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Multiday Diving and A Dive Computer of the Future

by
John E. Lewis, PhD

Introduction

The PADI Recreational Dive Tables and the OCEANIC Datamaster Sport Dive Computer are based on the same hypothesis, and they both can point to the DSAT experiments of Michael Powell as proof of their validity. Alas, they also share a common weakness. Neither has any memory of the previous day's diving, let alone many days of diving in a row. The potential hazards of multiday diving has only recently been raised as a possible issue, and it is largely an unknown. However, it is clear that a Dive Computer can be designed with a virtually unlimited memory, and I believe that it is useful to look into the future at what such a Dive Computer might offer. I shall begin with a brief discussion of its design, present its no-decompression (NoD) diving performance, and finally examine what it predicts for multiday dive control.

Decompression Algorithm

The theoretical basis for all Dive Computers that are marketed in the United States was invented by Haldane some eighty years ago. This theory predicts the nitrogen loading of various hypothetical tissues or compartments. Each compartment is characterized by a "half time" ,which is a measure of how fast it absorbs nitrogen, and an acceptable surfacing value that is derived from experimentally determined NoD limits. Haldane originally choose five compartments with half times varying from 5 min to 75 min, and Workman added a sixth compartment with a 120 min half time to construct the U.S. Navy Standard Air Decompression Tables. For all practical purposes, after twelve hours none of these compartments has any memory of a previous dive. Since our primary objective is to explore multiday diving, it is this limitation that will represent our primary thrust.

Actually HAL (I have decided our Dive Computer needs a name, and HAL seems to be appropriate) has over one-thousand compartments (1530 to be exact) with half times that vary from 6 sec to 24 hours. HAL's acceptable surfacing values were derived from Spencer's empirical formulae that cooresponds to 15% VGE, but rather than dwell on these laborous mathematical details, we shall proceed directly to HAL's performance and the role of his extraordinary new compartments.

NoDecompression Limits

For a single depth NoD dive with ascent and descent rates equal to 60 ft/min, HAL predicts the allowable bottom times presented in Table 1.

Depth (ft)	Powell Data	HAL
45	100 min	97.4 min
55	65	65.7
65	45	47.4
75	35	35.8
85	27	28.0
95	22	22.5
100	20	20.4
110	17	16.9
120	14	14.1
130	12	12.0

Table 1. HAL's NoD limits compared to Powell's test data.

I believe it is fair to say that for those depths tested by Powell, HAL's performance is quite accurate. Two additional predictions are also interesting. For 25 ft, HAL predicts a NoD limit of 308 min. This compares with the 720 min that Spencer tested and found produced Type I decompression sickness. For 10.75 ft, HAL predicts a No-D limit of 1610 min. This compares with Bassett's testing of 1440 min followed immediately by a safe ascent to an altitude of 16,000 ft. I include these later two examples to demonstrate that HAL's algorithm is consistent with the data base at shallower depths as well.

It is interesting to note that for depths between 30 and 130 ft, HAL's controlling compartments had half times that varied between 6.1 and 122 min. Out of curiosity, I calculated the same schedules using Workman's 6 compartments. Remarkably, the 6 compartment model succeeded in matching HAL's predictions within a few minutes, and when compared to Powell's test data it is not clear which is to be prefered. The benefits of over one thousand compartments is clearly questionable.

Multiday Diving

The preceeding discussions have been intended to establish that HAL has been designed to be consistent with the existing data base. We are now in a position to evaluate HAL's view of multiday diving. When faced with this question, the first issue that must be addressed is what preceeding multiday diving schedule is the most stressing. I have been unable to answer that question directly, but fortunately there is a mathematical option. We shall simply presume that there is some schedule of diving that will produce the ultimate acceptable nitrogen loading in <u>*all*</u> compartments. No combination of multiday diving can do more if we limit our diving to predicted NoD limits. Further, we shall assume that this occurs at 7 P.M. one evening, and ask HAL what he predicts as NoD limits twelve hours later at 7 A.M. of the next morning. HAL's predictions are presented in Table 2.

Depth	Worst Case Multiday	Clean First Day
10 ft	14 hr : 07 min	30 hr : 55 min
20	4 hr : 23 min	7 hr : 58 min
30	2 hr : 36 min	3 hr : 36 min
40	1 hr : 51 min	2 hr : 03 min
50	: 79 min	: 79 min
60	: 55 min	: 55 min

Table 2. HAL's worst case multiday diving predictions.

There is no doubt that HAL has a memory that can retain information for several days. However, the practical result of the preceeding worst case scenario is that for depths greater than 40 ft his extended memory predicts absolutely no variation from a clean first day dive. The reason for this seeming *nonsequitur* is that while some compartments have a long memory, they are by the same token sluggish. If you depended on a 480 min compartment to control your dive at 120 ft, you would be in for a big surprise when it allowed a bottom time of 79 min! The substantial variation HAL does predict is seen to occur at very shallow depths, where the bottom times are far beyond the limits of any practical diving, recreational or not.

Summary

If in the future multiday diving is demonstrated to be a hazard, it will require a design solution. However, short of a rejection of the basic premise of Haldane's theory, I conclude that no Dive Computer can predict relevant multiday constraints regardless of the number of compartments or the extent of their memories.*

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* If you suspect that HAL has somehow been rigged to produce this result, I suggest that you test your Dive Computer by viewing the pre-dive scroll the next morning after any number of days of serious NoD diving. I believe you will find the only overnight accomplishment that it can boast is a 12 hour reduction in its battery life.

Author

Dr. Lewis has degrees in physics, aeronautics, and applied mathematics. His PhD was awarded by Caltech in 1967. He has been an active diver for over thirty years, is the author of fifteen technical publications, and holds two U.S. Patents. He is one of the principal designers of the Oceanic Datamaster II, Datamaster Sport, and DataMax Sport Dive Computers.

A Review of Ascent Procedures for Scientific and Recreational Divers

by

John E. Lewis, PhD

Introduction

The Underwater Diving Manual published by DAN describes two "life-threatening conditions" that are directly related to ascent - air embolism and decompression sickness. Both are a result of gas bubbles but with differing origins. Air embolism is caused by "ruptured lung tissue releasing bubbles into the circulation", whereas decompression sickness occurs when "(absorbed) nitrogen comes out of solution and forms bubbles in the tissues and blood stream." The purpose of this article is to quantify the net benefit of differing ascent procedures in order that an informed decision can be made by the American Academy of Underwater Sciences (AAUS) and the recreational diving community as to what ascent procedure is best suited for both scientific and recreational divers.

What are the issues and options?

As illustrated in Figure 1, an ascent procedure consists of three distinct elements. It has a beginning, which for most scientific and virtually all recreational divers occurs when a no-decompression limit has been reached. It progresses at some defined rate or rates of ascent, and, if a safety stop is included, it ends with a stop at a shallow depth for a prescribed period of time. The issues are as stated previously: the prevention of air embolism and decompression sickness. The options under consideration are reduced no-decompression limits, a safety stop, and a reduced ascent rate.

No-Decompression Limits

There are three relatively recent experiments that deal with no-decompression (NoD) limits that are relevant to our discussion: Thalmann(1984), Spencer(1976), and Powell(1987).

Thalmann attempted to increase the Navy NoD limits, and he tested a total of 107 exposures without any occurrences of decompression sickness (DCS) to the following limits:

- 60 feet for 66 minutes
- 100 feet for 30 minutes
- 120 feet for 24 minutes
- 150 feet for 14 minutes

However, a careful reading of his report indicates that these experiments actually included a short decompression stop at 10 feet, although the actual time spent at 10 feet is not documented. More important is that during a second trial of 100 feet for 30 minutes, 4 cases of DCS occurred out of 20 exposures. Thalmann did not use Doppler monitoring of his test subjects, and this result leads me to conclude that if clinical symptoms of DCS is the only diagnostic, what does not work is far more important than what may work on occasion.

Spencer tested to the Navy limits. He also Doppler monitored his test subjects for nitrogen bubbles as well as recording clinical symptoms of DCS. Each of the following examples produced high grade bubbles and at least one case of DCS:

- 60 feet for 60 minutes
- 70 feet for 50 minutes
- 25 feet for 720 minutes

The one example of a bottom time that he tested that did successfully exceed U.S. Navy NoD limits was 150 feet for 10 minutes.

Powell tested reduced NoD limits that closely resemble Spencer's empirical formulae for 15% VGE. These bottom times closely resemble the U.S. Navy Dive Tables with the addition of 10 feet to the actual depth of a dive, and thus they do not differ greatly from the admonition in the U.S. Navy Diving Manual to "always select the next depth greater than the actual depth." Powell also Doppler monitored his test subjects. These experiments produced no DCS and at most low grade bubbles.

It seems probable that diving to the U.S. Navy NoD limits has worked so well for so long because a large percentage of diving was performed well within these limits. Lately, the diving community seems to be beseiged with well meaning but poorly founded new rules. Reduced NoD limits do not fit into this category. They are well documented and, in my judgment, should be adopted by scientific divers as well as recreational divers. For scientific divers that have a need for bottom times closer to those of the U.S. Navy, most dive computers can still be used for this purpose, despite the fact that they are based on reduced NoD limits. They will require a decompression stop, but as can be seen in Table 1, the required decompression stops are quite modest and are not unlike a "Pilmanis safety stop", which is discussed in the next section.

DEPTH	BOTTOM TIME	DECOMPRESSION TIME
50 FT	100 MIN	7.9 MIN
60	60	3.2
70	50	6.5
80	40	5.3
90	30	3.5
100	25	3.3
110	20	1.8
120	15	0.7
130	10	NoD
140	10	0.3
150	5	NoD

Table 1. Decompression required by Oceanic DataMax Sport when diving to U.S. Navy NoD limits.

While we are on the subject of NoD limits and dive computers, presently available dive computers seem to fit into three distinct groups:

Group 1.	U.S. Navy limits	Suunto USN
Group 2.	Spencer 15% VGE	Oceanic Datamaster II
		Oceanic Datamaster Sport
		Oceanic DataMax Sport
		ORCA EDGE
		ORCA Skinny Dipper
		Suunto SME-ML
		U.S. Divers Datascan 2
		U.S. Divers Datascan 3
Group 3.	"Buhlmann limits"	Beuchat Aladin
		DACOR Microbrain
		DACOR Microbrain Pro
		U.S. Divers Monitor

Table 2. NoD Limits of Presently Available Dive Computers.

We have already discussed the Spencer NoD limits. The so-called "Buhlmann limits" are considerably more conservative for intermediate depths, e.g., allowing as little as 12 minutes at 100 feet. In view of Powell's extensive testing of 20 minutes at 100 feet, Group 3 would appear to be unnecessarily restrictive, particularly for scientific divers.

The Pilmanis Safety Stop

The effectiveness and importance of a safety stop, i.e., a decompression stop that is not required by either a dive table or dive computer, was dramatically demonstrated by Pilmanis (1976). As can be seen in Figure 2, following a dive to 100 feet for 25 minutes, as little as 2 minutes at 10 feet was shown to reduce the Doppler monitored bubble count by a factor of 5, and a 5 minute stop virtually eliminated any trace of measurable bubbles. No one who has seen these data can seriously argue with the decision to include a safety stop in the ascent procedure recommended for both scientific and recreational divers.

Most Dive Masters, some much less politely than others, insist that divers *"never get back on the boat with less than 500 psi in their tanks."* An admirable rule that has been conceived to prevent drowning. However, I believe that there are times when the rule should be changed to *"never get back on the boat with more than 100 psi."* I am refering to situations where serious repetitive multilevel diving is involved, and the avoidance of decompression sickness is an issue. Finding the boat with an ample air reserve is absolutely necessary, however, having done so, the proper procedure should be to use this reserve for as long a decompression stop as it will permit. Decompression stops are the diver's best friend, and I believe that burning air in a decompression zone makes much more sense than surfacing with an unnecessary reserve.

Ascent Rate

The sole remaining element of our ascent procedure is the selection of a proper rate of ascent. The U.S. Navy Diving Manual specifies a rate of 60 feet per minute. The question is whether a reduction in this rate is necessary and of value.

Intuitively, the probability of an air embolism caused by a ruptured lung is bound to be decreased as the rate of ascent is decreased, since a slower rate of ascent provides the diver with a greater time to react to the discomfort of lung overpressure. On the other hand, with the possible exception of some individual medical problem such as lung damage or disease, thirty years of Navy experience coupled with the carefully controlled and monitored experiments of Spencer, Powell, Thalmann and many others leads one to the conclusion that with normal breathing a 60 feet per minute ascent rate can reasonably be expected to produce ascents that are free of air embolism. If this conclusion is correct, a slower ascent rate can only be justified by its effectiveness as a means of decompression.

Is slower better?

Unfortunately, intuition is of little value when it comes to the evaluation of the effect of a reduced ascent rate on the decompression status of a diver. Instead, it is necessary to descend into the depths of decompression theory and deal with compartments, half times, nitrogen loading, etc. Having taken this journey, I will spare the reader considerable pain by presenting only the results of this exercise, preceeded by a brief review of the theoretical basis of the U.S. Navy dive tables.

The Navy model is comprised of 6 compartments. Each compartment is assigned a half time and an allowable nitrogen loading like that illustrated in Figure 3. The faster compartments have greater allowable nitrogen tensions, and as it turns out they control deeper dives, an example of which is presented in Figure 4. Here, for a 110 foot dive for 20 minutes, the 10 minute compartment is seen to control the dive. By contrast, as illustrated in Figure 5, for a dive to 70 feet for 50 minutes, the controlling compartment is the 40 minute compartment. Note that the 5 and 10 minute compartments have both nearly saturated, however, neither can control this dive since neither can ever reach its allowable nitrogen loading at this depth. As the depth becomes progressively shallower, the control passes to slower and slower compartments.

We are now in a position to evaluate the effectiveness of a slower ascent rate, and for this purpose I have chosen to contrast 3 distinct ascent procedures: 1) a direct ascent to the surface at 60 feet per minute, 2) a reduced rate of 30 feet per minute beginning at a depth of 60 feet, and 3) a 60 feet per minute ascent followed by a 3 minute safety stop at 15 feet. The results of 3 representative examples are presented in Figures 6, 7, and 8. As can be seen, in every example the 30 feet per minute ascent rate produced a reduced nitrogen loading, but this gain was dwarfed by the reduction achieved by a 3 minute stop at 15 feet. As a final example of the ineffectiveness of a slower ascent rate, I calculated the time at 15 feet that would produce nitrogen loading that was equal to or less than that produced by the 30 feet per minute ascent rate. The ***maximum*** benefit of a 30 feet per minute ascent rate when diving to the Navy NoD limits is equivalent to 0.8 minutes at 15 feet!

If you are puzzled by these results, let me suggest that you think about the effect in the following way. The reduced ascent rate is approximately equivalent to a stop at one half the depth from which it began for a time equal to the increased ascent time. Our example of 30 feet per minute from 60 feet is equivalent to a 1 minute stop at 30 feet. No wonder it is ineffective when compared to a 3 minute stop at 15 feet.

Are all safety stops the same?

It is important to note that while the 3 minute safety stop is always a much more effective means of decompression than a reduced ascent rate, as can be seen in Figure 9, neither is particularly effective when diving to the Navy NoD limits at shallow depths. The fractional nitrogen loading (referenced to the Navy NoD limits) achieved by our two modified ascent procedures has less than a 5% effect for depths shallower than about 60 feet. Upon reflection, the reason for this is obvious. For dives greater than about 100 feet, the 5 minute compartment controls the dive, and thus the relevant time scale for decompression is 5 minutes. However, as stated earlier, as the depth becomes shallower, control shifts to slower and slower compartments, thereby rendering the 3 minute stop increasingly less effective.

If we turn the problem around and ask what safety stop is required to limit the fractional nitrogen loading to 90% of the Navy limits (a value that is comparable to Spencer's reduced NoD limits), the result is the strong depth dependence shown in Figure 10. A safety stop of as little as 1 minute following a NoD dive to 190 feet is quite effective, but a comparable result following a NoD dive to 40 feet requires over 20 minutes. Also shown in Figure 10 is a curve that represents 10% of the bottom time, which is seeen to be a reasonable approximation. Keeping in mind that this is a purely theoretical evaluation, it would seem that a proper safety stop should be the greater of 3 minutes or 10% of the bottom time.

Summary

In my judgment, the reduced NoD limits that were tested by Powell and are incorporated in at least 8 presently available dive computers are appropriate for both scientific and recreational divers. However, a reduced ascent rate is unwarranted. It is not necessary for the prevention of air embolism, and as a means of decompression it is theoretically ineffective and has no experimental basis. Is it harmful? Not directly. However, if divers are allowed to believe that it is an effective means of decompression, they are likely to skip a safety stop. Pilmanis demonstrated that a safety stop is as valid a concept as Newton's Laws of physics, but a slower ascent rate is more properly associated with alchemy; an even bigger hoax than cold fusion has turned out to be.

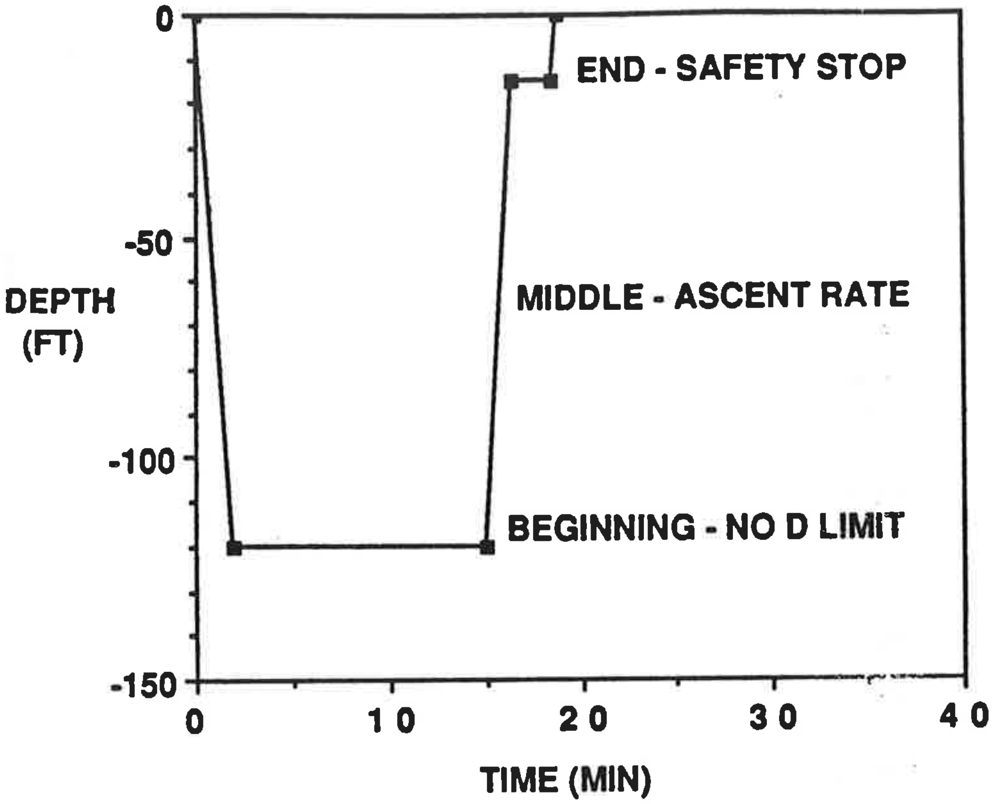


Figure 1. Basic elements of an ascent procedure.

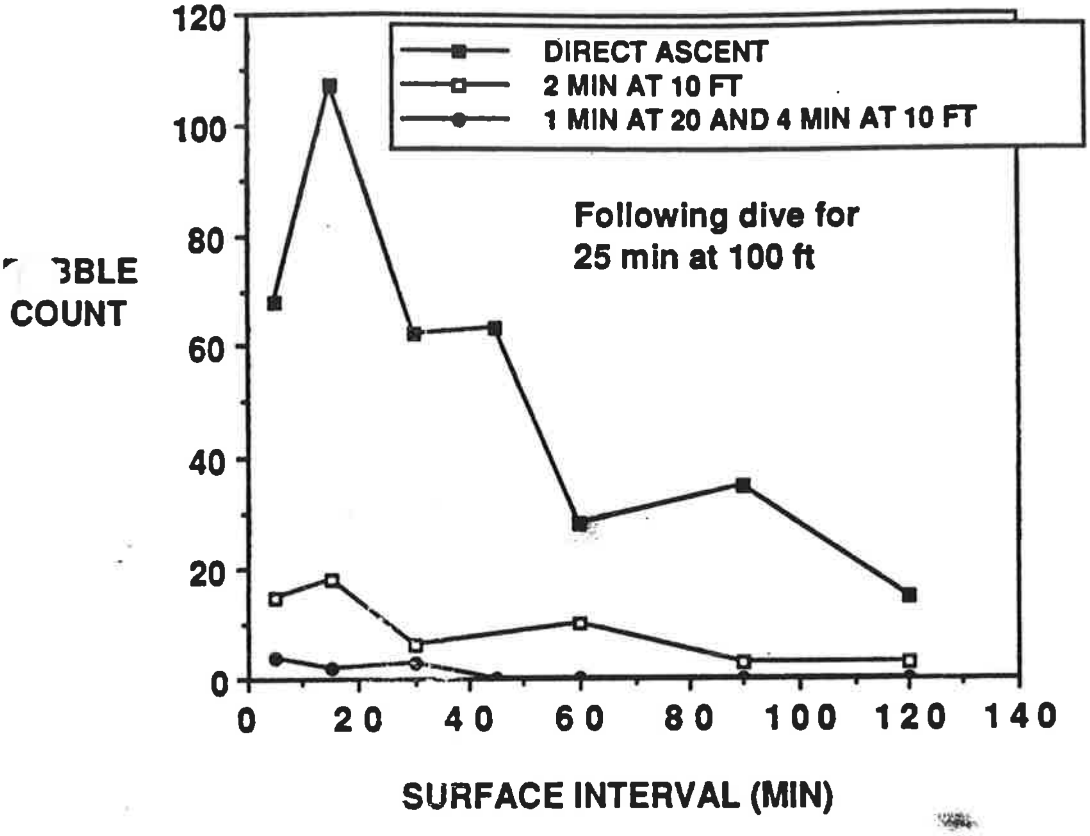


Figure 2. Pilmanis experiments on ascent procedures.

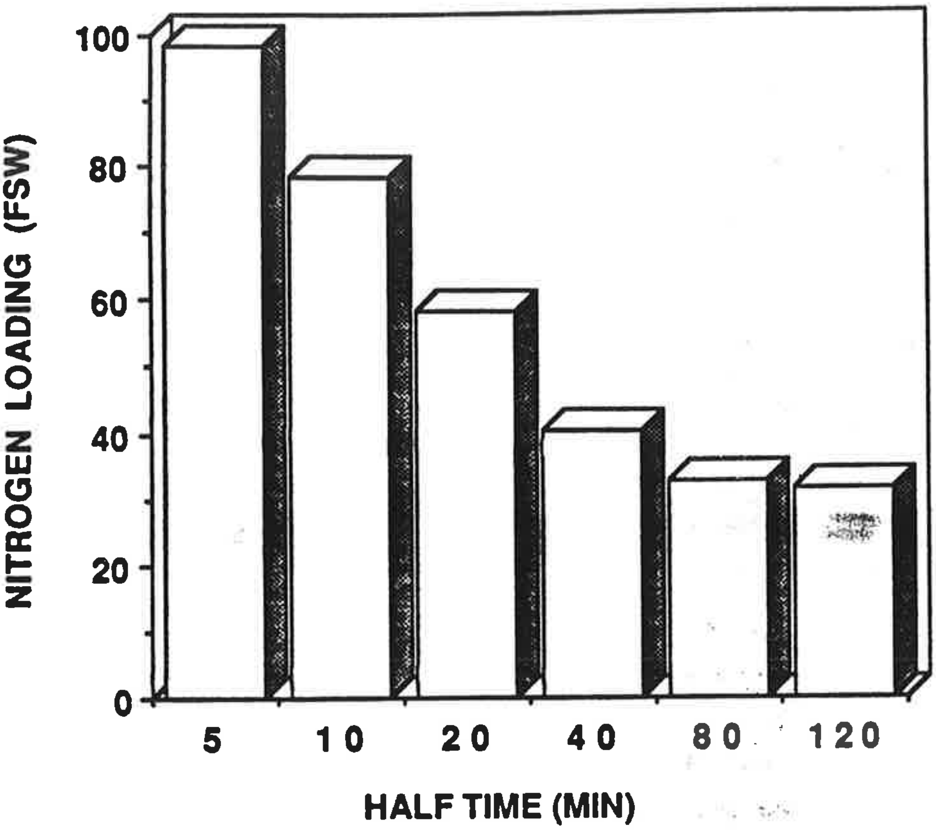


Figure 3. U.S. Navy theoretically allowable nitrogen loading.

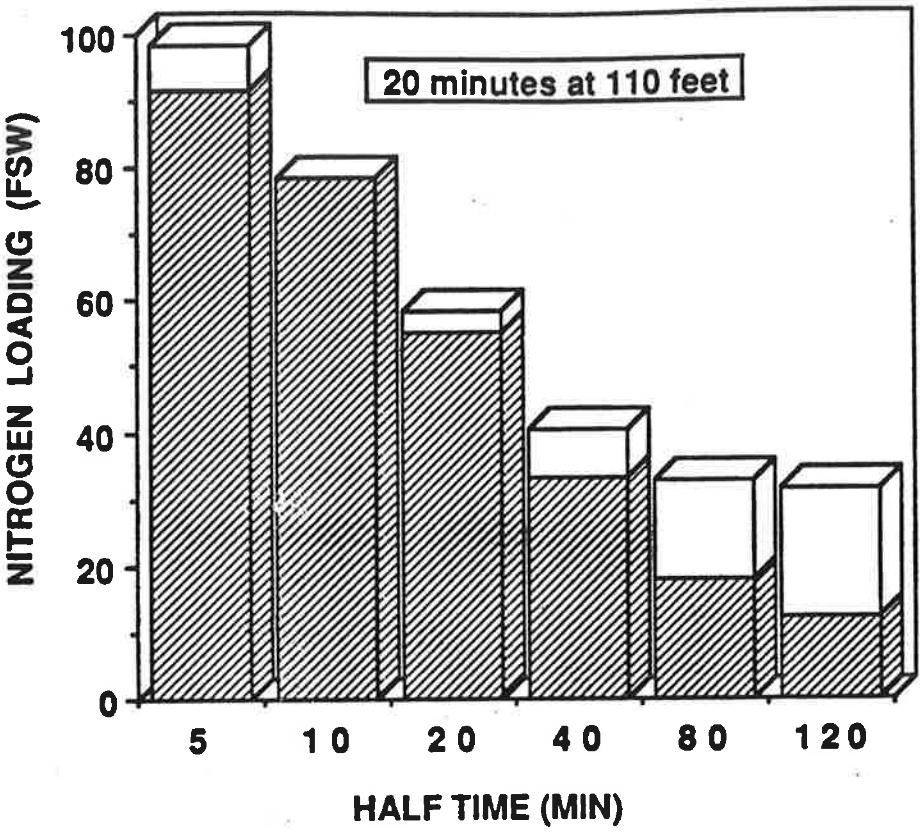


Figure 4. Example of U.S. Navy Theory.

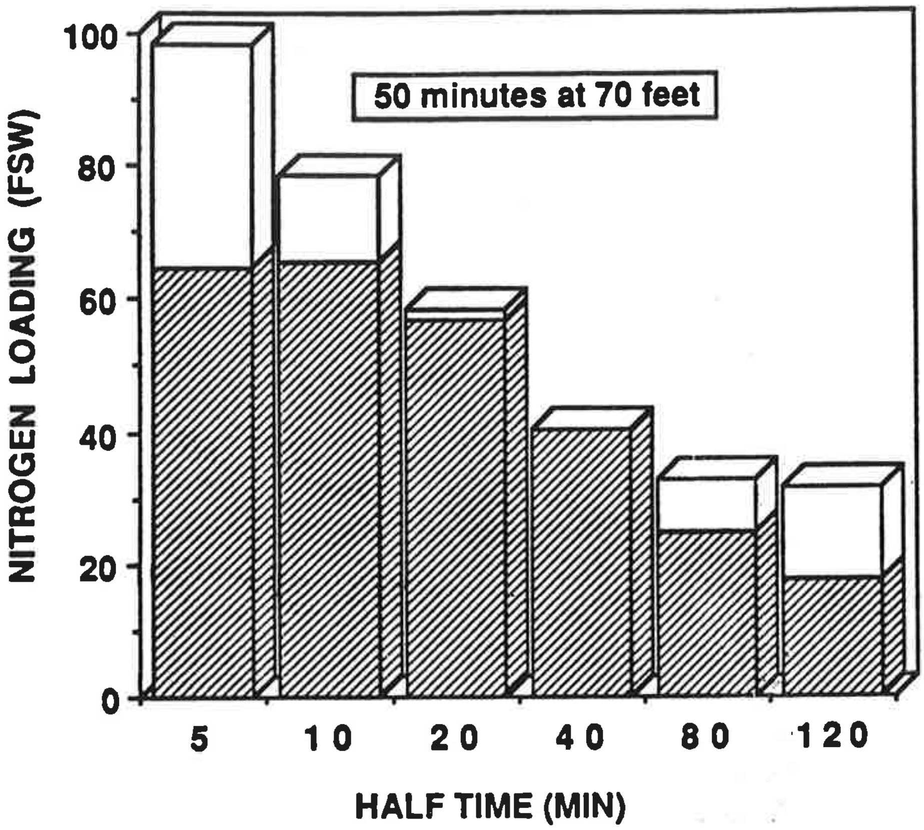
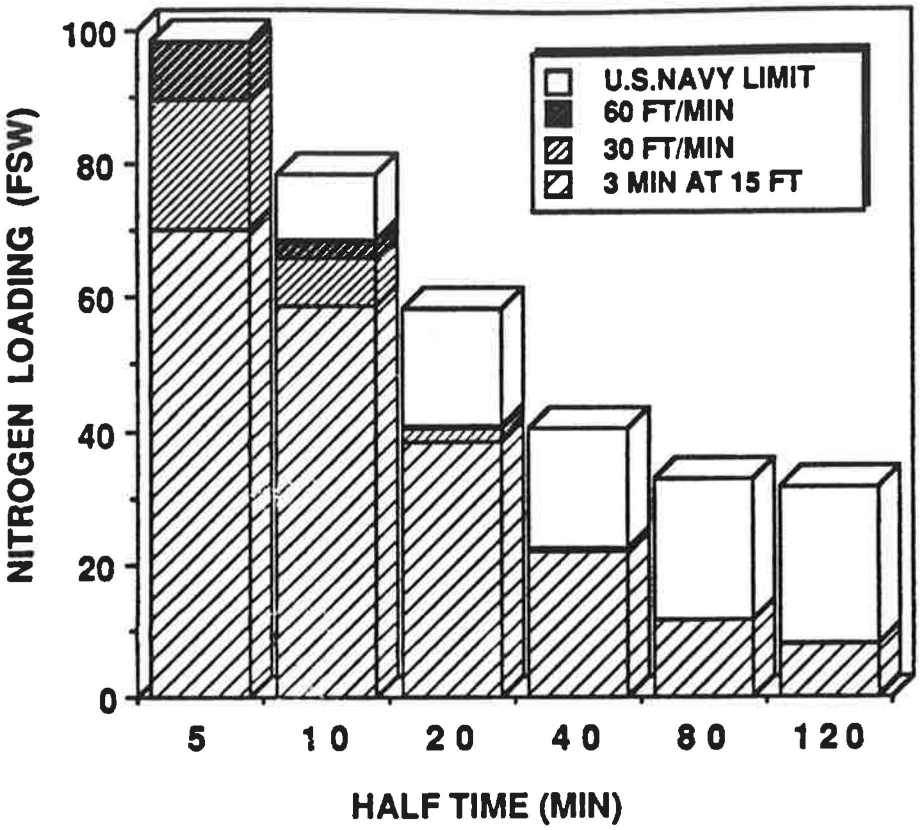


Figure 5. Example of U.S. Navy theory.



igure 6. Differing ascents following 5 minutes at 190 feet.

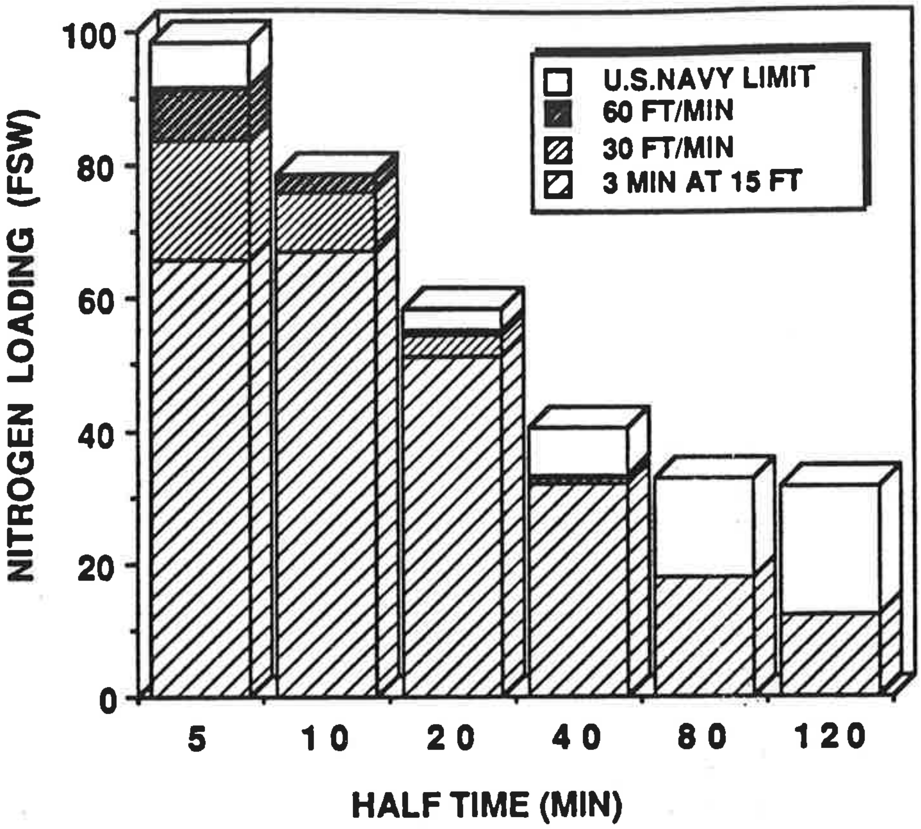


Figure 7. Differing ascents following 20 minutes at 110 feet.

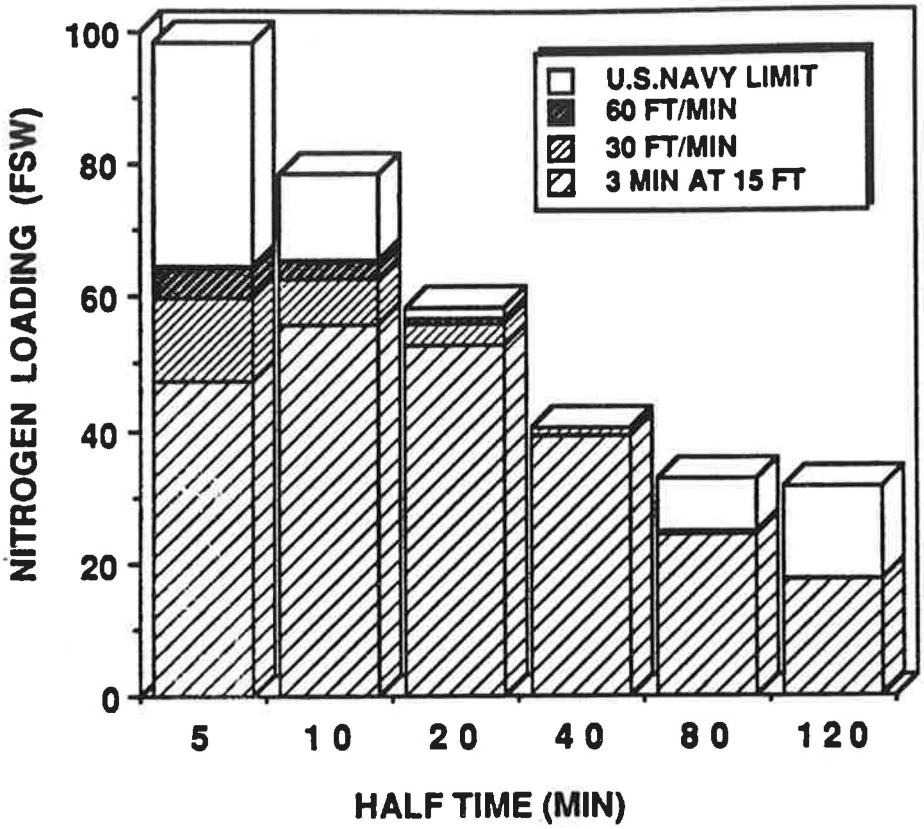


Figure 8. Differing ascents following 50 minutes at 70 feet.

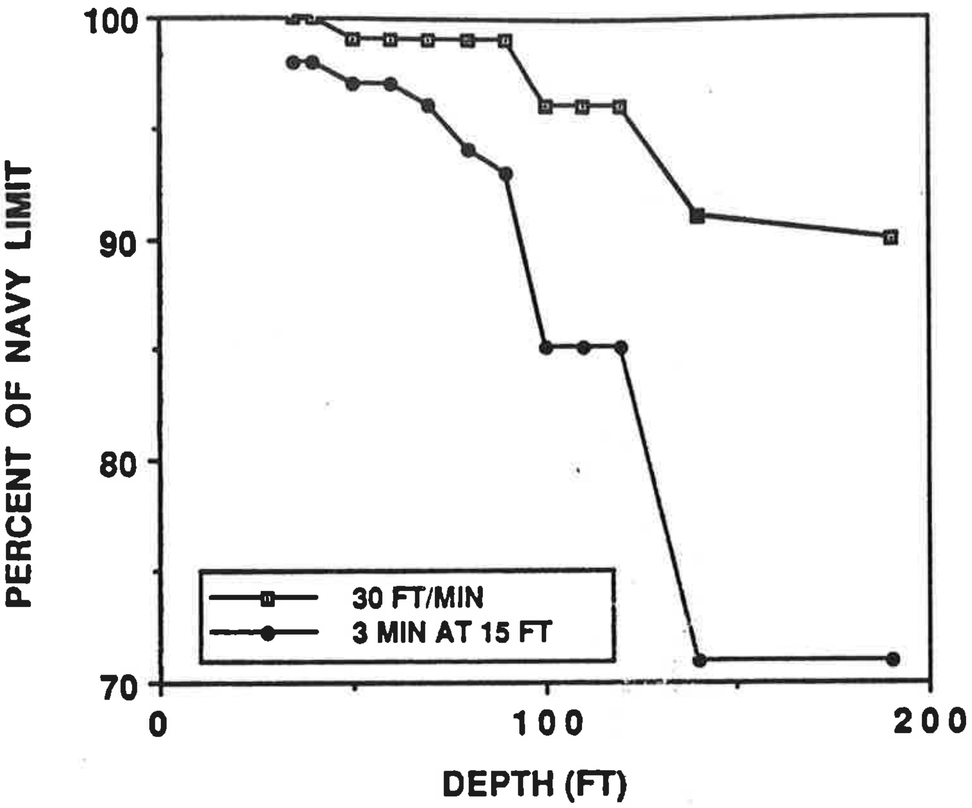


Figure 9. Depth dependence of modified ascent procedures.

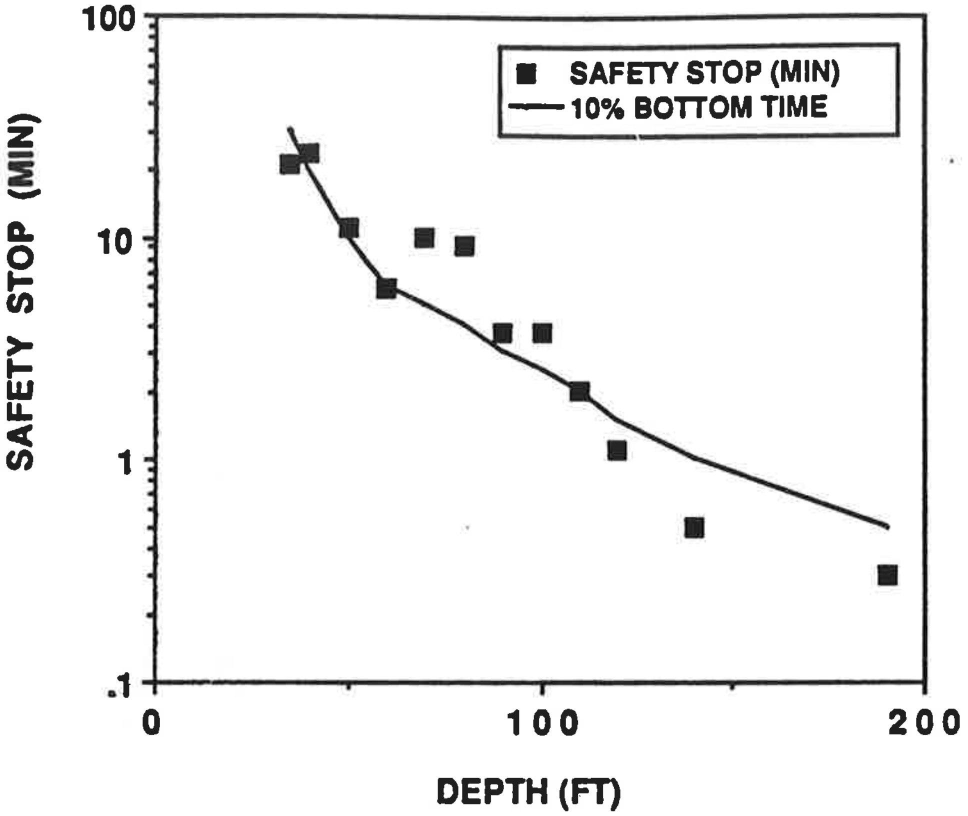


Figure 10. Safety stop required to produce 90% of Navy limits.

Summary

In my judgment, reduced no-decompression limits are a proper departure from the U.S. Navy Dive Table. In addition, a safety stop has been demonstrated to be effective and, in my opinion, it should be included in any ascent procedure recommended for recreational divers. However, I do not believe that a reduced ascent rate is a particularly good idea. It is virtually impossible for an experienced diver to achieve, let alone a new diver. There is no experimental evidence that any reduction from the U.S. Navy requirement of 60 ft/min is necessary for the prevention of air embolism. A slower ascent rate often results in an increased nitrogen loading, and where it does achieve a reduction, the reduction is dwarfed by that achieved by a safety stop. It probably doesnt really hurt anything, but it certainly should not be used in place of a safety stop.

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Author

Dr. Lewis has degrees in physics, aeronautics, and applied mathematics. His PhD was awarded by Caltech in 1967. He has been an active diver for over thirty years, is the author of fourteen technical publications, and holds two U.S. Patents with one other pending. He is one of the principal designers of the OCEANIC Datamaster II, Datamaster Sport, and DataMax Sport Dive Computers.

Vague Notions, Broad Assumptions, and Bold Guesses:
A Layman's Guide to Dive Tables and Dive Computers

By Karl W. Shreeves and John E. Lewis

Petty Officer Andrew Catto should have died. Or at least been writhing in agony. It is 1907, and Catto has survived an "impossible" dive. The Royal Navy considers diving below 110 feet extremely dangerous. Catto went to 180. No one before has spent more than 10 minutes that deep without getting bent. Catto stayed 29.

Catto's miraculous dive was based on Haldane's new decompression model and dive tables: Haldane's notions, assumptions and guesses -- vague notions, broad assumptions and bold guesses that today remain virtually unchanged in recreational dive tables and dive computers.

When Men were Men and Goats were Divers

All modern decompression models can trace their origin to John Scott Haldane, a Scottish physiologist who was commissioned by the Royal Navy to solve the decompression problem. He was a pragmatic scientist who applied his skills to real people with real problems. Before working for the Royal Navy, he studied mines and mine laborers; designing improved mine procedures, first aid methods and rules for miner safety. *Results* counted for Haldane, and he was guided by the principle that what worked was what counted.

Haldane approached dive tables looking for results. He first gathered all available documented dives; times, depths and whether the diver was bent. Next, to gain additional data, he put together a team to experiment with goats, which were known to have respiratory and circulatory systems similar to humans. From the goat experiments, Haldane derived his famous 2:1 ratio: A subject, diver or goat, can stay at a depth for an unlimited time and then ascend to a shallower depth without the bends provided the absolute pressure was no more than halved. This provided his starting point for a decompression model.

Haldane's Assumptions

In order to build his decompression model, Haldane began with some reasonable assumptions. He reasoned that during a dive, a diver's tissues absorb nitrogen, and upon surfacing the pressure of nitrogen in the tissues (*tissue pressure*) exceeds the surrounding pressure. Haldane concluded that the tissues tolerate a specific excess nitrogen *tension*, but beyond this limit bubbles form causing the bends. He called this limit the *metastable limit.*

Haldane also made some assumptions regarding how tissues absorb and release nitrogen. He knew that if the body absorbed nitrogen evenly, it would absorb the maximum possible at any given depth in about an hour; something that his experiments showed to be incorrect. He therefore conjectured that some body tissues absorb and release nitrogen quickly and others slowly. In order to predict the tissue absorption and release, he introduced the *half time* concept.

A half time works like this: A tissue at any depth absorbs nitrogen, and the deeper the depth the more nitrogen it can absorb. After a time equal to the half time, the tissue will absorb 50% of the potential nitrogen it can absorb at that depth. After an additional half time, half of the remaining tension will be absorbed, resulting in 75% of the maximum absorption possible. For all practical purposes, after 6 half times the tissue can be considered to be 100% saturated at that depth. When the diver surfaces, Haldane's theory predicted that the tissue releases nitrogen exactly the same way. It releases half its nitrogen loading with each half time until, after six half times, the tissue can be considered completely desaturated. Thus, a tissue with a 5 minute half time absorbs and releases nitrogen 4 times faster than one with a 20 minute half time.

Haldane's Model

Haldane believed that the body consisted of an infinite spectrum of tissues, but he recognized that decompression profiles could be calculated by choosing only a few representative theoretical tissues. He choose a 75 minute half time (commonly refered to as a "75 minute tissue") as the slowest in his model. He did not say that there were not any that were slower, but rather that none slower absorbed enough nitrogen to be consequential. Similarly, he picked a 5 minute tissue as the fastest. Haldane choose the remaining 10, 20, and 40 minute half times easily. He guessed.

Graphically, Haldane's model looks like Figure 1. Each box represents a theoretical tissue, and the 40 fsw (18 psig) level represents Haldane's metastable limit. According to this model, if a diver surfaces with more than this allowable nitrogen loading, he runs a high risk of being bent. Now let's look at a no-decompression (NoD) dive based on Haldane's model. Since we are concerned with recreational diving, all of our examples will be NoD dives. In Figure 2, the theoretical tissues have absorbed nitrogen during an 80 foot dive for 5 minutes, which is the no decompression limit (NDL) of Haldane's model. The 5 minute tissue has reached the metastable limit, making it the controlling tissue, i.e., the tissue that forces the dive to end. Because the 5 minute tissue is the fastest, it always controls NoD diving based on Haldane's model. Without decompression diving, Haldane would not have needed the other theoretical tissues.

What Works Is What Counts

At this point Haldane had a model and tables, which he knew had no validity unless successfully tested. During tests, his tables proved themselves as his dive team reached unprecedented depths and durations. Within 2 years, divers worldwide had universally accepted Haldane's tables (Although it took the U.S. Navy 5 years to adopt them). Haldane's model and tables are the ancestors of all recreational dive tables and dive computers available today.

The Right Way, the Wrong Way, and the Navy Way

The U.S. Navy adopted Haldane's tables in 1912, but by the late 1920s grew dissatisfied with them. Through their own experience and research, the Navy discovered that Haldane's model had flaws. During revisions starting in the 1930s and continuing through the 1950s, the Navy modified Haldane's model. For simplicity, we will discuss them all at once. Among the problems the Navy noted were:

- Some of Haldane's table profiles were too conservative. For example, a 100 foot dive for 20 minutes required 15 minutes of decompression.

- Other table profiles, particularly where long decompression was required, were not sufficiently conservative and frequently produced bends in divers.

- The invention of scuba in the 1940's produced a need for crediting a diver for nitrogen released between dives. Before scuba, divers seldom made more than one dive a day.

To correct these limitations, the Navy made the following changes:

1. The Navy hypothesized that the metastable limit for each theoretical tissue differed and that the faster tissues tolerated more tension than that allowed by Haldane's model.

2. The Navy introduced the M-value concept as a mathematically convenient way to express the metastable limit. The M-value is the allowable tissue tension expressed in units of feet of sea water (fsw).

3. The Navy developed Table 2 for repetitive dive procedures, which for the first time provided for surface interval credit.

4. The Navy added a 120 minute tissue to accomodate the long decompression dives for which Haldane's model had proven to be inadequate.

With these changes, the Navy model looks like Figure 3. It is readily apparent from this graph why 5 minutes at 80 feet (Haldane's NDL) is far from approaching the Navy NDL. It is interesting to note that for the Navy model a different theoretical tissue controls NoD diving at each different depth: the deeper the dive, the faster the controlling tissue.

An example of the Navy model is presented in Figure 4, where for a 110 foot dive the 10 minute tissue is seen to control the dive. By contrast, as illustrated in Figure 5, for a dive to 70 feet for 50 minutes, the controlling tissue is the 40 minute tissue. Note that the 5 and 10 minute tissues have almost the same amount of nitrogen. After 50 minutes, both have nearly saturated, however, neither of these tissues can control the 70 foot dive because at this depth neither can ever reach its allowable limit. As the depth becomes progressively shallower, the control passes to slower and slower tissues.

This change of control from a faster to a slower tissue makes *multilevel* diving possible with dive computers and some dive tables. The increased bottom time at shallower depths does not come from nitrogen release, but rather from the fact that a slower theoretical tissue, one which has not reached its allowable limit, becomes the controlling tissue. This is also why multilevel diving requires a computer or table specifically designed for this purpose.

Surface Interval Credit - A Problematic Wrinkle

The need to develop surface interval credit introduced a new problem for the Navy. Figure 6 illustrates the Navy model after a 60 foot dive for 60 minutes followed by 30 minutes at the surface. We see that for this example the 40 minute tissue has the greatest loading, but that does not mean that it will necessarily be the controlling tissue on the next dive. The problem is: which theoretical tissue will affect a repetitive dive? The answer is: it can be any theoretical tissue depending on the first dive, the surface interval, and the depth of the second dive.

Modern dive computers can calculate each theoretical tissue independently and determine how each affects a repetitive dive, but the Navy did not have this luxury in 1950. They needed a simple table that any diver could use regardless of the circumstance. In order to meet this goal, the Navy reasoned that if they based their repetitive dive control on the *slowest* tissue, any combination of decompression diving could be handled safely. The entire Navy Repetitive Dive Tables are based solely on the 120 minute tissue. This is equivalent to requiring that all the tissues release nitrogen at the same rate as the120 minute tissue regardless of the half time assigned to predict nitrogen absorption.

Like Haldane, the Navy recognized that any theory is only as good as its performance. It only counts if it works. The Navy evaluated these tables in a test program involving Navy divers, with test criteria being whether a diver developed decompression sickness. These tests demonstrated that the concept was valid, but they were limited to a single repetitive dive, leaving multiple repetitive diving uncharted territory until recently.

The Navy released their tables in the mid 1950s. Despite the fact that they were designed and tested for diving typical for working Navy divers, they have served recreational divers remarkably well.

The Empirical Strikes Back

Ironically, just as the Navy began to develop their tables, hyperbaric physiologists had begun to suspect that Haldane's basic assumptions, the very foundation of the Haldanian model, were wrong. They came to recognize that experimental and real-world data failed to support the Haldane concepts of a metastable limit and theoretical tissues.

First, bubbles form in the body too easily. In the laboratory, a pure liquid requires over 1000 times more dissolved nitrogen to form a bubble in the body. If the body were pure liquid, we could dive something like 6 miles, instead of less than 30 feet, without decompression sickness, regardless of dive time. This apparent contradiction led physiologists to suspect that some more complicated mechanism exists that helps bubbles form.

In the early 1970s, the Doppler ultrasound flowmeter, which detects bubbles in the blood stream, confirmed the presence of "silent" (nonsymptom producing) bubbles in volunteers after dives to or near the Navy NDL. This discovery cast strong doubt on Haldane's concept of a metastable limit. Dive tables seem to prevent decompression sickness by controlling the size and quantity of bubbles, rather than preventing them altogether.

About this same time, physiologists were also questioning the idea of theoretical tissues. While Haldane didnt think his model tissues corresponded to particular body tissues, he did believe that there was some relationship. Unfortunately, experience with many cases of decompression sickness puts this in some doubt. If there were some relationship, there could be expected to be some correlation between decompression sickness symptoms and the theoretical tissue that had been violated. In fact, symptoms such as limb and joint pain occur quite independently of the theoretical violation; whether it is the 5 minute or the 120 minute tissue, the symptomatic effect is the same.

Today hyperbaric physiologists question whether theoretical tissues relate to body tissues at all, and for this reason refer to them as "compartments". The simple fact is that no one knows what, if anything, is the relationship of Haldane's theoretical tissues and human physiology.

For all practical purposes, theoretical tissues are nothing more than a mathematical device that allow us to account for the fact that the body does not absorb and release nitrogen with a single characteristic time scale. The dive table or dive computer designer simply uses this mathematical model to predict time limits that are consistent with proven experimental data. There is no correct number of compartments or correct values for half times. Any model is acceptable if it conforms to experimental data. Once again, what works is all that counts.

Why even use the Haldanian model if its basic premises are in doubt? Because it works, . . . to a point. Haldanian models make predictions that are based on a limited set of tests, but sometimes the math, when applied to different circumstances, predicts that a particular diving practice is safe, when experience proves it is not. For example:

Repetitive deep dives. Dive tables and dive computers say that there is nothing wrong with planning multiple repetitive dives to depths of 120 feet and beyond. However, tests by both the U.S. Navy and the Royal Navy show problems. This type of diving seems to be outside the reliability of Haldanian theory.

Sawtooth Profiles. According to Haldanian models, there is no reason not to follow shallow dives with deep dives, or if multilevel diving, to go up and down at will. However, there is considerable anecdotal evidence that this practice can cause decompression sickness. The Haldanian model retains its validity best by starting deep and working shallower during a multilevel dive and by making each repetitive dive progressively shallower.

Rate of Ascent. The Haldanian model says little about rate of ascent. An increase in the ascent rate from 60 feet per minute to as much as 240 feet per minute produces only minor changes in predicted nitrogen loading. However, rates of ascent that are faster than 60 feet per minute have been found to cause problems, although more than likely a result of lung expansion injuries in most cases.

The fact is that there has been little or no study on rate of ascent. There is no proof that a rate slower than the standard 60 feet per minute is safer or *vice versa.* The only ascent procedure documented to benefit divers is the "safety stop", i.e., a decompression stop not required by a dive table or computer. Tests by Dr. Andrew Pilmanis of the University of Southern California demonstrated that this procedure substantially reduced Doppler detectable bubbles on dives to the Navy NDL.

Caveat Emptor

All this brings us to some points that divers evaluating dive tables and dive computers should keep in mind:

1. *An empirical data base is mandatory.* Only what works counts. Therefore, it is prudent to select a table or computer that is based on proven test data.

2. *Be aware that not all dive tables and dive computers have had extensive testing.* Some permit dive profiles far beyond the base of existing data.

3. *Know what the test "envelope" is.* Only documented dives to a model's depth and time limits are valid tests. Safe use of a computer or table by thousands of divers may prove it is being used safely, but it does not prove the model's validity.

4. *There is no such thing as a bends-free table or computer.* There are too many variables and the Haldanian model is imperfect. Any time you dive you incur some risk, however slight, of decompression sickness. The only sure way to avoid all risk is to stay in the boat.

The Recreational Dive Planner

So where does the Recreational Dive Planner (The RDP--The Wheel and Table versions) developed by Diving Science and Technology (DSAT) and distributed by PADI fit into the evolution of decompression models? How does it provide longer repetitive dives and shorter surface intervals? Did the RDP follow established practices for dive table development?

The RDP was developed by Dr. Raymond Rogers for recreational diving. Rogers began by analyzing the U.S. Navy model. He determined that while the 120 minute compartment was necessary for decompression diving, it had little to do with recreational diving. Extensive computer analysis showed that if a diver makes only NoD dives, particularly to reduced limits, the 120 minute compartment rarely absorbs a significant amount of nitrogen.

Rogers went on to comprise a model of 14 compartments with half times ranging from 5 minutes to 480 minutes. He found that 98% of all NoD repetitive dives can be controlled by a 60 minute compartment. (The other 2% occurs after long shallow repetitive dives, which are covered by a simple rule printed on the RDP.) The result is that while a 2 hour surface interval is required to reduce the residual nitrogen time in the Navy table by one half, the RDP requires only 1 hour.

Rogers' theory was interesting and conformed to Haldanian concepts, but it had to work. Therefore, DSAT tested the RDP, . . . and tested it, . . . and tested it. It has the most extensive testing of any contemporary model. Dr. Michael Powell of the Institute of Applied Physiology and Medicine in Seattle, Washington Doppler monitored over 1000 dives, including repetitive, multilevel, multiday dives (up to 4 dives per day for 6 days in a row) that are representative of recreational diving. During the test dives, there were no cases of decompression sickness, and Doppler detectable silent bubbles were minimal. Powell's tests validated Rogers' hypothesis.

The DSAT Tests and Dive Computers.

Prior to the 1987 DSAT experiments, repetitive diving beyond the limits set by the U.S. Navy Repet Table was at best uncharted territory; "at best" because both the U.S. Navy and the Royal Navy tried other theoretically based hypotheses and failed to safely exceed these limits. The successful DSAT experiments represent the only demonstrated basis for a liberalization of the U.S. Navy Table control of repetitive diving. The DSAT experiments validated Rodgers' hypothesis, and at the same time provided the basis for a new dive computer algorithm.

At present, three dive computers, the Oceanic Datamaster Sport and Datamax Sport and the U.S. Divers Datascan 3, use the same hypothesis for repetitive dive control that was used to construct the RDP. Typical examples of multilevel diving with these dive computers are presented in Table 1 together with identical multilevel dives that were successfully tested by DSAT. The differences are seen to be minor, typically less than one min.

Comparisons with the DSAT data for repetitive dives would show equally close results, but rather than present these data, the RDP has been used for comparison so that we can simultaneously examine the gains over the U.S. Navy Repet Table. These results are presented in Table 2, where the dive computers and the RDP are seen to have remarkably similar performance. This should not come as much of a surprise, since they are based on the same hypothesis.

Thanks to the DSAT test data, both the RDP and this new class of dive computer have the data base to prove their validity.

The Haldanian Outer Limits and How Not to Go There

With Haldane's original concepts in question, the only truly safe areas in dive table and dive computer usage are the *tested* areas. What counts is what works; what does not work must be avoided, and what has not been tested should be treated with great caution. The following points will help to keep you on the "safe side".

1. *Know the basis of your dive table or dive computer.* What is the mathematical model? More importantly, what empirical data is it based on? If it's a computer, will it permit dives based on surface interval credit more liberal than the RDP?

2. *Dive conservatively with any model.* Tables and computers are mathematical approximations of existing data. The closer you get to any limit, the more the risk. Dive well within the limits to minimize your risk.

3. *Ascend at 60 feet per minute or slower, and make a safety stop at the end of any serious dive.* A safety stop is the only ascent procedure with proven benefit.

4. *Avoid repetitive dives deeper than 100 feet.* Choose 80 feet as a limit if you really want to play it safe. Avoid this kind of

diving no matter what dive table or dive computer you use. Let the divemaster chase the anchor.

5. *Avoid sawtooth dive profiles.* Regardless of the table or computer you use, make the deepest dive of the day first, and make successive dives shallower. On multilevel dives, start deep and work shallower. Bouncing up and down can mean a trip to the recompression chamber.

Depth	DSAT Based Dive Computer	DSAT Data
130 ft	11.5 min	12 min
50	42.7	41
110 ft	16.5 min	17 min
65	10.2	11
100 ft	19.7 min	20 min
50	29.4	29

Table 1. DSAT Based Dive Computer multilevel dive performance compared to DSAT test data.

Depth	U.S. Navy Table	RDP	DSAT Based Dive Computer
130 ft	10 min	10 min	11.0 min
0	55 (SI)	60 (SI)	60 (SI)
90	14	18	16.9
0	37 (SI)	37 (SI)	37 (SI)
60	16	30	29.8
100 ft	20 min	20 min	19.7 min
0	46 (SI)	48 (SI)	48 (SI)
80	17	16	18.6
0	60 (SI)	60 (SI)	60 (SI)
60	16	36	35.6

Table 2. DSAT Based Dive Computer repetitive dive performance compared to RDP and U.S. Navy Tables.

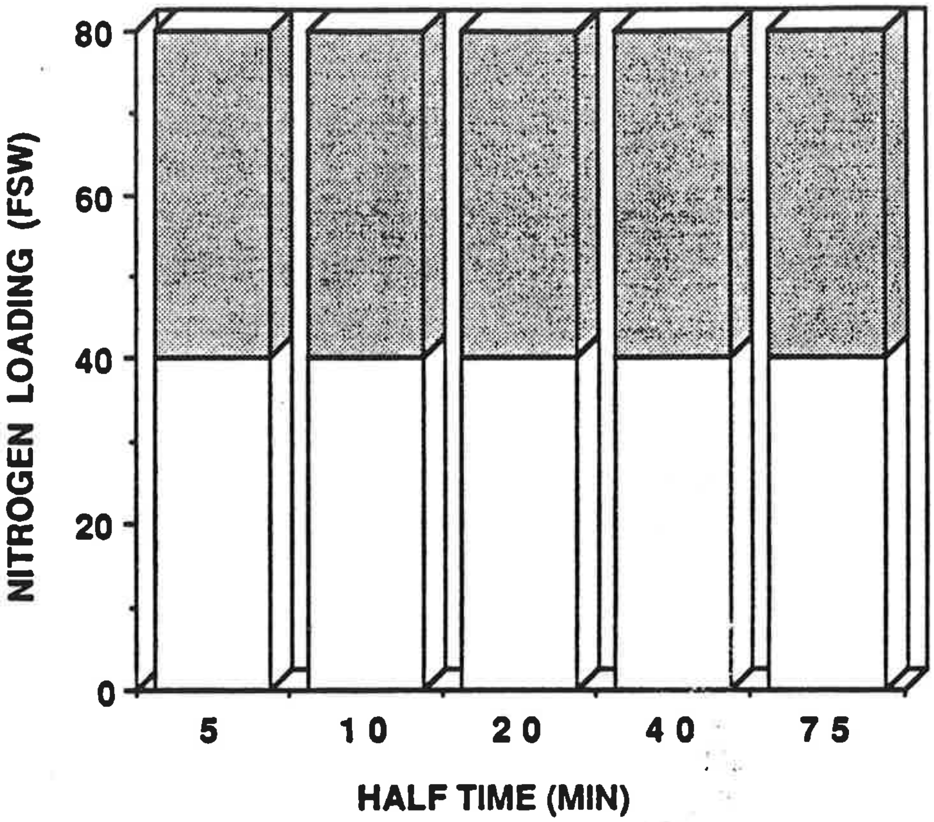

Figure 1. Haldane's Model.

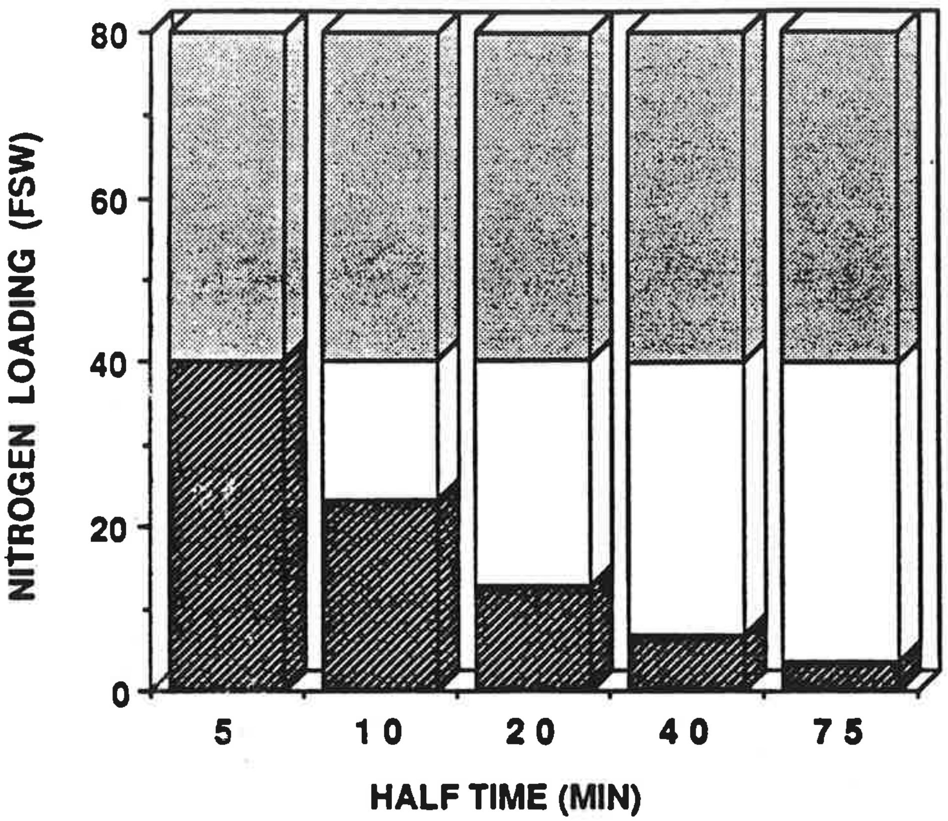

Figure 2. Haldane's Model in Action.

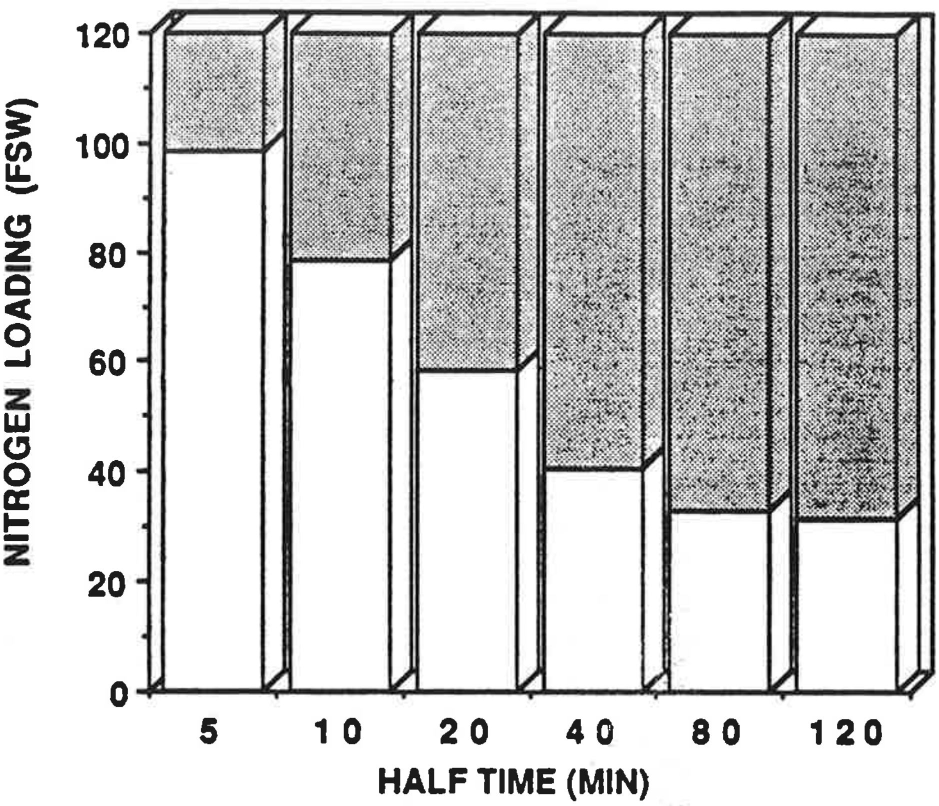

Figure 3. U.S. Navy Table Model.

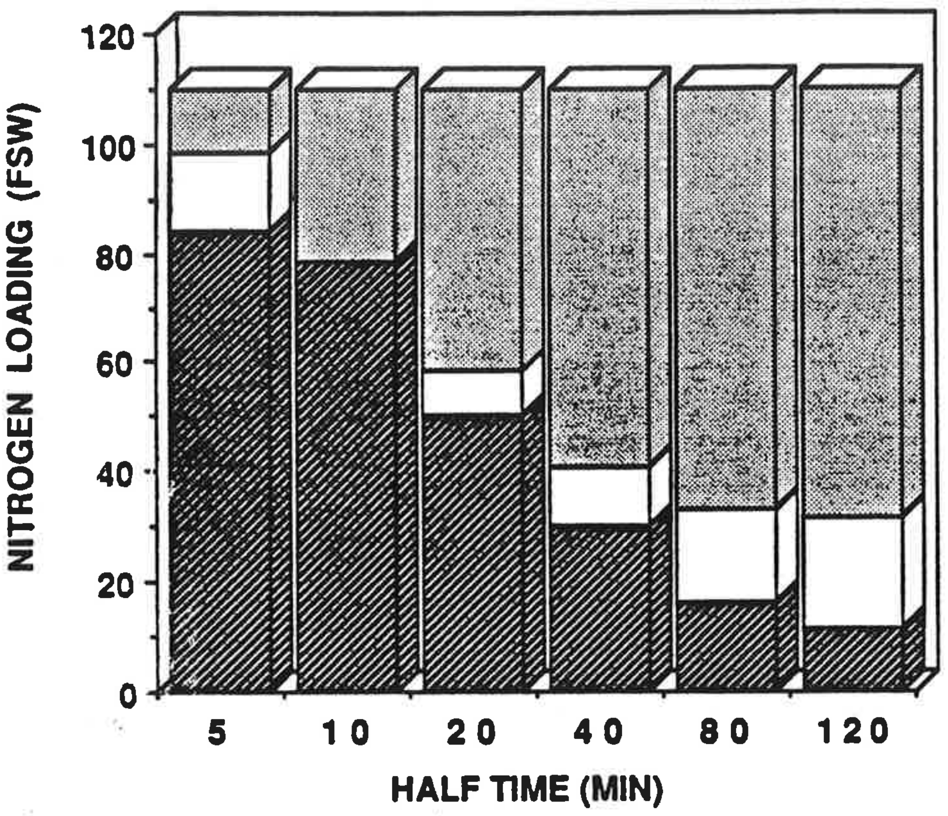

Figure 4. U.S. Navy Dive Control at 110 ft.

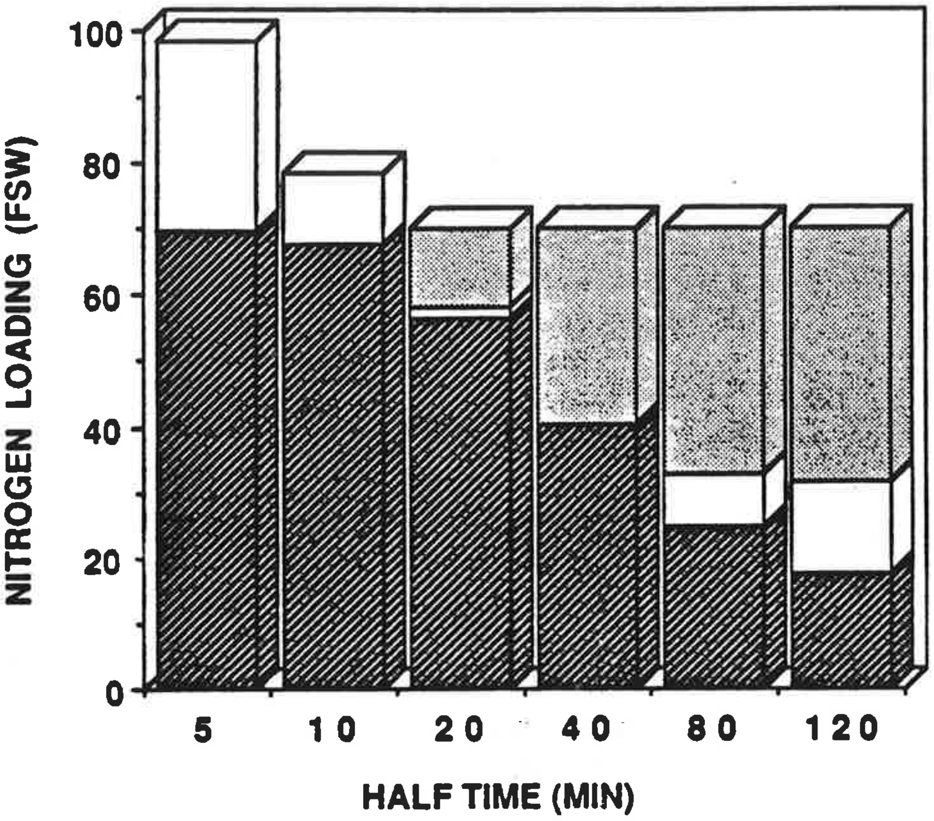

Figure 5. U.S. Navy Table 50 minutes at 70 feet.

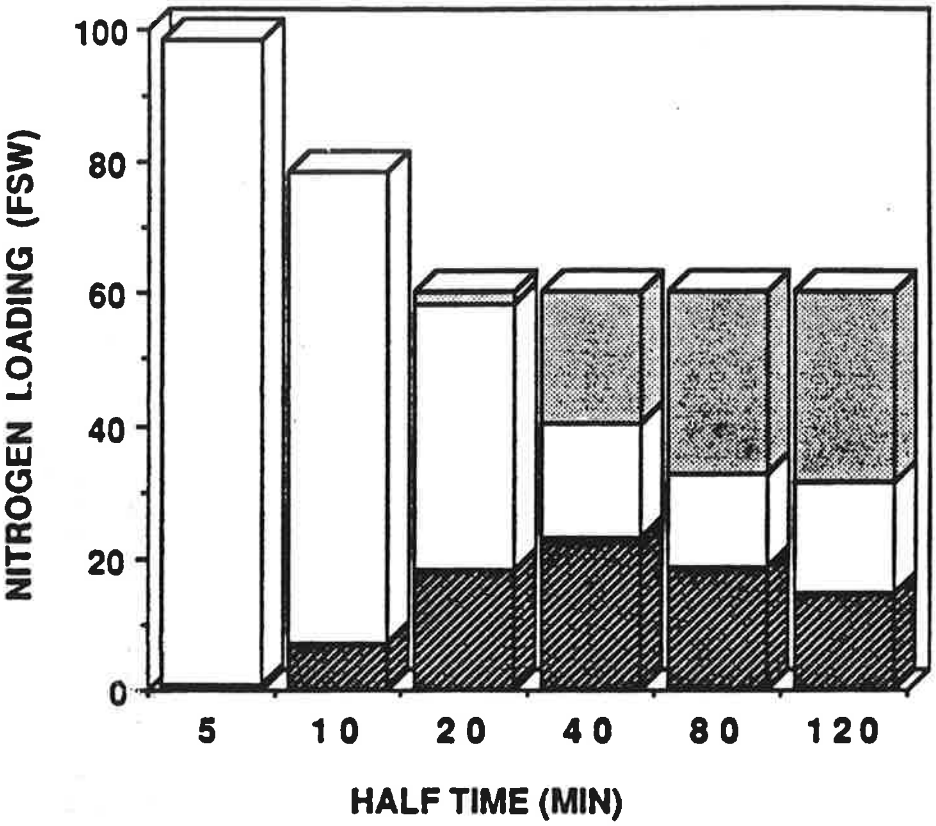

Figure 6. U.S. Navy Theory - 60 min at 60 ft
followed by 30 min Surface Interval.

Multilevel Diving

by
John E. Lewis, PhD

Introduction

If your diving consists of one single-depth no-decompression dive per day, you need only memorize ten numbers that are the No-D limits between 40 and 130 ft, and you dont really need either a Dive Table or a Dive Computer. If you choose to dive repetitively but still limit your dives to a single depth, a Dive Table is necessary. A Dive Computer will save you some work, but it is does not do anything that cannot be done with a Dive Table. However, add multilevel diving to your agenda, and a Dive Computer is an absolute necessity. The introduction of Dive Computers to recreational diving is truly revolutionary, and the basis of that revolution is multilevel diving.

What is multilevel diving and how does it work?

Plan your dive such that the deepest depth is first. Let us suppose that this is 120 ft. The Dive Computer's pre-dive scroll indicates a 13 min allowable No-D bottom time, and sure enough after 13 min, the Dive Computer will display zero No-D time remaining and indicate that you must ascend. If you happen to check your Dive Computer during your ascent, at a depth of 90 ft or so, a remarkable thing will occur. The No-D time remaining will begin to increase, and the shallower the depth, the greater the No-D time will become. Has nitrogen elimination during our ascent somehow allowed this additional time? Not really. It is a consequence of the mathematical model that in one form or another is used by all Dive Computers. This model, invented by Haldane some 80 years ago, consists of multiple compartments, each with its own time scale and allowable saturation depth. The fastest compartment has a 5 min "half-time". This means that at any depth, it will reach one-half of that value in 5 min. This fastest compartment also has the greatest allowable saturation depth, which is approximately 90 ft. It is this compartment that restricted the No-D time at 120 ft to 13 min. When we ascended above 90 ft, this compartment no longer plays any role since it is content to surface after saturation at any shallower depth. Since the other compartments have not reached their allowable limits, additional No-D time remains, and we are not talking about small increases in bottom time. Properly executed, our 120 ft maximum depth dive could have a bottom time in excess of 60 min, and ultimately be limited only by available air.

Sounds great. Is it safe?

Good question. No matter how logical they may sound, all decompression hypotheses or theoretical predictions require validation. When Dive Computers were first introduced, Carl Edmonds(1986) in reference to multilevel diving objected that *"There has been no satisfactory trial performed to test these concepts"*. At the time, he was quite right. Karl Huggins(1983) tests while significant were quite limited in scope. However, in 1987 Michael Powell presented the results of an extensive set (over 750 exposures) of multilevel and repetitive dives. These tests like those of Huggins used human volunteers in hyperbaric chambers where depth simulation could be accurately controlled. The test subjects were Doppler monitored for nitrogen bubbles, and over twenty examples of various depth combinations were tested. No cases of decompression sickness occured, and at most low grade bubbles were detected.

Cant I use my Dive Table to do the same thing?

You can, but you should not. Dennis Graver first described the technique in 1979. If you look at your Repet Dive Table, you will find that for a particular Group each depth has an equivalent time. For example, take U.S. Navy Group D. 12 min at 120 ft is equivalent to 29 min at 50 ft. Thus, if we ascended to 50 ft after 12 min at 120 ft, and if the equivalent time concept were valid, we could stay an additional 71 min at 50 ft. Interesting concept, and while it may be valid, it leads to multilevel diving that is well beyond those profiles that were tested as can be seen in the following examples:

	Powell Test	Dive Computer*	USN Table
Test No.1	100 ft/20 min	19.7 min	22 mi
	50 ft/29 min	29.4 min	53 min
Test No.2	130 ft/12 min	11.5 min	11 min
	50 ft/41 min	42.7 min	71 min

Table 1. Examples of multilevel diving.

Actually, even if it were not well beyond the tested envelope, using a Dive Table for multilevel diving is virtually impossible to perform under most circumstances.

Well, should I throw away my Table and buy a Dive Computer?

Buy the Dive Computer (mind you, of a particular brand), but dont throw away your Dive Table. It has one undeniable advantage over a Dive Computer - it is virtually indestructable. Further, with a minor addition to your Dive Log, it can be used as a backup in the event that your buddy drops his tank on your Dive Computer. The addition to your Dive Log that I have in mind is your Repet Group, which your Dive Computer knows, but most likely does not display [The OCEANIC Datamaster II(Lewis,1988) is an exception]. You can determine it for yourself by viewing the pre-dive scroll for a 60 ft repet dive. Suppose it reads 32 min, and you are using the DSAT Table. In the Repet Table 32 min allowable No-D time at 60 ft is Group H. Record this Group and the time that you surfaced, and you have just established a coherent procedure for returning to your Dive Table. The same technique can be used with the U.S. Navy Table, but here you must use the Residual Nitrogen Time since the No-D limits are different. Do this as soon as you get into the boat if you want to keep diving because even if your clumsy buddy offers you his Dive Computer it does not know your particular diving history, and you cant use it safely.

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* The OCEANIC Datamaster Sport was used for this evaluation, but all Dive Computers with comparable No-D limits will exhibit virtually identical multilevel diving performances.

U. S. Navy Dive Tables

by

John E. Lewis, PhD

Introduction

The U. S. Navy Dive Tables consist of at least four identifiable categories: no-decompression limits, decompression schedules, repetitive dive control, and other rules such as ascent rates. These Dive Tables have been used by the Navy and recreational divers for over thirty years, and the result has been a remarkable safety record. On the other hand, the introduction of live aboard dive boats and Dive Computers have dramatically changed the pattern of recreational diving, and if for no other reason, I believe it is useful to review the data base and identify known and potential limitations of these Tables.

No-Decompression Limits

There are three relatively recent experiments that deal with no-decompression (No-D) limits that are relevant to our discussion: Thalmann(1984), Spencer(1976), and Powell(1987).

Thalmann attempted to increase the Navy No-D limits, and he tested a total of 107 exposures without any occurrences of decompression sickness (DCS) to the following limits:

- 60 ft / 66 min
- 100 ft / 30 min
- 120 ft / 24 min
- 150 ft / 14 min

However, a careful reading of his report indicates that these experiments actually included a short decompression stop at 10 ft, although the actual time spent at 10 ft is not documented. More

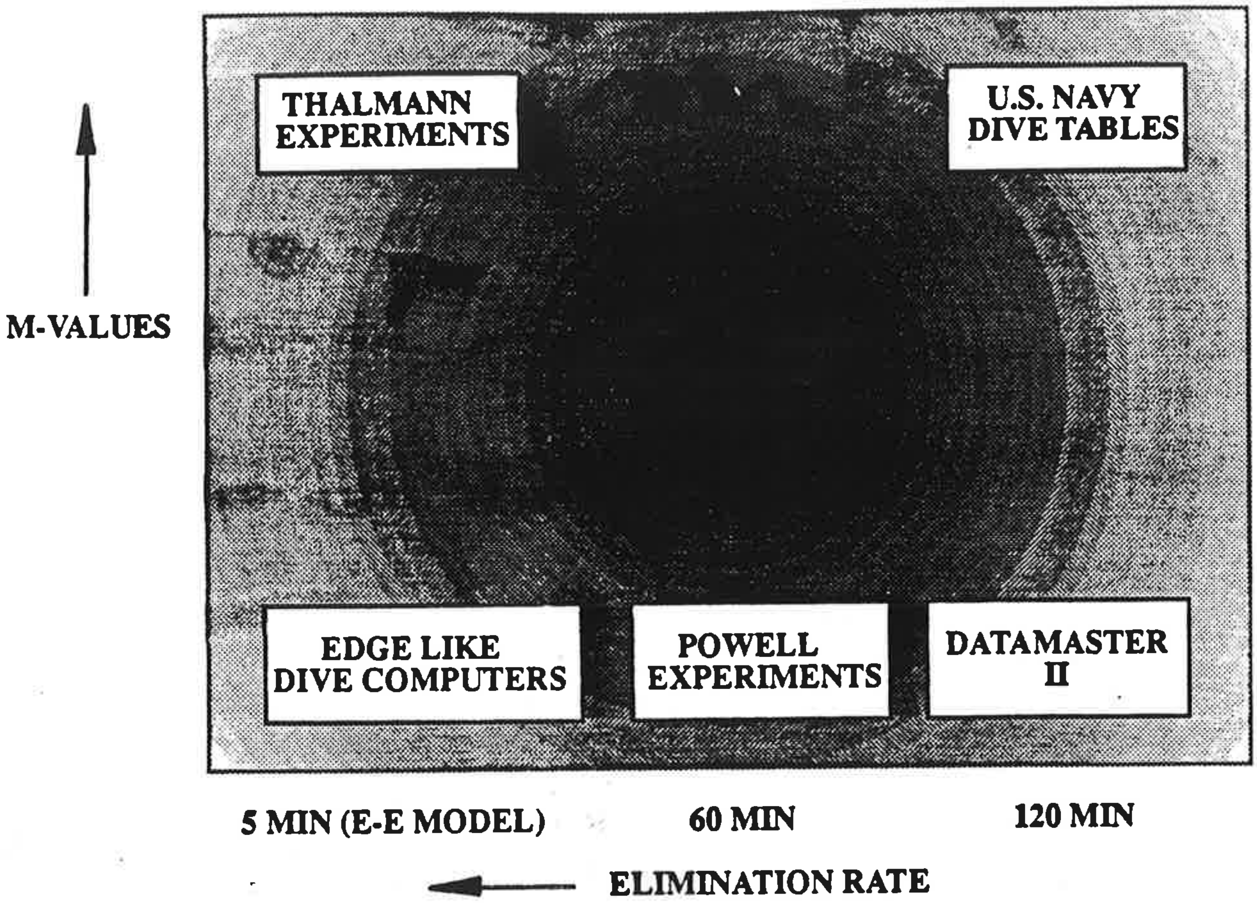

Figure 1. Dive Computer Design Envelope

important is that during a second trial of 100 ft / 30 min, 4 cases of DCS occurred out of 20 exposures. Thalmann did not use Doppler monitoring of his test subjects, and this result leads me to conclude that if clinical symptoms of DCS is the only diagnostic, what does not work is more important than what may work on occasion.

Spencer tested to the Navy limits. He also Doppler monitored his test subjects for nitrogen bubbles as well as recording clinical symptoms of DCS. Each of the following examples produced high grade bubbles and at least one case of DCS:

- o 60 ft / 60 min
- o 70 ft / 50 min
- o 25 ft / 720 min

The one example of a bottom time that he tested that did successfully exceed U.S. Navy No-D limits was 150 ft / 10 min.

Powell tested reduced No-D limits that closely resemble Spencer's empirical formulae for 15% VGE. These limits amount to approximately a 10 ft reduction from the Navy limit, e.g., 100 ft / 20 min, 90 ft / 25 min, etc. He also Doppler monitored his test subjects. These experiments produced no DCS and at most low grade bubbles.

It seems probable that diving to the U.S. Navy No-D limits has worked so well for so long because a large percentage of diving was performed well within these limits. Lately, the recreational diving community seems to be beseiged with well meaning but poorly founded new rules. Reduced No-D limits do not fit into this category. They are well documented and, in my judgment, deserve full acceptance by the entire community.

Decompression Schedules

"The success of the Standard Air No-Decompression Limits are in stark contrast to the abysmal failure of some of the Standard Air Decompression Tables" (Thalmann, 1986). Actually, Thalmann's

admonition refers to decompression diving that is well beyond the U.S. Navy No-D limits, and in general is not relevant to recreational divers. What is more important is that divers recognize that Haldane's model, which is the basis for the Navy Decompression Tables and all Dive Computers, is just that - a model. It frequently has problems when confronted with situations that Haldane never envisioned, such as extraordinary decompression schedules, and as we will discuss next, repetitive diving. Recreational divers, even experienced ones, should avoid exceeding the No-D limits, and this rigorously applies to divers using Dive Computers as well as the Navy Tables.

Repetitive Diving

If you are diving with the Navy Tables and your buddy is diving with a particular class of Dive Computer that has a decompression algorithm that is called the "E-E Model"*, he will probably be bragging about how much more bottom time he has for the next dive. But before you throw away your Dive Tables, let me show you an example of this Dive Computer in action:

o 120 ft/10 min for 6 dives in a row with 30 min surface intervals.

Isnt that great? It might be . . . except for the following example that was attempted by the Royal Navy (Leitch and Barnard,1982):

o 120 ft/10 min for 3 dives in a row with 120 min surface intervals.

This Royal Navy test produced a serious case of DCS , and other attempts by both the Royal Navy and the U.S. Navy to exceed the limits on repetitive diving set by the Navy Repet Table have largely met with failure. Further, while the Navy Table was

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* See Thalmann(1984) for a discussion of E-E Models, Edmonds(1987) for an evaluation of Dive Computers using this algorithm, and Lewis(1988) for the description of an alternative.

rigorously validated for a single repetitive dive, multiple repetitive diving was not tested.

Performing multiple repetitive dives is largely uncharted territory. Largely, but not entirely. Powell's experiments at reduced No-D limits include at least one example of four dives in one day, and these tests used surface intervals approximately one-half that required by the Navy Tables for the same residual nitrogen time. These tests were completely successful, and with the one reservation that the repetitive depths that were tested were limited to 90 ft, I believe that they validate the use of the Navy Tables for multiple repetitive diving providing reduced No-D limits are observed.

I am reluctant to propose an arbitrary rule, but multiple repetitive dives deeper than 100 ft can prove to be unsafe, and at best it is uncharted territory.

Ascent Procedures

The Navy Tables call for a 60 ft/min ascent rate. Recently, the recreational dive community has been confronted with numerous calls for a reduced ascent rate, with some proposals as low as 20 ft/min. First of all, for depths greater than about 60 ft, a reduced ascent rate will lead to an ***increased*** nitrogen loading. Since air embolism is not an issue here, any deviation from Navy procedure is clearly unwarranted. Second, while an ascent rate of 20 ft/min at shallower depths will theoretically work in the diver's favor, the value has not been demonstrated, and, more importantly, it is virtually impossible for an experienced diver to achieve, let alone a newly certified diver. What is the alternative? The demonstrated effective alternative is a decompression stop.

At the recent AAUS Workshop on Dive Computers on Catalina Island, Andy Pilmanis presented the results of a series of experiments that he conducted in 1976. He performed 3 clean dives to a depth of 100 ft for 25 min. Each dive had a different ascent procedure. Dive No. 1 had a direct ascent to the surface. Dive No. 2 had a 2 min stop at 10 ft. Dive No. 3 had a 1 min stop at 20 ft and a 4 min stop at 10 ft. He Doppler monitored the test subject (cleverly made anonymous by the use only of his initials A.P.), and I have taken the liberty of replotting his data, which are presented in Figure 1. As can be seen, the direct ascent produced a bubble count in excess of 100. A 2 min stop at 10 ft reduced this count by a factor of 5, and a 5 min decompression stop virtually eliminated any trace of bubbles.

In my judgment, following the U.S. Navy ascent rate of 60 ft/min but with the addition of a "Pilmanis decompression stop" is unambigously the proper ascent procedure for recreational divers.

Summary

All Dive Tables and Dive Computers require a decompression theory or hypothesis, and all decompression hypotheses require validation. The U.S. Navy Dive Tables are no exception. The data of Thalmann, Spencer, and Powell lead one to conclude that reduced No-D limits are a proper departure from the Navy Tables, and additional data of Thalmann clearly demonstrates that there are limits to the safe use of the Navy Decompression Table. Multiple repetitive diving beyond the limits validated by Powell are at best uncharted territory, and there are specific examples of repetitive dives to 120 ft or deeper that produce decompression sickness. There is nothing wrong with the U.S. Navy ascent rate of 60 ft/min, but a Pilmanis decompression stop is a demonstrably good addition.

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Author

Dr. Lewis has degrees in physics, aeronautics, and applied mathematics. His PhD was awarded by Caltech in 1967. He has been an active diver for over thirty years, is the author of twelve technical publications, and holds one U.S. Patent with two others pending. He is one of the principal designers of the OCEANIC Datamaster II, Datamaster Sport, and DataMax Sport Dive Computers.

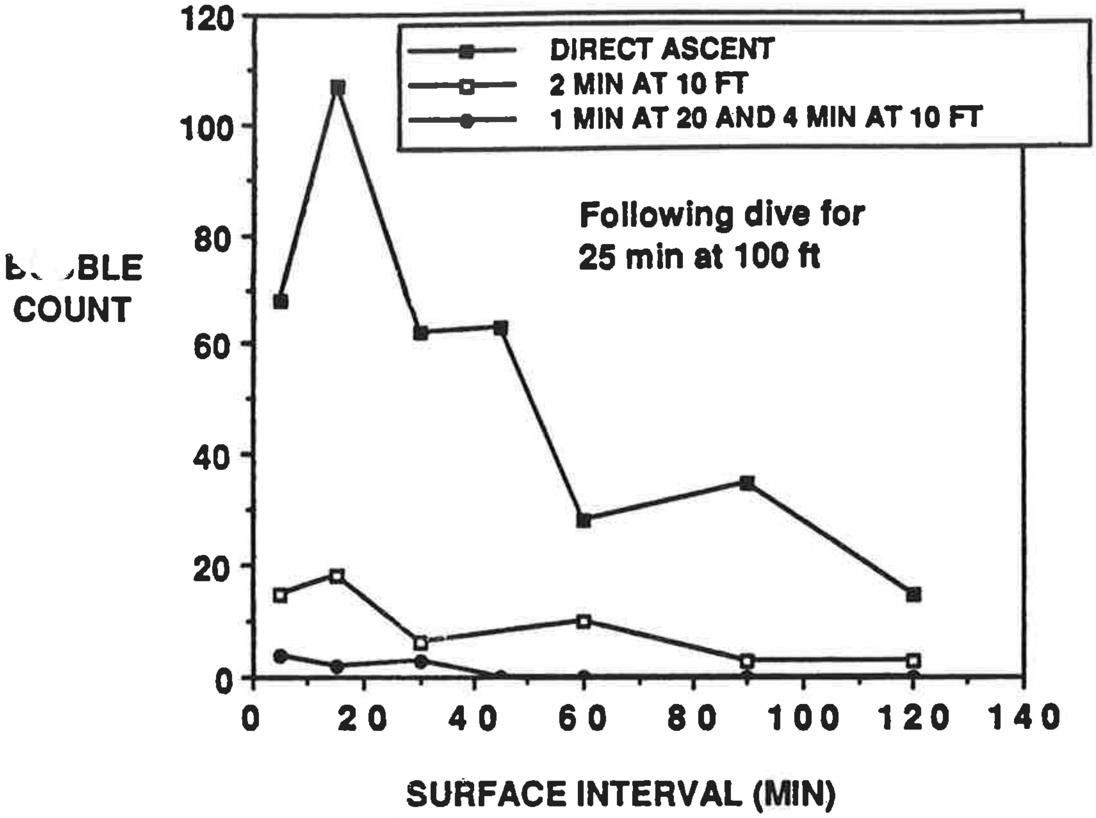

Figure 1. Pilmanis experiments on ascent procedures.

PADI Dive Tables, OCEANIC Dive Computers, and the DSAT Data Base

by

John E. Lewis, PhD

Introduction

If recreational diving were limited to a single no-decompression dive at one depth, decompression theory would be unnecessary. Allowable bottom times would be established experimentally and memorizing them would not be much more difficult than remembering your Social Security number. However, if we add either multi-level diving or repetitive diving to our agenda, a decompression theory is mandatory, and both dive tables and dive computers require one. Actually, the term decompression theory is something of a misnomer, because there is no theory of human physiology that can provide even our simplest requirement of No-D limits for a single dive. When it comes to decompression, what works is what counts, and a decompression theory is little more than a framework upon which we can place our experience. On the other hand, new ideas enrich our lives daily, and I am going to describe one that has recently contributed considerably to our sport. I shall begin by discussing this new idea, which is the hypothesis that forms the basis of the PADI Recreational Dive Tables, and I will attempt to provide a simple view of how the PADI Tables differ from the U.S. Navy Dive Tables. Next, we shall discuss the DSAT experiments, why they were required, and how they have contributed more to the recreational dive community than a new set of tables. Finally, I will share with you how these important data contributed to the design of a new Dive Computer, and present examples of what it has in common with the PADI Tables.

A New Hypothesis and a New Dive Table

The new hypothesis to which I referred was the idea of Ray Rodgers. He reasoned that since recreational divers limited their diving to No-D diving with reduced No-D limits, their repetitive diving could be governed by principles that were less restrictive than the U.S. Navy Repet Table. Without getting into the alternate theories used by the Navy or Rodgers, you can compare for yourself the predictions by the following exercise. Go into the U.S. Navy Repet Table to plan a repetitive dive to a particular depth following some exposure on an initial dive and any surface interval you choose. Note the Residual Nitrogen Time (RNT), and then increase your surface interval by two hours. For most examples, you will find that your RNT has decreased to approximately one-half of its former value. For example, reducing the U.S. Navy Group G to Group D requires two hours. At a depth of 100 ft, the Navy Repet Table indicates a decrease in RNT from 26 min to 14 min. If you performed the same exercise with the new PADI Tables, you would find that the required surface interval was one hour rather than two. Reducing the PADI Group H to Group B requires one hour, and at a depth of 100 ft, the PADI Table RNT decreases from 15 min to 7 min. Invent your own examples and try this rule of thumb. Some will work better than others, but the bottom line is that the surface interval required by the new hypothesis is effectively one-half of that required by the U.S. Navy Tables. Be sure that you use the RNT as the proper figure-of-merit, because the different No-D limits will paint a confusing picture if you try to use allowable No-D bottom time.

I believe that it is fair to say that any hypothesis that reduces your required surface interval by a factor of two can be called revolutionary....providing that it works. The later part of the preceding sentence is as important as the former. All decompression hypotheses require validation. PADI apparently concurred with this rule, and with all due respect to Ray's ideas, they elected to test them.

DSAT Multi-Level and Repetitive Dive Tests

Not long ago, the only data base specifically relevant to recreational diving consisted of the No-D limits tested by Merrill Spencer in 1976, a limited set of multi-level dives tested by Karl Huggins in 1983, and the repetitive dives tested some 30 years earlier by des Granges that are the basis of the U.S. Navy Repet Tables. In October 1987, that changed and changed dramatically. For the first time an extensive set of experimental data was presented to the public that dealt specifically with diving profiles that are characteristic of recreational diving: multi-level, repetitive, No-D dives at depths ranging between 40 and 130 ft. These experiments were conducted by Michael Powell of DSAT, and their purpose was the validation of the new PADI Tables and Rodgers's hypothesis. They consist of over seven hundred exposures, all of which were Doppler monitored. No cases of decompression sickness occurred, and only low grade bubbles were detected. These tests were rigorous, carefully controlled, and unambigously successful. They confirmed that as radical as Ray's ideas might have sounded, they had one important thing going for them. They worked! In addition, these experiments reaffirmed Huggins's earlier findings on multi-level diving, and further proved that multi-level diving and the new, more liberal repetitive diving could be safely combined.

These tests were clearly a major success for PADI, Rodgers, and Powell, but they represent more than that. They provide the only rational basis for any decompression algorithm that is more liberal than the U.S. Navy Repet Table.

A New Dive Computer

Prior to the 1987 DSAT experiments, repetitive diving beyond the limits set by the U.S. Navy Repet Table was at best uncharted territory. I say at best because both the U.S. Navy and the Royal Navy tried other theoretically based hypotheses and failed to safely exceed these limits. To my knowledge, the successful DSAT experiments represent the only demonstrated basis for a liberalization of the U.S. Navy Table control of repetitive diving. The DSAT experiments proved that Rodgers's hypothesis is valid, and at the same time they provided the basis for a new dive computer algorithm.

The OCEANIC Sport Dive Computers use the same hypothesis for repetitive dive control that was used to construct the PADI Recreational Dive Tables. I will not bore you with the gory mathematical details, but rather I will present examples of their performance compared to the data and the PADI Tables. Typical examples of multi-level diving with the OCEANIC Sport Dive Computer are presented in Table 1 together with identical multi-level dives that were successfully tested by DSAT. The differences are seen to be minor, typically less than one min.

Depth	OCEANIC Dive Computer	DSAT Data
130 ft	11.5 min	12 min
50	42.7	41
110 ft	16.5 min	17 min
65	10.2	11
100 ft	19.7 min	20 min
50	29.4	29

Table 1. OCEANIC Sport Dive Computer multi-level dive performance compared to DSAT test data.

Comparisons with the DSAT data for repetitive dives would show equally close results, but rather than present these data, I have chosen to use the PADI Dive Tables so that we can simultaneously examine the gains over the U.S. Navy Repet Table. These results are presented in Table 2, where the OCEANIC Sport Dive Computer and the PADI Recreational Dive Table are seen to have remarkably similar performance. This should not come as much of a surprise, since as advertized they are based on the same hypothesis. Note also the significant gains in bottom time of both beyond the U.S. Navy Repet Table.

Depth	U.S. Navy Table	PADI Table	OCEANIC Dive Computer
130 ft	10 min	10 min	11.0 min
0	55 (SI)	60 (SI)	60 (SI)
90	14	18	16.9
0	37 (SI)	37 (SI)	37 (SI)
60	16	30	29.8
100 ft	20 min	20 min	19.7 min
0	46 (SI)	48 (SI)	48 (SI)
80	17	16	18.6
0	60 (SI)	60 (SI)	60 (SI)
60	16	36	35.6

Table 2. OCEANIC Sport Dive Computer repetitive dive performance compared to PADI and U.S. Navy Tables.

Summary

OCEANIC's approach to dive computer algorithms have been one that I like to refer to as cautiously evolutionary. We believe that all decompression hypotheses require validation, and without a data base it is imprudent to rely on theory. The DSAT experiments have provided a data base that has allowed us to take a major step forward. The new OCEANIC Sport Dive Computers are based on the same hypothesis as the PADI Recreational Dive Tables, and thanks to the DSAT experiments they both have the data base to prove their validity.