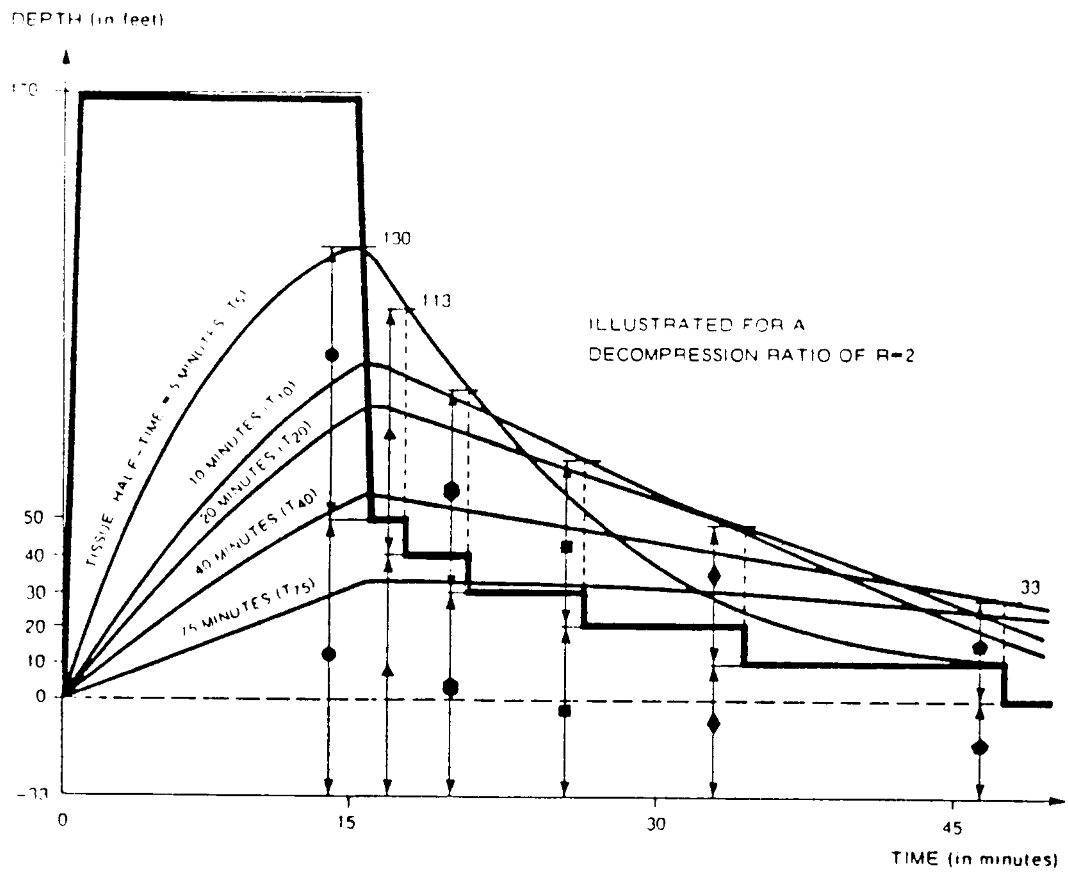

Fig. 1.1 Tissue pressures during decompression (From Edmunds, 1981).

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 caisson workers and hardhat divers.

The ratio of 2:1 in Haldane's model refers to the ratio of $P_{sat}:P_{amb}$, where P_{sat} is the pressure that corresponds to the equivalent saturation pressure and P_{amb} is the new ambient pressure. Another way of looking at the supersaturation ratio is to use the tissue nitrogen pressure, PN_2. This ratio, $PN_2:P_{amb}$, when looking at the Haldanian ratio of 2:1, produces a value of 1.58:1 (2 x 0.79 ATA nitrogen/ATA). In most of the subsequent work and literature the $PN_2:P_{amb}$ ratio is referred to as the supersaturation ratio.

The first tables for the U.S. Navy were produced in 1915. They were based on the Haldanian model and also included the use of oxygen during decompression. These tables, called the C and R tables, were used that year in the successful salvage of the submarine F-4 at a depth of 306 fsw -- well beyond today's accepted depth limitations for use of air.

TABLE 1.1
MODIFIED SUPERSATURATION RATIOS

TISSUE HALF-TIMES	HAWKINS, SHILLING & HANSEN	YARBOROUGH
5 min.	4.35	----
10 min	3.56	----
20 min.	2.21	1.94 - 2.21
40 min.	1.58	1.38 - 1.58
75 min.	1.42 - 1.58	1.38 - 1.58

In the 1930s, Hawkins, Shilling, and Hansen -- and later Yarborough -- determined that the allowable supersaturation ratio ($PN_2:P_{amb}$) was a function of the tissue half-time and depth and duration of the dive (Flynn, 1978c). Table 1.1 lists the tissue half-times and the modified supersaturation ratios.

Using only the 20-, 40-, and 75-minute half-time tissue groups, Yarborough computed a set of tables that was released to the U.S. Navy in 1937 (Appendix A). These tables were used until the current U.S. Navy Standard Air Decompression Tables were developed in the 1950s.

Since the development of these tables, many other models and tables have been proposed. Most follow Haldane's basic principles, with modifications to the number of tissue groups considered, tissue half-time values, and their supersaturation ratios. Along with the Haldanian models and tables, other types of decompression models have been proposed based on assumptions which differ markedly from Haldane's basic ideas.

PRESENT HALDANIAN MODELS

U.S. Navy Model & Tables

The present U.S. Navy Tables were developed in the 1950s to accommodate the introduction of scuba and to improve the earlier U.S. Navy Tables, published in 1937. The older tables had no acceptable provisions for performing repetitive dives, since most dives were done in the surface-supplied hardhat mode with an unlimited air supply. The model that was used in the computation of the newer tables was a modified Haldanian model (Dwyer 1956a & 1956b and DesGranges 1957).

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

$$P_t = P_o + (P_a - P_o) \times (1 - e^{(\ln .5)t/T1/2}) \quad [1.1]$$

Where:

P_t = Final nitrogen pressure in tissue group
P_o = Initial nitrogen pressure in tissue group
P_a = Ambient nitrogen pressure
t = Time tissue group is exposed to P_a
$T1/2$ = Half-Time of the tissue group in minutes

When air is used as a breathing gas, P_a is assumed to be:

$$P_a = 0.79 \times (D + 33) \text{ fsw} \quad [1.2]$$

Where:

D = Depth of the exposure in fsw
33 = Air pressure in fsw at sea level
0.79 = Fraction of nitrogen in air

The number of tissue groups used in the U.S. Navy model was expanded from five to six. The tissues had 5-, 10-, 20-, 40-, 80-, and 120-minute half-times. The longer 120-minute tissue assumes a saturation time of 12 hours.

The U.S. Navy model also indicated that the allowed supersaturation ratio for the tissue groups decreased with depth. This led to the development of the "M value" system to determine the allowable nitrogen pressure (in fsw) for a tissue group at a specific depth. The M value for the tissue groups that correspond to the supersaturation ratio permitted at sea level is referred to as M_o. The change in the M value per foot of sea water is referred to as ΔM (Delta M). In order to compute the M value for a specific depth (D), the following formula is used:

$$M = M_o + (\Delta M \times D) \quad [1.3]$$

The M_o and ΔM values for the six tissue groups used are listed in Table 1.2 with the corresponding supersaturation ratios for surfacing.

Using the M values in Table 1.2 the current U.S. Navy Standard Air Decompression Tables were developed. These tables are presented in Appendix B.

In addition to the standard decompression tables, it was necessary to create a set

TABLE 1.2
U.S. NAVY M_o AND ΔM VALUES

TISSUE HALF-TIME	SUPERSATURATION RATIO AT SURFACE	M_o (fsw)	ΔM
5 min.	3.15	104	2.27
10 min.	2.67	88	2.00
20 min.	2.18	72	1.71
40 min.	1.76	58	1.40
80 min.	1.58	52	1.29
120 min.	1.55	51	1.27

of tables that would allow divers to perform repetitive dives. If a repetitive dive was performed using the 1937 tables, the bottom times of the two dives would be added together, no matter how long the surface interval was, without considering the off-gassing that occurred during the surface interval.

The solution used for computing repetitive dives was the Repetitive Group Designation system. It is implemented in the current U.S. Navy Tables along with the Surface Interval Table and the Residual Nitrogen Time Table (Appendix B). The Repetitive Group Designators[1] "A" to "O" and "Z" represent increasing levels of residual nitrogen in the 120-minute half-time tissue group. Each group represents a tissue nitrogen pressure range of approximately 1.58 fsw. Following a dive (either no-decompression or decompression), the diver's nitrogen pressure level is represented on the table by a Group Designator. By using the initial Group Designator and the time spent at the surface, a new Group Designator is obtained using the Surface Interval Table. To obtain the time penalty the first dive places on the second dive, the Residual Nitrogen Time table is used. This translates the new Group Designator to the time it would have taken at the repetitive dive depth to reach the present Group Designation. This residual nitrogen time (RNT) is then added to the actual bottom time (ABT) of the 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.

The initial idea was to have repetitive dive tables for all six tissue groups. However, it was decided that six sets of tables would probably have been too complex for normal diving operations. A simple technique needed to be devised that would be easy to use in field operations. The technique also had to prevent any of the other five tissue groups from controlling a repetitive dive. Calculations were made to see how long a surface

[1] Alphabetic repetitive group designators are used in many tables. The residual nitrogen that they represent is unique to the table and they can **not** (in general) be cross-referenced to repetitive groups in another table.

interval was required for the other five groups to off-gas to levels where they would no longer have a controlling effect on a repetitive dive following any dive profile allowed by the the tables. The longest time generated was 9.7 minutes for the 40-minute tissue group. 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.

To test the tables, sixty-one repetitive dive combinations were devised. One hundred-twenty-one test dives, resulting in 3 cases of decompression sickness, were completed before the tables were released for Navy use. They were picked up by the fledgling sport diving community and have since been used by millions of divers around the world.

A recent recalculation of the current U.S. Navy Tables by the Navy Experimental Diving Unit (NEDU) found some computational and transcriptional errors (Thalmann, 1983). This was a surprise to some divers since they 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 (Table B-1, Appendix B). Every value in the table at a depth of 30 fsw and shallower is shifted one column to the left. If after a dive to 30 fsw the Repetitive Group Designation was G, it should actually be Repetitive Group H. Even with these transcriptional and computational errors, the U.S. Navy Tables have served divers well for 30 years.

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 (Beckman, 1976). The model differs somewhat from the U.S. Navy model in that it considers ten tissue half-times (up to 480 minutes) and has more conservative M_o and ΔM values. Table 1.3 presents the tissue half-times, M_o, and ΔM values for the PADUA model. Although the

TABLE 1.3
PADUA MODEL PARAMETERS

TISSUE HALF-TIME	M_o (fsw)	ΔM	TISSUE HALF-TIME	M_o (fsw)	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

PADUA model would produce tables which are more conservative than the U.S. Navy tables, no such tables have been produced for publication.

Buhlmann Model and Tables

The Buhlmann Tables, or Swiss Tables, were developed at the Laboratory of Hyperbaric Physiology in Zurich. The model has undergone various adjustments over the past few years to accommodate new data. Buhlmann's model uses sixteen tissue groups, or "*compartments*" (Buhlmann, 1983). He uses Equation 1.1 to compute the tissue pressures, and presents pressures in **bars** as opposed to fsw. (For conversion: 1 bar = 1.01325 ATA, or approximately 33.44 fsw). In addition, Equation 1.4, instead of the M value method, is used to compute allowable supersaturation pressures.

$$P_{amb.tot.} = (P_{i.g.t.} - a) \times b \quad [1.4]$$

Where:

$P_{amb.tot.}$ = Total ambient pressure to which the tissue group with pressure P_{igt} can be safely decompressed

$P_{i.g.t.}$ = Total nitrogen pressure in the tissue group

a & b = Constants corresponding to the specific tissue group

By rearranging the terms of Eq. 1.4 an equation is created that will produce the allowed $P_{i.g.t.}$ at a specific $P_{amb.tot.}$ (Eq. 1.5).

$$P_{i.g.t.} = a + (P_{amb.tot.} / b) \quad [1.5]$$

The sixteen half-times and the values of a and b which correspond to them are listed in Table 1.4.

Equation 1.5 allows supersaturation pressures (P_{igt}) to be calculated for total ambient pressures that are less than 1 ATA (the M value system is used primarily for ambient pressures $\geq$ 1 ATA). This permits the calculation of decompression schedules for altitude diving and other situations, such as flying after diving, where the final ambient pressures are less than 1 ATA.

The present Swiss Tables consist of four sets of tables to be used in various altitude ranges (Appendix C). The no-decompression limits and decompression schedules are generally more conservative than the U.S. Navy Tables. The depths in these tables are presented in meters. The repetitive dive system for these tables utilizes the same type of Repetitive Group and Surface Interval Table system as the U.S. Navy Tables.

TABLE 1.4
SWISS MODEL HALF-TIMES AND CONSTANTS

TISSUE HALF-TIME	a	b	TISSUE 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

Huggins Model and Tables

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 (Spencer, 1976). 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 by the reflection of the ultrasonic wave off the bubble surfaces. 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). Spencer presented the following formula (Equation 1.6) to compute reduced no-decompression limits that would hold the occurrence of VGE formation below 10% to 20%:

$$\text{Limit} = (465/D)^2 \quad [1.6]$$

Where:

Limit = No-Decompression Limit for Depth D in minutes

D = Depth in fsw

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 (Huggins, 1981). The

TABLE 2.4
M_o VALUES FOR HUGGINS MODEL

TISSUE HALF-TIME	M_o VALUE (fsw)	TISSUE HALF-TIME	M_o VALUE (fsw)
5 min.	102.0	40 min.	54.5
10 min.	85.0	80 min.	47.5
20 min.	67.5	120 min.	43.0

model uses the same six tissue group half-times as the U.S. Navy model. The M_o values for the tissues were determined by computing the maximum tissue pressures produced in the tissue groups following exposure to the new no-decompression limits. No ΔM values were necessary since the tables were computed exclusively for no-decompression diving. The new M_o values are listed in Table 1.5, along with the tissue 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 tissue groups instead of just the 120-minute tissue group. Each repetitive group represents a 3% range of the M_o values of the tissue groups. For example, group "E" represents 72% to 75% of the M_o value of any of the six tissue groups. This type of representation allows all six tissue groups to be considered in repetitive dive calculations and permits certain types of multi-level diving procedures (see Chapter II) to be performed without any of the tissue groups exceeding their M_o 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.

OTHER MODELS

Pseudo-Haldanian Model (U.S. Navy E-L Algorithm)

For the past five years NEDU has been developing a decompression model and algorithm to program into an underwater decompression computer. It will be used with their constant partial pressure of oxygen closed-circuit mixed gas system (Thalmann, 1980, 1983b, 1984). The algorithm that they have decided upon is called the E-L Algorithm. This model assumes that nitrogen is absorbed by tissue groups at an Exponential rate, as in the other Haldanian models. However, the nitrogen discharge is a slower Linear rate. This slows the surface off-gassing rate indicating higher residual nitrogen levels for repetitive dives.

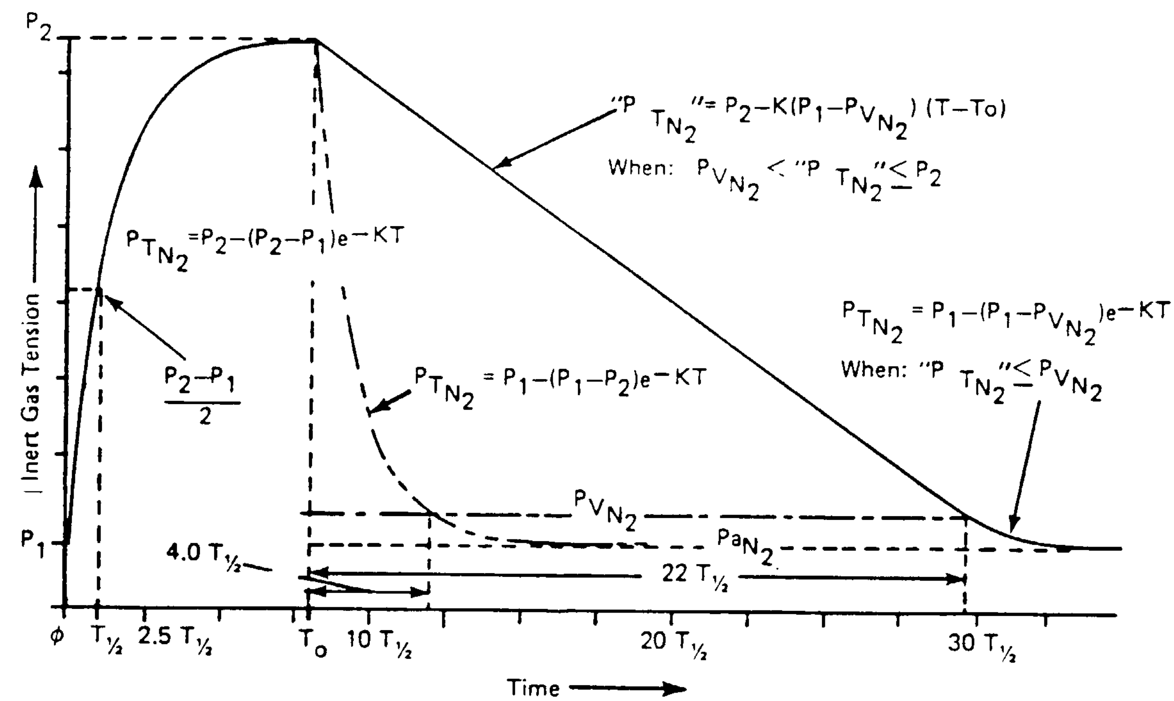

Fig. 1.2. E–L Algorithm vs. Haldanian Model. Solid line represents nitrogen absorption and elimination using E–L algorithm. Dashed line represents Haldanian model (From Thalmann, 1984).

Figure 1.2 compares nitrogen absorption and elimination between the E–L algorithm and the Haldanian model.

According to Commander Thalmann of NEDU (personal communication, 22 April 1985), 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 No-Decompression Limits are acceptable for Navy operations. Even if the E–L Algorithm was used to generate air tables, the model is, in many cases, less conservative than the present U.S. Navy Tables.

British (Royal Navy Physiological Laboratory) Model

The model used to generate the present Royal Navy Physiological Laboratory (RNPL) tables is called a "slab diffusion" model, that involves the linear bulk diffusion of gas into a tissue slab (Flynn, 1978b). This model represents the body as a tissue slab that ambient pressure diffuses into from one face (Figure 1.3). As the inert gas pressure increases on the exposed side, that pressure will migrate through the slab. 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.

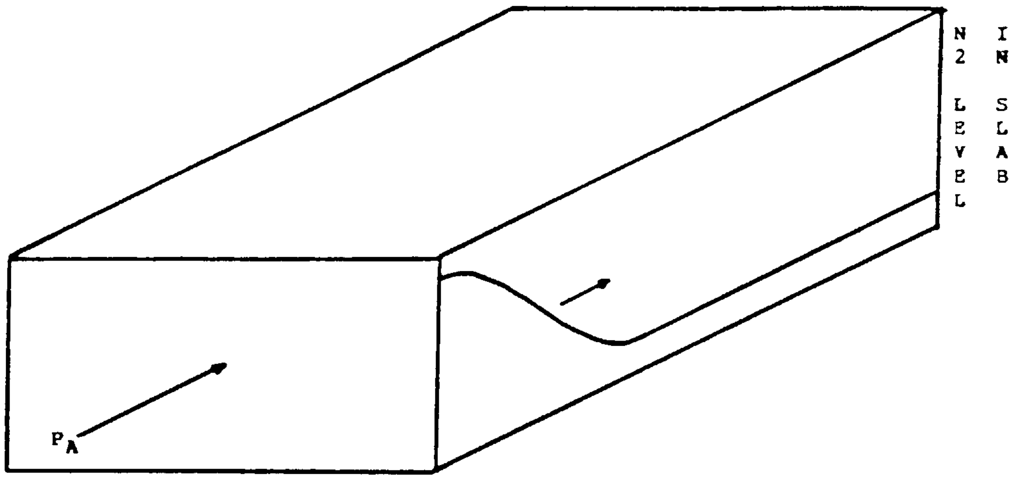

Fig 1.3. Tissue Slab Model used in RNPL Table computations.

The RNPL tables (Appendix E) are more conservative than the U.S. Navy tables and are used in modified form by the British Sub Aqua Club (the RNPL/BSAC tables) and by some research divers and clubs in the United States.

DCIEM Model & Tables

Over the past few years the Defence and Civil Institute of Environmental Medicine (DCIEM) in Canada has been modifying their decompression model based on ultrasonic Doppler studies. In September of 1984 DCIEM released their new No-Decompression and Decompression Tables (Lauchner, 1984c), presented in Appendix F. The DCIEM model is a **serial** model with four tissue groups (Nishi, 1984). The previously presented Haldanian models are parallel models, which assume all the tissue groups in the model are exposed to the ambient pressure with no interaction between the groups. A serial model assumes the tissue groups are connected in a series with only one tissue group exposed to the ambient pressure. Figure 1.4 compares the serial and parallel models.

Each of the four tissue groups 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 tissues in the series. The pressure levels in the last two tissues are not considered in the computation of the diver's safe ascent depth. This model approximates the British bulk diffusion slab model.

The DCIEM tables are based on hundreds of man-dives that were evaluated using ultrasonic Doppler detection (Lauchner, 1984a & b). DCIEM's primary goal with the modifications was to upgrade the decompression model that is programmed into their decompression computers (Chapter III).

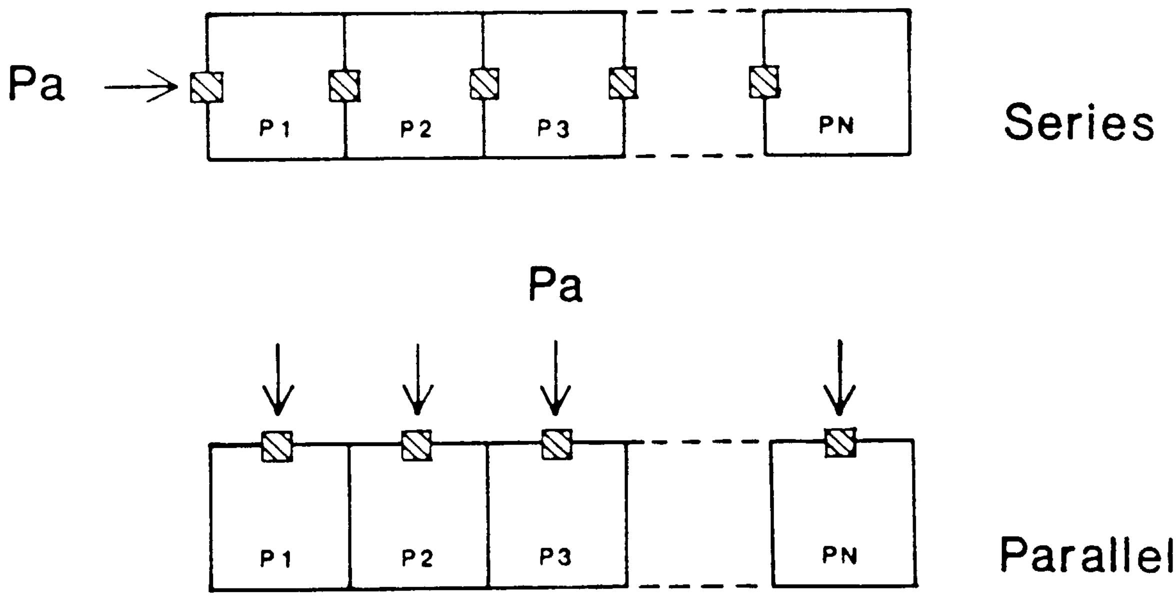

Fig. 1.4. Parallel vs. Series Model.

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, indicates that cavication nuclei, that 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*" (Hoffman, 1985). 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. Table 1.6 compares these no-decompression limits with values from the other models.

Maximum Likelihood Statistical Method

The Maximum Likelihood Statistical Method is a statistical approach to DCS developed by the Naval Medical Research Institute (NMRI). They consider decompression sickness a probabilistic risk dependant upon the "dose" (depth/time exposure) produced from a dive profile (Weathersby, 1985a). The model is based on a database that includes over 1,700 individual exposures from various decompression studies.

Using this statistical model, tables have been computed for DCS probabilities of 1% and 5% (Weathersby, 1985b). 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.

On 24 September 1985, Donald Chandler, Deputy Director of the Hyperbaric Medicine Center at NMRI, stated that the tables had yet to be submitted to the Navy Medical Review Panel. The panel then must approve the release of the tables for testing. Following this approval the tables will be sent to NEDU for testing and validation, a process that would take at least two to three years.

SUMMARY

Table 1.6 shows the no-decompression limits obtained from the various models. Even though the models differ in their hypotheses, the no-decompression limits for the more recent models correlate quite well for depths deeper than 50 fsw. Therefore the author recommends the use of the more conservative limits, especially in sport diving.

The basic limitation of any set of tables, no matter which set 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 five or ten 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.

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 leads to added 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 II, techniques have been developed that bypass this assumption and allow a diving technique called Multi-Level Diving or Step Diving to be performed.

TABLE 1.6

COMPARISON OF NO-DECOMPRESSION LIMITS FROM VARIOUS MODELS

DEPTH (FSW)	NO-DECOMPRESSION LIMITS (MINUTES)								
	U.S. NAVY	BUHLMANN*	SPENCER	NAVY E-L**	BRITISH*	DCIEM	TINY BUBBLE	NMRI 1%	NMRI 5%
30	None	300	225	296	232	380	323	170	240
40	200	120	135	142	137	175	108	100	170
50	100	75	75	81	72	75	63	70	120
60	60	53	50	57	46	50	39	40	80
70	50	35	40	44	38	35	30	25	80
80	40	25	30	37	27	25	23	15	60
90	30	22	25	31	23	20	18	10	50
100	25	20	20	27	18	15	15	8	50
110	20	17	15	24	16	12	12	7	40
120	15	15	10	20	12	10	11	5	40
130	10	12	5	17	11	8	10	5	30

*Metric conversion to next greater depth.
**Approximate computations from Thalmann, 1984.

CHAPTER II

NON-STANDARD USE OF TABLES (MULTI-LEVEL DIVING)

OVERVIEW

Most of the tables that have been generated, regardless of the model, generally present decompression status based upon the assumption that the diver spends the entire dive time at the deepest depth achieved. This "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 diving was being limited by these table restrictions. Because of these restrictions, various multi-level, or step, diving techniques have been devised to circumvent the maximum depth/entire dive-time rule.

With increasing frequency, sport divers are performing multi-level dives using these techniques. Thousands of dives per year are made using these procedures, even though the majority of these techniques have not been subjected to scientific testing to determine their validity. The extensive number of apparently harmless multi-level dives performed each year suggests that most of the techniques are relatively safe. However, there is the possibility of some hidden problems that may not be detected by the diver, such as "silent bubble" formation or the possible asymptomatic development of dysbaric osteonecrosis.

Few multi-level diving (MLD) techniques have been evaluated for safety. The MLD techniques that have been studied will be presented in this chapter along with results from these studies. Various other MLD techniques that have not been tested will be reviewed. Also, a summary of information obtained from a MLD questionnaire will be presented.

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 no-decompression or decompression tables, in this case the U.S. Navy Tables. Normally, when the rules of the Navy Tables are followed, the deepest depth of the dive is used to determine the allowable no-decompression time. Hence, the diver is adding to the safety of the dive by not staying at the maximum depth for the entire length of the dive. This added safety has probably been an important factor in the "safe" use of the U.S. Navy Tables, which are now being questioned. The MLD techniques that are 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 MLD techniques is that nitrogen is absorbed by the body more rapidly at deeper depths than it is 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, according to 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 the no-decompression time should be is what the various multi-level diving techniques attempt to determine.

There are two basic MLD techniques. The most frequently used techniques depend upon manipulations of existing tables, such as the U.S. Navy Tables. The other procedure involves multi-level computations using decompression models and algorithms, on which tables are based. The following MLD methods are variations of both of these techniques.

TABLE-BASED MULTI-LEVEL DIVING TECHNIQUES

Repetitive Group Method

The most popular table technique is the Repetitive Group Method or the "Graver" method, so called because it has been popularized by Dennis Graver in many publications (Graver, 1976, 1979). 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 a diver would have the same level of excess nitrogen following a dive to 80 fsw for 30 minutes as he/she would after 50 minutes at 50 fsw, since both dives place the diver in repetitive group G.

Using this assumption, a method of reading the U.S. Navy Tables "sideways" was developed. If, for example (as shcwn in Figure 2.1), 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 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! The U.S. Navy Tables would have required the divers to consider the entire 73 minutes spent at 110 fsw. This would have required 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 2.1. A variation of this method is said to be performed widely in commercial diving on oil rigs with a procedure called "Repetting Up".

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 that was used to compute the U.S. Navy Tables.

As indicated in Chapter I, the U.S. Navy decompression model, from which the standard air tables were computed, uses six tissue groups with half-times of 5, 10, 20,

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	2[illegible]0	310			
35	310	5	15	25	40	50	60	80	100	120	140	1[illegible]0	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	[illegible]0	70	80	90	100			
60	60	–	10	15	20	25	30	40	[illegible]0	55	60					
70	50	–	5	10	15	20	[illegible]	[illegible]	40	45	50					
80	40	–	5	10	15	[illegible]0	25	30	35	40						
90	30	–	5	10	12	[illegible]5	20	25	30							
100	25	–	5	7	10	[illegible]5	20	22	25							
110	20	–	–	[illegible]	10	13	15	20								
120	15	–	–	5	10	12	15									
130	10	–	–	5	8	10										

Fig. 2.1 Sample Multi-Level Dive

40, 80, and 120 minutes. All six of these tissue groups were considered in the calculation of the U.S. Navy no-decompression limits. However, only the 120-minute tissue group was used to compute Repetitive Group 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 tissues 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 tables. Graver recognized this problem, hence the modified limits indicated on the table in Figure 2.1.

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 tissue groups (Huggins, 1981). The basic reason for this build up of nitrogen pressures, primarily in the 40-minute tissue group, is that the tables were not designed to be used in this manner. Since a multi-level dive does not include the required 10 minute surface interval, the other five tissue groups are not permitted to off-gas to safe levels. An example of the tissue pressure build up in all six tissue groups is given in Table 2.1 (%MAP = % of the tissue group's M_0 value). As shown, the 20-minute tissue group's Mo value is exceeded at the surface and the 10-minute and 40-minute tissue groups are very close to their limits. This shows that the Repetitive Group Method can violate the underlying decompression model.

Another question to consider when the U.S. Navy model or tables are used to compute multi-level dives is the following: if a MLD technique (or even a single-level dive) pushes a diver to the limits allowed by a model based on Navy divers, what is happening to a sport diver?

TABLE 2.1
TISSUE NITROGEN PRESSURES (IN FSW) PRODUCED
DURING A MULTI-LEVEL DIVE PROFILE

PROFILE (Depth/Time) (fsw/min.)	TISSUE GROUPS [Half-Time(M_O 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%

Repetitive Group/Residual Nitrogen Time Method

The Repetitive Group/Residual Nitrogen Time Method is a table method similar to the Repetitive Group Method. The major difference between the two methods is that the secondary levels of a multi-level dive are considered to be repetitive dives without any surface interval. The residual nitrogen times for these steps are obtained from the repetitive group produced from the first level. If, as before, the initial step in a dive was to 110 fsw for 13 minutes, the repetitive group would be E. The residual nitrogen time for the next step at 70 fsw is found on the residual nitrogen table. The residual nitrogen time for group E at 70 fsw is 26 minutes. This results in a remaining no-decompression time at 70 fsw of 24 minutes, as opposed to the 30 minutes obtained with the repetitive group method. An additional 20 minutes at 70 fsw results in a group J designation. The residual nitrogen time for group J at 40 fsw is 116 minutes. By adding the 40 minutes actual time at 40 fsw to the 116 minutes residual nitrogen time, the equivalent dive time becomes 156 minutes. The repetitive group at the end of this dive is group M, or two groups higher than the K group obtained from the Repetitive Group Method.

Since there is no 10 minute surface interval, the same problem that occurs with the Repetitive Group Method exists with the Repetitive Group/Residual Nitrogen Time Method. Nitrogen pressures might build to unacceptable levels in the faster tissue groups, especially the 40-minute tissue group.

This technique, accompanied by restrictions for its use, was presented in the "RX for Divers" column in a major sport diving magazine in March 1983 (Bove, 1983). It is also taught by at least one commercial diving school as the "Shortcut" procedure.

Half & Half Method

The Half & Half method is not a table-based MLD technique in the true sense. With this method a diver may spend one-half of the no-decompression limit at one depth and then ascend to a shallower depth and stay at that depth for one-half of that depth's no-decompression limit. There is no set procedure for computing the repetitive group designation following a Half & Half dive.

When this method is compared with the U.S. Navy model, a majority of the possible dive profiles produce nitrogen pressures in excess of the tissue groups' Mo values. **It is highly recommended that this procedure be avoided.**

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" (Thalmann, 1983). 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 no reports on the testing have been published or made available to the public at this time.

Other Methods

There are many other MLD 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.

MODEL COMPUTATIONAL MULTI-LEVEL DIVING METHODS

Computer and Microprocessor Applications

The MLD technique that seems to hold the most promise at this time is the Model Computational Method. This procedure examines what is happening to all the tissue groups 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 tissue groups in a model given a multi-level dive profile at a much faster rate and with more accuracy than manual calculations. For example, Appendix G presents a FORTRAN program which computes the nitrogen levels in the six tissue groups of the U.S. Navy model based on a multi-level dive profile. This program was used to compute the safety level of the dive profile presented in Table 2.1. There are two ways the Model Computational Method can be used. The first method is to compute a safe according to the model multi-level dive profile before the dive and follow that set dive profile. The other way to use the Model Computation Method is to compute the safety of the multi-level dive as it is being performed using a real-time decompression 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 (Table 2.2).

Using standard U.S. Navy dive table procedures this dive would have required a total of 147 minutes of decompression. However, by using the Pre-Dive Evaluation technique the decompression requirements were reduced to only 37 minutes. Approximately 30 person-dives were completed using this profile without evidence of decompression sickness (Workman, 1963).

Real Time Evaluation of Multi-Level Dive Profiles

Various decompression 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. The 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 III.

TABLE 2.2
MULTI-LEVEL DIVE PROFILE PERFORMED WHILE TESTING
UNDERWATER COMMUNICATIONS EQUIPMENT

Depth (fsw)	Time (min.)
190	15
150	10
100	10
50	10
20	7
10	30

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 an ultrasonic Doppler detector 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 (Huggins, 1983). A full description of the development and testing of the EDGE is presented in Chapter IV.

SURVEY OF MULTI-LEVEL DIVING TECHNIQUES

The University of Michigan Underwater Technology Laboratory has conducted a survey of MLD techniques. A questionnaire was made available to sport divers through various diving publications. The following information was requested:

A. Diving History

B. Multi-Level Diving Technique Used

C. Commonly Performed Multi-Level Diving Profiles

D. How Many Multi-Level Dives Performed Each Year

E. Where Multi-Level Diving Technique Was Learned

F. Advantages of Multi-Level Diving

G. Any Problems Encountered With Multi-Level Diving

H. Future of Multi-Level Diving

The results of the survey (Huggins, 1986), based on the 68 responses, indicate that most of the divers who perform MLD have either less than five years of diving experience, or over 25 years of experience. The most frequently used method is the Repetitive Group Method and an average of 26 multi-level dives are performed each year. Most of the divers learned their MLD technique from a scuba instructor, even though none of the certifying agencies recognize MLD as an acceptable diving practice.

The consensus of the responders was that MLD had the advantage of increasing dive time without increasing decompression debt and allowed for more efficient use of air. Most agreed that MLD should be limited to advanced divers. Some indicated that the future of MLD lies in decompression computers, since the execution of a table-based MLD takes extensive pre-dive planning. There were very few indications of problems involving MLD. There was one case of first-hand decompression sickness reported and two reports of second-hand cases. All of these problems occurred while using table methods.

Another aspect of the survey was to compare the commonly performed dive profiles to various decompression models. It was determined that out of 51 multi-level dive profiles, 24 produced tissue pressures in excess of the M_0 values allowed in at least one of the six decompression models used.

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 MLD, such as asymptomatic bubble formation or development of dysbaric osteonecrosis? Or does MLD reduce the probability of these complications occurring? The data are not available.

Currently there is insufficient evidence or data to indicate whether most of the MLD techniques are safe or unsafe. The techniques that have been tested seem to indicate that some types of MLD can be safe, but there is still a great need for further studies in this area.

CHAPTER III

REAL TIME DECOMPRESSION DEVICES

OVERVIEW

Real time decompression devices are the most effective way to evaluate a diver's decompression status during a multi-level dive. These devices monitor the actual dive profile and, in some manner, compute the diver's decompression status. They allow for more dive profile flexibility than standard decompression tables, which assume the entire bottom time is spent at the maximum depth achieved during the dive. Figure 3.1 compares an actual dive profile to the square-wave profile that must be assumed if the diver uses a decompression table.

The shaded area indicates times during the dive when less nitrogen is absorbed than what the tables assume. In this case (a 40 min. dive to 80 fsw) the diver is at the end of the no-decompression time for the maximum depth, according to the U.S. Navy tables. However, since the entire dive was not spent at 80 fsw, the diver should be able to extend the no-decompression time for the dive. A decompression device can either compute the actual remaining no-decompression time or give some indication of decompression status based on the actual dive profile.

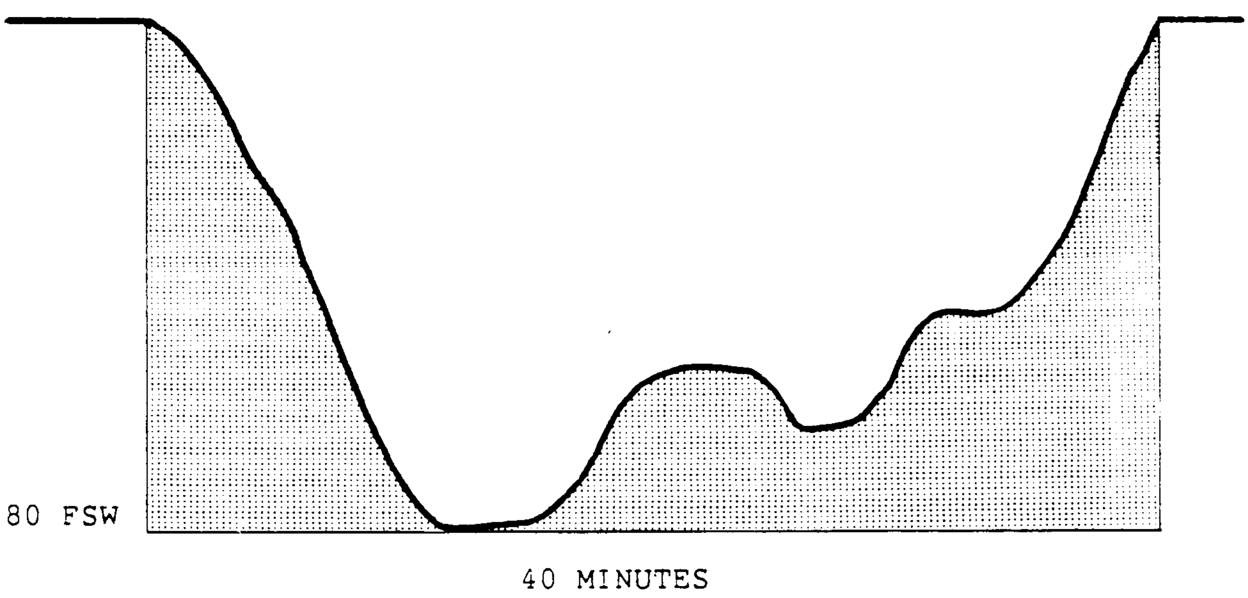

Fig. 3.1 Actual Dive Profile vs. Square-Wave Dive Profile

A decompression device has an advantage over the tables even if the dive profile is a square-wave. profile because decompression status is based on the actual dive depth. Most tables list decompression information in discreet increments of depth and time. Depths are usually indicated every 10 fsw and time normally every 5 or 10 minutes. Normal practice is to round the dive profile up to the next deeper depth and longer time entry in the table. A 51 fsw dive for 42 minutes would be considered a 60 fsw dive for 50 minutes. A decompression device will base the diver's decompression status on the actual dive depth and time, thus giving a more accurate representation of the dive.

The pre-dive Model Computational Method of planning multi-level dives is more flexible than using decompression tables. However, it is still inflexible in its execution since the diver must stay within a set profile, whereas a decompression device can accommodate unplanned variations to a dive plan.

Decompression devices base the diver's decompression status on models which are built into the device. These models may be approximated by some type of analog device or computed by a digital computer. Disadvantages of decompression device use include:

A. There is no safety margin associated with a decompression device unless it is included in the model. If the device is pushed to the limit of safe operation the decompression model used in it is also pushed to its limit.

B. There is the potential for mechanical or electrical failure.

C. There are mechanical limits and decompression model limits to consider. Both limits may be exceeded during operation.

These problems can be virtually eliminated by thoughtful designs and responsible use.

Decompression devices should be designed with the user in mind. The design should be such that:

A. Decompression status is continually displayed in an easy-to-read manner.

B. The device has high integrity in both the physical design and decompression model design.

C. Relevant information such as depth and bottom time is displayed so that the diver can make an emergency "bailout" decision in case the device fails.

There have been many attempts to design and produce a reliable decompression device since 1956. The following section will look at the history of decompression devices and some of the problems that have been encountered in the past 30 years.

HISTORY OF DECOMPRESSION DEVICES

Initial Concept

During World War II the concept of deep sea diving changed with the introduction of SCUBA. Up to this time 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 which had to be considered:

A. 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.

B. 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.

C. 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 NEDU report (Searle, 1956), 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.*

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 dealing with this problem, (Groves & Monk, 1953), 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.

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 stepwise 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.

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

Analog Devices

Prior to the advent of microprocessors, 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 tissue pneumatic design was based on the Groves and Munk report. The two tissue groups to be simulated had half-times of 40 and 75 minutes and surfacing ratios of 1.75:1 for both tissues (Fredreickson, 1956). The computer used five bellows to determine decompression status (Figure 3.2).

Nitrogen absorption and elimination from the tissue groups was simulated by the flow of gas through porous resistors between bellows, which were exposed to the

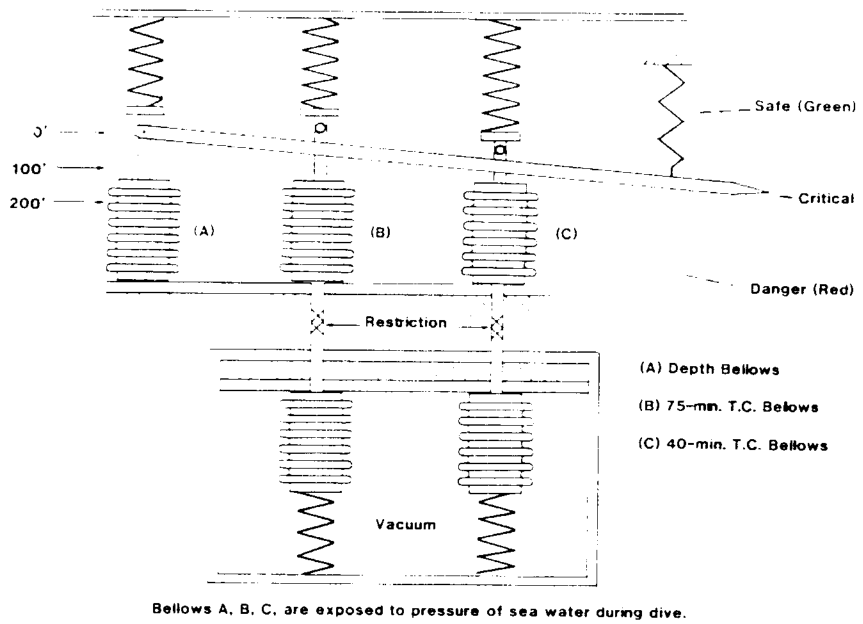

Fig. 3.2 Foxboro Decomputer Mark I Schematic (from Fredrickson, 1956).

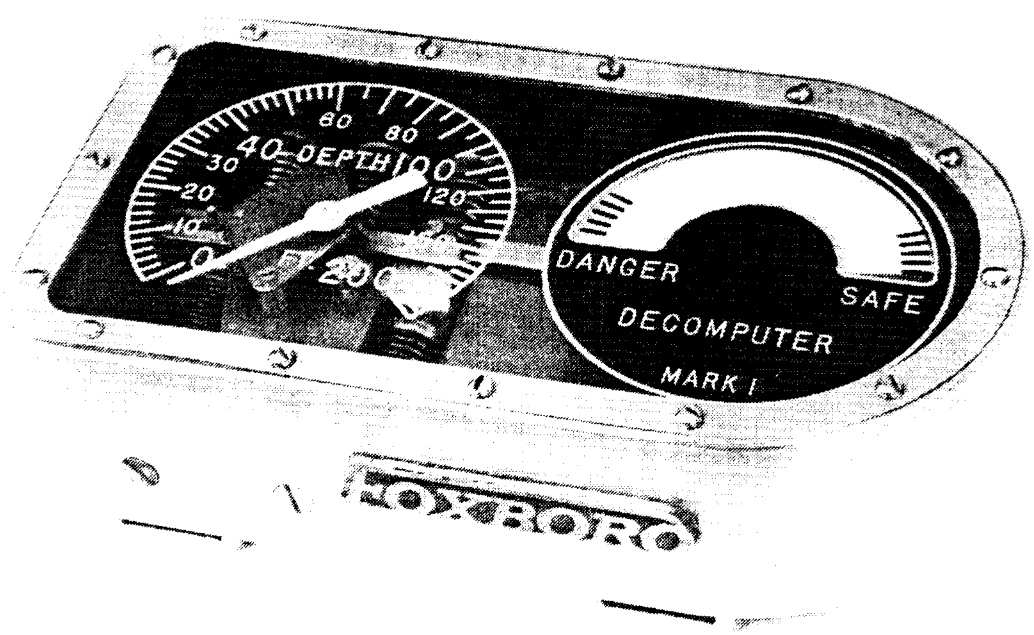

Fig. 3.3 Foxboro Decomputer Mark I (photograph courtesy of Mead Bradner).

ambient pressure, and bellows sealed in a vacuum, kept under a constant pressure by a spring.

This device (Figure 3.3) was the result of communications between two brothers, Dr. Hugh Bradner (member of the Committiee 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 (Searle, 1956) stated that the device gave readings within the U.S. Navy Table decompression ranges for some dives and outside the ranges for others. The major reason for this was that tissue half-time values were mistaken for the time constants of the bellows. The actual tissue 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

The SOS decompression meter is probably the most well known decompression device. It was designed in 1959 by Carlo Alinari and manufactured by an Italian firm, SOS Diving Equipment Limited (Gordon, 1978). 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" (Kuehn, 1981). Due to the design of the DCP, the simulated tissue half-time varies with the pressure differential across the ceramic resistor.

Figure 3.4 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.

A major problem with the DCP is its deviation from the U.S. Navy no-decompression limits at deeper depths. Howard (1975a) evaluated ten DCPs and 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, but less conservative at depths deeper than 60 fsw (Table 3.1).

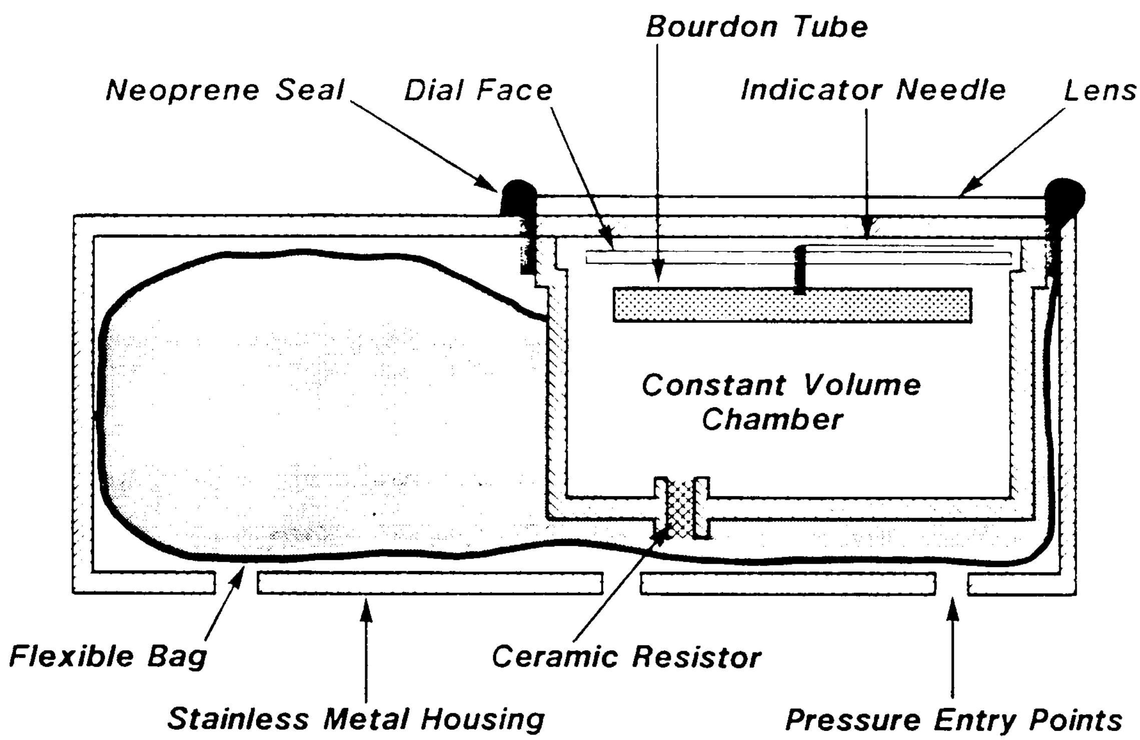

Fig. 3.4 Schematic Diagram of SOS Decompression Meter (from Gordon, 1978)

TABLE 3.1
COMPARISON OF DCP AND U.S. NAVY NO-DECOMPRESSION LIMITS

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

(from Howard, 1975a)

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 series resistors and parallel capacitors 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° 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, (Workman, 1963), 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.*

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

DCIEM Analog Computer Series

In 1962, the Defence 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. Table 3.2 shows test results for the various versions of the device (Flynn, 1978).

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 (Nishi, 1978). The display 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 3.5 gives the schematic diagram for both the MARK VS & VIS.

TABLE 3.2
INCIDENCE OF DCS PRODUCED WITH VERSIONS OF THE
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%

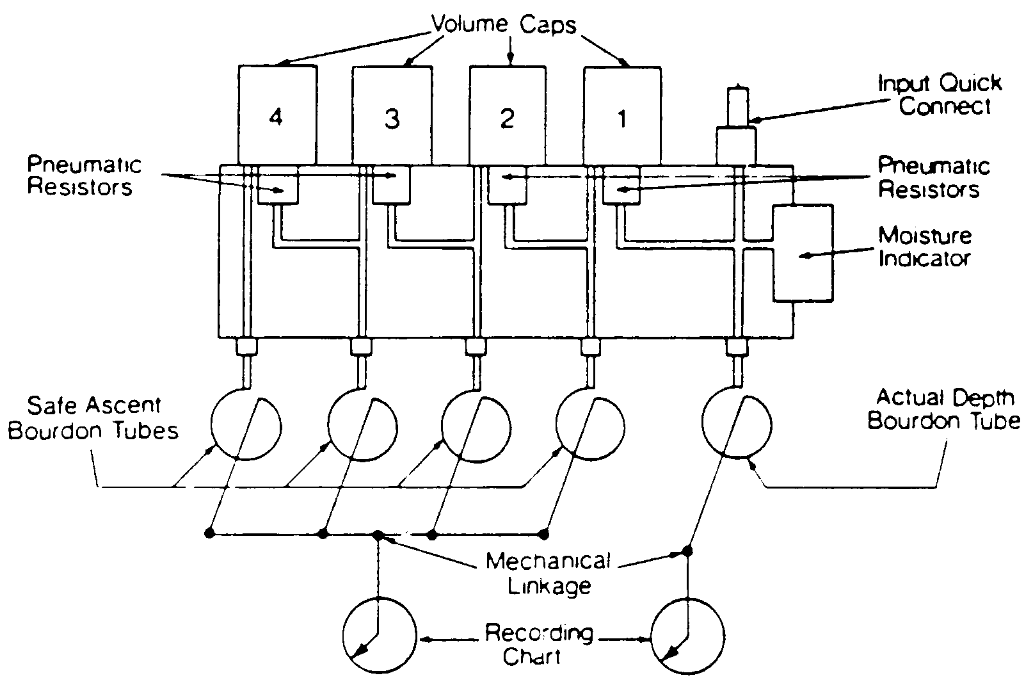

Fig. 3.5 Schematic of the Mark VS & VIS Pneumatic Analog Decompression Computers (from Nishi, 1978).

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 (Borom & Johnson, 1973). These membranes are better than porous resistors because 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 tissue 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 3.6 shows the schematic of this device.

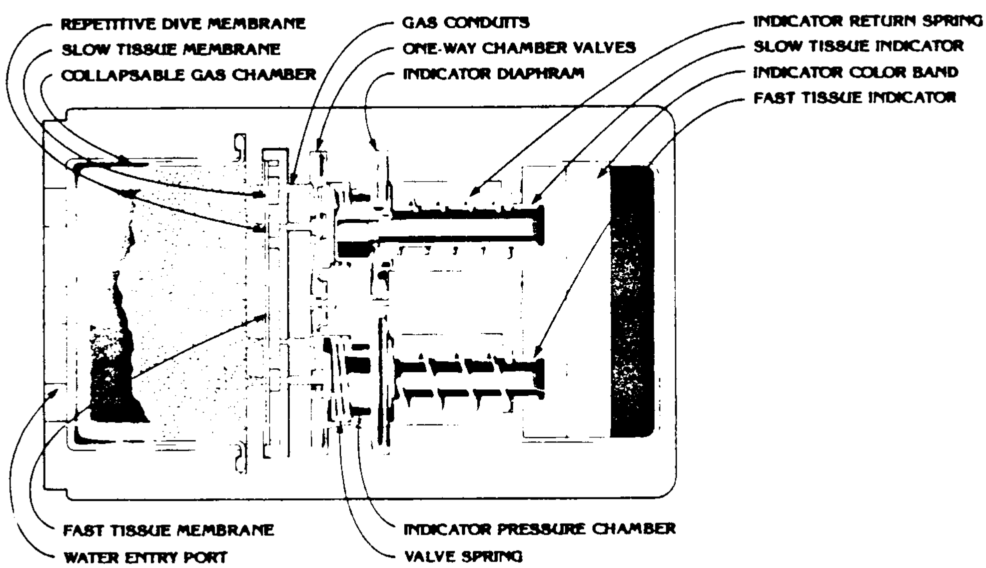

Fig. 3.6 Farallon Decomputer (from Farallon, 1975)

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 tissue 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 through the 'repetitive dive membrane'. Both tissue simulators 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 (Howard, 1975). 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 (Flynn, 1978).

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 digital computers has been 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 the success of their previous work with pneumatic decompression computers, they elected to use the Kidd-Stubbs decompression model with their digital computers.

DCIEM's first computer, the XDC-1 (Figure 3.7), is a desk-top model. It is 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 tissue groups of the Kidd-Stubbs model.

During the dive, the operator can extrapolate the dive profile and determine required decompression debt based on numerous dive options (Lomnes, 1975). The XDC-1 was manufactured by Canadian Thin Films Systems Inc. in British Columbia and successfully used in laboratory hyperbaric facilities. However, the design is not practical for open water diving situations.

To handle the rigors of diving operations, DCIEM designed the XDC-2 (Figure 3.8). 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**"[1] on the diver's umbilical. The basic decompression model in the XDC-2 is 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:

A. Depth

B. Elapsed Dive Time

C. Safe Depth (depth to which the diver can ascend safely without violating the model).

D. No-Decompression Time/Ascent Time Display. When the diver is within the no-decompression limits this display will display the no-decompression time remaining if the diver stays at that depth (negative number). If the diver goes into a decompression dive this display will give the optimum ascent/ decompression time (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. 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.

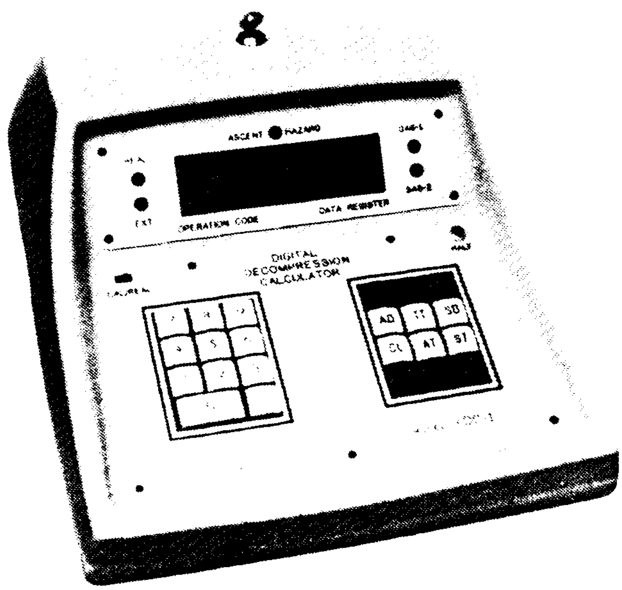

Fig. 3.7. XDC-1 Decompression Computer (from CTF Systems, inc).

[1] The pneumo hose is an air line which is open to the water where it terminates at the diver. When the hose is pressurized the air will force the water out the open end of the hose. The resulting internal pressure will equal the pressure of the depth the diver is at. If a small flow of air is maintained through the pneumo hose during a dive, the hose pressure will track the diver's depth.

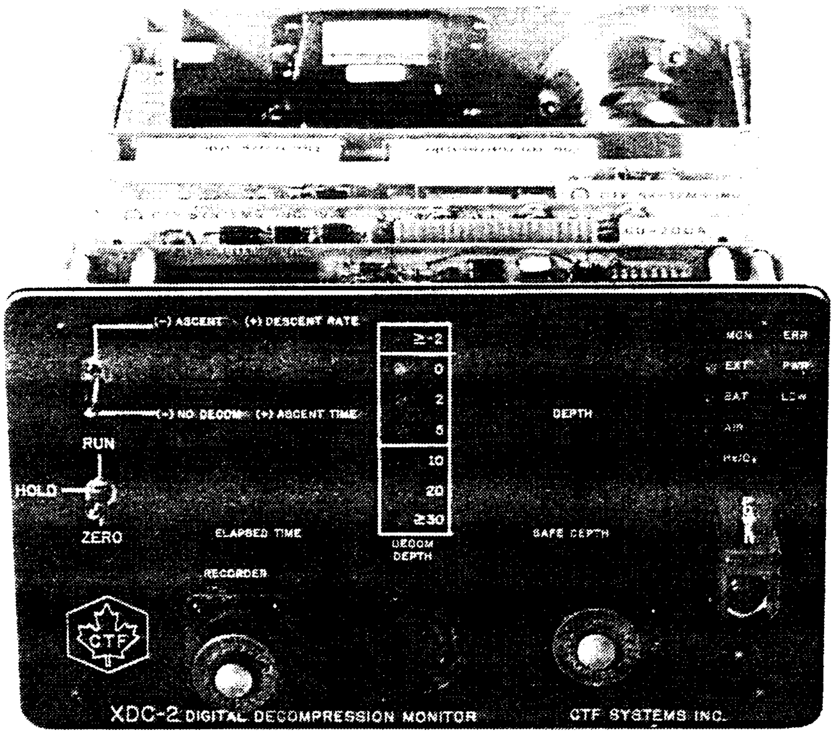

Fig. 3.8. XDC-2 Decompression Computer (from CTF Systems, Inc).

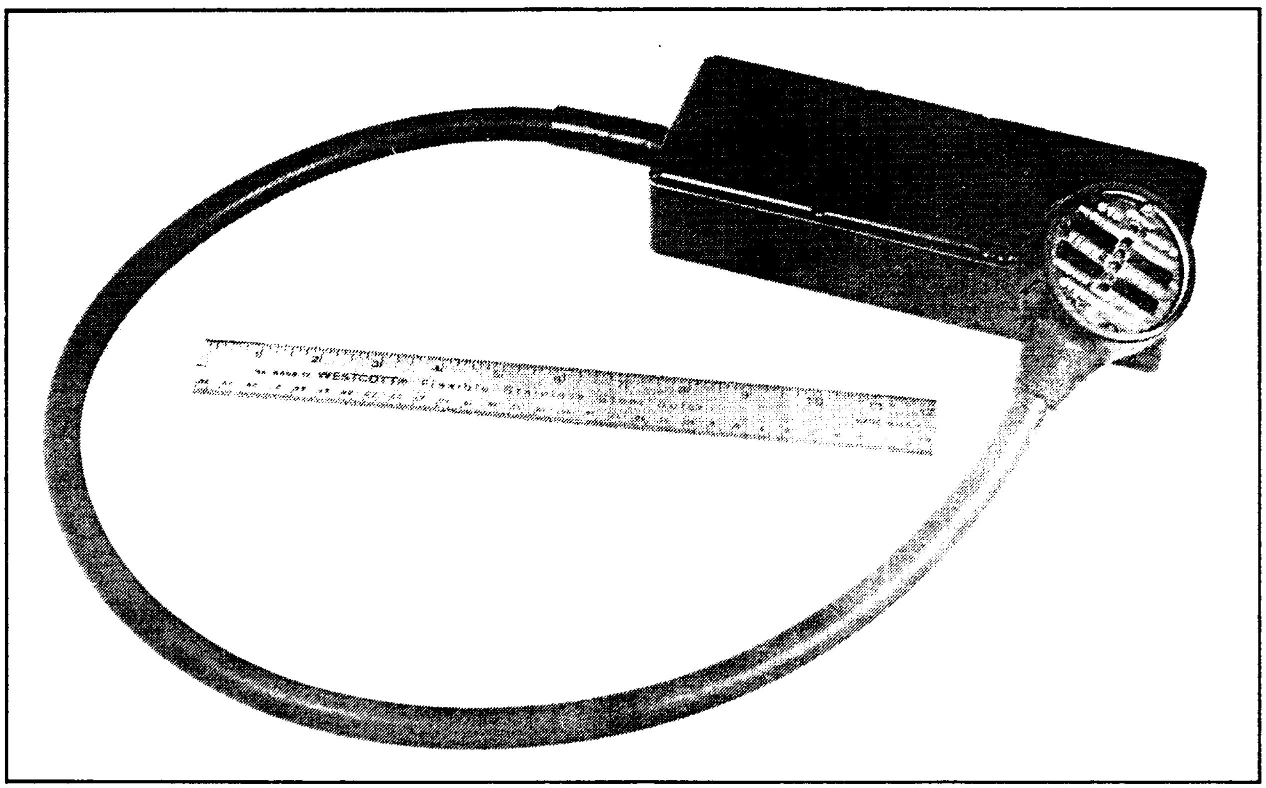

Fig. 3.9. XDC-3 Decompression Computer / Cyberdiver (from CTF Systems, Inc).

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 (Figure 3.9).

The device attached to the diver's tank and the 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 since its initial cost and the cost of four 9V batteries every four hours on a diving excursion were too high for the average sport diver.

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 use microprocessors in a diving computer 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 (Foley, 1979). 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. According to the company, two-thousand units were ready to ship as soon as the batteries arrived, but the factory that produced the batteries was destroyed by fire and the project was shelved.

Cyberdiver II

Kybertec (now Newtec) in British Columbia which worked 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 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. 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

Newtec returned to a decompression model instead of a table to determine decompression status with the Cyberdiver III in 1981. 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. Even though Newtec is not advertising the unit, it is still available.

Decobrain I

Two new decompression computers specifically designed for sport divers were released in 1983. These were the EDGE No-Decompression/Decompression Computer (which will be exclusively covered in Chapter IV) and the Decobrain I.

The Decobrain I is a table-based decompression device. The five sets of Swiss tables were programmed into its memory. It was manufactured by a company in Liechtenstein called Divetronic. The unit (Figure 3.10), worn on the wrist, displays the diver's depth, bottom time, ascent time, and initial decompression stop. When the diver gets within two minutes of the no-decompression limit, two zeros blink in the decompression stop display. If a diver enters a decompression dive, the decompression stop display presents the first decompression stop depth and time. When the diver comes within 5 fsw of the stop depth, the decompression time counts down to zero and the next decompression stop is displayed. At the surface, the Decobrain displays 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 is a rechargable NiCd pack which allows 80 hours of operation on a full charge (Hass, 1984).

When the unit is turned on it reads the ambient air pressure and determines which of the five sets of tables to use. The decompression information for the subsequent dive is based on the table range that covers the ambient pressure sensed at initialization.

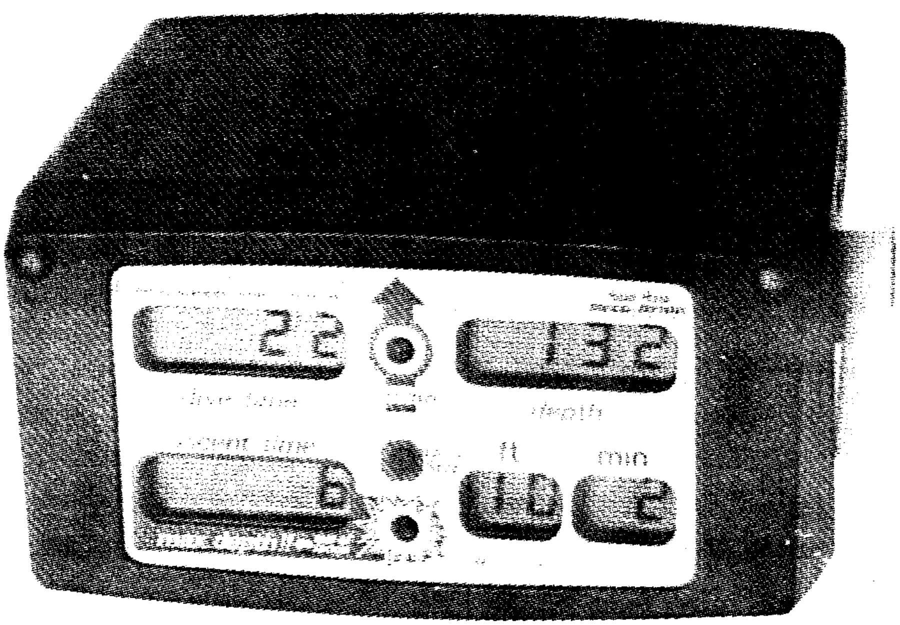

Fig. 3.10. Decobrain Decompression Computer (from Divetronics).

A unique aspect of the Decobrain I is that, even though it is table-based, it allows multi-level dives. This is 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 (see Chapter III). In this case it is the 80-minute half-time tissue. None of the other seven tissues 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"* (Bassett, 1983).

In 1985, Divetronic released new software for the Decobrain package, Decobrain II. This version is based on the Swiss decompression model, not the tables. At this time, no known evaluations of the Decobrain II are available.

SUMMARY

The diving community is becoming more aware of the advantages decompression computers offer in terms of multi-level diving credit and computation of decompression status. But, studies of multi-level diving and development of reliable and safe decompression computers must make up the 30-year head start of table-based scuba diving techniques.

As more decompression computers become available, they must be thoroughly tested to ensure operational and decompression model integrity and reliability. Even so, the final responsibility of the diver's decompression falls upon the diver. All a decompression computer can do is provide decompression status information based on a general model. The diver may or may not choose to use that information and should make common sense decisions based on personal limitations and environmental conditions.

It is interesting to speculate about the present state of scuba diving if the Foxboro Decomputer Mark I had performed properly and had been adopted for U.S. Navy use in 1956. If so, the present U.S. Navy air decompression tables might not have been computed and the standard tool used to determine decompression status might have been a decompression computer. Decompression computer technology would be far more advanced, and more information and studies about the effects of multi-level diving would be available today.

CHAPTER IV

DEVELOPMENT AND TESTING OF A DIVER-CARRIED NO-DECOMPRESSION/DECOMPRESSION COMPUTER*

OVERVIEW

Since 1981 the author has worked with ORCA Industries, Inc. on the development and testing of an underwater decompression computer called the EDGE (Electronic Dive GuidE) shown in Figure 4.1. This chapter will cover the initial concept, algorithm design, operation, testing, and follow-up information from field use of the EDGE. At this time the EDGE appears to be a commercially viable, safe decompression computer for the general sport diving population.

Fig. 4.1. The EDGE No-Decompression/Decompression Computer

BACKGROUND

The concept of a diver-carried no-decompression/decompression computer was not new. There have been many attempts to design and produce such a device since the introduction of scuba in the 1950s. Initial sketches were completed by the author in 1980 for a small underwater decompression computer for sport divers. The unit would be small enough to wear on the wrist and would be attached to the first stage of the scuba regulator in order to display tank pressure. The decompression status would be displayed by four LCD numerical displays.

In 1981, after presenting a lecture on decompression theory, tables, and devices to an Instructors Training Course at Wright State University, the author was approached by Craig Barshinger, one of the instructor candidates. Mr. Barshinger had also been working on the idea of a decompression computer for sport divers. He had founded a corporation in Delaware, but lacked background in decompression theories and models. During the next year he continued to develop this company (ORCA Industries, Inc.) while work progressed on an algorithm for a decompression computer. The algorithm work included:

A. Selection/creation of a safe decompression model.

B. Developing the decompression algorithm (from the model) that would be programmed into the unit.

C. Design and configuration of an easy-to-read display screen to show the diver's decompression status.

D. Human subject testing to determine the safety of the decompression algorithm.

Others who were indispensable in the successful development of the EDGE were: James Fulton, business and marketing; Len Anderson, hardware design; John Harris, software programmer; John Dalton and Robert Roder, case design.

By December 1986 there were over 5000 EDGE computers in use, and ORCA had become a leader in the field of decompression computers.

DEVELOPMENT OF THE DECOMPRESSION MODEL AND ALGORITHM

The initial problem in EDGE development was selecting the model that the diver's decompression status would be based on. Some of the criteria were:

A. The model type must be established.

B. It must be safe enough for all sport divers.

C. It must give results which are always more conservative than results obtained from the U.S. Navy standard air decompression model.

D. It must consider the type of diving to which the majority of sport divers subject themselves (multi-level dives, multiple dives per day, and multiple days of diving).

A Haldanian decompression model similar to the U.S. Navy standard air decompression model was selected. This would allow a diver to compare the EDGE decompression model to the U.S. Navy model, used to compute the tables which are the standard of the sport diving community. This comparison helps a diver comprehend the operation of the device.

Next the following parameters had to be determined:

A. The number of tissue groups to include in the model.

B. The range and specific values of the tissue half-times.

C. The M_0 values for the selected tissue groups.

D. The ΔM values used to compute safe ascent depths in decompression dives.

E. The tissue pressure update interval, or how often the ambient pressure was sampled and the tissue pressures recomputed.

Twelve tissue groups were selected, twice the number of tissue groups in the U.S. Navy air decompression model. This allows for a wider range of tissue half-times. All the tissue pressures are shown in bar graph form in the graphical section of the display (see Display Configuration section).

The range of tissue group half-times in the U.S. Navy air decompression model is 5- to 120-minutes. This assumes that a diver has eliminated all residual nitrogen 12 hours after a dive. More recent models have indicated that longer tissue group half-times should be considered (Beckman, 1976). Some of these models have tissue group half-times up to 1200 minutes for dealing with decompression from saturation dives. This half-time is probably too long to consider for normal sport diving situations. However, there is some concern that a 120-minute half-time is not long enough when multiple dives are completed each day for many consecutive days, a normal practice of vacationing sport divers. After consideration, the slowest tissue group half-time in the Haldanian model used for the EDGE was 480 minutes. The fastest tissue half-time selected was 5 minutes, which is standard in most air decompression models.

The M_0 values and tissue group half-times were selected to obtain a smooth "tissue surface limit line" on the display. They were determined using no-decompression limits based on Spencer's equation and therefore are more conservative than the U.S. Navy values. The tissue group half-times and their corresponding M_0 values are listed in Table 4.1, with the U.S. Navy values listed for comparison. There is a good representation of tissue groups between 10-minute and 80-minute half-times (5 of the 12 groups), which are the tissue groups of primary concern in normal multi-level dives.

TABLE 4.1
TISSUE HALF-TIMES AND M_o VALUES FOR THE EDGE AND U.S. NAVY MODELS

U.S. Navy		EDGE	
Half-Time (min)	M_o Value (fsw)	Half-Time (min)	M_o Value (fsw)
5	104.0	5	100.0
10	88.0	11	81.8
20	72.0	17	71.5
40	58.0	24	63.7
80	52.0	37	55.9
120	51.0	61	50.7
		87	46.8
		125	43.0
		197	39.1
		271	36.5
		392	33.9
		480	33.0

The 480-minute tissue group was assigned a M_o value of 33 fsw nitrogen, which does not allow for any level of supersaturation. (This decision has caused some annoyance to some of the divers who do extensive diving. This problem will be addressed later). All of the ΔM values were set equal to 1.0. This added conservatism to the model and simplified computation of the safe ascent depth.

The update interval selected was 3 seconds. This allows a good integration of the dive profile since the normal diver's depth changes little in three seconds. It also allowed the pressure transducer and other components to be turned off for approximately two out of three seconds in order to reduce power consumption.

The formula used to calculate the tissue pressure nitrogen levels is the basic exponential equation used in all Haldanian decompression models:

$$P_t(i) = P_o(i) + (P_a - P_o(i)) \times (1 - e^{(k/T1/2(i))}) \quad [4.1]$$

Where:

- $P_t(i)$ = Total nitrogen pressure in tissue group i
- $P_o(i)$ = Initial nitrogen pressure in tissue group i
- P_a = Ambient pressure of nitrogen in the breathing medium
- k = −0.034657 min. [ln(.5) x 3 seconds]
- T1/2(i) = Half-time of tissue group i

The decompression information to be displayed by the device included:

A. **Remaining No-Decompression Time**. If the diver was within the no-decompression realm of the model the computer would display the amount of no-decompression time remaining at the present depth.

B. **Remaining Decompression Time**. If the diver was within the decompression realm of the model, the computer would show if decompression could be performed at the present depth. If it could not, the diver would be warned. If decompression could take place, the computer would display the required decompression time for that depth.

C. **Safe Ascent Depth or Ceiling**. If the diver was in the decompression realm of the model, the computer would display the shallowest depth to which the diver could safely ascend.

The formula used to compute the no-decompression time remaining and the decompression time remaining for a specific depth is the same. The result is the time it will take a tissue group to reach its M_o value:

$$t = \frac{(\ln((M_o(i) - P_a)/(P_t(i) - P_a)) \times T1/2(i))}{\ln(.5)} \quad [4.2]$$

Where:

$M_o(i)$ = M_o value for tissue group i
$T1/2(i)$ = Half-time for tissue group i
t = Time it will take at ambient pressure P_a for tissue group i to reach pressure $M_o(i)$ from the tissue pressure of $P_t(i)$

Figure 4.2 shows the six possible relationships between P_t, P_a, and M_o that are possible in the model.

Only conditions #1 and #4 produce a usable result from equation 4.2. Condition #1 indicates a no-decompression situation where P_t is less than the M_o value and P_t will have to exceed the M_o value in order to equilibrate with P_a. In this case, remaining no-decompression time can be computed.

In condition #4, the tissue group is in the decompression realm and P_t will become less than M_o as it moves toward P_a. Decompression time required for the tissue group can be calculated.

	P_a	
1	P_t ---> M_o	
2	P_t --->	M_o
3	M_o	<--- P_t
4		M_o <--- P_t
5	M_o P_t --->	
6.		<--- P_t M_o

Fig. 4.2. Possible Relationships Between P_t, P_a, and M_o values.

Of the remaining four conditions, #2 and #6 represent no-decompression relationships since both P_t and P_a are less than M_o. In either case, the tissue is in a safe no-decompression situation and its pressure is not considered in the computation of the decompression status for the present cycle.

In conditions #3 and #5, both P_a and P_t are at greater pressures than M_o, indicating a decompression situation. Since P_a is greater than M_o, decompression of that tissue group cannot take place at that depth. In these situations a warning is displayed indicating that ambient pressure must be reduced to achieve decompression.

The calculation of the safe ascent depth, or ceiling, was performed by using the simple formula:

$$SAD = P_t(i) - M_o(i) \quad [4.3]$$

Where:

SAD = Safe ascent depth in fsw
$P_t(i)$ = Total nitrogen pressure in tissue group i
$M_o(i)$ = M_o value of tissue group i

With this model it is possible that a tissue group may be in either condition #3 or #5, but the ceiling prevents the diver from ascending to a depth where decompression may occur. In this situation the diver can ascend to the ceiling and proceed toward the surface as the ceiling decreases. In this manner the P_t, M_o, and P_a relationships can move from condition #5 to #3 and finally to condition #4 where required decompression can be computed.

During each update interval the nitrogen pressure, no-decompression or decompression time, and safe ascent depth for each of the twelve tissue groups must be computed. Three situations can occur in any update interval :

A. All tissue group pressures ($P_t(1)$ – $P_t(12)$) are less than their corresponding M_o values.

B. All tissue group pressures are greater than their corresponding M_o values.

C. Most of the tissue group pressures are less than their M_o values and the rest are greater than their M_o values.

In situation "A" the times required for all twelve tissue groups to reach their M_o values are computed and the shortest of the twelve times is displayed as the Remaining No-Decompression Time.

In situation "B" the time for all tissue groups to reach their M_o values is handled in the same manner as "A". However, if any of the tissue groups cannot reach their M_o value at the present P_a, the warning will be displayed that indicates decompression is not possible at the present depth. If all tissue groups can decompress to their M_o at the present P_a, then the longest of the twelve decompression times will be displayed as Remaining Decompression Time.

The tissue pressure situation "B" occurs very rarely. A decompression situation will usually be represented by situation "C". In this case tissue groups are in both the no-decompression and decompression state. As in situation "B", if one of the tissue groups which require decompression cannot reach its M_o value at the present P_a, the "decompression not possible" warning will be displayed. Another possibility is that all tissue groups which require decompression may be able to do so at the present P_a, but while they are decompressing one of the other tissue groups may move past its M_o value, making decompression impossible at P_a. Therefore all the no-decompression times are compared to the required decompression time. A five-minute buffer was added to the model to prevent the situation wherein a diver re-enters a decompression state immediately following decompression. If the remaining no-decompression time for any tissue group is less than the required decompression time, or if less than five minutes of no-decompression time is left following decompression, the algorithm indicates that complete decompression is not possible at the present depth.

Additional features and warnings built into the final algorithm allowed for such contingencies as exceeding the maximum depth of the unit, violating the decompression ceiling, and a weakened battery.

The maximum depth registered by the pressure transducer in the EDGE is 160 fsw–165 fsw (depending on the calibration of the pressure transducer). Once this depth is exceeded the pressure transducer's A/D converter becomes saturated. If this occurs the algorithm assumes a depth of approximately 200 fsw and displays a warning that the depth range has been exceeded. The calculations in this mode will be satisfactory for approximately two minutes, after which the tissue pressure storage registers will begin to saturate, starting with the 5-minute tissue group. This feature was designed to handle an accidental out-of-range situation which could be readily corrected by ascending back into the device's depth range. It was not designed to allow divers to use the instrument at depths greater than 160 fsw.

If during decompression the diver ascends past the ceiling, a warning is displayed informing the diver to descend to a depth deeper than the ceiling. Although this situation violates the underlying decompression theory, the tissue pressures continue to be computed normally. This is because a diver is expected to constantly monitor the unit during decompression and any accidental violation of the ceiling will be corrected within a few seconds.

A low-battery power indicator is another warning feature. This was designed to give the diver four hours in which to replace the battery. This allows ample time to complete a dive if the warning comes on during the dive.

DISPLAY CONFIGURATION

The format used to present information is of major importance in any design. The ratio of obtainable information to display space should be high. However, the user should not be overwhelmed by too much information. He/she should be able to obtain general information on decompression status at a glance and more exact information upon closer examination of the display.

Necessary information, to display, included:

A. Remaining No-Decompression Time

B. Remaining Decompression Time

C. No Decompression Possible Warning

D. Ceiling (Safe Ascent Depth)

E. Warning if Ceiling is Exceeded

F. Current Depth

G. Maximum Depth Achieved

H. Warning if Depth Range has been Exceeded

I. Dive Time

J. Surface Interval Time

K. Low Battery Warning

Most of this information lends itself to digital representation, permitting the most accurate presentation of data. However, under environmental pressures (such as nitrogen narcosis or onset of hypothermia) and/or stressful situations, a digital format may require more mental concentration than the diver can muster. In those situations it is easier to understand information presented in a pictorial or graphical manner. Also, more information can be presented in a graphical output format, but it is not as precise as information in digital format.

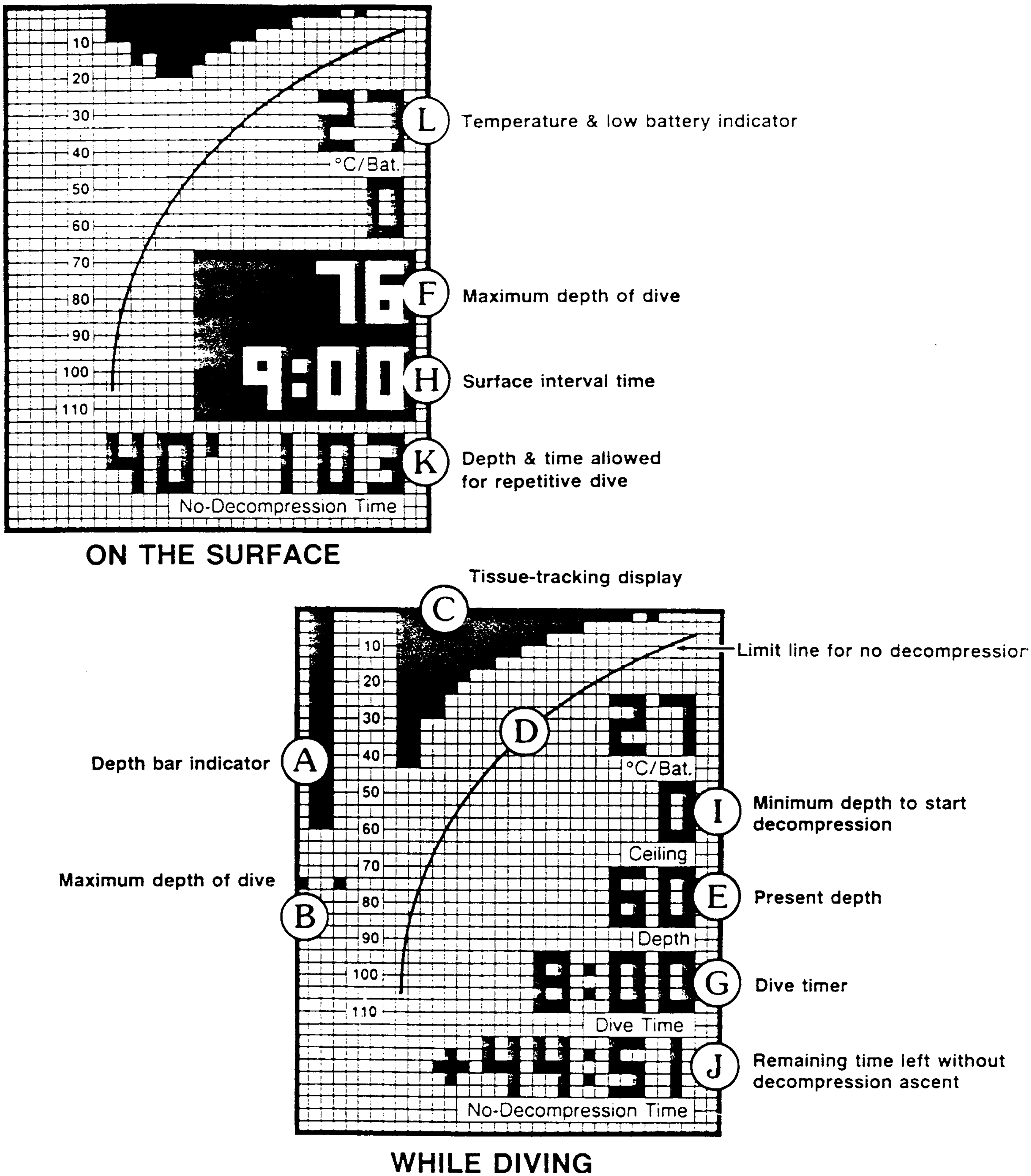

Fig 4.3. EDGE Display Configuration.

For these reasons, a split-screen option was selected to display information in both graphical and digital form. Although slightly redundant, this display offered the most concise means to present the relevant information to the diver. By using a 32 X 40 square pixel LCD matrix, both graphical and digital information can be displayed on a single display screen.

The display presents information in two modes. The information displayed during "surface" mode differs slightly from the information displayed while in "diving" mode. Figure 4.2 shows the final display configurations for these two modes.

The "Limit Line" (D) separates the graphical and digital sections of the display. The limit line represents the M_O values of the twelve tissue groups. During a dive, the "Depth Bar" (A) descends along the depth scale, "pushing" the two "Maximum Depth" pixels (B) in front of it. Each row of pixels on the display represents 1 meter of seawater (msw), giving the depth bar a 40 msw (or 131 fsw) range. Since two columns represent the depth bar, a resolution of 0.5 msw is obtained by activating first the left pixel and then the right pixel. The "Tissue-tracking Display" (C) produces a bar graph of the nitrogen build-up in the twelve tissue groups. As with the depth bar, each tissue bar utilizes two columns of the display. The 5-minute tissue bar is immediately to the right of the depth scale and the 480-minute tissue bar is represented by the last two columns on the right. At any given time, all the tissue bars are moving toward the level of the depth bar in an attempt to equilibrate the tissue nitrogen pressures with the ambient nitrogen pressure.

As long as all the tissue bars are above the limit line no decompression is required, and the diver may surface at any time. If any of the tissue bars cross the limit line, decompression is required. If the depth bar is deeper than the depth where the overpressurized tissue bar and limit line cross, then that tissue group cannot be decompressed. The diver must ascend to a depth where the depth bar is shallower than the limit line at that point. In the decompression mode, the ceiling is also presented in a graphical manner by two pixels which migrate up and down the depth bar (not shown in Figure 4.2). As long as the depth bar is not "pulled up" past the ceiling indicators a safe decompression can be performed, according to the model. By using the graphical section of the display the diver can, at a glance, tell if the dive is still within the no-decompression limits. The tissue pressure levels and their distance from the limit line can be controlled by varying dive depth. The graphical display quickly shows the diver which tissue groups are on-gassing or off-gassing at any given time. At the surface, the maximum depth pixels continue to be displayed and residual nitrogen is indicated by the remaining tissue bars.

The digital section of the display presents the diver with information in a more precise format. During a dive the remaining no-decompression or remaining decompression time is displayed on the bottom line in minutes and seconds (J). If the time displayed is remaining no-decompression time it is preceded by a plus (+) sign. If the time is remaining decompression time, it is preceded by a minus (−) sign. If decompression cannot occur at the present depth, an up arrow (↑) is displayed on the line. The second line from the bottom presents the dive time in minutes and seconds (G). Above the dive time, the present depth (E), is displayed in feet of seawater (or meters and tenths of meters of seawater for the metric version). The ceiling is displayed above the depth (I).

The two depth indicators (depth and ceiling) are together so that the diver can easily watch them during decompression without jumping across other numbers.

The most important number, the no-decompression/decompression time, was placed at the bottom of the screen away from the rest of the numbers.

At the surface, the maximum depth achieved during the dive is displayed (F) in reverse video (black background with white numbers). The dive time from the last dive is also displayed in reverse video (H) but is alternated every three seconds with the surface interval, which is displayed in normal video (in hours and minutes).

The allowable no-decompression limits for depths between 30 fsw and 150 fsw are displayed on the bottom line (K). The depth and its no-decompression limit are presented on the same line For example, 60 53 indicates that the no-decompression limit for a single-depth dive to 60 fsw is 53 minutes. After displaying the 60 fsw no-decompression limit for 3 seconds the no-decompression limit for 70 fsw is displayed. In this manner the no-decompression limits for depths between 30 fsw and 150 fsw (in 10 fsw increments) are presented. After the no-decompression limit for 150 fsw is displayed, the cycle starts again at 30 fsw. The no-decompression limit displayed is based on the residual nitrogen in the tissue groups at that time.

The top line of the display (L) presents both the temperature (in degrees Celsius) and the low power battery warning when less than four hours of use remain in the battery.

The warning screens that are displayed if the ceiling is violated or if the depth range is exceeded are shown in the EDGE Owner's Manual (Appendix H). The "ceiling violated" warning is shown in Figure 38 (page 19, Appendix H) of the manual and the "out-of-range" indicators are shown in Figure 39 and 40 (page 23, Appendix H).

OPERATION OF THE EDGE

The operation of the EDGE, and examples of the display during various dive profiles is presented in the Owner's Manual (Appendix H). No-decompression and repetitive dive examples are listed on pages 12-16. Pages 17-19 describe a decompression dive using the EDGE.

TESTING THE DECOMPRESSION ALGORITHM

A series of multi-level dive profiles were developed to test the safety of the decompression algorithm programmed into the EDGE. Human subjects were exposed to these profiles and monitored for VGE formation and/or symptoms of DSC. These tests were essential prior to the release of the device since there is very little literature dealing with multi-level diving safety.

Determination of the Dive Profiles

The test profiles were designed to represent common dive profiles performed by sport divers and were intended to extend the algorithm to its limits. Since the EDGE was designed primarily as a no-decompression device, nine of the ten test profiles were no-decompression multi-level dives. The maximum duration of each dive was limited by the air supply from a standard 80-cubic-foot tank and an air consumption rate of 0.5 cubic feet/min.

The nine no-decompression multi-level dive profiles were also limited by the following:

A. Maximum depth allowed was 130 fsw.

B. Three no-decompression multi-level dives were performed each day for three successive days.

C. The first dive of the day was a deep dive mid-morning.

D. The second dive was a late morning shallow dive.

E. The final dive of the day was either an afternoon or night dive to a deep or moderately deep depth.

F. Each profile extended the algorithm as close to its limit as possible in at least one tissue group. However, at no time during the dive were the tissue pressures allowed to exceed their M_O values.

The nine no-decompression test dive profiles are listed in Table 4.2 along with the decompression dive profile.

The decompression dive (dive #10) was performed on the fourth day of testing. It was designed to test the single-stop decompression ability of the EDGE algorithm by allowing the subjects to decompress at 30 fsw instead of doing a stepped decompression.

Table 4.3 shows the nitrogen pressure build up in the twelve tissue groups upon surfacing from the ten dive profiles.

Testing Protocol

The University of Southern California's Catalina Marine Science Center hyperbaric chamber facility was used for the tests. The chamber is a 9' x 30' double-lock chamber, and is one of the major hyperbaric facilities in California for treating diving accidents. Thus support personnel were on hand who were familiar with the symptoms and treatment of decompression sickness. The only disadvantage was that the facility is one of the most active treatment centers in the country, and the treatment of a diving accident could interrupt the testing time schedule.

Following submission of the testing protocol, human subject approval was obtained from the University of Southern California Human Subject Board.

Test Schedule

Because the possibility of interruption existed, the schedule was designed to permit the best chance of exposing at least one group of subjects to the full schedule. The twelve subjects were divided into three groups of four. Each of the three groups was exposed to the ten test profiles during a four-day period. The experiment took twelve days. During this twelve-day period one emergency diving accident case was treated at the chamber. However, it did not interfere with the time schedule and all thirty test dives were performed on schedule.

TABLE 4.2
EDGE TEST DIVE PROFILES

DAY I	DAY II	DAY III	DAY IV
Dive #1	**Dive #4**	**Dive #7**	**Dive #10**
Start 10:00	Start 10:00	Start 10:00	Start 16:00
130' --- 8 min	90' --- 12 min	130' --- 5 min	125' --- 20 min
To 70' - 3 min	To 130'- 1 min	To 50' - 2 min	To 30' - 2 min
70' --- 16 min	130' --- 2 min	50' --- 20 min	30' --- 12 min
To 40' - 2 min	To 50' - 2 min	To 130'- 2 min	To sfc - 1 min
40' --- 18 min	50' --- 30 min	130' --- 3 min	Stop 16:35
To sfc - 1 min	To sfc - 2 min	To 30' - 2 min	
Stop 10:48	Stop 10:49	30' --- 10 min	
		To sfc - 1 min	
		Stop 10:45	
Dive #2	**Dive #5**	**Dive #8**	
Start 11:33	Start 11:49	Start 11:36	
25' --- 59 min	25' --- 15 min	40' --- 25 min	
To sfc - 1 min	To 60' - 5 min	To 25' - 2 min	
Stop 12:33	60' --- 15 min	25' --- 40 min	
	To 25' - 5 min	To sfc - 1 min	
	25' --- 19 min	Stop 12:44	
	To sfc - 1 min		
	Stop 12:49		
Dive #3	**Dive #6**	**Dive #9**	
Start 15:33	Start 19:00	Start 15:30	
60' --- 15 min	60' --- 10 min	70' --- 15 min	
To 100'- 2 min	To 110'- 2 min	To 40' - 2 min	
100' --- 10 min	110' --- 5 min	40' --- 7 min	
To 60' - 1 min	To 50' - 3 min	To sfc - 1 min	
60' --- 6 min	50' --- 20 min	Stop 15:55	
To 40' - .5 min	To sfc - 1 min		
40' --- 4 min	Stop 19:41		
To sfc - 1 min			
Stop 16:13			

Monitoring the Subjects

For each profile the following data was taken for each subject:

A. Precordial Ultrasonic Doppler reading for detection of venous gas emboli (VGE).

TABLE 4.3

END-OF-DIVE TISSUE PRESSURES PRODUCED BY EDGE TEST DIVES

(Final Pressure [fsw]/% of M_O Value)

Half Time	DIVE NUMBER				
	1	2	3	4	5
5	58.0/58%	45.0/45%	62.0/62%	64.0/64%	47.0/47%
11	63.0/77%	45.0/55%	67.1/82%	66.3/81%	49.9/61%
17	62.9/88%	44.3/62%	**65.1/91%**	**64.4/90%**	49.3/69%
24	**59.9/94%**	44.0/69%	**60.5/95%**	**60.5/95%**	48.4/76%
37	**54.2/97%**	43.0/77%	**53.7/96%**	**54.2/97%**	46.4/83%
61	**46.6/92%**	42.1/83%	**46.6/92%**	**46.6/92%**	44.1/87%
87	41.7/89%	40.2/86%	**43.1/92%**	41.7/89%	41.7/89%
125	37.8/88%	38.3/89%	**40.4/94%**	37.8/88%	**39.1/91%**
197	34.0/87%	**35.2/90%**	**37.5/96%**	34.0/87%	**36.0/92%**
271	32.1/88%	**33.6/92%**	**35.8/98%**	32.5/89%	**34.3/94%**
392	30.2/89%	**31.5/93%**	**33.6/99%**	**31.2/92%**	**32.9/97%**
480	**30.0/91%**	**31.0/94%**	**33.0/100%**	**31.0/94%**	**32.3/98%**

Half Time	DIVE NUMBER				
	6	7	8	9	10
5	65.0/65%	58.0/58%	45.0/45%	62.0/62%	61.0/61%
11	65.4/80%	63.8/78%	45.8/56%	58.9/72%	70.3/86%
17	61.5/86%	62.2/87%	46.5/65%	53.6/75%	**68.6/96%**
24	56.7/89%	**58.6/92%**	45.9/72%	48.4/76%	**63.1/99%**
37	49.8/89%	**52.5/94%**	45.3/81%	43.0/77%	**55.3/99%**
61	43.1/85%	45.1/89%	43.1/85%	39.0/77%	**46.6/92%**
87	39.3/84%	40.2/86%	41.2/88%	37.4/80%	41.7/89%
125	36.6/85%	37.0/86%	**39.1/91%**	36.6/85%	37.4/87%
197	34.4/88%	33.6/86%	**36.0/92%**	34.8/89%	33.6/86%
271	**33.6/92%**	32.1/88%	**34.3/94%**	**33.9/93%**	31.8/87%
392	**32.5/96%**	**31.2/92%**	**32.9/97%**	**32.9/97%**	**30.5/90%**
480	**32.3/98%**	**31.0/94%**	**32.7/99%**	**32.7/99%**	**30.4/92%**

(Tissue pressures over 90% of Mo value presented in **bold** print)

B. Self Evaluation on how the subject "felt" following the dive to determine any potential symptoms of decompression sickness.

The Doppler readings were obtained using a Doppler Bubble Detector Model 1032G (Institute of Applied Physiology and Medicine, Seattle WA) with a precordial 5 MHz ultrasonic transducer. The audio signal output was recorded using a Sony TCS-310 stereo recorder.

The Doppler transducer produces an ultrasonic beam which is focused within the pulmonary artery. When the beam is reflected off moving blood cells the frequency of the beam is changed due to Doppler shift. The altered beam is then received by the transducer and its frequency compared to the output frequency. The operator hears an audio signal that simulates the sound of the flow of blood cells. If a gas bubble (diameter > 100µ) flows through the focal area, the beam's reflection off the gas bubble is stronger than off normal blood cells. The sound produced is a sharp whistle or chirp, "like a bullet flying by". Since all the venous blood flows through the pulmonary artery, gas bubbles occurring in or released into the venous system will eventually flow through the beam focus.

The resulting Doppler readings were graded using the standard grading system.

GRADE 0 – Complete lack of VGE signals

GRADE 1 – An occasional bubble with majority of cardiac periods free of any bubble signal

GRADE 2 – Many, but less than half of the cardiac cycles contain bubble signals.

GRADE 3 – Most of the cardiac periods contain bubble signals but do not override the cardiac signals.

GRADE 4 – Maximum detectable bubble signal, heard continuously, throughout systole and diastole of every cardiac period and overriding the amplitude of the cardiac motion signals.

To obtain a signal the transducer is placed on the chest approximately two inches to the left of the sternum. A transmission gel is used to reduce the attenuation of the beam between the transducer and the body. The transducer is then adjusted to obtain the clearest signal from the pulmonary artery. If the focus is too close to the heart the signal will be obscured by the sound of the pulmonary semilunar valve.

Doppler readings were taken:

A. 15 minutes prior to the dive.

B. Immediately following the dive.

C. Every 10 minutes following the dive for the first 30 minutes.

D. Every 30 minutes until three hours surface interval had elapsed or until the next dive began (whichever came first)

The readings consisted of one minute of clear signals with the subject sitting still followed by one minute of signals after the subjects had flexed their arms and legs (to dislodge bubbles in the extremities). Recordings were made of each of the readings to allow reevaluation on questionable signals.

One variation in the Doppler reading protocol was made with the decompression dive (#10). In this case Doppler readings were made inside the chamber upon reaching 30 fsw.

Any symptoms described by the subjects in their self evaluation were recorded and coded in the following manner:

CODE A – Vague uneasy feeling

CODE B – Skin Itching

CODE C – Mild Pain

CODE D – Moderate Pain

CODE E – Severe Pain

CODE F – Slightly Fatigued (added during tests)

CODE T – Slight Tingling (added during tests)

An emergency protocol was established to treat a subject who might have developed severe VGE bubble formation or signs of decompression sickness.

Emergency Protocol

Due to the conservative nature of the decompression algorithm used in the testing, the possibility of a test subject requiring treatment for decompression sickness was minimal. However, a hyperbaric physician was either present or on call at all times during the testing. If a subject had developed severe VGE formation or decompression sickness symptoms they would have been treated according to the following protocol:

A. If any pain develops or if GRADE 3 or 4 bubbles are produced, the subject will immediately be treated on Treatment Table V. If pain does not clear within 10 minutes at 60 fsw, Table VI will be used.

B. If the subject develops GRADE 2 bubbles without developing decompression sickness pain, or if bubbles progress to GRADE 3, the subject will breath 100% oxygen at the surface for 1 hour or until the bubbles reach GRADE 0.

C. Any subject who develops symptoms listed in A & B or develops GRADE 1 bubbles will be excluded from the remaining dive profiles.

Sufficient time was available to evacuate the chamber if it was needed to treat an outside diving accident. If the profile in progress was a no-decompression dive, the subjects would be returned to the surface immediately and placed on surface oxygen for 15 minutes. If the profile in progress was the decompression dive, subjects would be decompressed on the U.S. Navy Standard Air Decompression Tables, breathing oxygen at all decompression stops 30 fsw or shallower.

Acceptable Results

Since the M_O values were derived from limits that expect an occurrence of VGE in the 10%-20% range, it was expected that there would be little or no VGE formation in the tests.

The results would be acceptable if:

A. No bubbles of GRADE 2 or higher were produced in any of the subjects.

B. No pain or decompression sickness symptoms developed.

C. The occurrence of GRADE 1 bubble formation fell below 20%.

Selection of Subjects

Twelve subjects were selected to represent the average sport diving community. All were active scuba divers and full-time or part-time hyperbaric chamber operators, quite familiar with the risks and symptoms of decompression sickness. As shown in Table 4.4, the subjects represented a wide age range (21 - 62 years). Male and female subjects were selected. Body composition was not measured, but a wide range of body fat composition was present among the subjects (especially in the males).

All subjects were asked to complete a personal health evaluation prior to the experiment. Then they were briefed on all aspects of the test and given the opportunity to withdraw if they did not feel comfortable with the procedure. All subjects elected to proceed. Subject GP was not exposed to the decompression profile due to a scheduling conflict. Subject RD indicated that she had been treated for "possible" decompression sickness symptoms once. The symptoms were tingling in the left arm and leg that continued to persist somewhat following the treatment. She had been examined by two hyperbaric physicians following the treatment. The tingling was diagnosed by one as diving related and by the other as not diving related.

Results

The results of the study are shown in Table 4.5. The data shows the highest bubble grade obtained from a dive followed by the symptom code. None of the no-decompression multi-level dive profiles produced any signs of VGE formation or decompression sickness symptoms. The decompression profile produced asymptomatic VGE bubbles of GRADE 1 in one of the subjects and skin itches in another.

Discussion

The results of the study were well within the pre-determined acceptable guidelines. All results indicated that the algorithm was safe, and could be released without modifications.

TABLE 4.4
TEST SUBJECTS

SUBJECT	AGE (yrs)	SEX	WEIGHT (lbs.)
RD	32	F	135
JE	33	M	175
HF	61	M	200
KG	28	M	180
CG	47	M	170
JJ	21	F	125
BM	25	M	170
GP	30	M	210
BR	25	M	185
DR	23	F	130
LS	46	M	190
JW	62	M	215

TABLE 4.5
RESULTS FROM EDGE ALGORITHM TEST DIVE SERIES
(Doppler Grades & Symptoms)

	Dive Number									
Subject	1	2	3	4	5	6	7	8	9	10
RD	0-	0-	0-	0-	0T	0-	0-	0-	0-	0-
JE	0-	0-	0-	0-	0-	0-	0-	0-	0-	0-
HF	0-	0-	0-	0-	0-	0-	0-	0-	0-	0-
KG	0-	0-	0-	0-	0-	0-	0F	0-	0-	0-
CG	0-	0-	0-	0-	0-	0-	0F	0-	0-	0B
JJ	0-	0-	0-	0-	0-	0-	0-	0-	0-	0-
BM	0-	0-	0-	0-	0-	0-	0-	0-	0-	0-
GP	0-	0-	0-	0-	0-	0-	0-	0-	0-	**
BR	0-	0-	0-	0-	0-	0-	0-	0-	0-	0-
DR	0-	0-	0-	0-	0-	0-	0-	0-	0-	0-
LS	0-	0-	0-	0-	0-	0-	0-	0-	0-	1-
JW	0-	0-	0-	0-	0-	0-	0-	0-	0-	0-

(T)-slight tingling in left leg; (F)-slightly fatigued; (B)-skin itches;
(-)-no symptoms; (**)-subject not exposed

The almost complete lack of VGE formation shows that decompression stress was low. Aside from the development of Grade 1 bubbles in subject LS and skin itches in subject CG following the decompression, the only other indications of potential decompression stress were fatigue and tingling.

The tingling in the left leg of subject RD was recorded because the tingling was slightly stronger than normal following the dive.

It is difficult to conclude whether the slight fatigue in subjects KG and CG was a result of decompression stress or other factors. The dive (No. 7) was performed the morning of the third day and included two relatively rapid descents to 130 fsw. This may have placed more physical stress and/or decompression stress on the subjects than did the other dive profiles.

Skin itches are not unusual following hyperbaric chamber exposures. It was unusual that there was only one reported instance of skin itches (subject CG; dive No. 10).

This study also documented the validity of a multi-level diving procedure. If the no-decompression dives had been performed using the U.S. Navy Standard Air Decompression Tables, an extensive decompression debt would have built up. However, no decompression steps were taken and all divers returned from the no-decompression dives free of VGE formation and symptoms of decompression sickness.

IN-FIELD USE OF THE EDGE: FOLLOW-UP

The EDGE was released for sale by ORCA Industries in June 1983 after completion of the human subject tests. Since then approximately 5,000 units have been placed in the field. This section deals with the reception of the EDGE by the diving community, follow-up owner surveys, and the general safety record of the device.

Dr. Bruce Bassett published a review of the EDGE in July 1983 (Bassett, 1983). He presented the operation and underlying theory of the unit, and heralded the EDGE as "an innovation to sport divers equal to the original introduction of scuba." Despite this praise, the high price limited initial market demand. However, acceptance of the EDGE has gradually increased due to its safety record and proven reliability.

An owner survey was conducted to help assess the usefulness and quality of the EDGE. Information requested was:

A. Features of the EDGE divers liked the best.

B. Features of the EDGE divers felt needed improvement.

C. How many dives they made using the EDGE.

Thirty-seven owners responded to the survey. The features which they liked the best were:

A. Multi-level diving capability

B. Graphical presentation of information

C. Remaining no-decompression time display

Areas the owners felt needed improvement included:

A. Backlight for display

B. LCD display angle limited

C. Smaller size

D. Greater depth range

E. Incorporate tank pressure and air consumption

F. Battery life too short

G. Problems with paint finish crusting

H. Better battery compartment o-ring seal

I. Inability to perform decompression at 10 fsw in some situations.

J. Required decompression time in excess of one hour with a ceiling of 1 fsw.

Improvement and changes in the components and manufacturing procedures have eliminated the problems of LCD viewing angle and battery life. Another case manufacturer was hired to eliminate the problem with the finish.

Comments I and J deal directly with the decompression algorithm and specifically with the decision to set the 480-minute half-time M_o value to 33 fsw. If the diver performs enough dives within a set time period, the 480-minute tissue group will not have a chance to off-gas and will start to control most of the dive profiles. If the 480-minute tissue requires decompression, the diver must ascend to a depth shallower than 8.77 fsw since the ambient nitrogen pressure at any deeper depth will be greater than 33 fsw. This can cause problems for the average diver since the last decompression stop depth in most decompression tables is at 10 fsw, and it is unusual to decompress at a depth shallower than 10 fsw.

The long time required to decompress is the other problem that occurs if the 480-minute tissue group passes into a decompression mode. Since the off-gas rate is so slow, the decompression requirement may be more than one hour, with a ceiling of 1 fsw.

These problems with the 480-minute tissue group will usually occur only if four or more extensive multi-level dives are performed each day. However, due to the conservative nature of the M_o values in the slower tissue groups, there is room to adjust the M_o values upward to eliminate the problem of decompression not being allowed at 10 fsw. Even if the M_o values are adjusted slightly upward, this author fully expects divers will press the device to its new M_0 limits and once again run into problems decompressing the slow tissue groups.

The field safety record of the EDGE is impressive. Information from the survey was used to estimate the number of dives performed using the EDGE. At the time of the survey (early 1985) 1900 units were in use. The thirty-seven responders had performed 2935 dives for an average of 79 dives per unit. The number of dives per respondent ranged from 7 to 250, which produced a standard deviation of 62. If the average of 79 is taken as the high end of a range, and 17 dives (79 − 62) taken as the low end, a range of 32,300 − 150,100 dives (17 x 1900 and 79 x 1900) using the EDGE is established. In the two years since the release of the EDGE, there had been just two confirmed instances of decompression sickness occuring while the diver was using the device. Both occurred off the East Coast where diving conditions are normally deep, arduous, and cold. Both were decompression dives. One dive was to 151 fsw for 15 minutes (according to the diver) which is close to the depth limit for the EDGE. The other dive was to 110 fsw for 30 minutes, followed by another dive to 110 fsw for 24 minutes after a two hour and forty minute surface interval (according to the diver). The diver had performed the same profile the week before with no ill effects. Both of the divers were successfully treated at the University of Pennsylvania Institute for Environmental Medicine. There are unsubstantiated reports of two cases from the East Coast which were treated at a facility in New York. The facility has not responded to requests for data about these reports. Using the estimate of the number of dives using the EDGE (32,300 − 150,100 dives) and four cases of decompression sickness, a DCS incidence range of 0.0027% to 0.0124% is calculated.

EPILOGUE

Present evidence indicates that the EDGE is a safe and reliable product. The initial concerns of the diving community about the multi-level diving capabilities seem to be fading. At a conference on underwater education in 1985, the EDGE was prominent in presentations on research diving operations and cave and cavern diving. In 1986, ORCA Industries and Divetronics were the only companies producing decompression computers for sport divers. However, at the 1987 Diving Equipment Manufacturers Association show, eight new different decompression computers were displayed with the hopes of having production units available by the summer diving season.

The decompression computer's time has come, and while there is room for improvement, the EDGE has contributed to the acceptance of decompression computers by the sport diving community.

CHAPTER V

CONCLUSIONS

APPLICATIONS OF COMPUTERIZED DECOMPRESSION DEVICES

Computers were first used in decompression theory applications to help compute tables based on a specific model. Tables were generated more rapidly and with greater accuracy than before. During the past fifteen years modern computer technology applications have shifted more to the development of dedicated decompression devices. These new devices can integrate a complicated dive profile and determine decompression status and requirements in real time. This shift is evidenced by the number of decompression computers that have been introduced to diving since the early 1970s.

Decompression computers can be "active" or "passive" systems. Active systems are usually associated with hyperbaric chambers. The computer controls the chamber pressure through Digital to Analog (D/A) connections to inlet and outlet solenoids. Many of these computers "read" established treatment tables and follow these tables instead of computing decompression schedules. A major advantage of active chamber systems is the ability to regularly and automatically ventilate the chamber (balance inward and outward flow of air to prevent carbon dioxide build up). Some active decompression computers can compute and execute the decompression requirements of a chamber dive based on a specific decompression model. These computers have advantages when the chamber must be evacuated rapidly. These active decompression computers also have extensive manual override options.

Most decompression computer systems are passive. These systems compute and display information about decompression status and requirements. The person monitoring the system must decide how to use that information. There are two basic types of passive decompression computers:

A. **Portable units** - Computers carried by the user who directly reads the information.

B. **Stationary units** - Units not carried by the user (like the XDC-2). Pressure data is fed to the unit by a remote sensing method. The information is displayed to a tender who then informs the diver of his/her decompression status.

The primary benefit of decompression computers is their ability to integrate a virtually infinite number of dive profiles (or any change in pressure situation). This permits decompression status to be based on an actual profile instead of a square-wave profile (that most tables are based on). Integrated dive profiles are more realistic and can be used in many situations where people are exposed to pressure changes which could potentially produce decompression sickness

By using decompression computers **sport divers** can perform multi-level diving within the constraints of the decompression model. It allows the divers to exceed set square-wave no-decompression limits without violating the model. This provides additional dive time resulting in more efficient use of limited and expensive vacation time

Another group that can save money and time by using decompression computers are **research divers**, especially those who perform water column or blue water diving studies. In these studies, biological, physical, or chemical activities are studied throughout the water column, not just at one depth. In diving these columns for collection/observation of organisms or equipment maintenance, the research diver must swim the extent of the column (i.e., 0 to 100 fsw). Using tables, the diver is limited by decompression requirements set by the maximum depth achieved during the dive. Many dives with long surface intervals may be required to cover the entire column and stay within table safety limits. If a decompression computer is used, the researcher can potentially cover the entire column in a single dive. This results in more efficient use of dive time, reduces the number of dives necessary, and can reduce the cost of a project.

The same idea applies to **commercial divers**. For example, it may be necessary to work on an oil rig at various levels. It is more efficient to use one diver moving up the rig using multi-level techniques than to have a number of divers working at various levels so that a set of tables is not violated.

Military divers can use decompression computers that allow multi-level diving. Combat swimmers may be required to swim for long periods at shallow depths but may need to descend to perform their operations or avoid detection. This dive profile is almost impossible to establish with decompression tables. A decompression computer, however, can easily compute the diver's decompression status for most profiles.

Divers who perform research or work from saturation benefit because their storage depth is greater than sea level, which permits greater time at depth with fewer decompression requirements. A decompression computer that computes both upward and downward excursion limits could increase the efficiency of diving from saturation by allowing multi-level dives to be performed.

Other applications for decompression computers can include pressure reductions from 1 ATA or less, such as in high altitude or space environments.

One example is the decompression requirements prior to extra vehicular activities (EVAs) from a space shuttle, and eventually from a space station. A shuttle's atmosphere is air at 1 ATA. A space suit's atmosphere is pure oxygen at 0.29 ATA (4.3 pounds per square inch [psi]). If the astronaut went directly into an EVA from the shuttle atmosphere, the sudden pressure drop would probably cause decompression sickness (Rice, 1985). To avoid this problem the pressure of the shuttle is dropped to 0.7 ATA with an oxygen percentage of 26.5% for at least 12 hours prior to the EVA. The astronauts performing the EVA then breath pure oxygen at that pressure in the air lock for 40 minutes before the EVA to "wash" additional nitrogen from their bodies (Covault, 1982). Another more rapid pre-EVA procedure can be performed by breathing 100% oxygen at 1 ATA for 3.5 hours before exiting the shuttle.

These procedures show that there is no safe procedure for performing an immediate emergency EVA at this time. Several procedures are being considered for the space station atmosphere and EVA protocol. These include various drops in pressures from sea level to space suit pressures (Vann, 1984; Hills, 1985). In these situations astronauts could use a decompression computer to monitor the ambient pressure and could also switch computations based on the gas mixture breathed. The computer would inform astronauts of their status to perform EVAs and what type of decompression to undergo prior to EVA.

FUTURE SOLUTIONS TO AIR DECOMPRESSION PROBLEMS

Decompression computers are here to stay. They will become more sophisticated as hyperbaric physiologists and manufacturers combine expertise to utilize the benefits of the electronic and computer revolution.

At present most decompression models, and therefore computer algorithms, rely on two basic variables, depth and time. As more information becomes available, individualized computers may be developed that consider more variables, such as water temperature, physiological makeup of the user, and exertion during exposure.

A decompression computer may ultimately be developed that will monitor the body for decompression stress instead of using a model to predict the development of decompression sickness. Such a device might monitor the amount of nitrogen inhaled and exhaled by the diver. Divers would then be aware of their absorbed nitrogen levels during decompression.

Many other solutions will be developed, but much research must be done in the field of decompression before such devices can become a reality.

SUMMARY

The potential applications of decompression computers cover the entire range of pressures mankind experiences. These computers are more versatile than traditionally used standard tables. They permit the performance of multi-level dive profiles that are often more cost effective than standard square-wave profiles. They also eliminate the task of computing decompression status, which frees the diver to concentrate on the dive objective.

Regardless of the future applications or designs of decompression computers, the user will continue to be responsible for his/her own safety. A device can provide the user with a wide range of information. How the user utilizes that information is up to the user alone. A decompression computer is no substitute for comprehensive training and knowledge of the potentially dangerous underwater environment. The user must also be aware that there is always the possibility of mechanical or electrical failure, so it is prudent to carry secondary or back-up instrumentation.

The future of decompression computers in diving appears to be secure. Smaller decompression computers, well designed and constructed and incorporating properly tested decompression algorithms, should continue to evolve as primary instrumentation for divers.

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APPENDIX A

1937 U.S. NAVY AIR DECOMPRESSION TABLES

TABLE A-1

1937 U.S. NAVY STANDARD AIR DECOMPRESSION TABLES

Ascent Rate
25 ft. Per Minute

Depth of dive (feet)	Time on bottom (minutes)	Stops (feet and minutes) Feet 90	Feet 80	Feet 70	Feet 60	Feet 50	Feet 40	Feet 30	Feet 20	Feet 10	Sum of times at various stops (minutes)	Approximate total de-compression time (minutes)
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.

TABLE A-2 (cont.)

1937 U.S. NAVY STANDARD AIR DECOMPRESSION TABLES

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

U.S. NAVY STANDARD AIR DECOMPRESSION TABLES (1957)

TABLE B-1

U.S. NAVY NO-DECOMPRESSION LIMITS AND REPETITIVE GROUP DESIGNATION TABLE FOR NO-DECOMPRESSION AIR DIVES

Depth (feet)	No-Decompression Limits (min)	Group Designation														
		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											

TABLE B-2

U.S. NAVY SURFACE INTERVAL AND RESIDUAL NITROGEN TIME TABLES FOR REPETITIVE AIR DIVES

Repetitive Group at the beginning of the surface interval

Repetitive Group \ New Group Designation	Z	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A
A																0:10 12:00
B															0:10 2:10	2:11 12:00
C														0:10 1:39	1:40 2:49	2:50 12:00
D													0:10 1:09	1:10 2:38	2:39 5:48	5:49 12:00
E												0:10 0:54	0:55 1:57	1:58 3:22	3:23 6:32	6:33 12:00
F											0:10 0:45	0:46 1:29	1:30 2:28	2:29 3:57	3:58 7:05	7:06 12:00
G										0:10 0:40	0:41 1:15	1:16 1:59	2:00 2:58	2:59 4:25	4:26 7:35	7:36 12:00
H									0:10 0:36	0:37 1:06	1:07 1:41	1:42 2:23	2:24 3:20	3:21 4:49	4:50 7:59	8:00 12:00
I								0:10 0:33	0:34 0:59	1:00 1:29	1:30 2:02	2:03 2:44	2:45 3:43	3:44 5:12	5:13 8:21	8:22 12:00
J							0:10 0:31	0:32 0:54	0:55 1:19	1:20 1:47	1:48 2:20	2:21 3:04	3:05 4:02	4:03 5:40	5:41 8:40	8:41 12:00
K						0:10 0:28	0:29 0:49	0:50 1:11	1:12 1:35	1:36 2:03	2:04 2:38	2:39 3:21	3:22 4:19	4:20 5:48	5:49 8:58	8:59 12:00
L					0:10 0:26	0:27 0:45	0:46 1:04	1:05 1:25	1:26 1:49	1:50 2:19	2:20 2:53	2:54 3:36	3:37 4:35	4:36 6:02	6:03 9:12	9:13 12:00
M				0:10 0:25	0:26 0:42	0:43 0:59	1:00 1:18	1:19 1:39	1:40 2:05	2:06 2:34	2:35 3:08	3:09 3:52	3:53 4:49	4:50 6:18	6:19 9:28	9:29 12:00
N			0:10 0:24	0:25 0:39	0:40 0:54	0:55 1:11	1:12 1:30	1:31 1:53	1:54 2:18	2:19 2:47	2:48 3:22	3:23 4:04	4:05 5:03	5:04 6:32	6:33 9:43	9:44 12:00
O		0:10 0:23	0:24 0:36	0:37 0:51	0:52 1:07	1:08 1:24	1:25 1:43	1:44 2:04	2:05 2:29	2:30 2:59	3:00 3:33	3:34 4:17	4:18 5:16	5:17 6:44	6:45 9:54	9:55 12:00
Z	0:10 0:22	0:23 0:34	0:35 0:48	0:49 1:02	1:03 1:18	1:19 1:36	1:37 1:55	1:56 2:17	2:18 2:42	2:43 3:10	3:11 3:45	3:46 4:29	4:30 5:27	5:28 6:56	6:57 10:05	10:06 12:00
New --> Group Designation	Z	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A

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

RESIDUAL NITROGEN TIMES (MINUTES)

TABLE B-3

U.S. NAVY STANDARD AIR DECOMPRESSION TABLE

DEPTH (fsw)	BOTTOM TIME (min)	TIME TO FIRST STOP (min:sec)	DECOMPRESSION STOPS (fsw)					TOTAL ASCENT (min:sec)	REPETI-TIVE GROUP
			50	40	30	20	10		
40	200						0	0:40	N
	210	0:30					2	2:40	N
	230	0:30					7	7:40	N
	250	0:30					11	11:40	O
	270	0:30					15	15:40	O
	300	0:30					19	19:40	Z
	360	0:30					23	23:40	*
50	100						0	0:50	L
	110	0:40					3	3:50	L
	120	0:40					5	5:50	M
	140	0:40					10	10:50	M
	160	0:40					21	21:50	N
	180	0:40					29	29:50	O
	200	0:40					35	35:50	O
	220	0:40					40	40:50	Z
	240	0:40					47	47:50	Z
60	60						0	1:00	J
	70	0:50					2	3:00	K
	80	0:50					7	8:00	L
	100	0:50					14	15:00	M
	120	0:50					26	27:00	N
	140	0:50					39	40:00	O
	160	0:50					48	49:00	Z
	180	0:50					56	57:00	Z
	200	0:40				1	69	71:00	Z
	240	0:40				2	79	82:00	*
	360	0:40				20	119	140:00	*
70	50						0	1:10	J
	60	1:00					8	9:10	K
	70	1:00					14	15:10	L
	80	1:00					18	19:10	M
	90	1:00					23	24:10	N
	100	1:00					33	34:10	N
	110	0:50				2	41	44:10	O
	120	0:50				4	47	52:10	O
	130	0:50				6	52	59:10	O
	140	0:50				8	56	65:10	Z
	150	0:50				9	61	71:10	Z
	160	0:50				13	72	86:10	Z
	170	0:50				19	79	99:10	Z

* Exceptional Exposure Dive – No Repetitive Dive Allowed

TABLE B-3 (cont.)

U.S. NAVY STANDARD AIR DECOMPRESSION TABLE

DEPTH (fsw)	BOTTOM TIME (min)	TIME TO FIRST STOP (min:sec)	DECOMPRESSION STOPS (fsw) 50	40	30	20	10	TOTAL ASCENT (min:sec)	REPETITIVE GROUP
80	40						0	1:20	I
	50	1:10					10	11:20	K
	60	1:10					17	18:20	L
	70	1:10					23	24:20	M
	80	1:00				2	31	34:20	N
	90	1:00				7	39	47:20	N
	100	1:00				11	46	58:20	O
	110	1:00				13	53	67:20	O
	120	1:00				17	56	74:20	Z
	130	1:00				19	63	83:20	Z
	140	1:00				26	69	96:20	Z
	150	1:00				32	77	110:20	Z
	180	1:00				35	85	121:20	*
	240	0:50			6	52	120	179:20	*
	360	0:50			29	90	160	280:20	*
90	30						0	1:30	H
	40	1:20					7	8:30	J
	50	1:20					18	19:30	L
	60	1:20					25	26:30	M
	70	1:10				7	30	38:30	N
	80	1:10				13	40	54:30	N
	90	1:10				18	48	67:30	O
	100	1:10				21	54	76:30	Z
	110	1:10				24	61	86:30	Z
	120	1:10				32	68	101:30	Z
	130	1:00			5	36	74	116:30	Z
100	25						0	1:40	H
	30	1:30					3	4:40	I
	40	1:30					15	16:40	K
	50	1:20				2	24	27:40	L
	60	1:20				9	28	38:40	N
	70	1:20				17	39	57:40	O
	80	1:20				23	48	72:40	O
	90	1:10			3	23	57	84:40	Z
	100	1:10			7	23	66	97:40	Z
	110	1:10			10	34	72	117:40	Z
	120	1:10			12	41	78	132:40	Z
	180	1:00		1	29	53	118	202:40	*
	240	1:00		14	42	84	142	283:40	*
	360	0:50	2	42	73	111	187	416:40	*

* Exceptional Exposure Dive – No Repetitive Dive Allowed

APPENDIX C

SWISS DECOMPRESSION TABLES

TABLE C-1

SWISS DECOMPRESSION TABLE OF INTERVALS AT THE SURFACE

Repetitive group at the end of the interval at the surface											
L	K	J	H	G	F	E	D	C	B	A	"0"
L	160	240	300	400	530	600	700	800	1000	1200	48
	K	120	150	210	270	330	420	480	560	660	34
		J	45	70	90	120	160	210	300	420	24
			H	30	45	60	90	150	180	260	17
				G	25	45	60	75	100	130	12
					F	20	30	45	75	90	8
						E	10	15	25	45	4
							D	10	15	30	3
								C	10	25	3
									B	20	2
										A	2

Duration of the intervals in minutes, for group "0", in hours. This table is valid for up to 3500 m above sea level.

TABLE C-2

SWISS TIME SUPPLEMENTS FOR REPETITIVE DIVES

Repetitive Group	Depth attained in the repetitive dives (m)															
	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54
L	450	300	240	180	160	140	120	110	100	90	80	75	75	65	60	60
K	430	270	200	150	100	100	90	75	70	65	55	55	50	50	45	40
J	410	220	150	100	80	75	70	60	55	50	40	40	40	40	35	35
H	300	150	100	90	75	60	55	50	50	45	35	35	30	25	25	25
G	145	115	80	65	55	45	40	35	30	25	25	23	23	20	20	18
F	115	100	57	60	50	40	35	30	25	23	20	18	17	16	15	14
E	90	75	45	40	35	30	25	23	22	20	18	16	14	12	11	10
D	70	50	35	30	25	23	20	18	17	16	15	14	12	10	9	8
C	45	30	25	20	20	20	18	16	14	12	10	10	9	8	7	7
B	30	25	20	18	15	12	10	10	9	8	7	7	6	6	5	5
A	20	18	15	14	12	10	9	7	6	6	6	6	5	5	5	5

The time supplements are valid for up to 3500 m above sea level.

TABLE C-3

SWISS AIR DECOMPRESSION TABLE
(0-700 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 24	21	18	15	12	9	6	3	Total ascent time min:sec	Repetitive Group
9	300										1 00	H
12	120										1 10	G
	150	0 50								9	9 50	G
	180	0 50								14	14 50	H
	210	0 50								18	18 50	H
	240	0 50								24	24 50	J
	270	0 50								29	29 50	K
	300	0 50								34	34 50	K
15	75										1 30	G
	90	1 10								6	7 10	G
	120	1 10								20	21 10	G
	140	1 10								25	26 10	H
	160	1 10								31	32 10	H
	180	1 10								38	39 10	H
	200	0 50							2	43	45 50	J
	220	0 50							5	46	51 50	K
	240	0 50							6	49	55 50	K
18	53										1 50	F
	60	1 30								4	5 30	F
	70	1 30								9	10 30	G
	80	1 30								16	17 30	G
	90	1 30								23	24 30	G
	100	1 30								28	29 30	G
	110	1 10							1	31	33 10	H
	120	1 10							3	33	37 10	H
	130	1 10							7	35	43 10	H
	140	1 10							10	38	49 10	H
	150	1 10							13	41	55 10	J
	160	1 10							15	44	60 10	J
	170	1 10							17	46	64 10	K
	180	1 10							19	48	68 10	K
	190	1 10							20	50	71 10	K
	200	1 10							21	52	74 10	K

TABLE C-3 (cont.)

SWISS AIR DECOMPRESSION TABLE
(0-700 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 24	21	18	15	12	9	6	3	Total ascent time min:sec	Repetitive Group
21	35										2 10	E
	50	1 50								6	7 50	F
	60	1 50								13	14 50	G
	70	1 50								23	24 50	G
	80	1 30							3	28	32 30	G
	90	1 30							7	31	39 30	H
	100	1 30							10	33	44 30	H
	110	1 30							15	36	52 30	H
	120	1 30							20	39	60 30	J
	130	1 30							23	43	67 30	J
	140	1 30							26	46	73 30	K
24	25										2 30	E
	40	2 10								6	8 10	F
	50	2 10								15	17 10	G
	60	1 50							3	23	27 50	G
	70	1 50							8	29	38 50	G
	80	1 50							13	32	46 50	H
	90	1 50							18	33	52 50	H
	100	1 30						1	24	38	64 30	H
	110	1 30						4	26	43	74 30	J
27	22										2 40	E
	30	2 20								4	6 20	F
	40	2 10							1	12	15 10	F
	50	2 10							4	22	28 10	G
	60	2 10							10	28	40 10	G
	70	1 50						1	16	32	50 50	H
	80	1 50						4	21	34	60 50	H
	90	1 50						8	25	39	73 50	H
30	20										3 00	D
	25	2 40								4	6 40	E
	30	2 20							2	6	10 20	F
	40	2 20							5	16	23 20	G
	50	2 10						1	10	26	39 10	G
	60	2 10						3	16	31	52 10	H
	70	2 10						7	21	34	64 10	H

TABLE C-3 (cont)

SWISS AIR DECOMPRESSION TABLE
(0-700 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 24	21	18	15	12	9	6	3	Total ascent time min:sec	Repetitive Group
33	17										3 20	D
	25	2 40							2	6	10 40	F
	30	2 40							4	10	16 40	F
	40	2 20						2	7	22	33 20	G
	50	2 20						4	14	30	50 20	G
	60	2 20						8	20	33	63 20	H
	70	2 10					2	13	25	39	81 10	J
36	15										3 40	D
	20	3 00							2	4	9 00	E
	25	3 00							4	7	14 00	F
	30	2 40						2	5	14	23 40	G
	40	2 40						4	10	26	42 40	G
	50	2 20					1	8	16	33	60 20	H
	60	2 20					4	12	23	37	78 20	H
39	12										3 50	D
	15	3 40								4	7 40	E
	20	3 20							3	6	12 20	F
	25	3 00						2	4	11	20 00	G
	30	3 00						3	6	17	29 00	G
	40	2 40					2	6	13	29	52 40	G
	50	2 40					4	10	20	33	69 40	H
42	10										4 10	D
	15	3 40							2	4	9 40	E
	20	3 20						1	4	7	15 20	F
	25	3 20						3	5	14	25 20	G
	30	3 00					2	3	8	22	38 00	G
	40	2 40				1	3	8	16	31	61 40	G
	50	2 40				2	6	13	24	37	84 40	H
45	10	4 10								2	6 10	E
	15	3 50							3	5	11 50	E
	20	3 40						3	4	10	20 40	F
	25	3 20					2	3	6	17	31 20	G
	30	3 20					3	5	10	25	46 20	G
	40	3 00				2	5	9	18	34	71 00	H

TABLE C-3 (cont.)

SWISS AIR DECOMPRESSION TABLE
(0-700 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 24	21	18	15	12	9	6	3	Total ascent time min:sec	Repetitive Group
48	10	4 30								4	8 30	E
	15	3 50						1	4	5	13 50	F
	20	3 40					1	3	5	13	25 40	F
	25	3 40					3	4	8	21	39 40	G
	30	3 20				2	3	6	13	28	55 20	G
	35	3 20				3	4	8	17	32	67 20	H
	40	3 00			1	3	6	12	22	34	81 00	H
51	10	4 30							1	4	9 30	E
	15	4 10						2	4	7	17 10	F
	20	3 50					2	4	5	15	29 50	G
	25	3 40				1	4	5	9	25	47 40	G
	30	3 40				3	4	7	15	30	62 40	G
	35	3 20			1	4	5	10	20	33	76 20	H
54	10	4 50							2	5	11 50	E
	15	4 30						3	4	8	19 30	F
	20	4 10					3	4	6	18	35 10	G
	25	3 50				3	3	6	12	27	54 50	G
	30	3 40			2	3	5	8	17	32	70 40	G
57	10	5 10							3	5	13 10	E
	15	4 30					1	4	4	11	24 30	F
	20	4 10				2	3	4	8	22	43 10	G
	25	3 50			1	3	4	6	15	29	61 50	G
	30	3 50			3	3	6	9	20	33	77 50	H
60	10	5 10						1	4	5	15 10	E
	15	4 50					2	4	5	13	28 50	F
	20	4 30				3	3	5	9	25	49 30	G
	25	4 10			2	4	4	8	16	31	69 10	H
	30	3 50		2	3	4	6	12	22	35	88 50	J

TABLE C-4

SWISS AIR DECOMPRESSION TABLE
(700-1500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min:sec	Repetitive Group
9	180									1 00	G
12	90									1 10	G
	100	1 00							2	3 00	G
	110	1 00							6	7 00	G
	120	1 00							10	11 00	G
	130	1 00							13	14 00	G
	140	1 00							15	16 00	G
	150	1 00							17	18 00	H
15	63									1 30	F
	70	1 10							4	5 10	G
	80	1 10							9	10 10	G
	90	1 10							15	16 10	G
	100	1 10							20	21 10	G
	110	1 10							24	25 10	G
	120	1 10							27	28 10	H
18	43									1 50	F
	50	1 40							2	3 40	F
	60	1 40							9	10 40	G
	70	1 40							17	18 40	G
	80	1 40							24	25 40	G
	90	1 20						3	27	31 20	G
	100	1 20						5	30	36 20	H
	110	1 20						9	31	41 20	H
	120	1 20						13	33	47 20	H
21	30									2 10	E
	40	1 50							3	4 50	F
	50	1 50							11	12 50	G
	60	1 40						1	20	22 40	G
	70	1 40						5	25	31 40	G
	80	1 40						9	29	39 40	H
	90	1 40						14	30	45 40	H
	100	1 30					6	17	32	56 30	H
	110	1 30					6	19	36	62 30	H

TABLE C-4 (cont)

SWISS AIR DECOMPRESSION TABLE
(700-1500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min:sec	Repetitive Group
24	25									2 20	E
	30	2 10							3	5 10	E
	35	2.10							5	7 10	F
	40	2 00						1	9	12 00	F
	50	2 00						3	18	23 00	G
	60	2 00						8	25	35 00	G
	70	1 50					2	12	29	44 50	H
	80	1 50					6	15	30	52 50	H
	90	1 50					10	18	34	63 50	H
	100	1 30				2	12	20	39	74 30	H
27	18									2 20	E
	25	2 30							3	5 30	E
	30	2 20						1	5	8 20	F
	35	2 20						2	10	14 20	F
	40	2 20						3	14	19 20	G
	50	2 10					2	7	24	35 10	G
	60	2 10					5	11	29	47 10	G
	70	1 50				1	9	15	30	56 50	H
	80	1 50				4	11	19	35	70 50	H
30	16									3 00	E
	20	2 50							3	5 50	E
	25	2 40						1	5	8 40	F
	30	2 40						3	8	13 40	F
	35	2 20					1	4	14	21 20	G
	40	2 20					2	6	19	29 20	G
	50	2 10				1	5	10	27	45 10	G
	60	2 10				3	9	14	30	58 10	H
33	14									3 20	E
	20	2 50						1	4	7 50	E
	25	2 40					1	3	6	12 40	F
	30	2 40					2	4	12	20 40	G
	35	2 20				1	3	5	18	29 20	G
	40	2 20				2	4	7	24	39 20	G
	50	2 20				4	7	12	30	55 20	H
	60	2 20				8	11	18	32	71 20	H

TABLE C-4 (cont.)

SWISS AIR DECOMPRESSION TABLE
(700-1500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min:sec	Repetitive Group
36	11									3 40	D
	15	3 20							4	7 20	E
	20	3 10						3	5	11 10	F
	25	3 00					2	3	10	18 00	G
	30	2 40				2	3	4	16	27 40	G
	35	2 40				3	4	6	23	38 40	G
	40	2 40				4	5	11	26	48 40	G
	50	2 20			1	8	10	15	30	66 20	H
39	10									3 50	D
	15	3 30						1	4	8 30	E
	20	3 20					2	3	6	14 20	F
	25	3 00				2	3	3	13	24 00	G
	30	3 00				3	4	6	20	36 00	G
	35	2 40			1	4	5	10	25	47 40	G
	40	2 40			2	6	6	12	30	58 40	H
	50	2 40			5	9	11	18	34	79 40	H
42	15	3 50						3	4	10 50	F
	20	3 20				1	3	3	8	18 20	G
	25	3 20				3	3	5	16	30 20	G
	30	3 00			2	4	4	8	24	45 00	G
	35	3 00			3	5	6	12	28	57 00	H
	40	2 40		1	3	8	9	14	30	67 40	H
45	10	4 20							3	7 20	D
	15	3 50					2	3	4	12 50	F
	20	3 40				3	3	4	12	25 40	F
	25	3 20			2	3	4	6	20	38 20	G
	30	3 20			3	5	5	10	27	53 20	G
	35	3 00		1	4	6	9	12	30	65 00	H
48	10	4 20						1	4	9 20	D
	15	3 50				1	2	3	6	15 50	F
	20	3 40			1	3	3	4	15	29 40	G
	25	3 40			3	4	4	8	23	45 40	G
	30	3 20		2	3	6	6	12	29	61 20	H
	40	3 00	1	3	6	11	12	19	35	90 00	J

TABLE C-4 (cont)

SWISS AIR DECOMPRESSION TABLE
(700-1500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min:sec	Repetitive Group
51	10	4 40						2	4	10 40	E
	15	4 10				2	3	3	7	19 10	G
	20	3 50			2	4	4	5	17	35 50	G
	25	3 40		1	4	5	5	9	26	53 40	H
	30	3 40		3	4	7	8	13	30	68 40	H
54	10	4 50					1	3	4	12 50	E
	15	4 30				3	3	3	10	23 30	G
	20	4 10			3	4	4	6	21	42 10	G
	25	3 50		3	3	6	6	11	28	60 50	H
	30	3 40	2	3	5	8	10	15	31	77 40	H

TABLE C-5

SWISS AIR DECOMPRESSION TABLE
(1500-2500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min:sec	Repet-itive Group
9	135									1 00	G
12	82									1 10	G
	90	1 00							2	3 00	G
	100	1 00							7	8 00	G
	110	1 00							11	12 00	G
	120	1 00							15	16 00	G
	130	1 00							18	19 00	H
	140	1 00							21	22 00	H
	150	1 00							23	24 00	H
15	55									1 30	G
	60	1 20							2	3 20	G
	70	1 20							7	8 20	G
	80	1 20							14	15 20	G
	90	1 20							20	21 20	G
	100	1 20							25	26 20	H
	110	1 20							29	30 20	H
	120	1 20							33	34 20	H
18	40									1 50	F
	50	1 40							5	6 40	G
	60	1 40							12	13 40	G
	70	1 40							22	23 40	G
	80	1 20						1	28	30 20	H
	90	1 20						4	32	37 20	H
	100	1 20						8	33	42 20	H
	110	1 20						14	35	50 20	H
	120	1 20						16	39	56 20	H
21	30									2 10	E
	40	1 50							5	6 50	G
	50	1 50							14	15 50	G
	60	1 40						2	24	27 40	G
	70	1 40						7	29	37 40	G
	80	1 40						11	32	44 40	H
	90	1 30					2	15	34	52 30	H
	100	1 30					5	18	38	62 30	H

TABLE C-6 (cont)

SWISS AIR DECOMPRESSION TABLE
(1500-2500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min							Total ascent time min:sec	Repetitive Group
			18	15	12	9	6	4	2		
24	23									2 20	E
	30	2 10							4	6 10	F
	35	2 10							7	9 10	G
	40	2 00						1	12	15 00	G
	50	2 00						4	22	28 00	G
	60	1 50					1	9	29	40 50	H
	70	1 50					3	13	33	50 50	H
	80	1 50					8	16	35	60 50	H
	90	1 50					11	20	40	72 50	J
27	17									2 40	D
	25	2 30							4	6 30	F
	30	2 20						1	7	10 20	G
	35	2 20						2	13	17 20	G
	40	2 10					1	4	17	24 10	G
	50	2 10					3	8	27	40 10	H
	60	2 10					6	12	33	53 10	H
	70	1 50				2	10	16	35	64 50	H
30	15									3 00	D
	20	2 50							4	6 50	E
	25	2 40						2	5	9 40	F
	30	2 20					1	3	11	17 20	G
	35	2 20					2	4	17	25 20	G
	40	2 20					3	6	23	34 20	G
	45	2 10				1	4	9	28	44 10	H
	50	2 10				2	5	12	31	52 10	H
	60	2 10				4	10	15	34	65 10	H
33	12									3 20	D
	15	3 10							3	6 10	D
	20	2 50						2	4	8 50	F
	25	2 40					1	3	8	14 40	G
	30	2 40					3	3	15	23 40	G
	35	2 40				1	3	6	23	35 20	G
	40	2 20				2	5	8	28	45 20	H
	45	2 20				4	6	11	31	54 20	H
	50	2 20				5	8	13	34	62 20	H

TABLE C-5 (cont)

SWISS AIR DECOMPRESSION TABLE
(1500-2500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min:sec	Repetitive Group
36	10									3 40	D
	15	3 20							4	7 20	E
	20	3 10						4	5	12 10	F
	25	3 00					3	3	12	21 00	G
	30	2 40				2	3	5	20	32 40	G
	35	2 40				3	5	7	27	44 40	G
	40	2 20			1	4	6	11	31	55 20	H
	45	2 20			1	6	8	14	33	64 20	H
39	9									3 50	D
	15	3 30						2	4	9 30	E
	20	3 20					2	3	8	16 20	G
	25	3 00				2	3	4	16	28 00	G
	30	3 00				4	4	6	25	42 00	G
	35	2 40			2	4	6	10	30	54 40	H
	40	2 40			3	6	7	13	33	64 40	H
42	10	4 00							3	7 00	D
	15	3 40					1	3	4	11 40	F
	20	3 20				1	3	3	11	25 20	G
	25	3 20				4	4	5	20	36 20	G
	30	3 00			2	4	5	9	28	51 00	G
	35	3 00			3	6	7	12	32	63 00	H
45	10	4 20							4	8 20	D
	15	3 50					2	3	5	13 50	F
	20	3 40				3	3	4	14	27 40	G
	25	3 20			2	4	4	6	25	44 20	G
	30	3 20			4	5	6	11	30	59 20	H
	35	3 00		2	3	7	9	14	33	72 00	H
48	10	4 20						1	4	9 20	E
	15	3 50				1	3	3	7	17 50	G
	20	3 40			1	3	4	4	18	33 40	G
	25	3 40			3	4	5	9	27	51 40	H
	30	3 20		2	4	6	7	13	32	67 20	H
	35	3 20		3	5	9	10	17	34	81 20	H

TABLE C-5 (cont.)

SWISS AIR DECOMPRESSION TABLE
(1500-2500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min:sec	Repetitive Group
51	10	4 40						3	4	11 40	E
	15	4 10				2	3	3	10	22 10	G
	20	3 50			2	4	4	5	22	40 50	G
	25	3 40		2	3	5	6	11	29	59 40	H
	30	3 40		3	5	7	9	14	34	75 40	H
54	10	4 50					1	3	4	12 50	F
	15	4 30				3	4	4	13	28 30	G
	20	3 50		1	3	4	4	7	25	47 50	G
	25	3 50		3	4	6	6	13	31	66 50	H
	30	3 40	2	3	5	9	11	16	34	83 40	H

TABLE C-6

SWISS AIR DECOMPRESSION TABLE
(2500-3500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min:sec	Repetitive Group
9	125									1 00	G
12	76									1 10	G
	90	1 00							6	6 00	G
	100	1 00							10	11 00	G
	110	1 00							15	16 00	G
	120	1 00							18	19 00	H
	130	1 00							21	22 00	H
	140	1 00							24	25 00	H
	150	1 00							26	27 00	H
15	55									1 30	G
	60	1 20							4	5 20	G
	70	1 20							10	11 20	G
	80	1 20							18	19 20	G
	90	1 20							24	25 20	G
	100	1 20							29	30 20	H
	110	1 20							33	34 20	H
	120	1 10						3	34	38 10	H
18	38									1 50	F
	50	1 40							7	8 40	G
	60	1 40							16	17 40	G
	70	1 40							25	26 40	G
	80	1 20						3	30	34 20	H
	90	1 20						7	33	41 20	H
	100	1 20						12	33	46 20	H
	110	1 20						16	37	54 20	J
	120	1 10					1	20	40	62 10	J
21	25									2 10	F
	40	1 50							7	8 50	G
	50	1 50							18	19 50	G
	60	1 40						3	27	31 40	G
	70	1 40						9	31	41 40	H
	80	1 40						14	34	49 40	H
	90	1 30					4	17	36	58 30	H
	100	1 30					7	20	41	69 30	J

TABLE C-6 (cont.)

SWISS AIR DECOMPRESSION TABLE
(2500-3500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min:sec	Repetitive Group
24	20									2 20	E
	25	2 10							3	5 10	E
	30	2 10							5	7 10	F
	35	2 00						1	9	12 00	G
	40	2 00						2	14	18 00	G
	50	2 00						5	25	32 00	G
	60	1 50					2	11	30	44 50	H
	70	1 50					5	15	33	54 50	H
	80	1 50					10	18	37	66 50	J
27	17									2 40	E
	20	2 30							3	5 30	E
	25	2 30							5	7 30	F
	30	2 20						2	8	12 20	G
	35	2 20						3	14	19 20	G
	40	2 10					1	4	21	28 10	G
	45	2 10					2	7	26	37 10	G
	50	2 10					3	10	29	44 10	H
	60	1 50				1	7	14	34	57 50	H
	70	1 50				3	12	18	37	71 50	J
30	15									3 00	D
	20	2 50							5	7 50	E
	25	2 40						2	7	11 40	G
	30	2 20					1	3	13	19 20	G
	35	2 20					2	5	20	29 20	G
	40	2 10				1	3	7	26	39 10	G
	50	2 10				3	6	13	32	56 10	H
	60	2 10				6	11	17	36	72 10	H
33	12									3 20	D
	15	3 10							3	6 10	E
	20	2 50						2	5	9 50	F
	25	2 40					2	3	10	17 40	G
	30	2 20				1	3	4	17	27 20	G
	35	2 20				2	4	6	25	39 20	G
	40	2 20				3	5	10	30	50 20	H
	50	2 20				6	10	15	34	67 20	H

TABLE C-6 cont.

SWISS AIR DECOMPRESSION TABLE
(2500-3500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min:sec	Repetitive Group
36	10									3 40	D
	15	3 10						1	4	8 10	E
	20	3 00					1	3	6	13 00	G
	25	2 40				1	3	3	14	23 40	G
	30	2 40				3	3	6	23	37 40	G
	35	2 40				4	5	9	29	49 40	H
	40	2 20			1	5	7	12	33	60 20	H
39	8									3 50	D
	10	3 40							2	5 40	D
	15	3 30						2	5	10 30	F
	20	3 20					3	3	9	18 20	G
	25	3 00				3	3	4	19	32 00	G
	30	2 40			1	4	4	8	27	46 40	G
	35	2 40			2	5	6	12	31	58 40	H
	40	2 40			3	7	9	15	33	69 40	H
42	10	4 00							3	7 00	D
	15	3 40					1	3	5	12 40	F
	20	3 20				2	3	3	13	24 20	G
	25	3 00			1	4	4	6	23	41 00	G
	30	3 00			3	4	5	11	30	56 00	H
	35	3 00			4	6	8	13	34	68 00	H
45	10	4 10						1	4	9 10	D
	15	3 50					3	3	6	15 50	F
	20	3 40				3	4	4	16	30 40	G
	25	3 20			2	4	5	8	26	48 20	G
	30	3 00		1	4	5	7	12	32	64 00	H
48	10	4 20						2	4	10 20	E
	15	3 50				2	3	3	9	20 50	G
	20	3 40			1	4	4	6	20	38 40	G
	25	3 20		1	3	5	5	10	30	57 20	H
	30	3 20		2	4	7	8	14	34	72 20	H

TABLE C-6 (cont.)

SWISS AIR DECOMPRESSION TABLE
(2500-3500 m above sea level)

Depth m	Bottom time min	Time to first stop min:sec	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min:sec	Repetitive Group
51	10	4 40						3	4	11 40	F
	15	4 10				3	3	4	12	26 10	G
	20	3 50			3	4	4	6	25	45 50	G
	25	3 40		2	4	5	7	12	31	64 40	H
54	10	4 50					2	3	4	13 50	F
	15	4 10			1	4	4	4	14	31 10	G
	20	3 50		1	4	4	5	8	27	52 50	G
	25	3 50		4	4	6	8	13	33	71 50	H

APPENDIX D

HUGGINS NO-DECOMPRESSION TABLES

SURFACE INTERVAL TABLE

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

RESIDUAL NITROGEN TIME TABLE

NEW GROUP	20	30	35	40	50	60	70	80	90	100	110	120	130
A	12	8	7	6	5	4	4	3	3	3	3	2	2
B	28	18	16	14	11	9	8	7	6	6	5	5	4
C	45	29	25	21	17	14	12	9	8	6	6	5	5
D	65	41	34	30	23	19	15	10	8	7	6	5	5
E	86	53	44	37	28	22	17	12	9	8	7	6	5
F	111	66	53	43	32	24	19	14	11	9	7	6	6
G	140	80	62	49	36	27	22	17	12	10	8	7	6
H	175	96	73	57	40	30	24	19	14	11	9	8	7
I	219	113	86	65	45	34	26	21	16	12	10	8	7
J	279	132	103	75	51	38	29	23	18	13	11	9	8
K	369	154	122	88	57	43	32	26	20	15	12	10	8
L	-	178	139	103	64	47	35	28	22	18	13	11	9
M	-	207	158	124	71	52	40	30	25	20	15	12	10
N	-	225	165	135	75	53	41	31	26	21	16	13	11

DEPTH

DEPTH (FT.)	NO DECOM. LIMITS	BOTTOM TIME AND REPETITIVE GROUP CODE													
		A	B	C	D	E	F	G	H	I	J	K	L	M	N
20	-	10	25	40	60	85	110	135	170	215	275	325			
30	225	5	15	25	40	50	65	75	95	110	130	150	175	205	225
35	165	5	15	20	30	40	50	60	70	85	100	120	135	155	165
40	135	5	10	20	25	35	40	45	55	60	70	85	100	120	135
50	75	-	10	15	20	25	30	35	37	40	50	55	60	70	75
60	50	-	5	10	15	20	23	25	27	30	35	40	45	47	50
70	40	-	5	10	13	15	17	20	23	25	27	30	33	35	40
80	30	-	5	7	→	10	13	15	17	20	→	25	27	→	30
90	25	-	-	5	7	→	10	→	13	15	17	→	20	23	25
100	20	-	-	-	5	7	→	→	10	→	→	13	15	17	20
110	15	-	-	-	-	5	→	7	→	→	10	→	→	13	15
120	10	-	-	-	-	-	5	→	→	7	→	→	10		
130	5	-	-	-	-	-	5								

* NEW *

NO-DECOMPRESSION TABLES

APPENDIX E

BRITISH (RNPL) DECOMPRESSION TABLES

AIR DIVING TABLES 1972

INTRODUCTION

As a result of testing present RN and other air decompression tables at depths in excess of 30m (100 ft) and for bottom times in excess of 15 minutes, it has been realised that these schedules yield a higher number of bends than is desirable, in some instances over 20% in a group of healthy young divers. Selection of resistant men could reduce this value, but there is no method of doing this other than in retrospect. Further, there is considerable evidence that whereas some men are resistant for long dives at shallow depths, this may not be true when the diving changes to short dives at deep depths. The desirable solution to the problem in the light of these unresolved complexities is to evolve decompressoin schedules which markedly reduce the overall bends incidence.

1. Caisson and tunnel work in compressed air has encountered similar difficulties and minor modifications of their schedules have failed to influence the situation. Accordingly, entirely new decompression procedures were requested from the Royal Naval Physiological Laboratory. These tables have been called "The Blackpool Trial Tables" because they were first tested on compressed air work at Blackpool in 1966. A certificate of exemption from the table printed in the statutory instrument (The Work In Compressed Air Special Regulations 1958) to enable contractors legally to employ these new Tables is readily granted on request by HM Factory Inspectorate, and all major compressed air work in this country, since their introduction, has been carried out using them. Over 50,000 entries into compressed air in caissons and tunnels have been made at pressures in excess of 10m (30 ft) of sea water, including some working times in excess of 8 hours at pressures of nearly 30m (100 ft) of sea water. To date there have been no fatalities, only few cases of serious acute decompression sickness and a low incidence of bends.

Further, as regards bone necrosis, it has been established, after approximately 6 years of usage, that no cases of bone necrosis sufficiently serious to require surgical intervention have occurred, and that the incidence of radiologically detectable bone lesions has been reduced. Thus, by adopting a more conservative decompression schedule there is a good basis for believing that diving may be conducted more safely and for longer periods and at greater depths than hitherto. The new Air Diving Tables as given in Table 1 have been calculated on exactly the same principles as those of the Blackpool Trial Tables.

2. However, experience gained with the Air Diving Tables (1968) issued via Construction Industries Research and Information Association and tested by Royal Navy Divers, has confirmed beyond doubt that the no-stop dives currently available in the RN Diving Manual (BR 2806) are adequately safe, and that the modifications proposed in the Air Diving Tables 1968 were slightly over-cautious. Accordingly, a return has been made to these old established no-stop dive times.

3. Further, although tests at sea by Royal Navy Divers revealed that such dives as 1 hour at 60 m (200 ft) could be performed without even minor occurrences of decompression sickness, there were indications in subsequent laboratory testing, that some sensitive persons would not escape ill-effects.

4. It was proposed therefore to alter the decompression requirement for this dive and others in the Air Diving Tables 1968 of similar severity, but, a worldwide survey of air diving by military, commercial and sporting organisations, showed that such dives as 1 hour at 60 m breathing air were never used. Clearly, therefore, there seemed little point in attempting minor modifications to schedules that would never be used in the foreseeable future.

Consequently, the limits of depth and time given in Table 1 represent what is considered to be normal usage plus allowance for any emergencies or unusual commitments that may occur on rare occasions. These Tables have now been tested over a range of pressures, times, water conditions and numbers of different men necessary to establish their reliability. It is now completely certain that the new Tables will be less liable to provoke attacks of decompression sickness than those currently is use. However, there is always a small number of seemingly unavoidable incidents which occur following the use of even extremely well established procedures. No relaxation of recognised safe practices is permissible.

USING THE TABLES

Notes

1. The bottom time is taken as the time between leaving the surface and leaving the bottom.
2. All descents to depth are to be not faster than 30 metres/min.
3. All ascents are at 15 metres/min.
4. All time spent ascending from one stop to another – including from depth to the first stop – is included in the stop time. The final pressure change from 5 metres to the surface, which takes 20 secs, is also included in the final stop time.
5. Air and pure oxygen decompression commences for any dive where decompression time on air alone would exceed 31 minutes. Such dives are indicated below the double black line drawn in the tables.
6. If pure oxygen is not available or in case of emergency multiply the oxygen stop time by 2 and add to the air stop time (if any) to give the equivalent air decompression stop time.
7. Ascent to the first stop must always be on air.

DOUBLE DIVES

1. For regular diving no more than 8 hours in any period of 24 hours must be spent under pressure (bottom times plus decompression times).
2. If the surface interval between two dives is *2 hours or less*, add the bottom times of the two dives together, and decompress for this bottom time at the deeper of the two dive depths.
3. If the surface interval between two dives is *greater than 2 hours but less than 4 hours*, add one half of the bottom time of the first dive to the bottom time of the second dive, and decompress for this bottom time, and the deeper of the two dive depths.
4. If the surface interval is *greater than 4 hours but less than 8 hours* add one quarter of the bottom time of the first dive to the bottom time of the second dive, and decompress for this bottom time, and the deeper of the two dive depths.
5. If the surface interval is *greater than 8 hours but less than 16 hours* add one eigth of the bottom time of the first dive to the bottom time of the second dive, and decompress for this botom time, and the deeper of the two dive depths.
6. After a *16 hours* surface interval the diver need not take any account of the previous dive.
7. If *both* dives are at *depths less than 40 m and above the double black line* in Table I then the above rules can be amended to state that if the surface interval is *greater than 4 hours but less than 6 hours* then add one quarter of the bottom time of the first dive to the bottom time of the second dive and decompress for this bottom time and the deeper of the two dive depths. After a 6 hours surface interval the diver need not take any account of the previous dive.
8. If the *second* dive does not exceed a depth of 9 metres then it is safe to surface from this second dive without stoppages.

SURFACE DECOMPRESSION

No attempt must be made to use this method unless a well-drilled and experienced team is available.

1. **Rate of Ascent in the Water.** 15 m per minute.
2. **Chamber Pressure.** Immediately the diver surfaces he is assisted into a pressure chamber and this chamber is then pressurised to the air pressure equivalent to the maximum depth of the dive. The time from commencing ascent in the water to arriving at this maximum pressure in the chamber must not exceed 5 minutes, and the diver is kept at this pressure for 5 minutes, after which the pressure in the chamber is reduced in accordance with the decompression tables.
3. **Decompression.** An extra 10 minutes must always be added to the actual bottom time of the dive and the total combined bottom time thus obtained is used to determine the decompression required. This total combined bottom time should never exceed the last entry in the table.

DIVING AT ALTITUDE

If a diving operation is carried out at altitude (eg in a mountain lake) adjustments should be made to the decompression schedules to compensate for the surface pressure being less than 1 bar (1 atmosphere). Adjustments should be made as follows :

1. Altitudes of less than 100 m (approx 300 ft) – no adjustment.

2. Dives between altitudes of 100 and 300 m (approx 300 and 1000 ft) – add one quarter of the depth to give the depth of dive.

3. Dives between altitudes of 300 and 2000 m (approx 1000 and 6500 ft) – add one third of the depth to give the depth of dive.

4. Dives between altitudes of 2000 and 3000 m (approx 6500 and 10 000 ft) – add one half of the depth to give the depth of dive.

DECOMPRESSION – FLYING RESTRICTIONS

It is inadvisable to fly above 600 m (approx 2000 ft) in any aircraft within 24 h of completing a dive.

A period of 2 h should elapse between diving operations and flying in a pressurised aircraft, if dives were carried out with no stops, and a period of 24 h if dives were carried out with stops.

If flying following diving operations is essential ,then the following rules will minimise the risk.

Type of dive	Time interval between diving and flying	Max altitude (or effective altitude in pressurised aircraft)
Requiring no stops	Up to 1 h	300 m (approx 1000 ft) (eg Helicopter)
	1 to 2 h	1500 m (approx 5000 ft)
	Over 2 h	5000 m (approx 16 500 ft)
Requiring stops	Up to 4 h	300 m (approx 1000 ft) (eg Helicopter)
	4 to 8 h	1500 m (approx 5000 ft)
	8 to 24 h	5000 m (approx 16 500 ft)

NOTE : Commercial aircraft normally fly at an effective cabin altitude of 1500 – 3000 m.

RNPL AIR DIVING TABLES 1972
TABLE 1

DEPTH NOT EXCEEDING: 9 METRES (Approx 30 ft)
NO LIMIT

DEPTH NOT EXCEEDING: 10 METRES (Approx 33 ft)								
BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRES-SION (mins)
	AIR			OXYGEN OR AIR				
				O_2	AIR	O_2	AIR	
	25m	20m	15m	10m		5m		
230								1
420							5	5
480							10	10

<u>READ TABLE NOTES</u>

RNPL AIR DIVING TABLES 1972
TABLE 1

DEPTH NOT EXCEEDING: 15 METRES (Approx 49 ft)

BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRES-SION (mins)
	AIR			OXYGEN OR AIR				
				O_2	AIR	O_2	AIR	
	25m	20m	15m	10m		5m		
80								1
85							5	5
90							10	10
100							15	15
110							25	25
120							30	30
150						25	-	25
180						30	-	30
240						40	-	40

READ TABLE NOTES

RNPL AIR DIVING TABLES 1972
TABLE 1

DEPTH NOT EXCEEDING: 20 METRES (Approx 66 ft)								
BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRESSION (mins)
	AIR			OXYGEN OR AIR				
				O_2	AIR	O_2	AIR	
	25m	20m	15m	10m		5m		
45								1½
50							5	5
55							10	10
60							15	15
65							25	25
70							30	30
75						20	-	20
90						30	-	30
120						45	-	45
150						55	-	55
180				5	-	55	-	60
240				5	-	60	-	65

<u>READ TABLE NOTES</u>

RNPL DIVING AIR TABLES 1972
TABLE 1

DEPTH NOT EXCEEDING: 25 METRES (Approx 82 ft)								
BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRESSION (mins)
	AIR			OXYGEN OR AIR				
				O_2	AIR	O_2	AIR	
	25m	20m	15m	10m		5m		
25								2
30					5	-	5	10
35					5	-	10	15
40					5	-	15	20
45					5	-	20	25
50				5	-	15	-	20
55				5	-	20	-	25
60				5	-	30	-	35
75			5	-	-	40	-	45
90			5	5	-	50	-	60
105			5	5	-	60	-	70
120			5	10	-	60	-	75
150			5	15	-	60	-	80
180		5	-	20	-	60	5	90

RNPL AIR DIVING TABLES 1972
TABLE 1

DEPTH NOT EXCEEDING: 30 METRES (Approx 98 ft)

BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRESSION (mins)
	AIR			OXYGEN OR AIR				
				O_2	AIR	O_2	AIR	
	25m	20m	15m	10m		5m		
20								2
25					5	-	5	10
30					5	-	10	15
35					5	-	20	25
40				5	-	20	-	25
45				5	-	25	-	30
50			5	-	-	35	-	40
55			5	5	-	40	-	50
60			5	5	-	45	-	55
75			5	5	-	55	-	65
90			5	10	-	60	-	75
120		5	-	20	10	60	5	100

READ TABLE NOTES

RNPL DIVING AIR TABLES 1972
TABLE 1

DEPTH NOT EXCEEDING: 35 METRES (Approx 115 ft)

BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRESSION (mins)
	AIR			OXYGEN OR AIR				
				O_2	AIR	O_2	AIR	
	25m	20m	15m	10m		5m		
15								2½
20					5	-	5	10
25					5	-	15	20
30					5	-	25	30
35				5	-	20	-	25
40			5	5	-	30	-	40
45			5	5	-	40	-	50
50			5	5	-	45	-	55
55			5	5	-	50	-	60
60			5	5	-	55	-	65
75		5	-	15	-	60	-	80

READ TABLE NOTES

RNPL AIR DIVING TABLES 1972
TABLE 1

DEPTH NOT EXCEEDING: 40 METRES (Approx 131 ft)

BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRES-SION (mins)
	AIR			OXYGEN OR AIR				
				O_2	AIR	O_2	AIR	
	25m	20m	15m	10m		5m		
11								3
15					5	-	5	10
20					5	-	10	15
25					5	-	25	30
30			5	-	-	25	-	30
35			5	5	-	35	-	45
40			5	5	-	45	-	55
45			5	5	-	50	-	60
50		5	-	10	-	55	-	70
55		5	-	10	-	60	-	75
60		5	-	15	-	60	-	80

READ TABLE NOTES

RNPL DIVING AIR TABLES 1972
TABLE 1

DEPTH NOT EXCEEDING: 45 METRES (Approx 148 ft)

BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRESSION (mins)
	AIR			OXYGEN OR AIR				
				O_2	AIR	O_2	AIR	
	25m	20m	15m	10m		5m		
9								3
15					5	-	10	15
20					5	-	20	25
25			5	5	-	20	-	30
30			5	5	-	35	-	45
35			5	5	-	45	-	55
40		5	-	5	-	50	-	60
45		5	-	10	-	55	-	70
50		5	5	15	-	60	-	85
55		5	5	20	-	60	5	95

READ TABLE NOTES

RNPL AIR DIVING TABLES 1972
TABLE 1

DEPTH NOT EXCEEDING: 50 METRES (Approx 164 ft)								
BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRESSION (mins)
	AIR			OXYGEN OR AIR				
				O_2	AIR	O_2	AIR	
	25m	20m	15m	10m		5m		
7								3½
10					5	-	5	10
15					5	-	10	15
20			5	5	-	15	-	25
25			5	5	-	30	-	40
30			5	5	-	40	-	50
35		5	-	5	-	50	-	60
40		5	5	10	-	60	-	80
45		5	5	15	-	60	-	85
50	5	-	5	20	-	60	5	95

READ TABLE NOTES

RNPL DIVING AIR TABLES 1972
TABLE 1

DEPTH NOT EXCEEDING: 55 METRES (Approx 180 ft)

BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRES- SION (mins)
	AIR			OXYGEN OR AIR				
				O_2	AIR	O_2	AIR	
	25m	20m	15m	10 m		5m		
6								4
10					5	-	5	10
15			5	-	-	-	15	20
20			5	5	-	20	-	30
25			5	5	-	35	-	45
30		5	-	5	-	50	-	60
35		5	5	10	-	60	-	80
40		5	5	15	-	60	-	85
45	5	-	5	20	5	60	5	100

<u>READ TABLE NOTES</u>

RNPL DIVING AIR TABLES 1972
TABLE 1

DEPTH NOT EXCEEDING: 60 METRES (Approx 197 ft)								
BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRESSION (mins)
	AIR			OXYGEN OR AIR				
				O_2	AIR	O_2	AIR	
	25m	20m	15m	10m		5m		
5								4
10					5	-	10	15
15			5	-	5	-	20	30
20			5	5	-	25	-	35
25		5	-	5	-	45	-	55
30		5	5	10	-	55	-	75
35	5	-	5	15	-	60	-	85
40	5	-	5	20	5	60	5	100
45	5	-	10	20	20	60	5	120

READ TABLE NOTES

RNPL AIR DIVING TABLES 1972
TABLE 2

DEPTH NOT EXCEEDING (metres)	BOTTOM TIME NOT EXCEEDING (mins)	STOPPAGES AT DIFFERENT DEPTHS (mins)							TOTAL TIME FOR DECOMPRES-SION (mins)
		AIR			OXYGEN OR AIR				
					O_2	AIR	O_2	AIR	
		25m	20m	15m	10m		5m		
65m (213')	10					5	-	10	15
	15			5	5	-	15	-	25
70m (230')	10			5	-	5	-	10	20
	15			5	5	-	20	-	30
75m (246')	10			5	-	5	-	15	25
	15		5	-	5	-	25	-	35

READ TABLE NOTES

APPENDIX F

DCIEM AIR DECOMPRESSION TABLES

DCIEM 1983 AIR DIVING TABLE 1 (FEET)
STANDARD AIR

Depth (fsw)	Bottom Time (min)	Stop Times (min) at Different Depths (fsw)							Decom. Time (min)	Repet. Dive Group
		70	60	50	40	30	20	10		
30	30	-	-	-	-	-	-	-	-	A
	60	-	-	-	-	-	-	-	-	C
	90	-	-	-	-	-	-	-	-	D
	120	-	-	-	-	-	-	-	-	F
	150	-	-	-	-	-	-	-	-	G
	180	-	-	-	-	-	-	-	-	H
	380	-	-	-	-	-	-	-	-	
	390	-	-	-	-	-	-	7	7	
	400	-	-	-	-	-	-	10	10	
	420	-	-	-	-	-	-	14	14	
	450	-	-	-	-	-	-	19	19	
	480	-	-	-	-	-	-	23	23	
40	30	-	-	-	-	-	-	-	-	B
	60	-	-	-	-	-	-	-	-	D
	90	-	-	-	-	-	-	-	-	G
	120	-	-	-	-	-	-	-	-	H
	150	-	-	-	-	-	-	-	-	J
	160	-	-	-	-	-	-	-	-	K
	180	-	-	-	-	-	-	2	2	L
	190	-	-	-	-	-	-	9	9	
	200	-	-	-	-	-	-	14	14	
	210	-	-	-	-	-	-	18	18	
	220	-	-	-	-	-	-	22	22	
	240	-	-	-	-	-	-	28	28	
	270	-	-	-	-	-	-	38	38	
	300	-	-	-	-	-	-	48	48	
	330	-	-	-	-	-	-	57	57	
	360	-	-	-	-	-	-	66	66	

DCIEM 1983 AIR DIVING TABLE 1 (FEET)
STANDARD AIR

Depth (fsw)	Bottom Time (min)	Stop Times (min) at Different Depths (fsw)							Decom. Time (min)	Repet. Dive Group
		70	60	50	40	30	20	10		
50	20	-	-	-	-	-	-	-	-	A
	30	-	-	-	-	-	-	-	-	C
	40	-	-	-	-	-	-	-	-	D
	50	-	-	-	-	-	-	-	-	E
	60	-	-	-	-	-	-	-	-	F
	70	-	-	-	-	-	-	3	3	G
	80	-	-	-	-	-	-	4	4	G
	100	-	-	-	-	-	-	6	6	I
	120	-	-	-	-	-	-	12	12	K
	130	-	-	-	-	-	-	18	18	L
	140	-	-	-	-	-	-	24	24	M
	150	-	-	-	-	-	-	29	29	
	160	-	-	-	-	-	-	33	33	
	170	-	-	-	-	-	-	38	38	
	180	-	-	-	-	-	-	43	43	
	200	-	-	-	-	-	-	53	53	
	220	-	-	-	-	-	-	63	63	
	240	-	-	-	-	-	-	74	74	
	260	-	-	-	-	-	-	86	86	
	280	-	-	-	-	-	-	97	97	
60	10	-	-	-	-	-	-	-	-	A
	20	-	-	-	-	-	-	-	-	B
	30	-	-	-	-	-	-	-	-	D
	35	-	-	-	-	-	-	-	-	D
	40	-	-	-	-	-	-	3	3	E
	50	-	-	-	-	-	-	5	5	F
	60	-	-	-	-	-	-	7	7	G
	80	-	-	-	-	-	-	10	10	I
	90	-	-	-	-	-	-	19	19	J
	100	-	-	-	-	-	-	26	26	K
	110	-	-	-	-	-	-	32	32	L
	120	-	-	-	-	-	2	37	39	M
	130	-	-	-	-	-	2	43	45	
	140	-	-	-	-	-	3	49	52	
	150	-	-	-	-	-	3	55	58	
	160	-	-	-	-	-	4	62	66	
	170	-	-	-	-	-	4	70	74	
	180	-	-	-	-	-	5	77	82	
	190	-	-	-	-	-	5	85	90	
	200	-	-	-	-	-	11	90	101	
	210	-	-	-	-	-	15	96	111	
	220	-	-	-	-	-	19	102	121	
	230	-	-	-	-	-	23	108	131	
	240	-	-	-	-	-	27	114	141	

DCIEM 1983 AIR DIVING TABLE 1 (FEET)
STANDARD AIR

Depth (fsw)	Bottom Time (min)	Stop Times (min) at Different Depths (fsw)							Decom. Time (min)	Repet. Dive Group
		70	60	50	40	30	20	10		
70	10	-	-	-	-	-	-	-	-	A
	20	-	-	-	-	-	-	-	-	C
	24	-	-	-	-	-	-	-	-	D
	30	-	-	-	-	-	-	4	4	D
	40	-	-	-	-	-	-	8	8	F
	50	-	-	-	-	-	-	10	10	G
	60	-	-	-	-	-	2	11	13	H
	70	-	-	-	-	-	3	19	22	J
	80	-	-	-	-	-	4	27	31	K
	90	-	-	-	-	-	5	34	39	M
	100	-	-	-	-	-	6	41	47	N
	110	-	-	-	-	-	7	48	55	
	120	-	-	-	-	-	8	56	64	
	130	-	-	-	-	-	9	65	74	
	140	-	-	-	-	-	11	74	85	
	150	-	-	-	-	-	17	81	98	
	160	-	-	-	-	-	22	89	111	
	170	-	-	-	-	-	27	98	125	
	180	-	-	-	-	-	31	107	138	
	190	-	-	-	-	-	36	115	151	
	200	-	-	-	-	2	39	123	164	
80	10	-	-	-	-	-	-	-	-	A
	15	-	-	-	-	-	-	-	-	C
	19	-	-	-	-	-	-	-	-	D
	25	-	-	-	-	-	-	6	6	E
	30	-	-	-	-	-	-	8	8	F
	40	-	-	-	-	-	2	10	12	G
	50	-	-	-	-	-	4	12	16	H
	55	-	-	-	-	-	5	17	22	I
	60	-	-	-	-	-	6	22	28	J
	65	-	-	-	-	-	7	27	34	J
	70	-	-	-	-	-	8	31	39	K
	75	-	-	-	-	-	9	35	44	L
	80	-	-	-	-	-	9	40	49	M
	85	-	-	-	-	-	10	44	54	
	90	-	-	-	-	-	11	48	59	
	95	-	-	-	-	-	11	53	64	
	100	-	-	-	-	2	10	58	70	
	110	-	-	-	-	3	14	66	83	
	120	-	-	-	-	3	20	76	99	
	130	-	-	-	-	4	24	87	115	
	140	-	-	-	-	5	29	98	132	
	150	-	-	-	-	5	35	109	149	
	160	-	-	-	-	6	40	120	166	

DCIEM 1983 AIR DIVING TABLE 1 (FEET)
STANDARD AIR

Depth (fsw)	Bottom Time (min)	Stop Times (min) at Different Depths (fsw)							Decom. Time (min)	Repet. Dive Group
		70	60	50	40	30	20	10		
90	10	-	-	-	-	-	-	-	-	A
	15	-	-	-	-	-	-	-	-	C
	20	-	-	-	-	-	-	6	6	D
	30	-	-	-	-	-	3	9	12	F
	40	-	-	-	-	-	6	11	17	H
	45	-	-	-	-	-	7	16	23	I
	50	-	-	-	-	-	9	21	30	J
	55	-	-	-	-	-	10	27	37	K
	60	-	-	-	-	2	9	32	43	L
	65	-	-	-	-	3	9	37	49	
	70	-	-	-	-	4	9	42	55	
	75	-	-	-	-	4	10	47	61	
	80	-	-	-	-	5	10	53	68	
	85	-	-	-	-	5	11	59	75	
	90	-	-	-	-	6	15	62	83	
	95	-	-	-	-	6	18	68	92	
	100	-	-	-	-	7	21	73	101	
	110	-	-	-	-	8	26	87	121	
	120	-	-	-	-	8	33	101	142	
100	5	-	-	-	-	-	-	-	-	A
	10	-	-	-	-	-	-	-	-	B
	12	-	-	-	-	-	-	-	-	C
	15	-	-	-	-	-	-	5	5	D
	20	-	-	-	-	-	-	9	9	E
	25	-	-	-	-	-	3	10	13	F
	30	-	-	-	-	-	6	10	16	G
	35	-	-	-	-	-	8	11	19	H
	40	-	-	-	-	-	9	18	27	I
	45	-	-	-	-	3	8	25	36	J
	50	-	-	-	-	4	9	30	43	K
	55	-	-	-	-	5	9	37	51	L
	60	-	-	-	-	6	9	43	58	
	65	-	-	-	-	7	10	48	65	
	70	-	-	-	-	8	10	55	73	
	75	-	-	-	-	8	15	59	82	
	80	-	-	-	-	9	18	65	92	
	85	-	-	-	2	8	22	71	103	
	90	-	-	-	2	8	25	79	114	
	95	-	-	-	3	8	29	87	127	
	100	-	-	-	3	9	32	95	139	
	105	-	-	-	4	8	36	104	152	
	110	-	-	-	4	9	39	112	164	

DCIEM 1983 AIR DIVING TABLE 1 (FEET)
STANDARD AIR

Depth (fsw)	Bottom Time (min)	Stop Times (min) at Different Depths (fsw)							Decom. Time (min)	Repet. Dive Group
		70	60	50	40	30	20	10		
110	5	-	-	-	-	-	-	-	-	A
	11	-	-	-	-	-	-	-	-	C
	15	-	-	-	-	-	-	7	7	D
	20	-	-	-	-	-	3	9	12	F
	25	-	-	-	-	-	6	10	16	G
	30	-	-	-	-	-	9	11	20	H
	35	-	-	-	-	4	7	19	30	I
	40	-	-	-	-	5	8	26	39	J
	45	-	-	-	-	6	9	33	48	K
	50	-	-	-	-	8	9	39	56	M
	55	-	-	-	-	9	9	46	64	N
	60	-	-	-	3	7	11	53	74	
	65	-	-	-	3	8	16	58	85	
	70	-	-	-	4	8	20	64	96	
	75	-	-	-	5	8	23	73	109	
	80	-	-	-	5	8	28	81	122	
	85	-	-	-	6	8	32	91	137	
	90	-	-	-	6	9	35	101	151	
	95	-	-	-	7	9	40	111	167	
	100	-	-	-	7	10	44	120	181	
	105	-	-	-	8	13	46	129	196	
	110	-	-	-	8	16	50	136	210	
120	5	-	-	-	-	-	-	-	-	A
	9	-	-	-	-	-	-	-	-	B
	10	-	-	-	-	-	-	3	3	C
	15	-	-	-	-	-	-	10	10	D
	20	-	-	-	-	-	6	9	15	F
	25	-	-	-	-	-	9	11	20	G
	30	-	-	-	-	5	7	17	29	I
	35	-	-	-	-	6	9	25	40	J
	40	-	-	-	-	8	9	33	50	K
	45	-	-	-	3	7	9	41	60	M
	50	-	-	-	4	7	10	49	70	N
	55	-	-	-	5	7	15	54	81	
	60	-	-	-	6	8	19	61	94	
	65	-	-	-	7	8	23	70	108	
	70	-	-	-	7	9	27	80	123	
	75	-	-	2	6	9	32	91	140	
	80	-	-	3	6	9	37	103	158	
	85	-	-	3	7	10	41	114	175	
	90	-	-	3	7	14	44	124	192	
	95	-	-	4	7	16	49	134	210	
	100	-	-	4	7	20	53	142	228	

DCIEM 1983 AIR DIVING TABLE 1 (FEET)
STANDARD AIR

Depth (fsw)	Bottom Time (min)	Stop Times (min) at Different Depths (fsw)							Decom. Time (min)	Repet. Dive Group
		70	60	50	40	30	20	10		
130	5	-	-	-	-	-	-	-	-	A
	8	-	-	-	-	-	-	-	-	B
	10	-	-	-	-	-	-	5	5	C
	15	-	-	-	-	-	4	9	13	E
	20	-	-	-	-	-	8	10	18	G
	25	-	-	-	-	5	7	12	24	H
	30	-	-	-	-	7	8	23	38	J
	35	-	-	-	3	6	9	32	50	K
	40	-	-	-	5	6	10	40	61	M
	45	-	-	-	6	7	10	50	73	N
	50	-	-	-	7	8	16	55	86	
	55	-	-	2	6	8	21	64	101	
	60	-	-	3	6	8	26	75	118	
	65	-	-	4	6	9	31	86	136	
	70	-	-	5	6	9	36	100	156	
	75	-	-	5	7	11	40	113	176	
	80	-	-	6	7	15	44	125	197	
	85	-	-	6	7	18	49	135	215	
	90	-	-	7	7	22	54	144	234	
140	7	-	-	-	-	-	-	-	-	B
	10	-	-	-	-	-	-	7	7	D
	15	-	-	-	-	-	6	9	15	F
	20	-	-	-	-	4	7	11	22	G
	25	-	-	-	-	7	8	19	34	I
	30	-	-	-	4	6	9	29	48	K
	35	-	-	-	6	6	10	39	61	L
	40	-	-	-	7	7	10	49	73	N
	45	-	-	3	6	7	17	56	891	O
	50	-	-	4	6	8	22	65	105	
	55	-	-	5	6	9	27	78	125	
	60	-	-	6	6	9	33	91	145	
	65	-	-	7	6	11	38	106	168	
	70	-	2	5	7	15	42	120	191	
	75	-	3	5	8	18	47	133	214	
	80	-	3	6	8	21	54	143	235	
	85	-	4	6	8	25	61	151	255	
	90	-	4	6	8	30	68	157	273	

DCIEM 1983 AIR DIVING TABLE 1 (FEET)
STANDARD AIR

Depth (fsw)	Bottom Time (min)	Stop Times (min) at Different Depths (fsw)							Decom. Time (min)	Repet. Dive Group
		70	60	50	40	30	20	10		
150	7	-	-	-	-	-	-	-	-	B
	10	-	-	-	-	-	-	9	9	D
	15	-	-	-	-	-	8	10	18	F
	20	-	-	-	-	6	8	11	25	H
	25	-	-	-	4	6	8	25	43	J
	30	-	-	-	6	7	9	35	57	K
	35	-	-	3	5	7	10	46	71	M
	40	-	-	4	6	8	16	54	88	O
	45	-	-	6	6	8	22	65	107	
	50	-	-	7	6	9	28	78	128	
	55	-	3	5	6	10	34	94	152	
	60	-	4	5	7	13	39	110	178	
	65	-	4	6	7	17	44	125	203	
	70	-	5	6	7	21	50	139	228	
	75	-	6	5	8	25	58	148	250	
	80	-	6	6	8	29	67	155	271	
160	6	-	-	-	-	-	-	-	-	B
	10	-	-	-	-	-	3	9	12	D
	15	-	-	-	-	4	7	10	21	G
	20	-	-	-	3	5	8	16	32	H
	25	-	-	-	6	6	9	30	51	K
	30	-	-	4	5	6	10	42	67	M
	35	-	-	5	6	7	14	52	84	N
	40	-	-	7	6	8	21	62	104	
	45	-	3	5	6	9	28	76	127	
	50	-	4	5	7	9	35	93	153	
	55	-	5	6	7	14	39	112	183	
	60	-	6	6	7	18	45	129	211	
	65	3	4	6	8	22	53	142	238	
	70	3	5	6	8	27	62	152	263	
170	5	-	-	-	-	-	-	-	-	B
	10	-	-	-	-	-	5	9	14	D
	15	-	-	-	-	6	7	10	23	G
	20	-	-	-	5	6	8	22	41	I
	25	-	-	3	5	6	10	35	59	K
	30	-	-	6	5	7	11	48	77	M
	35	-	3	4	6	8	19	58	98	O
	40	-	4	5	6	9	26	72	122	
	45	-	6	5	6	10	34	91	152	
	50	3	4	5	7	14	39	111	183	
	55	3	5	5	8	19	45	129	214	
	60	4	5	6	8	23	54	144	244	
	65	5	5	6	8	29	64	154	271	
	70	5	5	7	12	31	76	160	296	

DCIEM 1983 AIR DIVING TABLE 1 (FEET)
STANDARD AIR

Depth (fsw)	Bottom Time (min)	Stop Times (min) at Different Depths (fsw)								Decom. Time (min)	Repet. Dive Group
		80	70	60	50	40	30	20	10		
180	5	-	-	-	-	-	-	-	-	-	B
	10	-	-	-	-	-	-	7	9	16	E
	15	-	-	-	-	-	8	7	11	26	H
	20	-	-	-	-	7	6	8	27	48	J
	25	-	-	-	5	5	7	10	40	67	M
	30	-	-	3	5	5	8	15	53	89	O
	35	-	-	5	5	6	8	24	66	114	
	40	-	3	4	5	6	9	32	85	144	
	45	-	4	4	5	7	14	38	107	179	
	50	-	5	4	6	7	19	45	127	213	
	55	-	5	5	6	8	24	53	144	245	
	60	3	3	5	7	9	29	65	155	276	
190	5	-	-	-	-	-	-	-	-	-	
	10	-	-	-	-	-	-	8	10	18	
	15	-	-	-	-	4	5	8	13	30	
	20	-	-	-	4	5	6	9	31	55	
	25	-	-	3	4	5	7	11	46	76	
	30	-	-	5	5	5	8	20	58	101	
	35	-	3	4	5	6	9	29	76	132	
	40	-	5	4	5	7	12	36	100	169	
	45	-	6	4	6	7	18	43	123	207	
	50	3	4	4	6	8	24	52	141	242	
	55	4	4	5	6	10	28	65	154	276	
200	5	-	-	-	-	-	-	-	4	4	
	10	-	-	-	-	-	4	6	10	20	
	15	-	-	-	-	6	5	8	18	37	
	20	-	-	-	6	4	7	9	36	62	
	25	-	-	5	4	5	8	14	51	87	
	30	-	3	4	5	6	8	24	67	117	
	35	-	5	4	5	7	9	34	89	153	
	40	3	3	5	5	8	16	40	115	195	
	45	4	4	4	6	8	22	49	137	234	
	50	5	4	5	6	10	27	62	153	272	

DCIEM 1983 AIR DIVING TABLE 1 (FEET)
STANDARD AIR

Depth (fsw)	Bottom Time (min)	Stop Times (min) at Different Depths (fsw)										Decom. Time (min)
		100	90	80	70	60	50	40	30	20	10	
210	5	-	-	-	-	-	-	-	-	-	6	6
	10	-	-	-	-	-	-	-	5	7	10	22
	15	-	-	-	-	-	-	7	6	8	22	43
	20	-	-	-	-	4	3	5	7	10	40	69
	25	-	-	-	-	6	5	5	8	18	55	97
	30	-	-	-	5	4	5	6	9	29	76	134
	35	-	-	3	4	4	5	7	14	36	103	176
	40	-	-	5	3	5	6	8	19	46	130	222
	45	-	-	6	4	4	7	8	27	57	149	262
	50	-	3	4	4	5	7	13	31	74	160	301
220	5	-	-	-	-	-	-	-	-	-	7	7
	10	-	-	-	-	-	-	-	7	7	10	24
	15	-	-	-	-	-	5	4	6	8	27	50
	20	-	-	-	-	5	4	5	7	10	46	77
	25	-	-	-	4	4	4	6	9	22	61	110
	30	-	-	3	4	4	5	7	9	33	87	152
	35	-	-	5	3	5	5	8	17	40	117	200
	40	-	3	3	4	5	6	8	24	52	142	247
230	5	-	-	-	-	-	-	-	-	-	8	8
	10	-	-	-	-	-	-	-	8	7	11	26
	15	-	-	-	-	-	6	4	7	9	30	56
	20	-	-	-	-	6	4	6	7	14	48	85
	25	-	-	-	6	4	4	7	8	26	69	124
	30	-	-	5	3	4	6	7	12	36	100	173
	35	-	4	3	3	5	6	8	20	46	131	226
	40	-	5	3	4	5	6	10	27	61	151	272
240	5	-	-	-	-	-	-	-	-	-	9	9
	10	-	-	-	-	-	-	5	5	7	11	28
	15	-	-	-	-	-	7	5	6	9	34	61
	20	-	-	-	5	3	4	6	8	17	53	96
	25	-	-	4	3	4	5	7	9	29	78	139
	30	-	4	2	4	4	6	7	16	39	113	195
	35	-	5	3	4	5	6	8	24	52	142	249
	40	4	2	4	4	5	7	13	30	71	159	299

DCIEM 1983 AIR DIVING TABLE 1S (FEET)
SHORT STANDARD AIR

Depth (fsw)	No Decompression Bottom Times (min)			Decompression Required Bottom Times (min)			
30	60 C 90 D	120 F 180 H	380				
40	60 D	120 H	175 L	185	190	199	206
50	30 C	50 E	75 G	95 I	115 K	122 K	127 L
60	20 B	30 D	50 F	60 G	80 I	84 J	88 J
70	15 B	25 D	35 E	40 F	50 G	63 I	66 J
80	10 A	20 D	25 E	29 F	35 G	48 H	52 I
90	10 A	15 C	20 D	23 E	27 F	36 H	43 I
100	5 A	10 B	15 D	18 D	21 E	29 G	36 H
110	5 A	10 B	12 C	15 D	18 D	23 F	30 H
120		5 A	10 C	12 D	15 D	19 F	25 G
130		5 A	8 B	10 C	13 D	16 F	21 G
140		5 A	7 B	9 C	11 D	14 F	18 G
150			6 B	8 C	10 D	12 E	15 F
Decompression Time (minutes)			20 fsw	-	-	5	10
			10 fsw	5	10	10	10

INSTRUCTIONS

1. Descent and ascent rates at 60 fsw/min.
2. Bottom time includes descent time.
3. Decompression stop times include ascent time to that stop.
4. Letter after bottom time gives repetitive dive group.

DCIEM 1983 AIR DIVING TABLE 4
REPETITIVE DIVE FACTORS

Repetitive Dive Group First Dive	Surface Intervals (hr:min)								
	0:30 →0:59	1:00 →1:29	1:30 →1:59	2:00 →2:59	3:00 →3:59	4:00 →5:59	6:00 →8:59	9:00 →11:59	12:00 →18:00
A	1.2	1.1	1.1	1.1	1.1	1.1	1.1	1.0	1.0
B	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.0
C	1.4	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.0
D	1.5	1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.0
E	1.6	1.5	1.4	1.3	1.3	1.2	1.2	1.1	1.1
F	1.7	1.6	1.5	1.4	1.3	1.3	1.2	1.1	1.1
G	1.9	1.7	1.6	1.5	1.4	1.3	1.2	1.1	1.1
H	-	1.9	1.7	1.6	1.5	1.4	1.3	1.1	1.1
I	-	2.0	1.8	1.7	1.5	1.4	1.3	1.1	1.1
J	-	-	1.9	1.8	1.6	1.5	1.3	1.2	1.1
K	-	-	2.0	1.9	1.7	1.5	1.3	1.2	1.1
L	-	-	-	2.0	1.7	1.6	1.4	1.2	1.1
M	-	-	-	-	1.8	1.6	1.4	1.2	1.1
N	-	-	-	-	1.9	1.7	1.4	1.2	1.1
O	-	-	-	-	2.0	1.7	1.4	1.2	1.1

INSTRUCTIONS

1. Determine the **First Dive** Group from the table used.
2. Find the **Repetitive Factor** (RF) from this table under the appropriate **Surface Interval**.
3. Multiply the **Bottom Time** of the **Second Dive** by this RF to obtain the **Effective Bottom Time** (EBT).
4. Decompress for the **Depth** and **EBT** of the **Second Dive**.

DCIEM 1983 AIR DIVING TABLE 5 (FEET)
DEPTH CORRECTION FOR DIVING AT ALTITUDE

Actual Depth (fsw)	Depth Correction (fsw) at Altitude (feet)								
	300 →1000	1000 →2000	2000 →3000	3000 →4000	4000 →5000	5000 →6000	6000 →7000	7000 →8000	8000 →10000
30	+0	+10	+10	+10	+10	+10	+10	+20	+20
40	+0	+10	+10	+10	+10	+10	+20	+20	+20
50	+0	+10	+10	+10	+10	+20	+20	+20	+20
60	+0	+10	+10	+10	+20	+20	+20	+20	+30
70	+0	+10	+10	+10	+20	+20	+20	+30	+30
80	+0	+10	+10	+20	+20	+20	+30	+30	+40
90	+0	+10	+10	+20	+20	+20	+30	+30	+40
100	+0	+10	+10	+20	+20	+30	+30	+30	+40
110	+0	+10	+20	+20	+20	+30	+30	+40	+50
120	+0	+10	+20	+20	+30	+30	+30	+40	+50
130	+0	+10	+20	+20	+30	+30	+40	+40	+50
140	+0	+10	+20	+20	+30	+30	+40	+40	+60
150	+10	+10	+20	+20	+30	+40	+40	+50	+60
160	+10	+20	+20	+30	+30	+40	+40	+50	+60
170	+10	+20	+20	+30	+30	+40	+50	+50	+70
180	+10	+20	+20	+30	+40	+40	+50	+50	
190	+10	+20	+20	+30	+40	+40	+50		
200	+10	+20	+20	+30	+40	+40			
210	+10	+20	+20	+30					
220	+10	+20							
230	+10								

Sea Level Stop Depth (fsw)	Actual Stop Depth (fsw) at Altitude (feet)								
	300 →1000	1000 →2000	2000 →3000	3000 →4000	4000 →5000	5000 →6000	6000 →7000	7000 →8000	8000 →10000
10	10	10	10	9	9	9	8	8	8
20	20	20	19	18	18	17	16	16	15
30	30	29	28	27	26	25	24	24	23
40	40	39	38	36	35	34	32	31	30
50	50	49	47	45	44	42	40	39	38
60	59	58	56	54	52	50	48	47	45
70	69	68	66	63	61	59	56	54	52

APPENDIX G

MULTI-LEVEL DIVE ANALYSIS PROGRAM

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C*********************************************************************
C
C                  MULTIPLE LEVEL DIVE ANALYSIS PROGRAM
C
C                           KARL E. HUGGINS
C
C            UNIVERSITY OF MICHIGAN UNDERWATER TECHNOLOGY LAB
C
C
C          THIS PROGRAM IS DESIGNED TO COMPUTE THE TISSUE PRESSURES
C     PRODUCED IN SIX TISSUE GROUPS DURING MULTI-LEVEL DIVES. THE
C     INITIAL TISSUE HALF-TIMES AND M0 VALUES ARE THOSE OF
C     THE U.S. NAVY STANDARD AIR DECOMPRESSION MODEL. HOWEVER, THESE
C     VALUES MAY BE REPLACED BY SIX OTHER HALF-TIMES AND M0 VALUES OF
C     THE USER'S CHOICE.
C
C          THE PROGRAM ASSUMES INSTANTANIOUS CHANGES IN DEPTH BETWEEN
C     TWO LEVELS. IF THE ASCENT  OR DESCENT  RATE IS SUFFICIENTLY SLOW,
C     THE AVERAGE DEPTH BETWEEN THE TWO LEVELS AND THE ASCENT  OR
C     DESCENT  SHOULD BE ENTERED. THE PROGRAM ALLOWS FOR A MAXIMUM OF
C     99 STEPS TO BE ENTERED. EACH STEP IS REQUIRED TO BE ENTERED WITH
C     THE DEPTH OF THE STEP, THE TIME SPENT AT THAT DEPTH, AND THE
C     PARTIAL PRESSURE OF NITROGEN BEING BREATHED AT THAT STEP.
C
C          THE VARIABLES USED IN THIS PROGRAM ARE AS FOLLOWS:
C
C               DEPTH - PRESENT DEPTH
C                TIME - TIME SPENT AT PRESENT DEPTH
C                PPN2 - AMBIENT PARTIAL PRESSURE OF NITROGEN
C                  P0 - TISSUE NITROGEN PRESSURE PRIOR TO STEP
C                  PT - TISSUE NITROGEN PRESSURE AFTER STEP
C
C           DEP(1-99) - ARRAY OF DEPTHS ENTERED
C           TIM(1-99) - ARRAY OF TIMES ENTERED
C          PPNA(1-99) - ARRAY OF PARTIAL NITROGEN PRESSURES ENTERED
C             HT(1-6) - ARRAY OF SIX HALF-TIMES
C             M0(1-6) - ARRAY OF SIX M0 VALUES CORRESPONDING TO THE
C                       SIX TISSUE HALF-TIMES
C        TP(1-6,1-99) - ARRAY OF TISSUE PRESSURES PRODUCED IN THE SIX
C                       TISSUE GROUP BY THE STEPS
C       PER(1-6,1-99) - ARRAY OF THE PERCENTAGE OF THE M0 VALUES IN THE
C                       SIX TISSUE GROUPS WHICH CORRESPOND TO THE
C                       PRESSUES IN TP(1-6,1-99)
C
C**********************************************************************
C
      REAL M0, DEPTH, TIME, PPN2, P0, PT
      DIMENSION DEP(99), TIM(99), HT(6), M0(6), TP(6,99), PER(6,99),
     1PPNA(99)
      INTEGER A, B, F, G, X, Y, Z, N
C
C     INITIALIZE THE SIX TISSUE GROUP HALF-TIMES AND M0 VALUES TO THE
C     U.S. NAVY MODEL
C
      DATA HT, M0/ 5.0, 10.0, 20.0, 40.0, 80.0, 120.0, 104.0, 88.0
```

```
     1, 72.0, 58.0, 52.0, 51.0 /
 099 CONTINUE
C
C    INITIALIZE SURFACE NITROGEN PRESSURE
C
     TYPE 100
 100 FORMAT(' ENTER SURFACE PARTIAL PRESSURE OF NITROGEN,
    1(EG. 0.790).')
     ACCEPT 101, PPN2
 101 FORMAT(1F5.3)
C
C    SELECT BETWEEN THE U.S. NAVY VALUES AND ENTERING NEW VALUES
C
     TYPE 090
 090 FORMAT(' DO YOU WISH TO USE THE STANDARD NAVY VALUES FOR THE'/
    1' TISSUE HALF-TIMES AND M0 VALUES OR DO YOU WISH TO ENTER'/' O
    1THER VALUES?'/'0   NAVY VALUES = 1'/'   OTHER VALUES = 2')
     ACCEPT 091, X
 091 FORMAT(1I1)
     IF (X .EQ. 1) GO TO 098
C
C    ENTER NEW HALF-TIME AND M0 VALUES
C
     DO 104 F=1,6
        TYPE 102, F
 102    FORMAT(' ENTER TISSUE HALF-TIME #', 1I1, ' IN MINUTES AND THE
    1   MAXIMUM'/' PRESSURE ALLOWED IN THE TISSUE GROUP (M0) IN FSW
    1   PRESSURE,'/' (EG. 005.0, 104.0)')
        ACCEPT 103, HT(F), M0(F)
 103    FORMAT(1F5.1, 2X, 1F5.1)
 104 CONTINUE

 098 CONTINUE
C
C    SET FLAG G (1-MORE STEPS, 2-END PROFILE) TO 1
C
     G=1
C
C    ENTER DEPTH, TIME, AND PARTIAL PRESSURE OF N2 FOR STEP
C
     DO 109 X=1,99
        TYPE 105, X
 105    FORMAT(' ENTER THE DEPTH (FSW), TIME (MIN) AND PPN2 FOR STEP
    1   #', 1I2 /' (EG. 100.0, 007.0, 0.150).')
        ACCEPT 106, DEP(X), TIM(X), PPNA(X)
 106    FORMAT(1F5.1, 2X, 1F5.1, 2X, 1F5.3)
C
C       IF 99 STEPS HAVE BEEN ENTERED WARN USER
C
        IF (X .EQ. 99) TYPE 110

C
C       INDICATE IF ANOTHER STEP IS TO BE ADDED
C
```

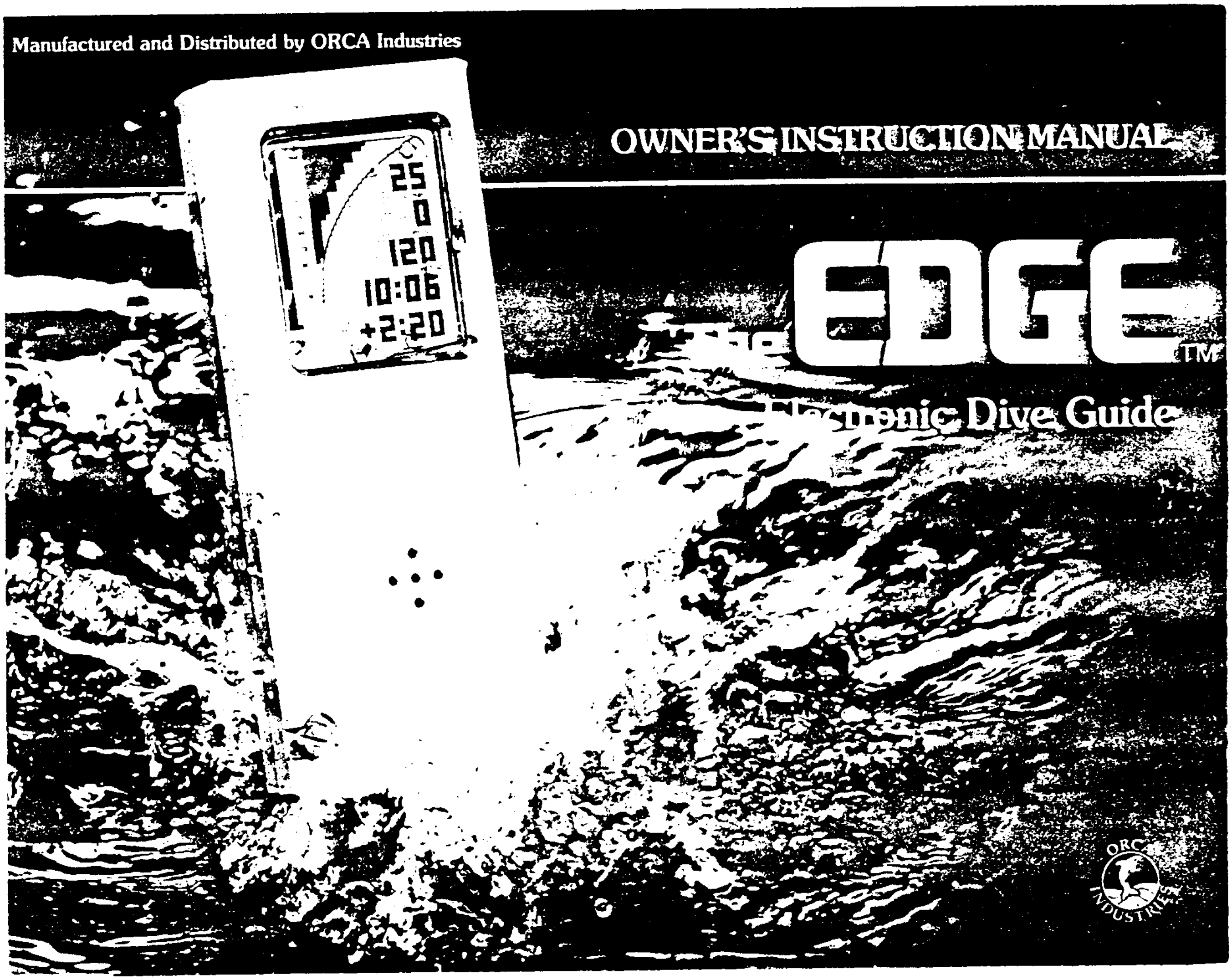
```
         TYPE 107
  107    FORMAT(' DO YOU WISH TO ADD MORE STEPS?'/ 6X, 'YES=1'/ 6X,
     1   'NO=2')
         ACCEPT 108, G
  108    FORMAT(1I1)
C
C        IF G=2 EXIT FROM LOOP AND BEGIN COMPUTATIONS
C
         IF (G .EQ. 2) GO TO 111
  110    FORMAT(' LIMIT OF 99 STEPS HAS BEEN REACHED.')
  109 CONTINUE
  111 CONTINUE
C
C     SET FLAG Z (1-TISSUE PRESSURES OVER 100% M0 DETECTED, 2-ALL
C     TISSUE PRESSURES UNDER 100% OF M0 VALUES) TO 2
C
      Z=2
C
C     SET INITIAL PRESSURE TO SURFACE NITROGEN PRESSURE
C
      P0=33.0*PPN2
C
C     COMPUTE THE SIX TISSUE PRESSURES PRODUCED BY FIRST STEP
C
      DO 130 Y=1,6
         TP(Y,1)=P0+(((DEP(1)+33.0)*PPNA(1))-P0)*(1.0-EXP((-0.69315*TI
     1   M(1))/HT(Y)))
         PER(Y,1)=(TP(Y,1)/M0(Y))*100.0
         IF (PER(Y,1) .GT. 100.0) Z=1
  130 CONTINUE
C
C     COMPUTE THE TISSUE PRESSURES IN THE SIX GROUPS PRODUCED IN STEPS
C     2 THRU X
C
      DO 150 F=2,X
         DO 140 Y=1,6
            P0=TP(Y,F-1)
            TP(Y,F)=P0+(((DEP(F)+33.0)*PPNA(F))-P0)*(1.0-EXP((-0.69315
     1      *TIM(F))/HT(Y)))
            PER(Y,F)=(TP(Y,F)/M0(Y))*100.0
            IF (PER(Y,F) .GT. 100.0) Z=1
  140    CONTINUE
  150 CONTINUE
C
C     INDICATE NUMBER OF COPIES REQUIRED
C
      TYPE 151
  151 FORMAT(' HOW MANY COPIES OF OUTPUT (UP TO 9) DO YOU WANT?')
      ACCEPT 152, G
  152 FORMAT(1I1)
C
C     PRINT G COPIES OF RESULTS
C
      DO 250 N=1,G
         F=0
```

```
          B=0
   153    CONTINUE
          B=B+1
          A=F+1
          WRITE (6,200) X, PPN2, B
          WRITE (6,201) (HT(Y), Y=1,6), (M0(Y), Y=1,6)
          DO 160 F=A,X
             WRITE (6,202) F, PPNA(F), DEP(F), (TP(Y,F), Y=1,6), TIM(F)
     1       ,(PER(Y,F),Y=1,6)
             IF (X .EQ. F) GO TO 160
             IF (F .EQ. B*12) GO TO 153
   160    CONTINUE
          IF (Z .EQ. 1) WRITE(6,203)
   250 CONTINUE
C
C INDICATE IF ANOTHER PROFILE IS TO BE RUN
C
       TYPE 300
   300 FORMAT(' DO YOU WISH TO RUN ANOTHER PROFILE?'/'    YES=1'
      1/'       NO=2')
       ACCEPT 310, N
   310 FORMAT(1I1)
C
C      IF NOT THEN END
C
       IF (N .EQ. 2) GO TO 500
C
C      INDICATE IF THE SAME MODEL IS TO BE USED
C
       TYPE 320
   320 FORMAT(' DO YOU WISH TO USE THE SAME VALUES FOR:'/'       PPN2'
      1/'       HT(1-6)'/'       M0(1-6)'/'0      YES=1'/'     NO=2')
       ACCEPT 330, N
   330 FORMAT(1I1)
C
C      RETURN TO BEGINNING OF PROGRAM
C
       IF (N .EQ. 2) GO TO 099
       GO TO 098
   500 CONTINUE
C
C      PRINTER FORMAT STATEMENTS
C
   200 FORMAT('1:', 77('-'), ':'/' : ', 7('*'), ' THE UNIVERSITY OF
      1MICHIGAN UNDERWATER TECHNOLOGY LABORATORY ', 7('*'), ' :'/
      1' : ', 20('*'), ' MULTI-LEVEL DIVE PROFILE ANALYSIS ', 20('*')
      1, ' :'/' :', 77('-'), ':'/' :', 10X, 'NUMBER OF STEPS = ',
      11I2, 9X, 'PPN2 = ', 1F5.3, 9X, 'PAGE #', 1I1, 10X,
      1':'/' :', 77('-'), ':')
   201 FORMAT(' :  DIVE   :', 6(' HT=', 1F5.1, ' :')/' :  PROFILE
      1:', 6(' M0=', 1F5.1, ' :')/' :', 11('='), ':', 6(10('='),
      1 ':'))
   202 FORMAT(' :  STEP #', 1I2, ' :', 3X, 1F5.3, '  :',  5(10(' '),':'
      1)/' : ', 1F5.1, ' FSW :', 6(' P=', 1F6.2, ' :')/' : '
      11F5.1, ' MIN :', 6(2X, 1F5.1, '%:')/' :', 11('-'), ':',
```

```
     16(10('-'), ':'))
 203 FORMAT('0***********', 4(' WARNING ********')/ 15X, 'THIS DIVE
     !PROFILE IS DANGEROUS!  IT PRODUCES TISSUE'/ 10X, 'PRESSURES
     !IN EXCESS OF THE MAXIMUM ALLOWED TISSUE PRESSURES.')
      STOP
      END
```

APPENDIX H

EDGE MANUAL



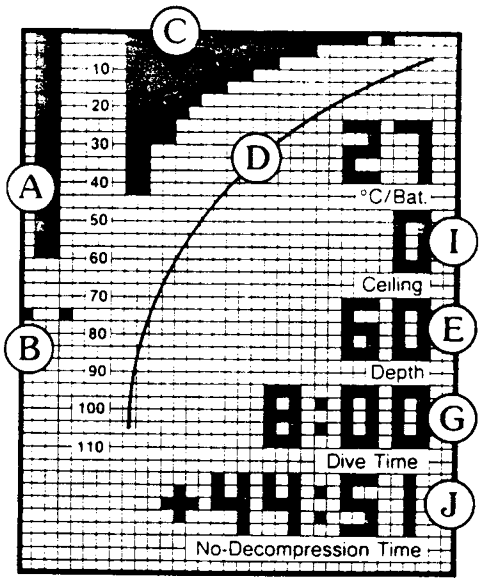
Introduction

This is the owner's manual for the EDGE™ Electronic Dive Guide™. It consists of a description of what the EDGE is and how it functions, followed by instruction on how to use it. The next sections lead you through some common dive profiles, showing you how to read the EDGE's display screen. Then the care and maintenance of the EDGE is described, followed by a section on the limitations you should be aware of. A section on background and theory is provided for those with a technical orientation or who simply wish a deeper understanding. A Question & Answer section is provided at the end; we urge you to call ORCA Industries if any additional questions come to mind.

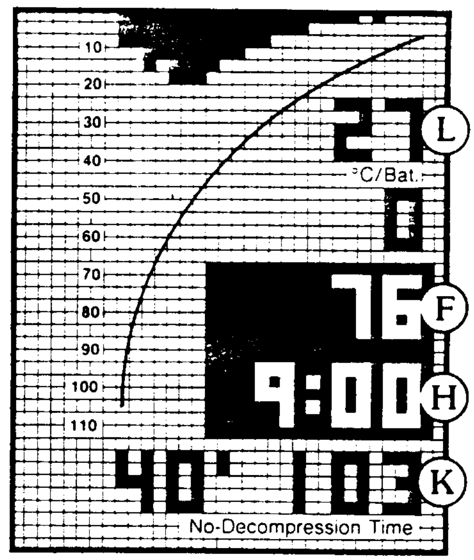
The EDGE itself is a compact, submersible computer which gives you the information you need to plan your dives and to avoid the bends. It is also a precision depth gauge, dive-timer, and surface interval timer. It takes care of repetitive dives as well as single dives. When using the EDGE, you get credit for the shallow portions of a dive, because the EDGE accounts for the fact that your body absorbs less nitrogen at shallower depths: typically divers using the EDGE get double the time allowed by U.S. Navy tables. You also get Orca Industries' patented tissue-tracking display of dissolved nitrogen, scrolling repetitive dive table, and maximum depth recorder.

The EDGE is not just a new product, it is a new way of diving. Rather than explaining further, allow this manual and a few exhilirating dives with the EDGE to tell you what we mean!

Reading the Display Grid Refer to page 9



While Diving



On the Surface

Table of Contents:

Manual by Craig Barshinger and Karl Huggins

The EDGE™ (Electronic Dive Guide™) is a MICROPROCESSOR BASED, DIVER CARRIED DECOMPRESSION-NO-DECOMPRESSION COMPUTER. The EDGE gives the diver a continuous readout of decompression status based on individual dive profiles. Unlike tables, the EDGE bases its information on a calculation procedure which updates decompression status continuously. This allows the EDGE to take into account the shallower portions of a dive profile instead of basing the decompression status solely on the maximum depth achieved during the dive. The EDGE in essence creates a custom-calculated table for any dive profile.

The EDGE is simple to use and read. You just turn it on at the surface and dive with it. The decompression status information is conveyed in both digital and graphical form. Once you have learned how to read it, decompression status can be obtained at a glance.

The EDGE contains state-of-the-art microprocessor and electronic technology all housed in a rugged, waterproof, alloy case. The pressure transducer is temperature compensated and is accurate to ± 1 fsw throughout its range from 0-160 fsw. The EDGE is powered by a normal 9v alkaline battery which provides at least 48 hours continuous use. It also has the capability of battery replacement without losing information from your previous dives.

The model programmed in the EDGE provides a safer dive than the U.S. Navy tables for dives with profiles where the Navy tables are marginal, while providing more dive time for multi-level dives. The model is based on the uptake and elimination of NITROGEN in twelve tissue groups with half-times ranging from 5 to 480 minutes. The combination of the ability to run the EDGE continuously and the longer tissue half times allow you to monitor decompression status over periods of days.

It should be remembered that the EDGE is a tool to help you dive with greater safety and freedom, but should not be used as a substitute

for thorough dive planning and safe diving techniques.

To be as safe as possible when using the EDGE:

1. Familiarize yourself thoroughly with its use before you begin diving with it. If you have any questions that cannot be answered by the manual or your dive shop, contact ORCA Industries directly.
2. Wear backup depth and time measuring devices.
3. Regularly confirm the calibration of the depth gauge.

The EDGE™ is warranted against defects in workmanship and materials for a period of one (1) year after purchase, subject to and in accordance with the terms and conditions set forth below. Buyer is responsible to obtain approval from Manufacturer before returning any unit, and any units returned must be well protected for shipping, insured, and shipped to the Manufacturer prepaid. Buyer shall enclose a written statement detailing the nature of any problem and the circumstances under which it occurred.

This Limited Warranty shall not be effective unless the enclosed warranty card is completed and returned to Manufacturer within ten (10) days after the date of purchase, together with a photocopy of Buyer's receipt or similar proof of purchase. This Limited Warranty shall apply only to the original Buyer of the unit, and shall not be effective with respect to units which have been used in rental, sharing, or similar multi-user arrangements.

Seller's and Manufacturer's responsibility and liability is limited to replacement or repair of any unit returned to Manufacturer within one (1) year after date of sale if such unit is determined by Manufacturer upon inspection to be defective in workmanship or materials. The battery clips and wires, however, are only warranted for 90 days from date of purchase. Replacement or repair shall include the cost of both materials and labor. Neither Seller nor Manufacturer shall be responsible to replace or repair any unit which has been damaged by improper or excessive use, alteration or tampering, accident or jolting, or any cause whatsoever other than defective workmanship or materials. It should be understood that the EDGE™ is a sensitive electronic device which is susceptible to damage if misused, abused, or subjected to accidental jolting or striking. It is intended only to provide an additional measure of safety to divers, and should not be relied upon by any user as his sole means of protection.

Disclaimer

It is expressly understood and agreed that by purchasing or using the EDGE, Buyer and any other person who may use it accepts it "as is", and with the understanding that Seller and Manufacturer disclaim any and all warranties and guarantees, whether express or implied, statutory or otherwise, except for the express limited warranty to repair or replace defective parts and materials set forth in the immediately preceding paragraph. Without limiting the generality of the foregoing, Seller and Manufacturer disclaim any other warranty or guaranty, whether express or implied, including, without limitation, any implied warranty of merchantability or implied warranty of fitness for any particular purpose. It is understood and agreed that neither seller nor manufacturer shall have any liability for any personal injury resulting from operation of the EDGE, or for any other damage, whether direct, consequential, or incidental, and Seller and Manufacturer disclaim such liability and Buyer and other users waive the right to assert such liability against Seller or Manufacturer.

The EDGE is to be used only by certified divers who are fully trained and are aware of and have an understanding of the risks and potential hazards of diving. If you are not trained, please seek training prior to using the EDGE.

5 Inserting the Battery and Sealing the Battery Door

Fig. 1

Fig. 2

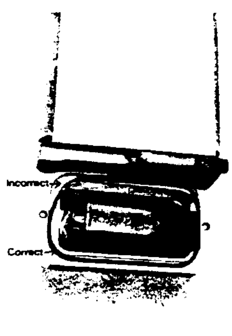


Fig. 3

Fig. 4

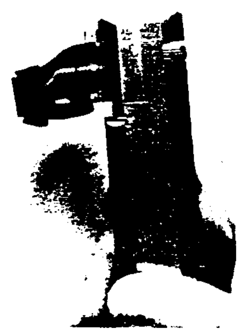


Fig. 5

1. Loosen the screws to the battery door with a coin and remove the Battery Door (Fig. 1). To prevent loss of the door place it in a secure place.

2. Connect a 9 volt alkaline battery to one of the battery clips. Snap the auxiliary clip into the holder (Fig. 2). Arrange the battery wires so that they are clear of the O-ring. The battery must seat firmly so that the cover will fit; take care that crossed wires do not get under the battery.

3. Slip the battery into place. Make sure the O-ring is in place (Fig. 3).

4. Replace the Battery Door and tighten the screws (Fig. 4) using a coin or similarly sized object. Tighten screws alternately, one or two turns at a time.

5. TIGHTEN until Door is FLUSH with the case (Fig. 5). If a gap remains, remove Door and check for interference.

Turning the Edge On.

Fig. 6

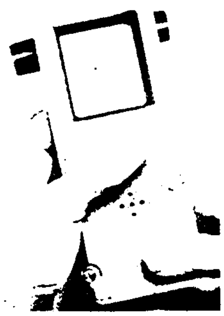


Fig. 7

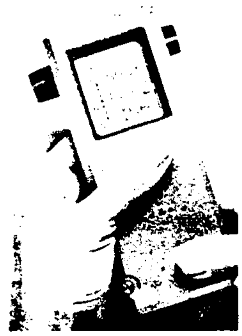


Fig. 8

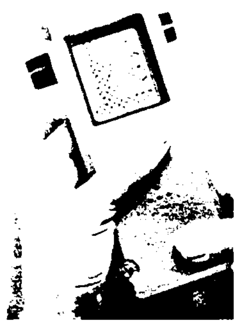


Fig. 9

Fig. 10

6. Make sure the Battery is installed properly (page 5). Flip the Magnetic switch on the case back to the ON position (Fig. 6).

7. The EDGE will first display an Orca pattern. During this time it performs a self check of its functional integrity (Fig. 7).

8. With all memory locations and calculations checked, the EDGE displays a reminder to read the manual thoroughly (Fig. 8).

9. Next a blinking checkerboard pattern is displayed as the EDGE determines ambient surface pressure (Fig. 9). This allows an accurate depth reading even when used at altitude. (If the pattern does not blink, you are trying to initialize the EDGE either underwater or at an altitude greater than 12,000 feet.)

10. The EDGE then shifts to the main display (Fig. 10). At this time the top number will display the present temperature (in Centigrade), and the Depth section will display a "0" in reverse video, the Time section will display "0:00" in reverse video alternating with your surface interval in normal video, and the bottom line will start to display your No-Decompression Limits. The main display is explained in detail on page 9.

Wearing the EDGE

Fig. 11

Fig. 12

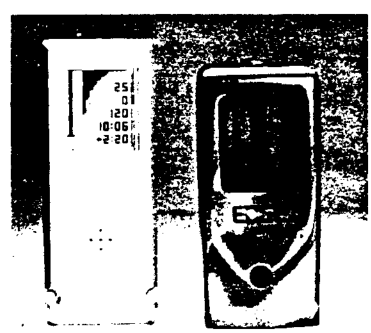


Fig. 13

11. Make sure the EDGE is turned on. The switch cannot be operated while the unit is being worn. Thread the hook side of the velcro straps through the pins, starting on the same side of the case "ON" is printed (Fig. 11).

12. Place the EDGE on the palm side of your forearm and connect the straps (Fig. 12). Holding the EDGE in place against your body, tighten the straps. An optional holster is available if you wish to wear your EDGE on your belt or as a console (Fig. 13).

Terminology

8

Here are some new terms (or new definitions for old terms) that go with the EDGE:

Dive time
Total time spent underwater during a dive.

Repetitive dive
Any dive made when the EDGE is still registering residual nitrogen on the tissue-tracker. Unlike the Navy tables, this may be longer than 12 hours after the previous dive, since the EDGE accounts for the slower tissues.

Residual dive
A more descriptive and accurate term for repetitive dives with the EDGE.

Clear dive
The first dive you make after turning the EDGE on

Ceiling
The shallowest depth to which you can ascend without getting the bends. Similar to a Decompression stop depth, except that it is OK to be DEEPER than your Ceiling. Also, Navy Decompression stops are multiples of 10 (10, 20, 30, etc.) whereas Ceilings can be any value (10, 23, 48, for example).

Ascent Rate
The rate at which you may ascend towards the surface during a No-Decompression dive. Twenty feet per minute is the recommended ascent rate with the EDGE; 40 feet per minute is the MAXIMUM ascent rate.

Reading the EDGE

9

Note: Open the fold-out of the EDGE display screen found on the inside front cover as you read the following section.

The EDGE's display is a 32 × 40 dot LCD matrix which is divided into a graphical and a digital section. **The graphical section gives you the following information:**

- Graphical Representation of Present Depth by using a DEPTH BAR Ⓐ. The DEPTH BAR indicates your present depth down to a depth of 132 fsw (40 meters). The depth is read by using the DEPTH SCALE.
- MAXIMUM DEPTH RECORDER Ⓑ indicates the maximum depth achieved during a dive.
- TISSUE-TRACKING DISPLAY™ — Graphical Representation of the Nitrogen Levels in the 12 Tissue Groups shown by the TISSUE PRESSURE BARS Ⓒ and their Distance from their Surface Nitrogen Limits represented by the TISSUE SURFACE LIMIT LINE Ⓓ. As long as the Bars remain above the Limit Line you are in a No-Decompression dive. If any of the Bars cross the Limit Line you must decompress long enough to pull the Bar(s) back above the Line.

  The "Fast" tissues, those which take on and give off nitrogen quickly, are closest to the depth bar. The "Slow" tissues, those which equilibrate slowly, are farthest from the depth bar.

  The Tissue Tracker™ permits you to:

  1) Visualize how much Nitrogen your body has absorbed. Deep bars close to or over the Line mean much dissolved Nitrogen, whereas shallow bars mean little dissolved Nitrogen.

  2) Control how much Nitrogen you absorb. Each bar is constantly traveling toward the level of the depth bar. By ascending until your depth bar is shallower than a given tissue bar, you can "pull" it away from the Limit Line.
- Graphical Representation of Ceiling (Safe Ascent Depth) (see page 18, Fig. 32). If the dive becomes a Decompression dive two "ears" will start to descend along either side of the DEPTH BAR showing your Ceiling (the shallowest depth you can safely ascend to).

The digital section, which has a SURFACE and DIVE mode, displays:

- ■ Present/Maximum Depth Ⓔ When the dive is underway this area displays your present depth. At the surface the maximum depth of the dive is displayed in reverse video Ⓕ so you may log it.
- ■ Dive Time/Surface Interval Timer Ⓖ The Dive Timer is activated when you descend below 2 meters (6.5 fsw) and freezes the time in reverse video Ⓗ when you ascend above 1 meter (3.3 fsw). If you descend again within 10 minutes the timer will continue to add time to the previous Dive Time. If over 10 minutes elapse before a new dive is started the EDGE will consider it a new dive and reset the Dive Time to zero. At the surface the Dive Time will alternate with the Surface Interval which will be displayed in normal video. Note that Surface Interval reads in hours & minutes (normal video) whereas the Dive Time reads in minutes & seconds (reverse video at surface but normal video during dive).
- ■ Ceiling Ⓘ. This section of the display gives the numerical display of your Ceiling. As long as the Ceiling remains 0 you can ascend to the surface. If a Decompression dive is being performed you cannot ascend to a depth shallower than the Ceiling. If you do ascend above the Ceiling a warning will be flashed telling you to DESCEND NOW (Fig. 38, page 19).
- ■ No-Decompression Time/Decompression Time/Repetitive Dive Time Display Ⓙ. This section conveys the decompression status information to you, showing Remaining No-Decompression Time (RNDT) or Remaining Decompression Time (RDT) during a dive, and a Repetitive Dive Time Table while on the surface.

During a dive, the RNDT or the RDT is displayed in minutes and seconds. A plus ("+") sign indicates the no-decompression time you have left if you stay at the PRESENT DEPTH. It is a precise calculation of the amount of time until any one of your TISSUE BARS crosses over the Limit Line.

If you descend the time will become shorter and if you ascend the time will increase. If you stay longer than the No-Decompression time the number will be replaced by an up arrow ("↑"). This indicates that you have entered a Decompression dive and will need to ascend when you wish to start

decompressing. As you ascend towards (but not above) the Ceiling the up arrow will be replaced by a negative ("−") sign followed by a time (in minutes and seconds). This is the DECOMPRESSION TIME REQUIRED at the PRESENT DEPTH in order for you to safely ascend to the surface. It is also the time required to pull all TISSUE BARS back above the Limit Line. After the Decompression time has elapsed the RNDT for the present depth will once again be displayed. The EDGE will not show a decompression time if the RNDT after decompression will be less than 5 minutes.

At the surface this section displays your Repetitive Dive Times Ⓚ The display will show the depth of a repetitive dive and the No-Decompression time for that depth based on the remaining nitrogen in your tissue groups. This information will be conveyed in 10 fsw increments from 30′ to 150′ and then recycle. For example the display 50′ 34 indicates that you could stay for 34 minutes at 50 fsw before Decompression is required. Unlike the Tables, ascent and descent times are NOT part of this time.

- ■ Temperature and Low Battery Indicator Ⓛ This section displays the temperature in degrees Celsius within the range of −15 to 50 degrees Celsius. When the temperature drops below 0 the temperature will be displayed in reverse video. When the battery weakens the Low Battery warning "Lo" is alternated with the temperature display. This warns you that the unit will operate approximately 4 more hours and that you should replace the battery as soon as possible.

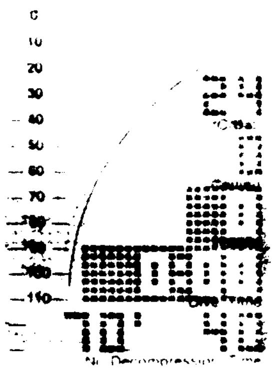


Fig. 16

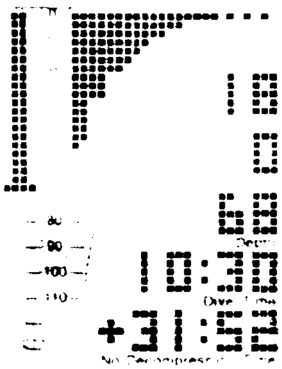


Fig. 17

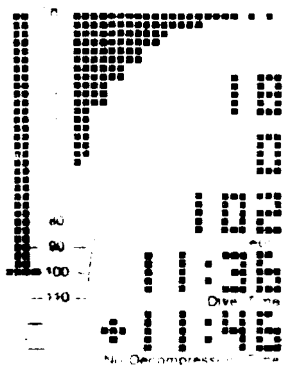


Fig. 18

Example: Suppose you set off from a dock to dive a wreck lying a few hundred yards offshore. A No-Decompression Dive is planned to 70 fsw. When you turn your EDGE on it will show the No-Decompression limit for 70 fsw to be 40 minutes (Fig. 16). You plan on a wreck dive to 70 fsw dive for 30 minutes and start your descent to 70 feet. During your descent the EDGE displays your present depth — a glance at the Depth Bar gives you a quick "feel" of where you are, and a look at the digital readout gives you a precise reading.

Ten and one half minutes into the dive you are 68 fsw (Fig. 17). Your Tissue Bars are working their way down towards this depth, although none are very close to the Limit Line yet. Your remaining No-Decompression Time tells you that you have 31 minutes and 52 seconds until you would cross over into a Decompression dive. Your dive timer reads 10 minutes and 30 seconds, and your temperature has dropped to 18 degrees C.

Following the chain of what appears to be the wreck's anchor line, you descend to 102 feet in a little over a minute. Your EDGE now appears as in Figure 18, with – 11:46

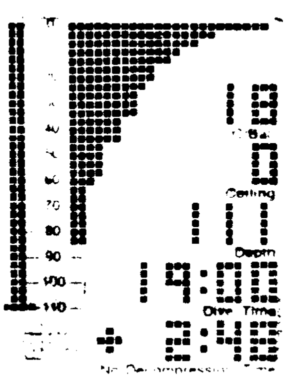


Fig. 19

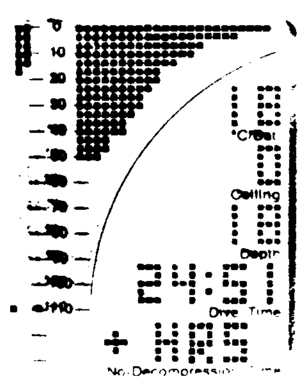


Fig. 20

RNDT. The EDGE automatically adjusts for the change in dive plan! You find the ship's anchor, and spend about seven minutes exploring it. Now the EDGE reads as shown in Figure 19, with only 2 minutes and 48 seconds remaining before decompression would be required. Notice that your fastest Tissue Bar is about to cross the Limit Line, and several others are close behind. You begin your ascent from 111 fsw, stopping for a few minutes at approximately 18 feet in order to pull your Tissue Bars back from the Limit Line (Fig. 20). This off-gassing is a good idea if you have been close to your No-Decompression Limits.

Important note regarding ASCENT RATE: The recommended ascent rate with the EDGE is 20 feet per minute. This is much slower than the 60 feet per minute used with the US Navy Tables. It is easy to maintain 20 feet per minute with the EDGE — regulate your ascent rate so that the depth readout changes by 1 foot at a time. Twenty feet per minute must be used in all cases where your tissue bars have been close to the line or when you are doing multiple bounce dives. Forty feet per minute is the MAXIMUM ASCENT RATE with the EDGE, for use in other cases, and emergencies. If the depth readout changes by 2 feet at a time, you are ascending at 40 ft/min

No-Decompression Diving With the EDGE 14

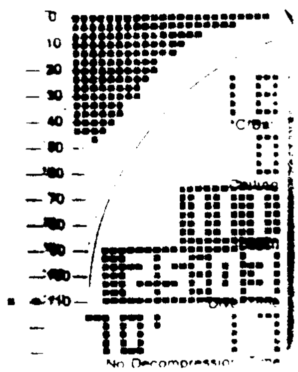


Fig. 21

Surfacing after your wreck dive, the EDGE reads as shown in Figure 21. Your maximum depth and total dive time are shown in reverse video. Underneath your dive time a Repetitive Dive Table begins to scroll. Here, you see that you would have 17 minutes at 70 feet. Your Tissue Bars are pulling back toward the surface, the fast Bars have already retracted considerably during your slow ascent and safety stop.

This example shows the flexibility of the EDGE. It has allowed you to perform a dive that according to the tables would have to be calculated as a 120 fsw dive for 30 minutes, involving stage decompression. It handled the alteration in the dive plan effortlessly and always told you how long you had before decompression was required.

How can the EDGE do this when the tables cannot? The answer is that the EDGE tracks your Nitrogen uptake CONTINUOUSLY, and compares the amount of gas you have absorbed to permitted limits of supersaturation. There exist millions of possible multi-level dive profiles; tables must make the approximation that you spent your whole dive at one depth, the maximum depth, to avoid having to carry literally millions of tables. The EDGE, which calculates directly, is not limited in this regard.

15 Repetitive Information and Surface Mode.

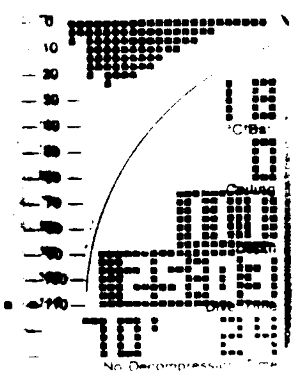


Fig. 22

Once you surface the EDGE will switch into Surface Mode. (The switch-over point is at 3.3 feet of seawater). In this mode the EDGE times your surface interval, continually updates your repetitive dive status, and displays the maximum Depth and Time of your previous dive so you may record it.

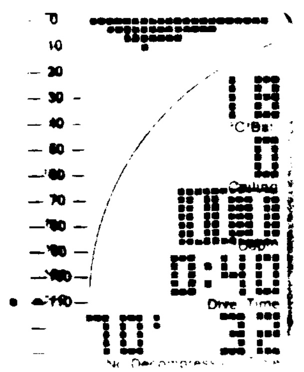


Fig. 23

Example. You surfaced from the wreck dive twelve minutes ago (Fig. 22). Your nitrogen levels are decreasing while on the surface, so your repetitive times are steadily increasing. The No-D limit for 70 fsw is now 24 minutes. Notice the changing shape of the Tissue Bar Profile. (With practice, you will be able to recognize what kind of diving someone has done in the past day or two just by the shape of his/her Tissue Bar Profile).

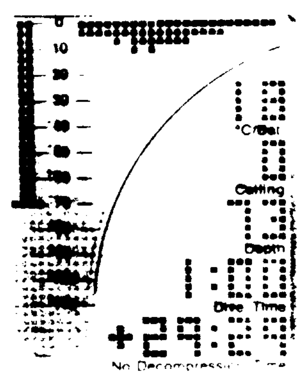


Fig. 24

Figure 23 shows the EDGE display after 40 minutes of surface interval. The Repetitive Table scrolls to 70' and you see that you have 32 minutes there. You gear up and plan a dive to explore the area surrounding the wreck. Your descent to 73 feet takes 1 minute, and you note that your RNDT is 29 minutes, 29 seconds (Fig. 24). After 27 minutes you are at 69 feet and your

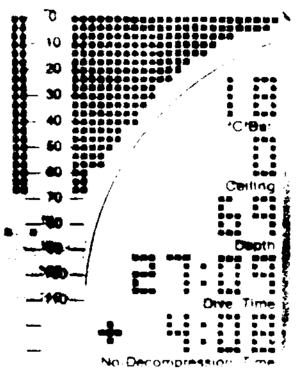


Fig. 25

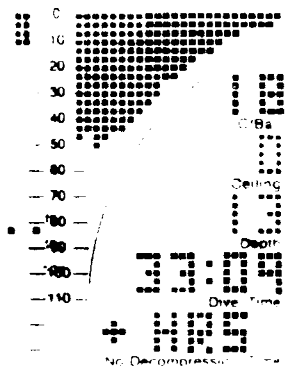


Fig. 26

RNDT is 4:08 (Fig. 25). (27:09 plus 4:08 is longer than the original 29:29 RNDT you had when you first arrived at 73 feet. Why? CREDIT for the shallower portions of the dive.) Since your RNDT is down to only +4:08 and you have many Tissue Bars close to the Limit Line, you start your ascent, using a 20 fsw per minute rate. Leveling off at 13 fsw, your RNDT there is +HRS, meaning that you could stay hours at this depth (Fig. 26). You then spend ten minutes photographing shrimp and anemones around the pilings of the dock from which you are diving, putting in your safety stop at the same time.

After Surfacing, your EDGE displays the information in Figure 27. Compare the Tissue Bar Profile after this second dive to that after the first dive (Fig. 22); you now have quite a bit more residual nitrogen in your slow tissues. This nitrogen in the slow tissues builds up slowly throughout a day (or days) of diving. It is only slowly released, as is illustrated by Figure 28, showing the display 2 hours and 10 minutes after the dive. The EDGE tracks the nitrogen even in these very slow tissues. If you are diving several times per day, for several days, you should keep your EDGE running continuously to avoid over-saturating your slow tissues.

Decompression with the EDGE can be performed in one of three ways (or any combination of the three) by using the Ceiling display and the Remaining Decompression Time display:

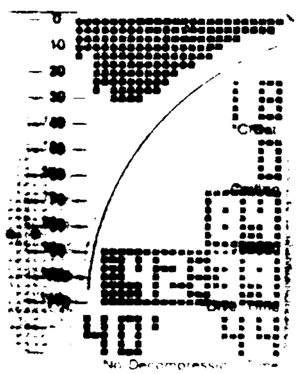


Fig. 27

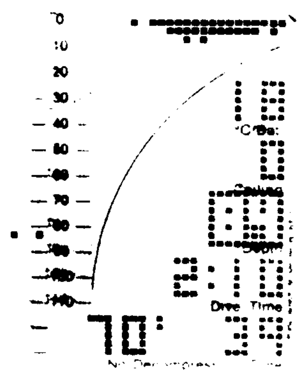


Fig. 28

One Level Decompression. You can ascend to a depth (deeper than the Ceiling) above where the bottom line display changes from an up arrow ("↑") to RDT and spend the entire Decompression Time and decompress at a single level (if you have enough air).

Normal Stepped Decompression. If your Ceiling is 27 fsw you can ascend to 30 fsw and wait until the Ceiling reaches 20 fsw. At this time you can ascend to 20 fsw and wait for the Ceiling to reach 10 fsw. You may then ascend to 10 fsw and finish your decompression there.

Continuous Decompression. Continuous Decompression is where you move up to the Ceiling and keep matching your Depth

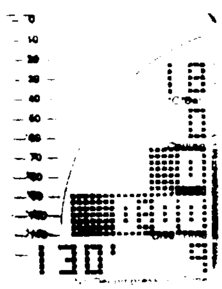


Fig. 29

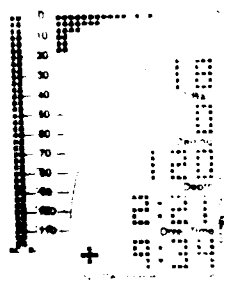


Fig. 30

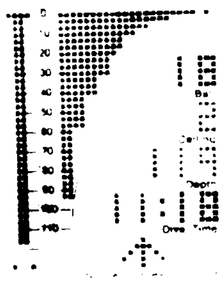


Fig. 31

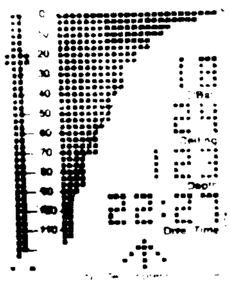


Fig. 32

Fig. 33

with the Ceiling. This method gives the shortest decompression time but may require a decompression line to maintain accurate depth. It is recommended that continuous decompression be performed only to a depth of 8-10 fsw since it is hard to maintain shallower depths, even with a line.

In fact, decompression can be performed at any depth between your Ceiling and the depth at which your up-arrow becomes a RDT; as long as you are in this zone, you are decompressing.

You can give yourself a safety factor by staying a given depth, say 10 feet, below your Ceiling. Additionally, when your Ceiling reaches zero, remain at 10 feet long enough to allow your tissue bars to pull back a few dots, or pixels, from the Limit Line.

If at any time during a decompression dive the Ceiling is violated a warning saying "DANGER DESCEND NOW" will be flashed on the screen (Fig. 38). If this should occur you must descend to a depth below the Ceiling IMMEDIATELY!

Example: A Decompression Dive is planned to 130 fsw for 25 minutes. The EDGE tells you that the No-Ceiling Limit for 130' is 9 minutes (Fig. 29). You descend to 120 feet; upon arrival your dive time is 2 minutes 21 seconds and your RNDT is +9:34 (Fig. 30). Eleven minutes later one of your Tissue

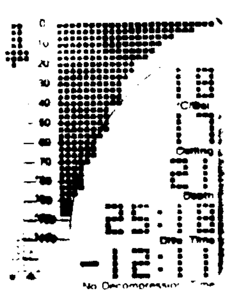


Fig. 34

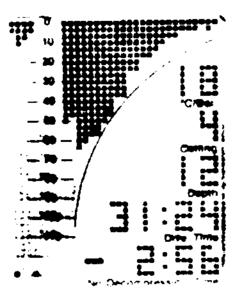


Fig. 35

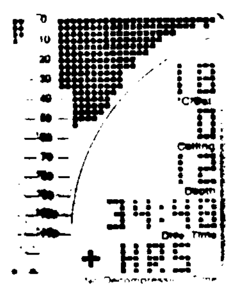


Fig. 36

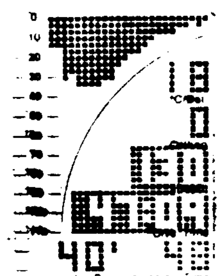


Fig. 37

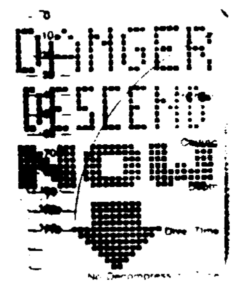


Fig. 38

Bars crosses the Limit Line and your Remaining No-Decompression Time is replaced by an up-arrow ("↑") which tells you that you need to ascend when you wish to start decompressing (Fig. 31). Whenever you have an up-arrow, you are still absorbing more nitrogen and incurring more decompression obligation.

Twenty two and a half minutes into the dive you are at 123 feet and your Ceiling is 24 feet (Fig. 32). You begin your ascent at 20' per minute. At 32 feet you level off. Your Ceiling has moved up ward to 20 feet, and your up-arrow has now been replaced by a REMAINING DECOMPRESSION TIME, RDT, of −29:25 (Fig. 33). RDTs are preceded by a minus sign to set them apart from RNDTs which have a plus sign). Although you can decompress at 32 feet, you can decompress more quickly by ascending closer to the Ceiling, so you go to 21 feet, where your RDT is only −12:11 (Fig. 34).

You decide to perform continuous decompression, and follow your Ceiling up, continuously matching the Ceiling and Depth numbers or by keeping the bottom of the Depth Bar between the Ceiling ears (Figures 34 & 35). Once the Ceiling reaches zero again you may surface, however, it is good practice to wait at 10 to 15 feet if possible until your Tissue Bars have pulled up from the Limit Line a few pixels (Figs. 36 & 37).

Replacing the Battery Without Loss of Information

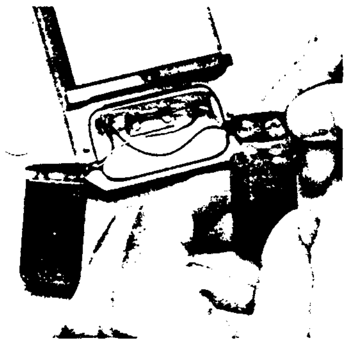


Fig. 14

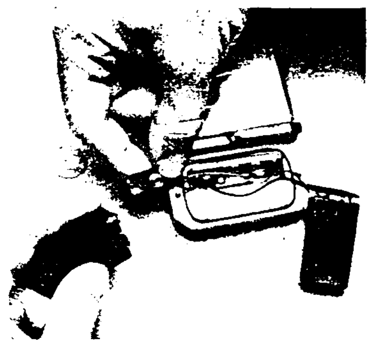
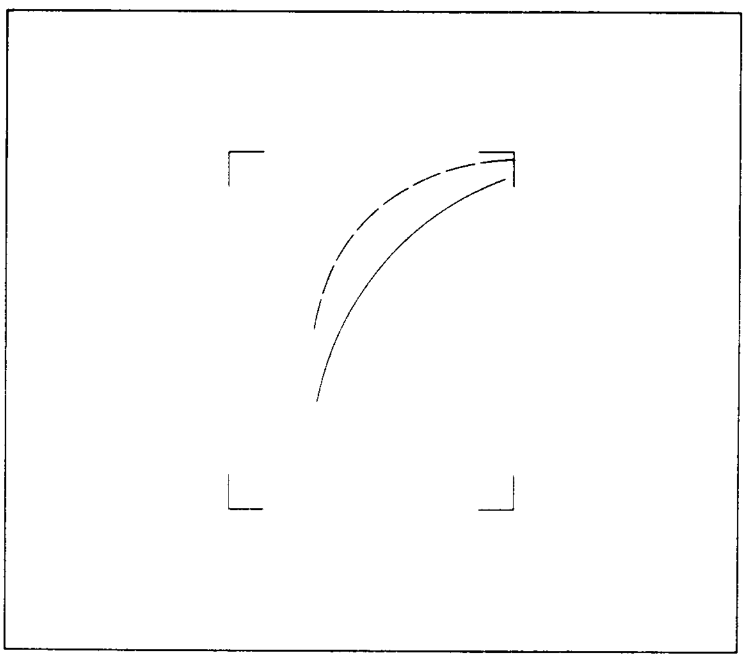


Fig. 15

1. Rinse your EDGE in fresh water and dry it off.
2. Remove the battery with the clip attached. DO NOT DISCONNECT THE BATTERY (Fig. 14). Please note that when the battery door is off, the actuator can FLIP OFF VERY EASILY. Take care not to let this happen, as if it did, all your repetitive dive information would be lost.
3. Take the auxiliary battery clip and attach a fresh battery to it. (Fig. 15).
4. Remove the old battery as soon as the new one has been connected and place the unused battery clip onto the holder. Please note that if the free clip contacts the metal housing, there can be a momentary short and consequent loss of power and information.
5. Slip the new battery into the battery compartment, check the "O"-ring, and replace the Battery Door (see page 5, "Inserting Battery").

Flying After Diving



You may fly in a commercial airliner (8000' cabin pressure) after all your tissue bars rise above the line shown in the figure at left.

If you turn your EDGE off after your last dive it is recommended that you wait at least 12 hours after a No-Decompression Dive and 24 hours following a Decompression Dive before flying.

Maintenance & Care

Although the EDGE is a rugged piece of equipment, proper care and maintenance can help prevent any possible problems. By following these suggestions the EDGE should last for years without requiring re-adjustment or repair:

A. Never leave the EDGE out in the direct sun or in a potentially hot place such as a car trunk. Excessive heating can cause damage to the internal components.

B. After use rinse the EDGE with fresh water, dry it, and replace it in its carrying case. This prevents the EDGE from being banged around and also prevents the accidental switching off of the device if you are planning a repetitive dive.

C. Do not drop the EDGE. It contains glass.

D. Never poke anything into the transducer ports as this could damage the special membrane. Do not dive with an EDGE that has silicone oil leaking from the transducer port; this would indicate a need for factory service.

E. If the EDGE is not going to be used for a period of time remove the battery from the battery compartment. DO NOT REMOVE THE BACK OF THE UNIT!!! Any unit that has had its back removed will not be covered by its warranty.

F. Periodically grease and inspect the "O"-Ring on the battery case door to maintain a good seal.

G. Periodically apply silicone grease to the Battery Door screws to keep them operating freely and prevent corrosion.

H. Do not allow water to enter the battery compartment. Water in contact with alkaline batteries can produce caustic compounds. Also, it is possible for water to pass through the protective barrier into the electronics compartment, such as might happen if you dived deeply with an open or unsealed battery door.

I. Do not expose the EDGE to solvents, petrochemicals, or strong cleaners; these can damage the seals.

Limitations

A. For use at altitudes greater than 500 m or 1600 feet please contact your dealer or Orca Industries. The Limit Line is shallower at higher altitudes, and this must be accounted for.

B. The maximum depth the EDGE can distinguish is 160 fsw. If the EDGE is taken below this level "OR" (Fig. 39) will be displayed in the depth display and the EDGE will flash a warning that the Depth Range was exceeded (Fig. 40) for the remainder of the dive. In order to provide a small safety factor, in case the depth range is exceeded, the EDGE will calculate nitrogen uptake as if you were at 200 fsw whenever it is Out of Range.

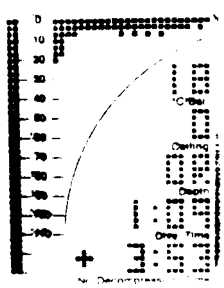


Fig. 39

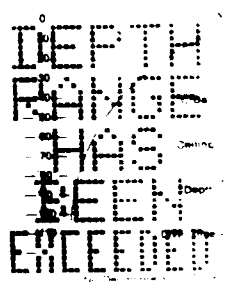


Fig. 40

C. The EDGE can be operated in any temperature of water (0 to 40 degrees C) but should not be left out in temperatures below or above this range. The Liquid Crystal Display may seem sluggish at the lower operating temperatures.

D. The Dive Timer times up to 199:59 and then recycles to 0:00.

E. Any No-Decompression or Decompression Time greater than 99:59 will be displayed as "HRS" ("HOURS").

F. The Ceiling will only display values up to 99 fsw.

G. The Magnetic Flip Switch will affect a compass if it is held within 1.5' (50 cm) of the EDGE.

H. A scrambled screen indicates a momentary loss of power (accidental switching off) and invalidates information.

I. Several minutes before the battery dies, the temperature reading will be incorrect.

Please mail us your questions if they are not answered here.

Q. Does the EDGE require a special container to carry it aboard an airplane?

A. No, it is a solid-state electronic device and can be carried in its regular carrying case.

Q. The EDGE's display sometimes flickers. What does this mean?

A. Flickering at high temperatures is a general property of multiplexed Liquid Crystal Displays; the EDGE has this type.

Q. Because of my body build and age I'm prone to the bends. Should I throw in an extra Safety Factor when using the EDGE?

A. Yes, in fact throwing in an extra safety factor is a good idea for all sport divers, and is very easy to do with the EDGE: 1) Don't get closer than five or ten minutes to your No-Decompression Limits. 2) Keep your Tissue Bars well away from the Limit Line. 3) Avoid decompression dives, and 4) Stay ten to twenty feet below your Ceiling if you must do decompression dives. You will still get all the advantages of the EDGE's multi-level capabilities.

Q. What if I accidentally turn the EDGE off during my day of diving?

A. You will have lost your repetitive dive information and will not be able to dive again that day. Take care not to accidentally switch it off, and keep a good spare battery in your carrying case.

Q. Why are only alkaline 9 volt batteries specified?

A. Regular carbon-zinc 9 volt batteries have a shorter life and often cease functioning when they get cold, as is often the

case underwater. Ni-Cads also have a short life, and they give only a few minutes warning on the Low Battery Indicator. (A rechargeable option is available from ORCA Industries consisting of a special high-energy battery and charger.) Alkaline batteries will give over 48 hours continuous running, operate well even when cold, and give at least four hours of low battery warning.

Q. I get a lot more than 48 hours out of a battery; what's the upper limit?

A. Using "Energizer" brand 9 volts, the record is over 80 hours continuous running.

Q. I don't have access to a pressure chamber. How can I check the calibration of my EDGE?

A. Measure a 30 foot depth of clothesline or other cord that is inelastic. Tie your EDGE onto one end and lower it down 30 feet, wait a few seconds, then pull it back up. The Maximum Depth will be displayed in reverse video. You can also ask your local dive shop to check it, as most have a small pressure chamber. (The EDGE is more accurate than the gauges commonly in use as pressure gauges and depth gauges; try to find a precision reference.)

Q. Why do the No-D limits I get when I first turn on my EDGE vary slightly?

A. Due to minute variations in air pressure readings after you have turned the EDGE on. The No-D limits for the shallow depths can vary by several minutes, those for the greater depths by one minute or less.

Q. The depth bar doesn't line up with the gradations on the depth scale. Why is this?

A. Each pixel actually equals one meter, which is 3.3 feet, so it would line up only if the depth scale were in meters.

Please mail us your questions if they are not answered here.

Q. Sometimes I get tissue bars only one pixel wide, mostly in the slow tissues. Why is this?

A. Each Tissue Bar is two pixels wide, like the Depth Bar, but is written one pixel at a time. The left one lights first, then the right one lights. The next pixel is the left one, one row down, and so forth. This essentially doubles the resolution of the Depth and Tissue Bars. Regarding your question, you saw several slow tissues with only one pixel lighted.

Q. Can I get the bends while using the EDGE?

A. Yes. Using the EDGE is not a guarantee of avoiding the bends. However experience from thousands of dives over the past year indicates that the EDGE is a better bet than the US Navy Tables: as of this time (8/84) no cases of bends have been reported. At the present time the EDGE is the best solution to the decompression problem, providing long bottom times along with excellent safety.

Q. I got a 1 foot Ceiling with "-HRS" of decompression on my second decompression dive. What does this mean and how should I deal with it?

A. This situation occurs when the slow tissues are near the Limit Line at the start of a residual (repetitive) dive, and then are pulled over during the dive, thus requiring decompression. The Ceiling will be shallow, such as 1 or 2 feet. If you could actually hold this depth, you could decompress rather quickly, but at 8 to 10 feet, you are actually still ON-GASSING or OFF-GASSING VERY SLOWLY in your slow tissues, so decompression there would be lengthy. The solution is to avoid going into decompression on residual dives.

In an emergency, you would probably not be bent if you surfaced despite a 1 foot Ceiling. No further diving should be done afterwards.

The optional EDGE holster can be worn on the high-pressure hose, the belt, or anywhere you find convenient.

The most popular location is on the high-pressure hose, which makes for a complete, compact console.

Needed to install on HP hose:

Hot water (boiling, if possible), a lubricant (silicone or dishwashing liquid), and a T-wrench (optional).

1. Remove your submersible pressure gauge (SPG) from regulator. If you are using soap as lubricant, use tape to block soap from entering HP hose. Lubricate the nut and hose at the end farthest from the SPG.
2. Immerse the holster in HOT water so that the channel into which the HP hose is to be inserted gets very soft. If possible, only heat the channel; this makes the holster easier to hold in the next step.
3. Remove the holster from water and immediately insert the nut-end of HP hose into the channel, twisting gently (make sure to insert into the end nearest the view window cutout!). Twist and push until at least 1 inch has been inserted, then insert the T-wrench from the other end, screw into place, and pull the hose all the way through. Slide the holster all the way down the hose until it comes to rest against the SPG. Push holster up onto the nut that links SPG and hose; this helps immobilize it.
4. Without a T-wrench, you must complete the installation by continuing to push and twist the HP hose until the nut clears the other end of the channel.

The key ingredient is HEAT. The hotter the water, the softer the channel and the easier the installation.

The algorithm used in the EDGE has evolved from two distinct backgrounds:

1. **Multi-Level Diving Techniques practiced using the U.S. Navy No-Decompression Tables.**
2. **Shorter No-Decompression Limits developed by Dr. Merrill Spencer.**

1. Multi-Level Diving Techniques:

The U.S. Navy No-Decompression Decompression Tables and procedures were designed for single depth dives. Divers are required to use the maximum depth attained during the dive profile to calculate the No-Decompression Limit or the Decompression schedule as if the entire dive had occurred at that maximum depth. Many divers feel that they are penalized and limited by this procedure since they do not spend all their time at the deepest depth. Consequently, divers have sought new procedures for reading and using the U.S. Navy dive tables that allowed longer bottom times. The technique that gained the most acceptance in the diving community are Multi-Level dive table interpretations.

Some diving authorities indicate that these or similar procedures have been tested and used in commercial oil-field diving although little published data is available. This lack of data has not prevented the use of these techniques by thousands of sport divers.

With the acceptance of these techniques there have been questions with respect to the safety involved. Mathematical analysis of "acceptable" Multi-Level profiles shows that in some of the permitted profiles tissue nitrogen levels exceeded the U.S. Navy surface nitrogen limits (Mo values). These excessive nitrogen values are due to the fact that the group designations in the U.S. Navy No-Decompression Tables were calculated using one tissue group (the 120 min. group). The unacceptable levels were generated in other tissue groups.

most noticeably in the 40 min. group. However an analysis of dive profiles performed by three dive guides at a Bahama resort showed that all their tissue nitrogen levels stayed below the U.S. Navy M values. Also, many hyperbaric physicians feel that the concept is valid and safe if specific precautions are followed.

The conclusion in these theoretical studies indicates that in some, but not all, Multi-Level dive profiles the tissue pressures remain below their Mo values. In order to be sure that none of the other tissue groups exceed their Mo values all the tissues must be taken into account when constructing tables or calculating decompression information.

The algorithm in the EDGE takes this conclusion into account. It calculates the divers' tissue and decompression status based on 12 different tissue groups ranging from 5 min. to 480 min.

2. Shorter No-Decompression Limits:

With the development of Ultrasonic Doppler detectors it was possible to detect the formation of venous gas emboli (VGE), or silent bubbles, in the body after decompression. Using this monitoring technique Spencer published New No-Decompression limits that would produce a low occurrence of VGE. These limits tend to be more conservative than the U.S. Navy limits. It is these limits that were used to calculate the Mo values for the 12 tissue groups (5 min - 480 min) used in the EDGE.

The algorithm used in the EDGE is a combination of these two backgrounds. The main ideas for Multi-Level Diving Techniques are merged with the new Mo values to form an algorithm which will theoretically yield no, or a minimal amount of, VGE. This is achieved by calculating the uptake and elimination of nitrogen in the 12 tissue groups every three seconds during the dive and comparing the pressures to the new Mo values. This technique guarantees that the nitrogen pressure in any tissue group will never exceed its Mo value (as long as the diver follows the information given by the EDGE).

In order to release the EDGE to the public ORCA Industries conducted a study to examine the effects of Multi-Level Dives (allowed by the EDGE) on human subjects. The results showed that the profiles tested were safe to all the divers exposed. A summary of the study can be obtained by writing ORCA Industries. The results are also published in the proceedings of IQ14, "Ultrasonic Doppler Study of Multi-level Diving Profiles," by Karl Huggins.

Additional information on these subjects can be obtained in the following published papers:

- Graver, Dennis, "A Decompression Table Procedure for Multi-Level Diving," in Fead, L. (ed.), PROCEEDINGS OF THE EIGHTH INTERNATIONAL CONFERENCE ON UNDERWATER EDUCATION, National Association of Underwater Instructors, Colton, CA 1976.
- Huggins, Karl E., Somers, L., MATHEMATICAL EVALUATION OF MULTI-LEVEL DIVING, Michigan Sea Grant Publication #MICHU-SG-81-207, Ann Arbor, MI, 1981.
- Huggins, Karl E., NEW NO-DECOMPRESSION TABLES BASED ON NO-DECOMPRESSION LIMITS DETERMINED BY DOPPLER ULTRASONIC BUBBLE DETECTION, Michigan Sea Grant Publication #MICHU-SG-81-205, Ann Arbor, MI, 1981.
- Spencer, M.P., "Decompression Limits for Compressed Air Determined by Ultrasonically Detected Blood Bubbles," JOURNAL OF APPLIED PHYSIOLOGY, Vol. 40, #2, pp. 229-235, 1976

Addresses:

- NAUI, P.O. Box 14650, Montclair, CA. 91763, (714) 621-5801
- MICHIGAN SEA GRANT OFFICE, 4107 I.S.T. Building, 2200 Bonsteal Blvd., Ann Arbor, MI. 48109, (313) 763-1437
- JOURNAL OF APPLIED PHYSIOLOGY, 9650 Rockvile Pike, Bethesda, MD 20014

31 Comparison of No-Decompression Limits

DEPTH (fsw)	LIMITS (min) EDGE	U.S. Navy	Spencer	Bassett
30	234	none	225	220
40	136	200	135	120
50	77	100	75	70
60	53	60	50	50
70	40	50	40	40
80	31	40	30	30
90	24	30	25	25
100	19	25	20	20
110	13	20	15	15
120	11	15	10	12
130	9	10	5	10
140	7	10		
150	7	5		
160	6	5		
170	5	5		

DEPTH (msw)	LIMITS (min) EDGE	Royal Navy
9	225	none
10	189	232
12	137	137
14	91	96
16	67	72
18	54	57
20	44	46
22	37	38
24	32	32
26	27	27
28	23	23
30	20	20
32	15	18
34	13	16
36	11	14
38	10	12
40	9	11
50	6	7

Decompression Model:
- Algorithm .... Modified Haldanean
- Number of Tissue Groups 12
- Tissue Half-Time Range .. 5 minutes to 480 minutes
- Tissue M Values .... Derived from No-Decompression Limits that were determined by Doppler studies, more conservative than U.S. Navy M values
- Decompression Functions .... Tissue nitrogen levels
  Remaining No-Decompression Times
  Remaining Decompression Time
  Repetitive No-Decompression Time

Depth Gauge:
- Transducer .... 0 to 100 psi absolute transducer, temperature compensated
- Accuracy .... ±0.3 msw (±1 fsw)
- Depth Display Range ... 0 to 49 msw (0 to 160 fsw)
- Depth Display Resolution .... 0.3 msw (1 fsw)
- Depth Bar Range .... 0 to 40 msw (0 to 132 fsw)
- Depth Bar Resolution ... 0.5 msw (1.6 fsw)
- Depth Functions .... Present Depth
  Maximum Depth Recorder
  Maximum Depth Display @ surface

Dive Timer:
- Accuracy .... ± 13 seconds per day
- Range .... 0 to 99 minutes 59 seconds
- Activation Depth .... 2 msw (6.6 fsw)
- Deactivation Depth .... 1 msw (3.3 fsw)
- Dive Timer Functions ... Present Dive Time
  Freezes Dive Time @ Surface
  Dive Time is set to 0 if a new dive is started (only if surface Interval > 10 min.)

Surface Internal Timer:
- Accuracy .... ± 13 seconds per day
- Range .... 0 to 99 hours 59 minutes

Temperature Display:
- Accuracy .... ±2°C (±3.6°F)
- Range .... -15°C to 50°C (16.8°F to 123°F)

Power:
- Battery .... One 9v alkaline battery
- Duration .... 48 hours @ 25°C
- Low Battery indicator ... Gives 4 hour warning
- Replacement .... Battery can be replaced without losing information
- On/Off Switch .... Magnetic Flip Switch
- Battery Door .... Removed/Replaced using any coin

Environmental Limitations:
- Depth Range .... 0 to 49 msw (0 to 160 fsw)
- Altitude Ranges:
  - Decompression Algorithm .... 0m to 350m above sea level (0′ to 1150′ above sea level
  - Tissue Calculations ... 0m to 6100m above sea level (0′ to 20,000′ above sea level)
- Temperature Ranges:
  - Operating .... -4°C to 50°C (24.8°F to 122°F)
  - Storage .... -40°C to 75°C (-40°F to 167°F)

Case:
- Construction .... Cast Aluminum Alloy
- Battery Compartment Seal .... 033 Square Ring
- Dimensions .... 182mm x 73mm x 33mm (7.2″ x 2.9″ 1.3″)
- View Window .... Mineral Glass
- View Window Dimensions .... 57.15mm x 47.65mm x 6.53mm (2.250″ x 1.875″ x 0.250″)
- Weight .... 680 gm (1.5 lbs)

Display:
- Configuration .... 32 x 40 Square Dot LCD Matrix
- Illumination .... Ambient Light

Warranty:
- Limited One-Year Warranty

Service:
- All servicing and repairs will be done by ORCA Industries' Consumer Service Department

(msw = meters of sea water; fsw = feet of sea water; °C = degrees Celsius; °F = degrees Fahrenheit)

Specifications subject to change without notice

ABOUT THE AUTHOR

Karl E. Huggins is a Research Associate, Department of Atmospheric and Oceanic Science, The University of Michigan. He also serves on the university's Diving Safety Board. He holds a M.S. degree in Bioengineering. Mr. Huggins is internationally known for his research on decompression theory. He has developed a set of no-decompression tables, based on no-decompression limits determined by Doppler ultrasonic bubble detection, useful for multi-level diving. He is also the co-inventor of the EDGE decompression computer. Mr. Huggins is a member of the Undersea Medical Society, the National Association of Underwater Instructors, and the American Academy of Underwater Sciences.

OTHER PUBLICATIONS BY KARL HUGGINS AVAILABLE FROM MICHIGAN SEA GRANT

New No-Decompression Tables Based on No-Decompression Limits Determined by Doppler Ultrasonic Bubble Detection
(MICHU-SG-81-205) $0.40, bulk copies $0.20

Mathematical Evaluation of Multi-Level Diving
(MICHU-SG-81-207) $1.50

Doppler Evaluation of Multi-Level Diving Profiles
(MICHU-SG-84-300) $0.40

For more information, to order any of the above, or for a list of additional diving publications, contact:

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The University of Michigan
Ann Arbor, Michigan 48109

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