12-2003

The Importance of Understanding How the Underlying Principles of Decompression Theory Apply Differently to Dive Computers Than to Dive Tables

Matthew R. Taitt

Matt Taitt

Senior Honors Thesis

The Importance of Understanding How the Underlying Principles of Decompression Theory Apply Differently to Dive Computers Than to Dive Tables

Thesis Director: Dr. Peter J. Carroll

University Honors Program

Southern Illinois University Carbondale

Fall 2003

Table of Contents

Even to those unfamiliar with the intricacies of diving terminology, "the bends" is probably a commonly known phrase. However, most outside the diving community do not fully realize the complexity of the ailment clinically known as Decompression Sickness (DCS) or Decompression Illness (DCI). It results from the nitrogen absorbed by the body under pressure being released too quickly as the ambient pressure around the body decreases. Unfortunately, it is not yet precisely known how much nitrogen the body can absorb or how quickly it can release the gas. H.V. Hempleman describes Decompression Sickness as a "man-made (disorder) for which the causative agent is easily established but the mechanism whereby the body reacts is not sufficiently understood."[1] Those in the diving world work on time-tested theories that have resulted in approximate limits on depth and time spent on a self-contained underwater breathing apparatus (scuba). For the typical recreational diver, these limits are imposed by one of two sources: a dive table or a dive computer. Divers use these devices to formulate a dive schedule, the planned maximum depth and the time of any given dive. Divers need to understand how the underlying principles of Decompression Theory apply differently to dive computers than to dive tables in order to curb the risk of DCS.

Diving Science

Contrary to Hollywood's erroneous images of secret agents jetting through the water on rocket-propelled fins, scuba divers are bound by the laws of science. Along with teaching students about diving equipment and skills, an introductory scuba course provides new divers with a rudimentary knowledge of physics. Obviously, people are surrounded by air at all times on land, but it is not so obvious that the air places weight on the human body along with all other things on earth. At sea level, a column of air measuring 1 inch by 1 inch reaching the limit of the planet's atmosphere weighs approximately 14.7 pounds. Therefore, this column exerts 14.7

pounds per square inch (psi) of pressure on all things. To simplify this number, 14.7 psi equals approximately 1 atmosphere (atm) of pressure. It should be apparent that a given volume of air will weigh less than the equivalent volume of water. In fact, water is roughly 800 times denser than air. The difference in density between air and water results in the column of air that is 1 inch by 1 inch and extends miles into the atmosphere exerting an equal amount of pressure as a column of salt water measuring 1 inch by 1 inch by 33 feet or a column of fresh water measuring 1 inch by 1 inch by 34 feet. Each of these columns also exerts a force of 1 atm; however, taking into consideration that a column of air always applies a force of 1 atm to water at sea level, a diver at 33 feet below the ocean's surface will be under 2 atmospheres of pressure absolute (ata). When dealing with pressure related to diving, measurements are taken in atmospheres absolute to ensure the inclusion of the column of air. So in the ocean, pressure increases by 1 ata for every 33 feet increment of depth – that is to say a diver is under 2 ata at 33 feet, 3 ata at 66 feet, and 4 ata of pressure at 99 feet. In addition to its relationship with depth, pressure is also related to volume. Working in the later half of the seventeenth century, Robert Boyle developed what is possibly the most important diving principle. Boyle's Law states that pressure and volume are inversely proportional as long as temperature is constant, so when pressure doubles then volume decreases by one-half. When scuba diving it is key for a diver to never hold his or her breath. For example, if a diver held his breath while at 33 feet and ascended to the surface, the pressure would fall by half, a decrease from 2 ata to 1 ata, but the volume of air in the lungs would double causing them to rupture. While Boyle's Law is primarily discussed regarding lung over-expansion injuries, it plays a significant role in the explanation of bubble growth in the body that will be discussed later. Another aspect of diving science key to Decompression Theory is air composition. As previously mentioned, nitrogen (N_2) is the gas of chief concern in the prevention of DCS. Air is comprised of roughly 79 percent nitrogen and 21 percent oxygen. Nitrogen is inert, having no effect on the body. Under normal breathing conditions, nitrogen enters and leaves the body at a ratio of 1:1.[2] However, at depth the "tissues take up (N_2) … under pressure and store larger than normal quantities of it."[3] Understanding pressure and how it affects the volume of a gas is crucial to the development of Decompression Theory.

Decompression Illness

To understand the importance of Decompression Theory, one must first be familiar with the severity of the illness. In an ongoing effort to understand DCS, Divers Alert Network (DAN) has been gathering information on reported cases since 1987.[4] While DAN has collected an enormous amount of data in the past 16 years, determining the probability of DCS occurring in recreational diving is nearly impossible given it is not known how many people participate in the sport each year; however, a 1963 study published by the United States Navy found that Navy divers had .69 percent frequency of DCS.[5] Of the 935 cases of DCS reported in the study, 54.7 percent reported noticeable symptoms within 1 hour of surfacing and 92.8 percent noticed signs within 12 hours.[6] A person suffering the effects of DCS can be recognized by several symptoms, but not limited to the following: headache, vertigo, fatigue, joint pain, burning or itching of the skin, sharp pain, motor weakness, loss of bladder or bowel control.[7] If left untreated, DCS can lead to permanent neurological damage, vascular diseases, severe headaches, a variety of emotional disorders, and in extreme cases death.[8] Given the harshness of DCS, a working knowledge of the malady should be understood to prevent it.

While the precise details of what is occurring in the body prior to the onset of DCS have yet to be determined, researchers, through the use of Doppler and X-ray technologies, have pieced together a general picture of the cause. At all times during a dive, a diver is intaking nitrogen into his body from the breathing gas, assuming nitrogen is some component of the mixture. Under pressure nitrogen saturates into the body's tissues due to the difference in blood pressure and tissue pressure. Since the blood pressure is higher than that in the tissues, the nitrogen that circulates through the blood via the lungs naturally flows into the tissues, and the rate of nitrogen movement from blood to tissue depends on the differential such that as the two pressures converge, the rate of gas uptake decreases.[9] Even though it is depth that affects pressure, the time spent underwater determines the degree of saturation.[10] While saturation is unavoidable, divers want to avoid supersaturation, the point at which the total gas pressure in the tissue is greater than what can be dissolved by the tissue under its current state of pressure.[11] It may seem illogical for a tissue to be saturated beyond 100 percent, but Boyle's Law can explain the phenomenon. As the diver descends, the pressure increases so the volume of gas saturated in the tissues decrease, but supersaturation can occur when a diver ascends too rapidly, allowing the pressure of the surrounding water to fall faster than that of the gas in the tissue, which results in the gas forming bubbles instead of being released into the blood as it would with proper ascent conditions.[12] Upon ascension, the pressure decreases so the volume of gas in the tissue increases, but when the ascent is rapid, the pressure change occurs faster than the N_2 can dissolve into the blood stream, resulting with tissues that are supersaturated with more nitrogen than they can hold. Fortunately, divers have the means to slow their ascent rate and have what some researchers believe to be the body's natural state of unsaturation, which creates "a margin of safety for prevention of supersaturation."[13]

In the discussion of tissue saturation, it should be noted that not all tissues uptake nitrogen at the same rate. Due to the differences in composition, a volume of fat can absorb 5.3 times as much nitrogen as the same volume of water. On short dives only watery tissues will become fully saturated. Since the blood stream is composed of a high percentage of water, any given volume of blood can only carry one-fifth of the nitrogen being released by the same volume of fat, which is another indicator of the need for a slow ascent.[14] Watery tissues can nearly reach complete saturation in 30 minutes, while others take up to 12 hours to reach this point, but not all dives are limited to 30 minutes.[15] Once watery tissues become saturated, fatty tissues can still absorb additional nitrogen. The problem occurs when the body can no longer hold the nitrogen in solution and bubbles form. During ascent, these bubbles, which can vary in size, inflict a diver with the maladies mentioned above. Unfortunately, it is not possible to determine a safe level of saturation for every individual diver. Bruce Wienke describes Decompression Illness as a "hit, or (hopefully) no-hit situation" because of the numerous variables involved.[16] Susceptibility to DCS varies not only from diver to diver, but can even vary in the same person from day to day depending on factors such as amount of work performed underwater, level of hydration, alcohol intake, and water temperature.[17] Additionally, obesity, poor physical condition, age, and preexisting injuries can all increase the risk of DCS. Given the wide variation of these variables, most research remains focused on gas uptake.

History of Decompression Study

While the general public has only had access to recreational scuba diving since the 1950s, scientists have been studying decompression for hundreds of years. While aspirations of venturing beneath the sea were still just dreams, work on the early stages of Decompression Theory began in the late seventeenth century. In 1650, Von Guericke developed an air pump that would remove air from a sealed container.[18] Later in 1670, experimenting on a viper placed in such a container, Robert Boyle reported seeing a bubble in the snake's eye, and he surmised that such a bubble could obstruct blood flow.[19] The first documented case of a human suffering from DCS would not be for another 200 years. During bridge construction across the Loire River in 1841, Triger designed a caisson for setting the pylons in the river, but when his workers emerged after 7 hours of pressure exposure, they complained of severe pain.[20] Following Triger's report, researches attempted to explain the illness known as caisson disease. After an 1857 repetition of Boyle's experiment, Hoppe-Seyler deducted that recompression might be a possible treatment, and 13 years later, Le Roy de Mericourt, along with Gal in 1872, connected caisson disease with an ailment attributed to breathing compressed air reported by sponge divers.[21] Then in a series of experiments between 1870 and 1890, Paul Bert was able to demonstrate that large volumes of inert gas bubbles, primarily nitrogen, in the blood and tissues caused these diseases.[22] These and other early researchers laid the groundwork for the development of the key concepts in Decompression Theory.

Haldanian Theory

While the pieces were developed in the late 1800s, the puzzle would not start to take shape until 1906 when the British Royal Navy commissioned physiologist John Scott Haldane to investigate underwater safety. Foremost, Haldane and his associates needed to choose a subject to study. Of the numerous animals exposed to environments of increased pressure, they chose the goat as the test subject on the basis that it showed visible signs of joint pain and that its circulatory system closely resembles that of a person.[23] The 1908 publication of their findings revealed that upon subjecting the animal to pressure equivalent to 165 feet of seawater (fsw), the subject did not develop DCS as long as pressure reduction was limited to no greater than half that of the ambient.[24]

From these experiments emerged the first four principles of Decompression Theory. The first principle states that both the uptake and the release of gas are exponential, that is to say tissues do not ingas or offgas at constant rates.[25] Haldane's second principle is that different tissues will saturate at different rates depending upon factors such as the tissue's solubility of nitrogen and the rate at which the gas is transported from the lungs to the tissue.[26] To this extent, tissues that absorb gas quickly will also offgas quickly, and in accordance with the first principle, the initial rate of gas release will be the quickest with all other rates falling off exponentially.[27] Since it would be impractical to measure every tissue in the body, Haldane based his decompression schedule on five hypothetical tissue compartments.[28] These compartments were classified by their half-life, the time until 50 percent saturation; with the exponential saturation rate, the tissue will be 98.5 percent saturated after six half-life periods.[29] While the first two rules are concurrent with most modern theories, the third principle is more controversial. Haldane promoted an initial large drop in ambient pressure such that the diver would reach the surface as quickly as possible without incurring DCS, which Strauss compares to running to the edge of cliff and stopping just before falling over the edge.[30] For Haldane, this principle was limited by the fourth. He concluded that as long as tissue gas pressure never exceed twice ambient, then a rapid ascent could be made, such as from 33 feet at 2 ata to the surface at 1 ata.[31] One should note that the 2:1 ratio is important, not the number of atmospheres, such that an ascent could be safely made from 6 ata to 3 ata, but not from 3 ata to 1 ata.[32] However, if this held true, then a diver who does not descend below 33 feet should be safe from DCS regardless of length spent underwater, yet cases exist where divers are stricken with pain on shallow dives.[33] In fact, modern thought is that bubbles are capable of forming in water only 20 feet deep.[34] As the understanding of Decompression Theory has progressed, the ratio has been adjusted, but Haldane's 2:1 change in atmospheres remains the basis for modern decompression.[35] He would use this ratio in the development of the first decompression table.

Research by the US Navy

With diving presenting several military advantages, the United States Navy picked up the study of decompression in the 1930s. Following the advancement of Haldane's table, the Navy continued his experiments. Nearly 25 years after the original tests, the Navy assigned Shilling the responsibility of investigating the weaknesses in the Haldanian model. Shilling started by gathering human volunteers for the experiments in replace of Haldane's goats. Much like the work done with goats, Shilling's study showed that men could withstand long periods of pressure exposure at shallow depths, but greater depths limited the time that could safely be spent underwater. [36] One major problem with Haldane's model was his assignment of the 2:1 ratio to all tissues. In an analysis of Shilling's experiments in 1935, Hawkins determined that each tissue should be assigned an individual decompression ratio.[37] Two years later, Yarbrough reanalyzed the data and found that the ratio changed not only for each hypothetical tissue compartment, but also varied depending on the duration of the dive.[38] He summarized that "fast" tissues having half-lives between 5 to 10 minutes could tolerate ratios so large as not to be a factor, and that tissues with large half-times should be based on smaller ratios, indicating the need for slower decompression from greater depths.[39] Building on the work of Shilling, Hawkins, and Yarbrough, mathematician J. V. Dwyer redesigned the Navy's dive tables in 1956. Where as the previous tables were based on five tissue compartments, the new tables would be founded upon mathematical models using six compartments simulating the body's uptake and release of nitrogen.[40] In addressing issues of repeated exposure to pressure, the new table incorporated half-times of 5, 10, 20, 40, 80, and 120 minutes.[41] The effectiveness of Dwyer's tables stems from him giving each tissue a depth dependent ratio based on the relationship of the tension of nitrogen in a tissue with the allowable supersaturation ratio.[42] Dwyer's formulas allowed for the calculation of the depths of decompression stops, a depth for allowing a diver to offgas nitrogen that was absorbed at a greater depth. If the development of Decompression Theory resembled building a house, then Haldane laid the foundation and Dwyer built the walls, for the Navy has used decompression tables based on his concepts for nearly the past 50 years.[43]

M-Values

While Dwyer's model formed the basis, the modern framework of tables depends heavily upon the Workman M-values. Yarbrough and Dwyer developed the theory beyond the original Haldanian model, but their initial tables failed to safely allow deep dives for durations beyond one hour. Previous work had been an extension of Haldane's ratio, but while working with the Navy Experimental Dive Unit (NEDU) in 1965, Dr. Robert Workman found that the 2:1 ratio took into account the total pressure of air which includes both nitrogen and oxygen, yet only the inert gas, nitrogen, needs to be considered, so a more accurate ratio would be 1.58:1.[44] He pursued the concept of each hypothetical tissue having a maximum value of inert gas pressure instead of a supersaturation ratio, such that the M-value, also known as a critical tension, acts as a ceiling for the tolerated pressure difference between the compartments' gas pressure and that of the ambient pressure.[45] Hempleman describes the M-value as the unique inert gas tension for a tissue that allows a diver to safely ascend to a depth specified by the critical tension.[46] In thinking of M-values as ascent limits, they allow for surfacing from a given depth in intervals of 10 fsw.[47] In his research, Workman made a "linear projection" of M-values as a function of depth, helping establish a linear relationship between depth and pressure that was supported by existing data.[48] Continuing Workman's study of M-values, Swiss cardiologist, Professor A.A. Bühlmann published Decompression – Decompression Sickness in 1983. Providing the general diving public access to decompression calculations, Bühlmann adjusted the M-value to diving at altitudes above sea level.[49] Professor Bühlmann's algorithms have been incorporated into desktop software as well as in water computers to allow them to adjust for altitude.[50] With application to diving at sea level and altitude, the work on M-values has added flexibility to the study of decompression.

Hempleman and Hills

With the growing popularity of diving by not only military, but also commercial and recreational divers, researchers outside of the US Navy, not unlike Professor Bühlmann, took interest in studying decompression. While the British Royal Navy had initiated the modern study of decompression with the employment of Haldane, its work in the field would be overshadowed by the US until the 1950s. For H.V. Hempleman, the work on M-values was the wrong approach to DCS. In accordance with the doctrine that implores physicians to treat the patient and not the symptoms, Hempleman, working in the Royal Navy Physiological Laboratory, felt that merely formulating a mathematical model to fit the existing data endangered divers, and professed that the mechanisms responsible for DCS should be identified so that formulas for calculating decompression limits would be indicative of the physiological changes occurring during the course of a dive.[51] He noticed that reports of pain frequently occurred in areas around the joints. Furthermore, he observed DCS in deep dives for short durations and in shallow dives for long durations. From his research, Hempleman developed a set of tables based on assumptions in complete contrast to the Haldanian line of thinking.[52] Instead of many tissue compartments, Hempleman's Bulk Diffusion Model bases all calculations on a single tissue, which necessitates the entire dive to be modeled on only one equation.[53] In another contrasting assumption to Haldanian Theory, Hempleman surmised that the rate at which body uptakes nitrogen is faster than the rate at which the gas can be eliminated.[54] Instead of working with a ratio of gas pressure to ambient like Haldane, Hempleman assumed that the body could tolerate a certain volume of inert gas saturation without the onset of DCS symptoms.[55] While the Bulk Diffusion Model is not as versatile as the tables using M-values, to his credit, tables designed in accordance with Hempleman's theories not only fit the existing US Navy data, but also prove more effective in preventing DCS in some cases of commercial diving requiring strenuous labor.[56] Later in the mid 1960s, Australian Brian Hills would add his take to the decompression issue. Hills became interested in the subject from observing pearl divers in Western Australia who worked from time proven schedules with decompression times much shorter than the tables used by the US Navy.[57] His inspection of the pearl divers led to the development of the Thermodynamic Model of decompression. Like many of the modern additions to Decompression Theory, comprehension of the details to Hills' work requires mastery of human physiology and physics, but from this complex model come two important concepts. First, Hills developed the idea of "inherent unsaturation," which theoretically gives the diver a margin of safety when ascending.[58] Secondly, Hills promoted deeper decompression stops than the US Navy. For instance, most modern recreational diving certification agencies recommend a safety decompression stop at 15 feet for 3 to 5 minutes, but at the time of Hills' research the US Navy suggested this stop be made at 10 feet. Hills lowered this stop to 20 feet and found a 40 percent reduction in incidence of DCS.[59] The work of Hempleman and Hills can be seen as intermediary between founding principles of Haldane and Workman and the modern theories.

Advanced Theories

While the works of the early decompression pioneers are complex in their own right, they can be understood by a layperson with general science comprehension, but the modern bubble theories elude such conception, yet divers should be aware of their existence for they are often incorporated in the latest dive computers. The first of the bubble theories, the Varying Permeability Model (VPM), suggests the existence of "gas seeds," potential bubbles that are excited into growth and contraction by compression and subsequent decompression.[60] The Reduced Gradient Bubble Model (RGBM) extends the VPM. RGBM presents assumptions as to the size of the distribution of these seeds and the volume to which they can be tolerated.[61] The third of the bubble theories is known as the Tissue Bubble Diffusion Model (TBDM). TBDM uses dynamic equations to track the growth of gas nuclei in tissues during decompression.[62] With the progression of Decompression Theory, these models should become increasingly more valuable in the prevention of DCS.

Saturation Diving

Before delving further into Decompression Theory as it relates to recreational diving, it should be noted that the US Navy developed dive tables with the intention of using them for saturation diving. Recreational divers ascend to the surface before becoming completely saturated, reaching the no-decompression limit. When it is necessary to spend great lengths of time underwater for military, commercial, or technical diving, divers surpass the point of saturation. At the point that a diver reaches saturation, he or she must make mandatory decompression stops at specific depths to allow nitrogen to offgas.[63] A diver spending 1 hour at 200 fsw, would require 3 hours and 20 minutes of decompression at various depths.[64] At the point when a diver's tissues become completely saturated with nitrogen, reaching equilibrium with the ambient pressure, the diver can remain at depth for great lengths of time without increasing the necessary decompression.[65] Recreational divers are advised to avoid mandatory decompression stops; however, recreational tables do list the time and depth for decompression stops in the event the diver exceeds the allotted time underwater.

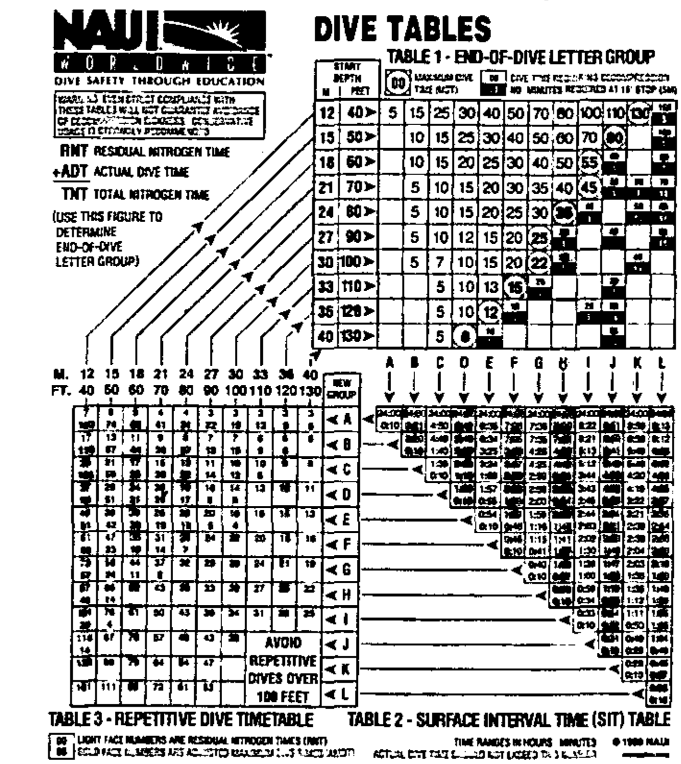
Dive Tables

In terms of diver safety, a working understanding of dive tables is one of the most important lessons a newly certified diver can take away from the initial open-water scuba class. Regardless of which model was used, the development of a dive table has only one concern, the prevention of DCS. Initially, tables deal with three factors: bottom time, maximum depth, and ascent rate. Bottom time, as defined by the US Navy Dive Manual, is the time from when the diver first descends till he or she starts ascending from the bottom.[66] For the purpose of this study, bottom time will be considered the time from when the diver descends beneath the surface till the point when the diver returns to the surface. Maximum depth is just that, the deepest depth reached in the course of single dive. Likewise, the ascent rate is just as it says, the speed at which a diver ascends to the surface; for instance, the National Association of Underwater Instructors (NAUI) table recommends an ascent rate of no faster than 1 foot every 2 seconds or 30 feet per minute. The design of a table is to limit nitrogen release from the body during ascent.[67] The only criterion for judging how successfully a table prevents DCS is to look at the empirical evidence of the illness occurring in divers using the table. While many models use sophisticated equations, it is the accuracy in preventing DCS that is important, not the complexity of the mathematical formulas.[68] When formulating decompression models, researchers develop series of equations then codify them into tables. However, a tradeoff ensues between model comprehensiveness and ease with which it can be coded into a table: the more complex and comprehensive the model, the harder it is to transform the archetype into a table.[69] As previously noted, the susceptibility to DCS differs from person to person, so to be safely used by a large population, tables must be conservatively designed to accommodate divers who uptake nitrogen quickly and offgas slowly.[70] For example, the abundance of fat tissue in an overweight, older person results in that person having more tissue mass available for nitrogen to saturate and poor circulation, which hinders the release of nitrogen.[71] Likewise, rough seas, extensive exertion, and dehydration, along with a host of other factors can increase a diver's vulnerability to DCS, tables must err on the side of caution.[72]

Table Function

Regardless of which set of tables a diver elects to use, all function in approximately the same manner. Before making any dive, a diver should plan his dive schedule. First, the diver will choose a maximum depth. Tables list depths in 10 feet increments; the US Navy Dive Tables begin at 10 feet, while the NAUI Dive Tables (see Figure 1.1[73]) begin at 40 feet and treat any depth less than that as a 40 foot dive. For every depth, there is a corresponding row of times in various increments up to the maximum time that can be spent at that depth without necessitating mandatory decompression stops. It should be noted that while a diver will spend time at various depths, tables assume the entire bottom time to be spent at the maximum depth. Once the diver has chosen a depth, he or she will choose a corresponding time to spend underwater. Now it is highly probable that the actual dive depth and time will vary somewhat from the intended schedule, but the deviation from the intended profile is not a problem. As the diver plans his schedule, he or she should know the maximum time allowed at

Figure 1.1



the intended depth and maximum time allowed at the next greater depth on the table. When doing calculations, the rule in diving is to always round up, for example a 45 foot dive for 51 minutes would be calculated as a 50 foot dive for 60 minutes. If a diver wanted to only experience one dive a day then as long as he or she did not exceed the depth and time limits, the discussion of tables would end here, but on a dive trip it is not uncommon to get in two to five dives a day. As discussed before, the body ingasses at a faster rate than it offgasses, so when a diver is standing on the boat deck at the end of the dive, residual nitrogen remains saturated in his system which will be gradually released over the proceeding 24 hour period, but till then all excess nitrogen must be calculated into the next dive schedule.

A dive table is in actuality a set of three tables. The first gives the depth/time relationships, while the second gives a series of surface intervals, the time spent on the surface in between dives, and the third gives allowable times for repetitive dives. In the first table (see Figure 1.2[74]), every column of times has a corresponding letter that corresponds to a column in the second table. In that column, the diver finds the time interval he will be spending on the surface. From the previous example, the 50 foot dive for 60 minutes would be designated letter "H" on the NAUI tables. The example diver then spends 1 hour and 10 minutes on the boat before his next dive. The surface interval fits into the time block of 1 hour and 41 minutes to 1 hour and 7 minutes. Since the diver has been offgassing for the 1 hour and 10 minutes spent on the surface, he receives a new letter group, "F," by the row on the

Figure 1.2

TABLE 1 - END-OF-DIVE LETTER GROUP

(00) MAXIMUM DIVE TIME (MDT) — 00/00 DIVE TIMES REQUIRING DECOMPRESSION / NO. MINUTES REQUIRED AT 15' STOP (5M)

START DEPTH M	FEET	A	B	C	D	E	F	G	H	I	J	K	L
12	40	5	15	25	30	40	50	70	80	100	110	130	150 / 5
15	50		10	15	25	30	40	50	60	70	80		100 / 5
18	60		10	15	20	25	30	40	50	55	60 / 5		80 / 7
21	70		5	10	15	20	30	35	40	45	50 / 5	60 / 8	70 / 14
24	80		5	10	15	20	25	30	36	40 / 5		50 / 10	60 / 17
27	90		5	10	12	15	20	25	30 / 5		40 / 7		50 / 18
30	100		5	7	10	15	20	22	25 / 5			40 / 15	
33	110			5	10	13	15	20 / 5			30 / 7		
36	120			5	10	12	15 / 5			25 / 6	30 / 14		
40	130			5	8	10 / 5					25 / 10		

second table (see Figure 1.3[75]). The third table (see Figure 1.4[76]) is a cross-reference of the new letter group with the intended depth for the second dive. The example diver wishes to go to 50 feet on the second dive so he follows the "F" row over to the column for dives up to 50 feet. The diver finds two numbers: 47 and 33 on the NAUI table. The table tells the diver that he can dive to 50 feet for a maximum of 33 minutes and that he has 47 minutes of residual nitrogen still absorbed in his tissues. On the second dive, the diver goes to 46 feet for 30 minutes. After the second dive, the diver adds his dive time to his residual nitrogen time to get a total nitrogen time of 77 minutes. Rounding the depth to 50 feet and the total nitrogen time to 80 minutes, the diver finds his letter group, "J," by using the first table. The diver will repeat this procedure for all subsequent dives. While this process may seem tedious at first, it is critical to the diver's safety. NAUI and PADI, the Professional Association of Diving Instructors, each report that when their tables are used correctly, risk of DCS is less than .001 percent.[77] The disadvantage of using tables comes from human error. With the number of steps, mistakes can be easily made under ideal conditions, but on a dive boat being rocked by waves, these calculations become even more difficult. Additionally, tables do not represent a true dive profile, the consequences of which will be discussed in the following section.

Figure 1.3

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

Figure 1.4

M.	12	15	18	21	24	27	30	33	36	40	NEW
FT.	40	50	60	70	80	90	100	110	120	130	GROUP
	7 123	6 74	5 50	4 41	4 31	3 22	3 19	3 12	3 9	3 5	A
	17 113	13 67	11 44	9 36	8 27	7 18	7 15	6 9	6 6	6	B
	25 105	21 59	17 38	15 30	13 22	11 14	10 12	10 5	9	8	C
	37 93	29 51	24 31	20 25	18 17	16 9	14 6	13	12	11	D
	49 81	38 42	30 25	26 19	23 12	20 5	18 4	16	15	13	E
	61 69	47 33	36 19	31 14	28 7	24	22	20	18	16	F
	73 57	56 24	44 11	37 8	32	29	26	24	21	19	G
	87 43	66 14	52	43	38	33	30	27	25	22	H
	101 29	76 4	61	50	43	38	34	31	28	25	I
	116 14	87	70	57	48	43	38	AVOID REPETITIVE DIVES OVER 30 METERS (100')			J
	138	99	79	64	54	47					K
	161	111	88	72	61	53					L

Table Inefficiency

Even though when used according to their specifications tables provide low risk of DCS, they are inherently inefficient for recreational diving. Certifying agencies such as NAUI, PADI, and YMCA all use their own table version, but all are in some form just more conservative measures of the US Navy Dive Tables. The problem lies in that Navy tables were designed for divers with an above average level of physical fitness who were going to a specific depth to do a specific job and then return to the surface. Recreational divers on the other hand will have multi-level dive profiles, spending time at various depths depending on what they are interested in seeing. Suppose a diver spends the first 10 minutes of a dive at 60 feet then ascends to 30 feet for the remainder of a 50 minute dive, a table will treat the dive as if all 50 minutes were spent at 60 feet. According to Decompression Theory, even though some tissues will be ingassing nitrogen at 30 feet, others will be releasing nitrogen ingassed at 60 feet.[78] Even if the diver only spent 1 minute at 51 feet, the entire dive would have to be calculated as a 60 foot dive. In effect, tables do not give credit for nitrogen released at shallower depths. Another problem with dive tables is that they only provide decompression calculations for a limited number of depth-time combinations.[79] A dive to 51 feet for 31 minutes would have to be rounded up to a dive to 60 feet for 40 minutes because tables do not give precise depth and time measurements. This method penalizes a diver with time and depth not actually spent underwater. When dealing with personal safety, it is wise to err on the side of caution, but since tables were not designed for multilevel diving, they are too conservative for the needs of recreational divers.

Decompression Meters

To eliminate the tedious calculations and limit human error, the process of tracking nitrogen uptake shifted from tables to decompression meters. The first attempts to mechanize decompression calculations were crude and ineffective. These first devices worn by the diver consisted of two compartments. The first would have been exposed to ambient pressure and joined to the second by a permeable membrane barrier. As the ambient pressure increased, gas from the first chamber would pass into the second in proportion to the change in surrounding pressure, supposedly analogous to the pressure changes ongoing in the divers body.[80] A pressure gauge attached to the second compartment indicated to the diver the amount of nitrogen supposedly taken up by the diver. While these decompression meters were a step beyond tables, they proved to be inaccurate given the complexity of nitrogen absorption in the body.

Dive Computers

With the onset of the computer age, digitizing decompression meters would be the next logical step. At a time when computers still required large amounts of room space, and the idea of having one in the home would be absurd, the dive community already had ideas of using the technology to calculate nitrogen absorption and decompression. In the 1976 publication of Diving Medicine, Dr. Richard Strauss suggests that the best device for calculating decompression would be "a small electronic computer that integrates time, depth, and possibly other factors."[81] Little did Strauss know that the innovation would not be far off. Probably unknown to most divers, the dive computer and handheld scientific calculator are closely related. While working for Texas Instruments in the 1970s, Michael Cochran led the research team that developed the microcomputer chip.[82] The chip that would allow for handheld calculations would be vital to the dive computer. By 1983, less than six years after Cochran's development, ORCA Industries introduced the first commercial dive computer known as the ORCA Edge.[83] Ten years later, Cochran and his brother Joey introduced the world to the first "wireless, wrist-worn dive computer."[84] While manufacturers sell computers with a wide array of capabilities, the basic design remains the same. Computers are comprised of a pressure transducer, an analog to digital converter, a power supply, an internal clock, a microprocessor, ROM, RAM, and a display.[85] The ROM, Read Only Memory, stores the program model, while the RAM, Random Access Memory, maintains current calculations sent to the display screen.[86]

There are several misconceptions in regards to using dive computers. Foremost, a dive computer does not monitor what is actually happening inside the body, nor can it account for the numerous factors that influence the body's absorption of nitrogen.[87] Computers use algorithms in an attempt to represent an approximate absorption and elimination of nitrogen based on depth and time, and do not follow any specific dive table.[88] Just as all car manufacturers don't use the same engine, different dive computers base these calculations on algorithms: some more conservative than others.[89] Wienke reports that the Reduced Gradient Bubble Model, which can be converted to a Haldanian algorithm, is currently becoming more widely used in both dive computers and dive planning software because it more accurately describes the processes occurring in the human body.[90] A dive computer functions by taking a pressure reading every 15 to 30 seconds and calculating the time remaining before the diver must make a mandatory decompression stop. The advantages of using a computer are longer dive times, shorter surface intervals, more accurate estimates of nitrogen absorption and release, and mandatory slower ascent rates.[91] A dive computer prevents mathematical errors by the diver, eliminates the need to carry multiple instruments for depth and time, and can make calculations based on diver's current depth, no matter what the original dive plan might have been.[92] Dive computers have become an integral tool for recreational divers.

Nitrox

To this point, all discussion of Decompression Theory has been based on a diver breathing air, but this is not always the case. Beginning in the 1980s, the world of technical diving introduced recreational divers to Nitrox. Enriched Air Nitrox (EAN) is simply a breathing gas composed of a higher percentage of oxygen than air. Air is considered to be comprised of approximately 79 percent nitrogen and 21 percent oxygen, so EAN mixtures have at least 22 percent oxygen and can reach up to 100 percent pure oxygen, but common mixtures contain 32 or 36 percent oxygen.[93] Using nitrox increases diver safety. Breathing oxygen increases the tissue to capillary nitrogen gradient, allowing for faster elimination of the inert gas.[94] A diver breathing an air mixture with a higher than normal percentage of oxygen at depth offgasses nitrogen at a faster rate than a diver breathing air.[95] While nitrox increases the time allowed underwater, the one possible downside to using it comes from depth limitations. Under pressure, oxygen can be toxic. With normal breathing air, oxygen toxicity occurs at 218 fsw, but as the percentage of oxygen increases, the depth at which toxicity occurs decreases such that a diver breathing an EAN of 36 percent oxygen (EAN36) should not exceed a depth of 110 fsw.[96] Just as tables exist for diving on air, divers choosing to use nitrox must follow specific nitrox table restrictions. Likewise, some computers can be adjusted so that their calculations are based upon the EAN mixture. With longer bottom times and increased safety, many divers elect to take specialty courses to learn how to properly use nitrox.

Instrument Comparison

While nitrox and saturation diving require special training, all divers, especially new divers, must understand the difference between tables and computers. Foremost, tables give divers boundaries. A newly certified NAUI diver exploring a reef at 60 feet could spend a maximum of 55 minutes under water, but a diver using a computer may not be aware of the restriction. Computers display the time remaining before saturation. When the diver with the computer becomes fully saturated at 60 feet, the computer will not signal the diver to ascend, instead; it will give the depth and time of the first required decompression stop. The previous statement should not be taken as an indication that dive computers are dangerous. When properly used, computers present nearly the same risk of DCS as tables when properly used. Computers have a variety of audible and visual alarms indicating ascent rate, decompression stops, and a host of other indicators depending on manufacturer and model. Furthermore, divers are constantly performing multiple tasks and must be aware of several variables: time underwater, time till ascent, current depth, and remaining breathing gas, along with environmental factors. A computer can be very useful by displaying much of this information, allowing the diver to more fully enjoy the dive.

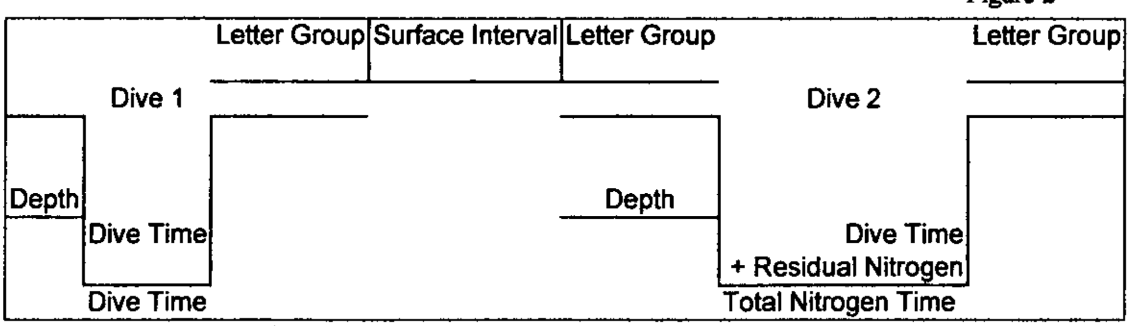
Dive Analysis

The easiest way to visually see the difference between the two methods is to map out the time spent underwater. The following five series of dives were conducted from May 2003 through August 2003. All dive times and depths were recorded on 30 second intervals using a Dive Rite NiTek Plus dive computer, which utilizes a Bühlmann algorithm with nine hypothetical tissue compartments. All table calculations will be made using NAUI Dive Tables. It should be noted a nitrox gas was used on some of the dives in the series, but the NAUI Dive Tables are based on air. However, instead of using a separate table set for those dives, an equivalent air depth (EAD) formula was used to convert the depth when using nitrox to an equivalent depth when breathing air, with regards to nitrogen saturation, so that the dive could be calculated with the NAUI tables. To find the EAD, multiply the fraction of nitrogen in the breathing gas (FN_2) by the sum of the depth (D) and 33 then divide by .79 and subtract 33.

$$EAD = (FN_2 * (D+33)/.79) - 33$$

While diving on nitrox is inherently safer than diving on air as long as the diver obeys the depth and time limits for the nitrox mixture, the allowable no-decompression time still differs when using tables compared to using a computer programmed to the percent of oxygen in the breathing gas. For the following series, dives on nitrox will be noted as such by EAN along with the percentage of oxygen in green lettering next to the dive profile. All table calculations will be done using the previously stated method and will be mapped according to the model in Figure 2. Figure 2 shows two dive profiles. The second of the two profiles is a repetitive dive, meaning that it occurred within 24 hours of the previous dive with residual nitrogen remaining in the body at the start of the dive. All depths in Figure 2 are given in feet and all dive and nitrogen times are given in minutes, while the surface intervals are given in hours and minutes. In the event of

Figure 2



more than one repetitive dive, the same procedure would be used for the third and subsequent profiles. Where the NAUI tables give specific amounts of residual nitrogen in the body at the end of the dive, the NiTek Plus does not. Instead, it shows a digital gauge of nine bars. The greater the number of bars filled at the end of the dive, the greater the amount of residual nitrogen calculated to still be in the body.

Since diving on tables requires the entire bottom time to be considered as if it were spent at the maximum depth, the dive is represented as a square profile. Graph 1 represents the dive in Table 1 as a square profile. Graph 2 shows the same dive except recorded by the computer. Where Graph 1 would be calculated as a 60 foot dive on the tables, the computer calculates the

Graph 1

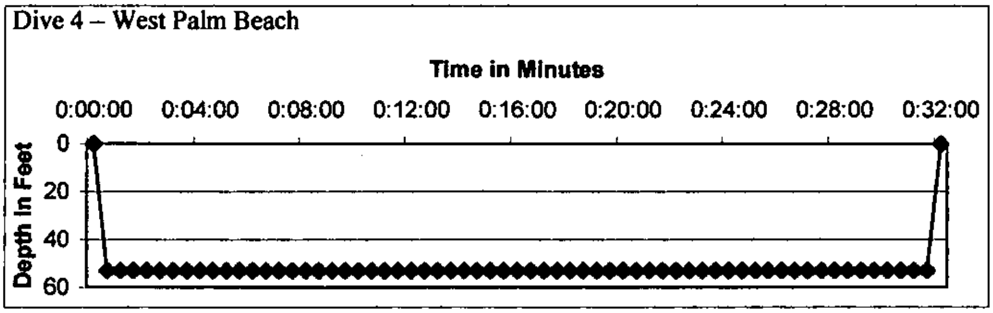
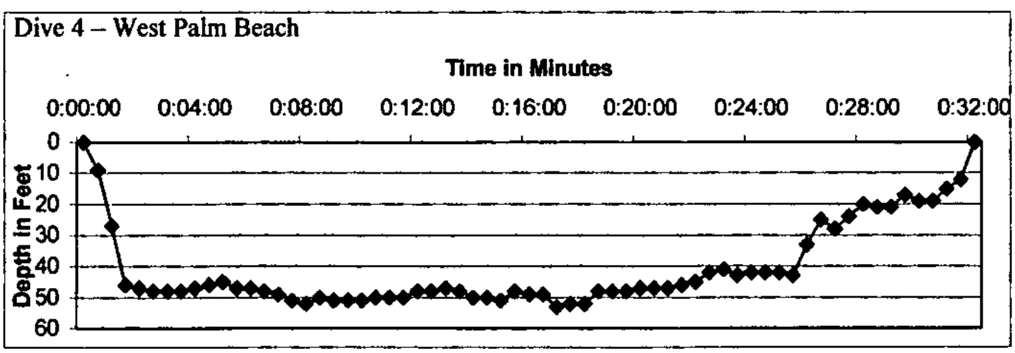


Table 1

Bottom Time	0:32:00
Maximum Depth	53 feet
Average Depth	40 feet

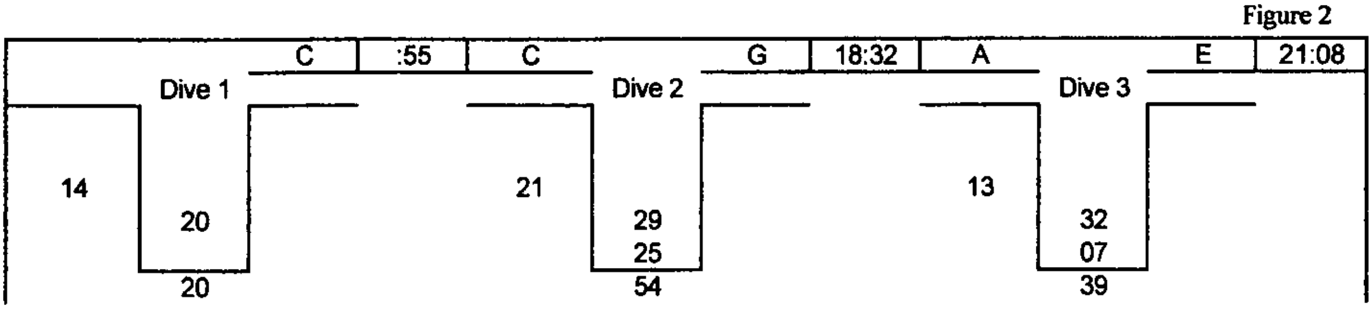
dive based on the actual depths. As Graph 2 shows, the majority of the dive was spent above the maximum depth of 53 feet, and the entire dive was spent above 60 feet so calculating the dive based on tables would result in a repetitive dive with more residual nitrogen than actually exists in the body.

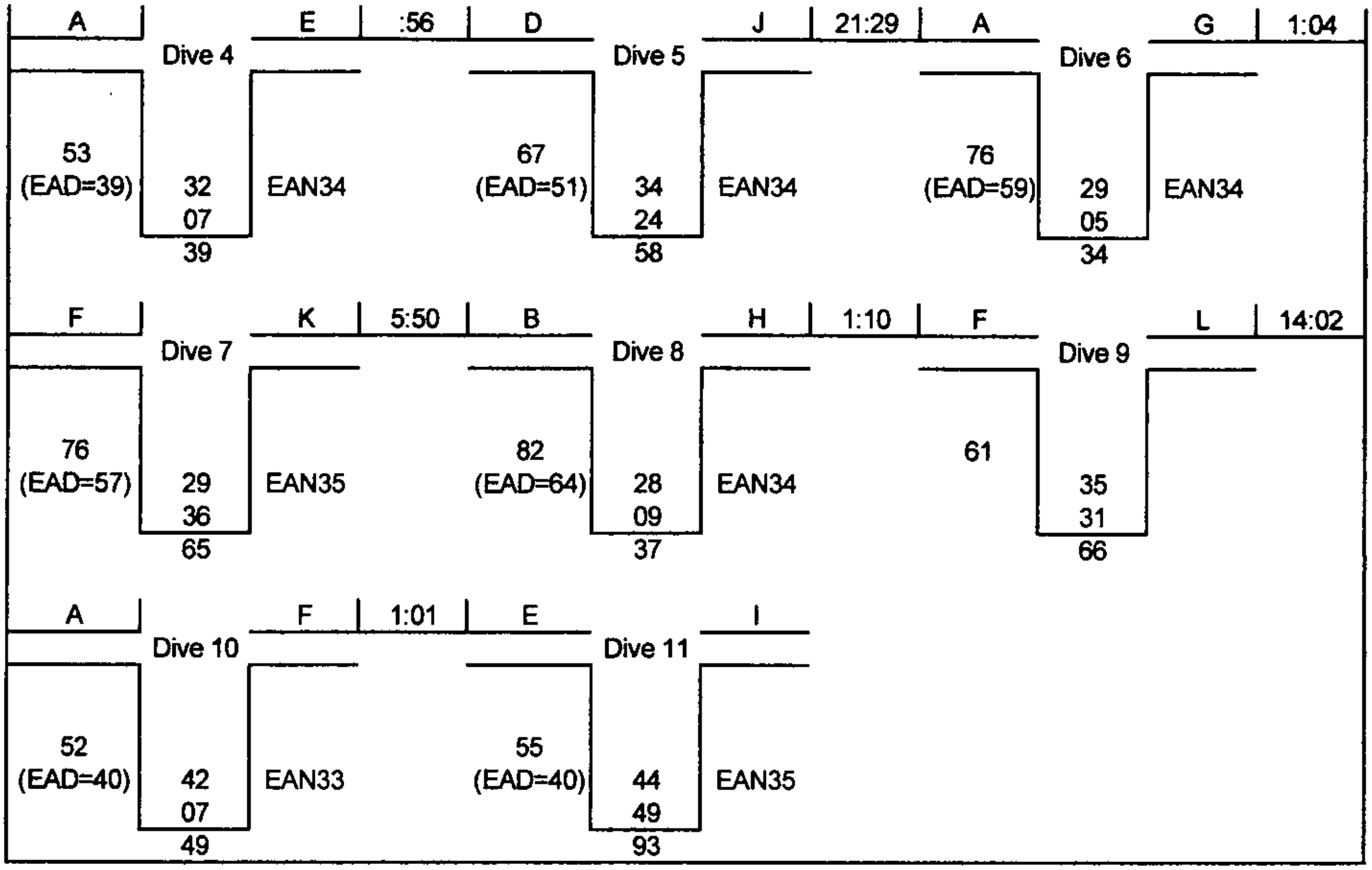
Graph 2



Dive Series 1

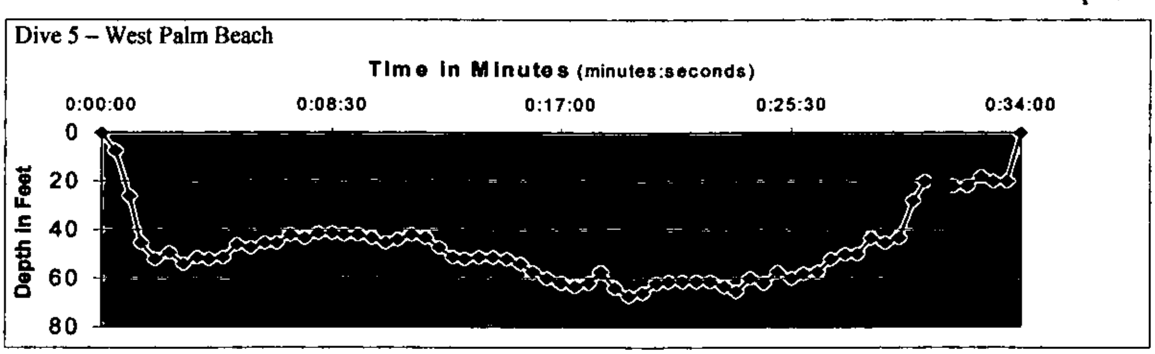
Figure 2





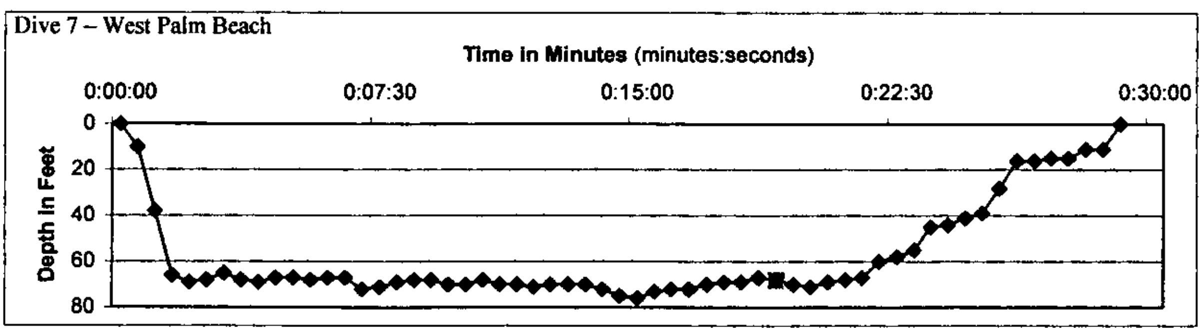
The first of the five series of dives was conducted at West Palm Beach, Florida, during the week of May 12-16, 2003. Dive 5 is the first that would require decompression if calculated on the NAUI table set. According to the table, a 5 minute stop at 15 feet would be mandatory before ascending. The computer did not require this stop. Dive 5 can be seen in Graph 3. The red square indicates the point at which the NAUI tables would have required the dive to end before a mandatory decompression stop.

Graph 3

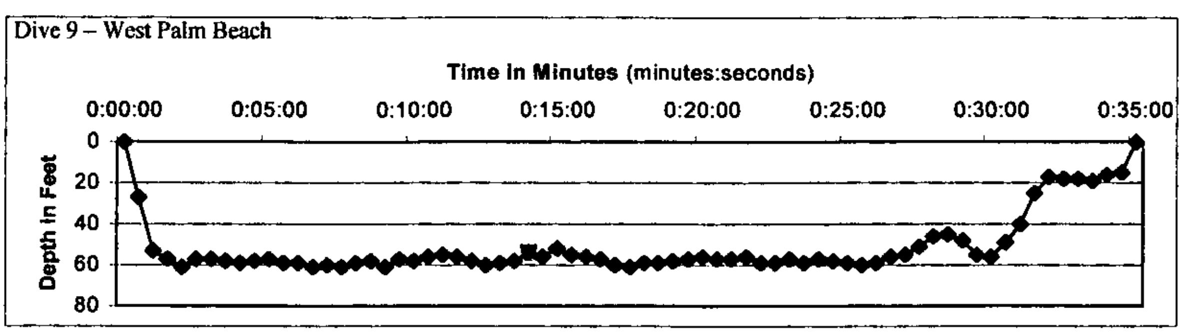


During the series of dives at West Palm Beach, two others would have required mandatory decompression stops if only tables were used. Dive 7 would have required 5 minutes at 15 feet, while Dive 9 would have mandated 14 minutes. While Dive 9 lasted 29 minutes, it would have been cut by 10 minutes had it been calculated by the NAUI table instead of by the computer. Where the tables required a decompression stop, the computer shows less than half of the residual nitrogen bars filled, indicating that this dive could have continued longer and still not necessitated a decompression stop by the calculations of the NiTek Plus. While the depth of Dive 7 was deeper than the depth of Dive 9, Dive 7 was conducted using nitrox and Dive 9 was performed using air, which results in the tables demanding the longer stop during Dive 9. At very few times during Dive 9 did the depth exceed 60 feet, yet due to the few instances that it did, the tables require the dive to be measured as a 70 foot dive. The computer is not bound by the rounding restraint. Since most of the dive stays between 50 to 60 feet, it does not require a decompression stop.

Graph 4



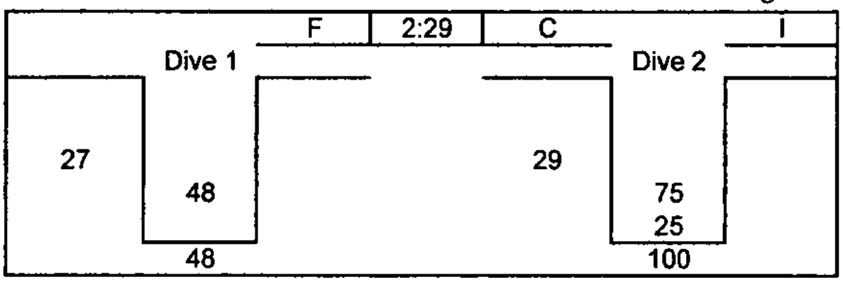
Graph 5



From examining the dives in this series that would have required decompression stops, three commonalities emerge. First, these dives were to depths greater than 60 feet. Second, all three dives occurred within 1 hour and 20 minutes of a prior dive. Finally, all the dives were preceded by dives to depths greater than 50 feet.

Dive Series 2

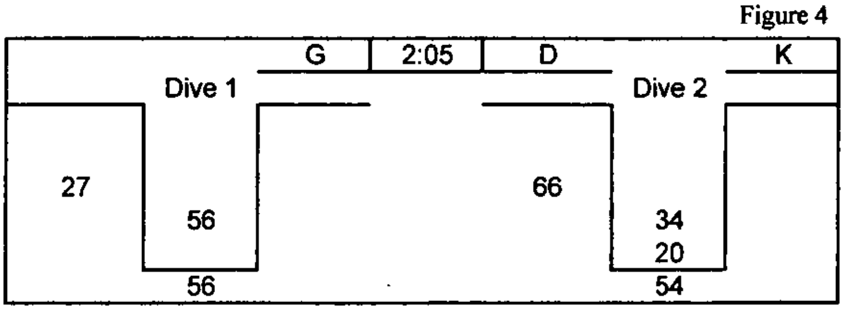
Figure 3



The second series of dives occurred on June 21, 2003 at a rock quarry near Cerulean, Kentucky. Both dives were performed using air and neither of these dives exceeded a depth of 30 feet. The first dive lasted for 48 minutes while the repetitive dive lasted for 1 hour and 15 minutes. By the standards of the NAUI Dive Table, the second dive could have lasted for an additional 30 minutes.

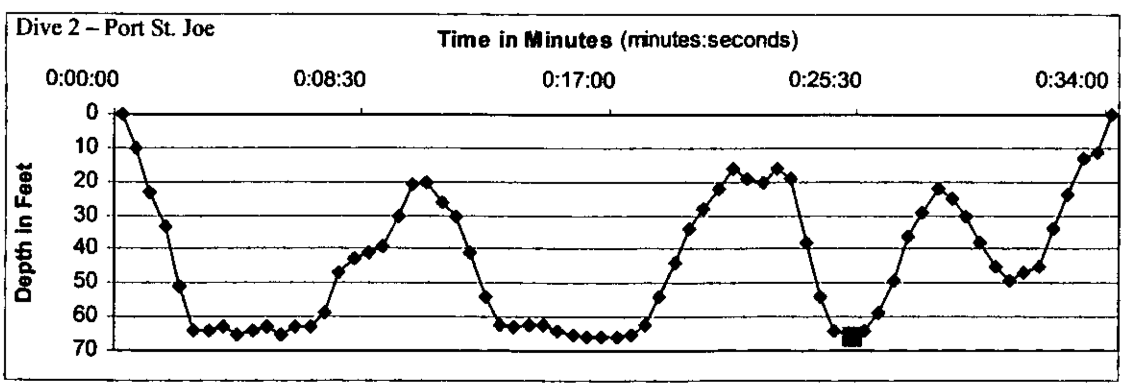
Dive Series 3

Figure 4



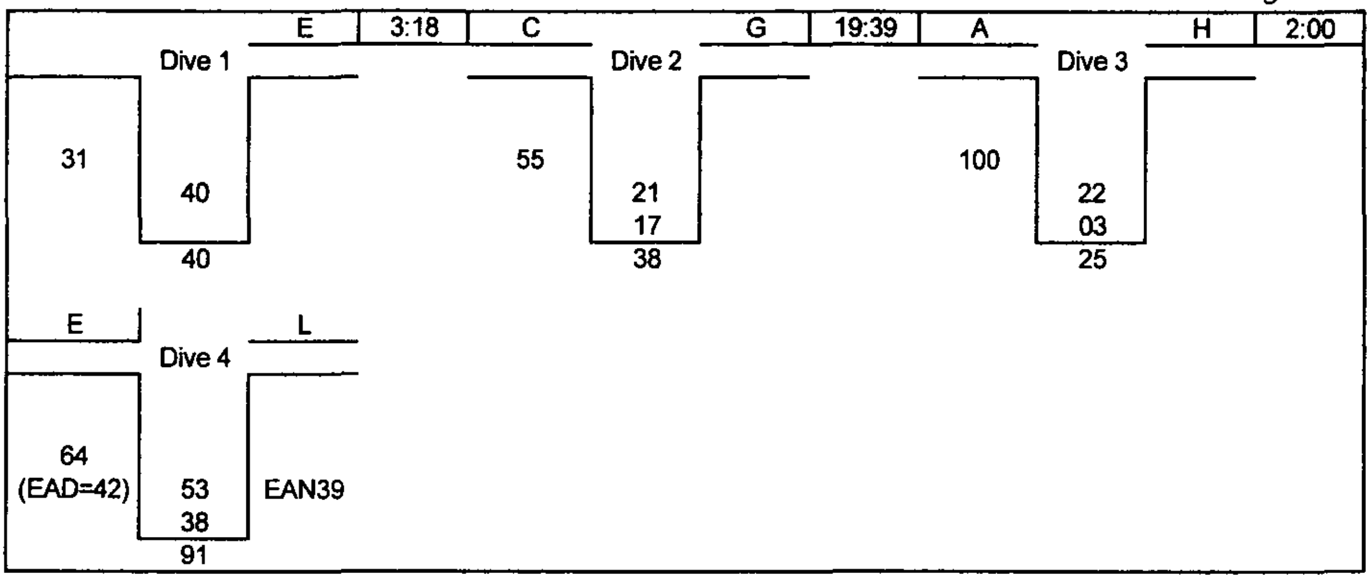
The third series of dives occurred a week later on June 28 near Port St. Joe, Florida. Again, both dives were executed on air, but in this series the second dive would have necessitated a decompression stop had it been on tables. NAUI would require an 8 minute stop at 15 feet before surfacing. This dive is visibly different than the three previous dives. The previous dives were over reefs and the depths did not vary greatly during the course of the dives, but Dive 2 at Port St. Joe was on a 70 foot communication tower lost at sea by the US Navy. The peaks and valleys of the graph represent the exploration of the tower. Had the dive been on tables, it would have most likely ended at the peak before the point of saturation. The tables would have had the diver ascending to the surface nearly 12 minutes before the end of the dive. The table calculations punish the diver for the one-third of the dive spent around 70 feet and ignore the other two-thirds spent at various depths. It should be noted that most certifying agencies recommend that all repetitive dives be of a shallower depth than the preceding dive, but the boat captain at Port St. Joe selected the order of the dive sequence, hence a 66 foot dive follows a 21 foot dive. Had the order of these dives been reversed then a decompression stop would not have been required. The commonality between this dive and the three previous requiring decompression stops is the maximum depth greater than 60 feet.

Graph 6



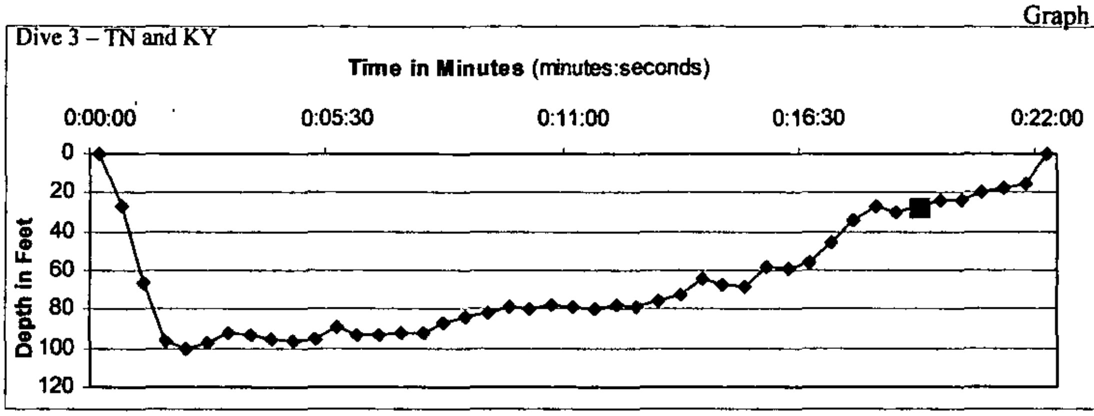
Dive Series 4

Figure 5

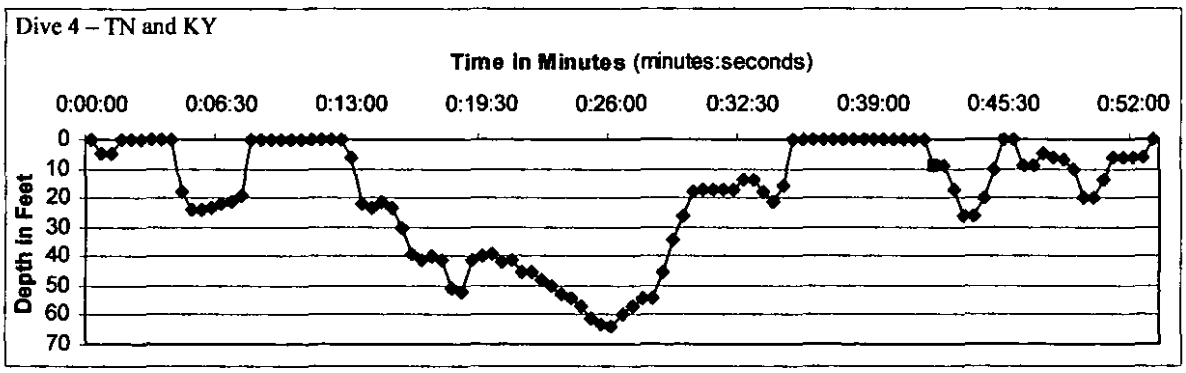


The fourth series of dives takes place over the weekend of July 12 and 13, 2003 in rock quarries in Tennessee and Kentucky. In Figure 5, Dive 3 would be the first to need a decompression stop: 5 minutes at 15 feet. By the NAUI table, the dive should have ended at 22 minutes instead of 25 minutes as can be seen by the red square in Graph 6. Another difference between the tables and the computer can be seen from Dive 4 in Graph 7. The NiTek Plus computer did not require a decompression stop, but by the procedures for table calculations, Dive 4 would have required a 5 minute stop at 15 feet. However, this discrepancy can partially be explained. Most computers start timing a dive when the diver reaches a depth of around 5 feet and cease recording dive time when the diver returns to the surface, but if the stint at the surface is less than 10 minutes then when the diver descends it will be considered part of the same dive. In Dive 4 there are four periods of surface time that are counted to be part of the dive time. During the time at the surface the body is offgassing nitrogen, which the computer can calculate, but the tables incorporate the time into the square profile, and include the time in the period of nitrogen ingassing. The two dives needing decompression stops share two factors with the dives from series one. Both dives exceed 60 feet, and both are preceded by a dive greater than 50 feet.

Graph 7

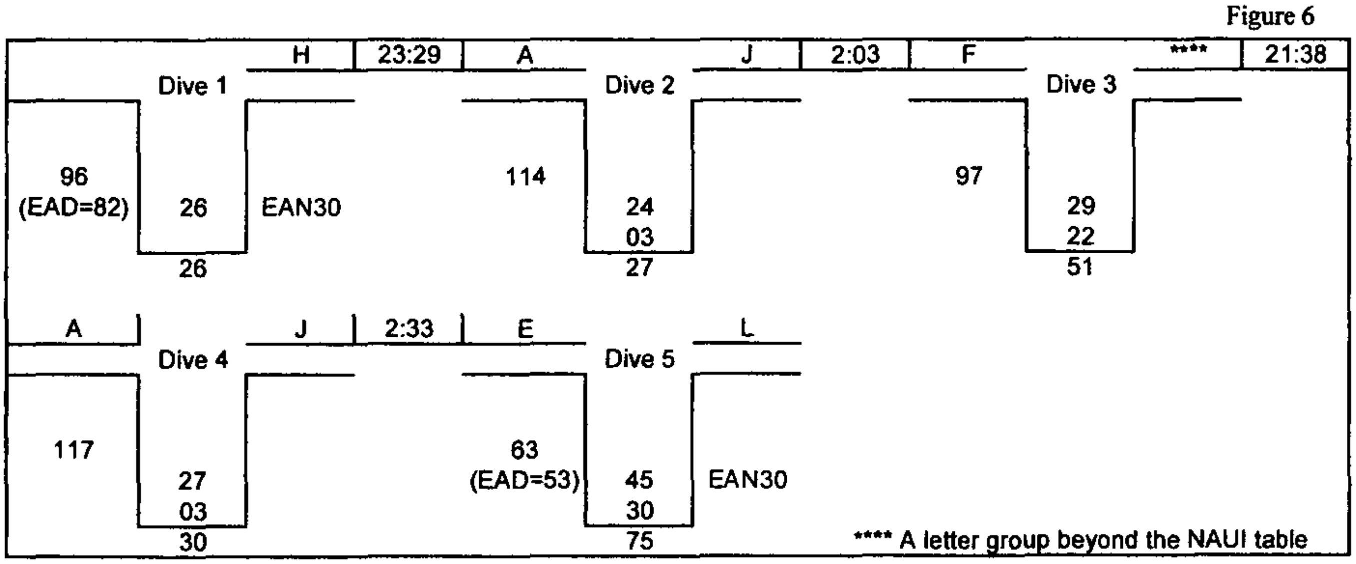


Graph 8



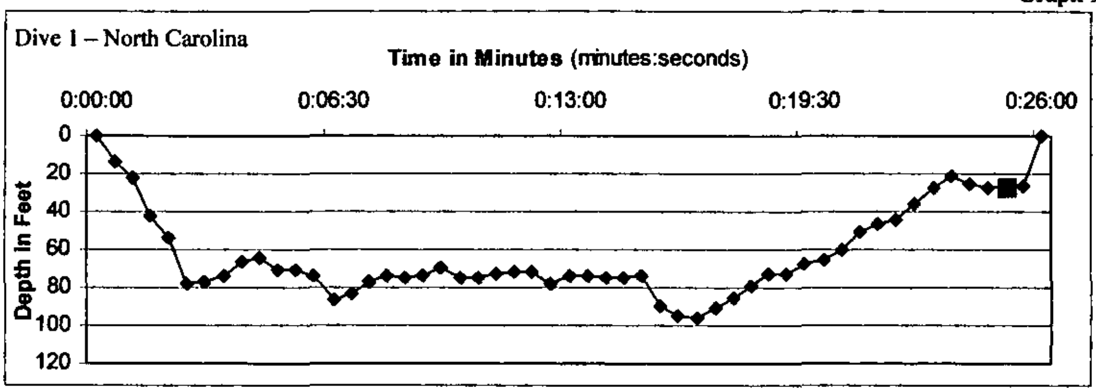
Dive Series 5

Figure 6

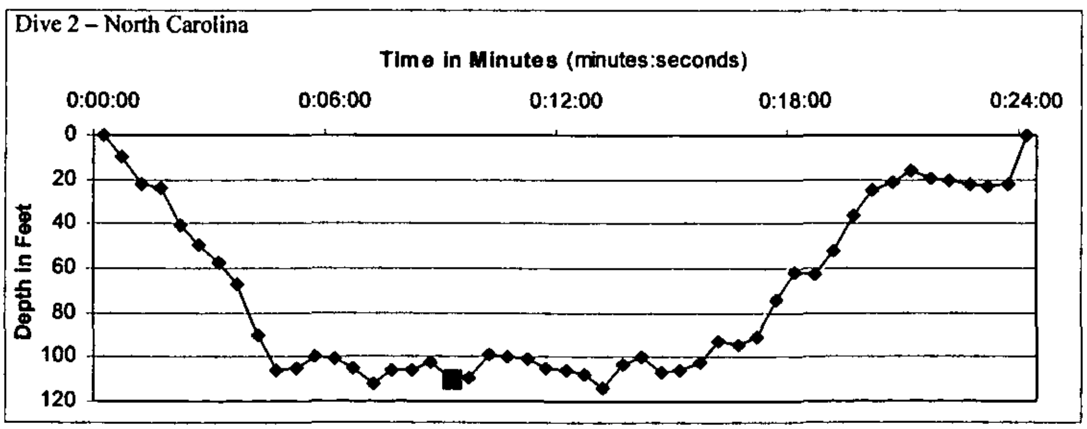


The final series of dives was at the Outer Banks of North Carolina, from August 4-6, 2003. These dives were over wrecks in what is known as the Graveyard of the Atlantic. Four of the five dives would reach depths greater than 90 feet. In accordance with the NAUI Dive Tables, all five dives in the series would require decompression stops, but diving with the computer, only one would require a stop. Like the dives in West Palm Beach, some in North Carolina were performed using nitrox. Even using nitrox, Dive 1 exceeds the tables' no-decompression limit by 1 minute, which would result in a 5 minute stop (see Graph 9).

Graph 9

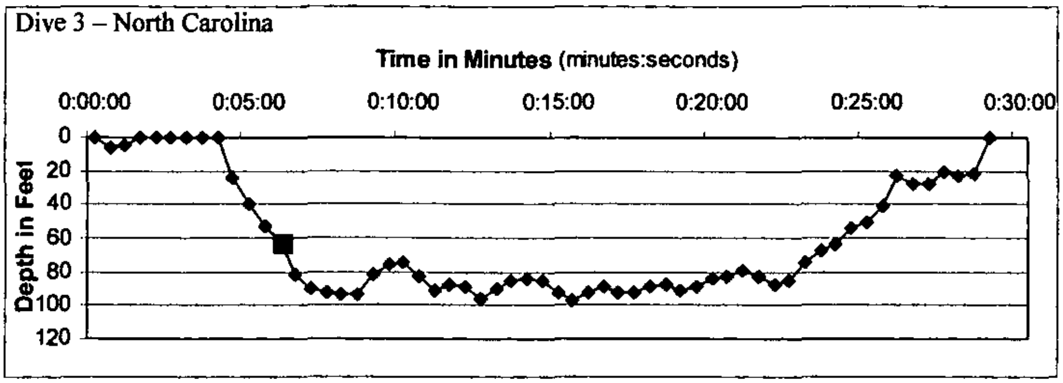


Graph 10

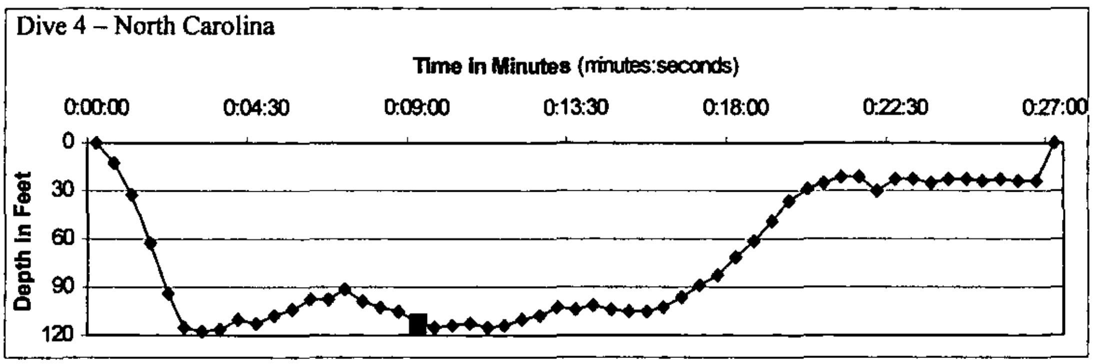


Dive 2 surpasses the NAUI no-decompression time by 15 minutes as can be seen in Graph 10. The computer still does not require a stop even though the dive reached 114 feet and lasted 24 minutes. Dive 3 goes beyond the decompression schedule of the NAUI tables, yet the computer does not require a stop (see Graph 11). It should be noted that given the previous depth and surface interval time, a repetitive dive could not be made past 80 feet going by the tables.

Graph 11



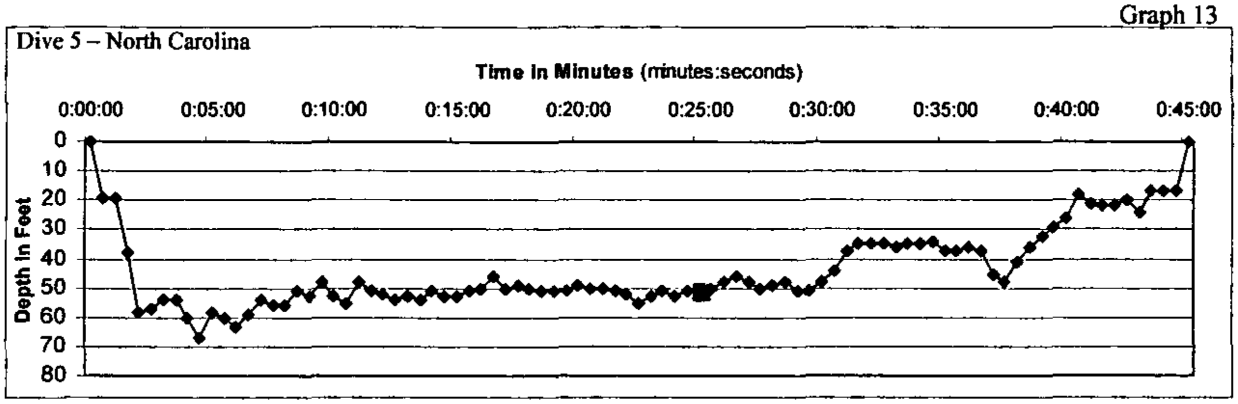
Graph 12



The fourth dive of the week went to a depth of 117 fsw for 27 minutes. This dive is unique in that it is the only dive in the study that would have required a decompression stop by both the computer and by the tables. However, where the computer required a stop at 10 feet for 5 minutes, the tables would have mandated a 14 minute stop at 15 feet. In actuality, the stop occurred around 20 feet, which reduced the required decompression stop time, as can be seen by the nearly horizontal set of data points at the end of Graph 12. For Dive 4, the red square in Graph 12 indicates that the dive would have to have ended at the 9 minute mark to not be a no-decompression stop dive by the NAUI tables. After a 2 hour and 33 minute surface interval, the final dive in the series went to 63 feet for 45 minutes. As can be seen in Graph 13, the dive would have had to end at the 25 minute mark in order to not incur a decompression stop by the

NAUI tables, but by using the computer, the dive was extended another 20 minutes. Like all other dives in the study requiring a decompression stop by the NAUI tables, these five dives all exceeded depths greater than 60 feet and all had bottom times greater than 20 minutes.

Graph 13



Conclusion

As can be seen from the dives in this study, there is often a significant difference between computers and dive tables in terms of the allowable bottom time before a mandatory decompression stop. From the dives in this study, five generalizations can be made. First, dives to depths less than or equal to 40 feet will most likely not require a decompression stop by neither tables nor by a computer. In the study, six dives fit this category: Dive 1, Dive 2, Dive 3, Dive 4, Dive 10, and Dive 11 from Series 1 along with Dive 2 from Series 2. At first glance Dive 10 and Dive 11 from Series 1 would not fit the category because the actual depths on these dives both exceeded 50 feet, but both were conducted on nitrox with equivalent air depths equal to 40 feet, thus they are treated as 40 foot dives on the tables. By the NAUI Dive Tables, a dive to 40 feet or less can last up to 130 minutes, but most divers will run out of air long before they are able to reach the time limit. Second, while diving nitrox is safer within a given depth restraint, using oxygen enriched gas does not eliminate the need for decompression stops. Of the 11 dives necessitating a decompression stop by the NAUI tables, five were conducted utilizing nitrox. In contrast, on the ten dives where an enriched-air nitrox breathing gas was used, the computer never required a decompression stop. Computers can require decompression stops when programmed to nitrox, but no such stops were required in this study. Next, the time spent at the surface between dives is a weak factor in whether or not the dive will require a decompression stop. In Series 1, a 56 minute surface interval preceded Dive 5 and it would have needed a 5 minute decompression stop according to the NAUI tables, yet Dive 2 and Dive 4 from Series 5 would have each required a 14 minute stop even though each had a preceding surface interval of over 20 hours. Dive 1 in Series 5 would have needed a decompression stop by the tables, but that was the first dive in the series meaning that the diver had not been underwater within the preceding 24 hours so no residual nitrogen was in the body. Both tables and computers use the time between dives in conjunction with the depth of the repetitive dive to formulate the residual nitrogen left in the diver's body, but the bottom time during the repetitive dive will determine whether or not a decompression stop is necessary. Furthermore, tables strictly limit the bottom time of repetitive dives to depths greater than 40 feet and of repetitive dives that have equivalent air depths greater than 40 feet. Of the 11 dives that would have required a decompression stop by tables, only one was not a repetitive dive. Out of those 11 dives, in nine cases it would have been possible for the diver to reach the maximum depth at the point in which the depth occurred in the dive without a required stop if the dive would have ended sooner than it did in reality. For example, the diver could have reached the maximum depth of 63 feet in Dive 5 of Series 5 if the dive had been limited to 25 minutes, as indicated by the red square in Graph 10. This goes to further demonstrate that dive time, not depth, is the leading factor in tables requiring a decompression stop. In line with this point, it can be said that computers give a more accurate reading of the allowable bottom time than tables. Dive 3 and Dive 4 from Series 4 are good examples of a computer allowing longer bottom times because the diver did not spend the entire dive at the maximum depth. Going by the tables, the diver would have been penalized by having to calculate the entire dive based on the time spent at the greatest depth. In Dive 3, for instance, the tables would have calculated the entire dive at 100 feet, but the average depth on the dive was only 61 feet. Consequently, a repetitive dive to an equivalent air depth of 42 feet (an actual depth of 64 feet) could have only lasted 42 minutes, but on the computer the diver recorded 53 minutes of bottom time during Dive 4. Understanding these generalizations can lead to safe diving practices.

While at this point it may be obvious that computers and tables function differently, a diver's safety depends on his or her ability to understand the significance of these differences. Foremost, neither computers nor tables take into account the diver's age, weight, or other physical conditions. Divers must know their own abilities and limitations. A young, physically-fit diver may be able to dive right up to the no-decompression stop limit set by either a computer or table and not suffer DCS, where as an older, overweight diver might be inflicted with DCS if attempting the same dive profile. While computers are great tools for tracking and recording depth, bottom time, water temperature, and a variety of other factors, the older, overweight diver might want to dive the more conservative time profile of the tables and use a computer just as a tool to record the dive. Another reason divers should understand both tables and computers would be in the event of computer failure. In the even that a computer fails underwater, for instance if the battery were to fail, there are two schools of thought on what actions the diver should take. The more conservative school of thought says that in the event of computer failure, the diver should safely ascend to the surface and not dive for at least 24 hours. The other line of thought is that if the diver carries a separate depth gauge and a watch and knows the table procedures then the diver can safely complete the dive and any repetitive dives without significant risk of DCS. Furthermore, since the golden rule of diving is to always dive with a buddy, it is possible for a buddy pair to consist of one person with a computer and one person diving on tables. In this situation, two dive industry rules come into play: no two divers can share the same single computer on dive, and in a buddy team, the team ends the dive in accordance with which buddy's instrument gives the more conservative allowable bottom time. In the situation where one buddy has a computer and one does not, the buddy with the computer must understand prior to the dive that they will have to end the dive by the time given by the table regardless of how much remaining bottom time is shown by his computer. Finally divers must realize that neither tables nor computers can guarantee safety. Both types of instruments make approximations of what is happening in a diver's tissues, but these approximations are based on observations, not proven facts. Since cases of Decompression Sickness are rare, it appears that the approximations are fairly accurate, but as Hempleman points out, these estimations are attempting to prevent the illness without truly understanding its cause. Since computers and tables are based on Decompression Theory rather than fact, a diver must understand the differences between the instruments so that he or she can evaluate his or her own personal risk of Decompression Sickness before every dive, and hopefully be able to take steps to lower that risk.

---

[1] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 4th ed. (London: W.B. Saunders Company Ltd, 1993), 342.

[2] George Lewbel, Ph.D., Multi-Level Diving: Computer Assisted Multi-Level Diving Work Book (Carlsbad, CA: Sea Quest, Inc., 1988), 3.

[3] Christopher Wayne Dueker, M.D., Medical Aspects of Sport Diving (Cranbury, NJ: A.S. Barnes and Co., Inc., 1970), 135.

[4] DAN, Report on Decompression Illness, Diving Fatalities and Project Dive Exploration: The DAN Annual Review of Recreational Scuba Diving Injuries and Fatalities Based on 2001 Data 2003 ed. [Report Online], (Durham: Divers Alert Network, 2003), accessed 6 November 2003; available from https:// www.diversalertnetwork.org/medical/report/2003/2003DANReport.pdf.

[5] Richard H. Strauss, M.D., ed., Diving Medicine (New York: Grune and Stratton, 1976), 63.

[6] Ibid., 64.

[7] DAN, Report on Decompression Illness, Diving Fatalities and Project Dive Exploration, 25.

[8] Carl Edmonds, Christopher Lowry, and John Pennefather, Diving and Subaquatic Medicine, 3rd ed. (Oxford: Butterworth-Heinemann Ltd, 1992), 176.

[9] Christopher Wayne Dueker, M.D., Medical Aspects of Sport Diving, 149.

[10] Ibid., 150.

[11] Carl Edmonds, Christopher Lowry, and John Pennefather, Diving and Subaquatic Medicine, 19.

[12] Richard H. Strauss, M.D., ed., Diving Medicine, 63.

[13] Ibid., 75.

[14] Christopher Wayne Dueker, M.D., Medical Aspects of Sport Diving, 140.

[15] Ibid., 150.

[16] Bruce Wienke, "Decompression Theory," [Paper Online], accessed 16 September 2003; available from ftp://ftp.decompression.org /pub/Wienke/deco.pdf.

[17] Richard H. Strauss, M.D., ed., Diving Medicine, 68.

[18] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 342.

[19] Christopher Wayne Dueker, M.D., Medical Aspects of Sport Diving, 140.

[20] Carl Edmonds, Christopher Lowry, and John Pennefather, Diving and Subaquatic Medicine, 140.

[21] Ibid., 141.

[22] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 343.

[23] Ibid., 344.

[24] Bruce Wienke, "Decompression Theory," 64.

[25] Richard H. Strauss, M.D., ed., Diving Medicine, 71.

[26] Ibid., 72.

[27] Christopher Wayne Dueker, M.D., Medical Aspects of Sport Diving, 150.

[28] Bruce Wienke, "Decompression Theory," 64.

[29] Christopher Wayne Dueker, M.D., Medical Aspects of Sport Diving, 149.

[30] Richard H. Strauss, M.D., ed., Diving Medicine, 73.

[31] Christopher Wayne Dueker, M.D., Medical Aspects of Sport Diving, 148.

[32] Carl Edmonds, Christopher Lowry, and John Pennefather, Diving and Subaquatic Medicine, 143.

[33] Christopher Wayne Dueker, M.D., Medical Aspects of Sport Diving, 151.

[34] Peter Oliver and Mike Williams, ed., NAUI Scuba Diver, (National Association of Underwater Instructors, 2000), 125.

[35] Richard H. Strauss, M.D., ed., Diving Medicine, 74.

[36] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 356.

[37] Ibid., 356.

[38] Carl Edmonds, Christopher Lowry, and John Pennefather, Diving and Subaquatic Medicine, 144.

[39] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 357.

[40] George Lewbel, Ph.D., Multi-Level Diving, 6.

[41] Bruce Wienke, "Decompression Theory," 64-65.

[42] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 358-359.

[43] Ibid., 359.

[44] Erik C. Baker, P.E., "Understanding M-values," [paper online], accessed 16 September 2003; available from ftp://ftp.decompression.org/pub/Baker/Understanding%20M-values.pdf, 1.

[45] Ibid., 1.

[46] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 359.

[47] James T. Joiner, ed., NOAA Diving Manual: Diving for Science and Technology, 4th ed. (Flagstaff: Best Publishing, 2001), 4-1.

[48] Erik C. Baker, P.E., "Understanding M-values," 1.

[49] Ibid., 2.

[50] James T. Joiner, ed., NOAA Diving Manual, 4-2.

[51] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 363.

[52] Carl Edmonds, Christopher Lowry, and John Pennefather, Diving and Subaquatic Medicine, 154.

[53] Bruce Wienke, "Decompression Theory," 65.

[54] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 362.

[55] Carl Edmonds, Christopher Lowry, and John Pennefather, Diving and Subaquatic Medicine, 154.

[56] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 362-363.

[57] Carl Edmonds, Christopher Lowry, and John Pennefather, Diving and Subaquatic Medicine, 145.

[58] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 364.

[59] Carl Edmonds, Christopher Lowry, and John Pennefather, Diving and Subaquatic Medicine, 145.

[60] Bruce Wienke, "Decompression Theory," 67.

[61] Ibid., 68.

[62] Ibid., 69.

[63] George Lewbel, Ph.D., Multi-Level Diving, 6.

[64] Department of the Navy, U.S. Navy Dive Manual, (Naval Sea Systems Command, 2001), 1-21.

[65] James T. Joiner, ed., NOAA Diving Manual, 17-4.

[66] Department of the Navy, U.S. Navy Dive Manual, 9-2.

[67] Christopher Wayne Dueker, M.D., Medical Aspects of Sport Diving, 150.

[68] James T. Joiner, ed., NOAA Diving Manual, 4-1.

[69] Bruce Wienke, "Decompression Theory," 94.

[70] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 362.

[71] Carl Edmonds, Christopher Lowry, and John Pennefather, Diving and Subaquatic Medicine, 161.

[72] Christopher Wayne Dueker, M.D., Medical Aspects of Sport Diving, 165.

[73] Peter Oliver and Mike Williams, ed., NAUI Scuba Diver, 130.

[74] Ibid., 130.

[75] Ibid., 131.

[76] Ibid., 132.

[77] Bruce Wienke, "Decompression Theory," 104.

[78] George Lewbel, Ph.D., Multi-Level Diving: Computer Assisted Multi-Level Diving Work Book, 8.

[79]Robert Ball and Sorell L. Schwartz, "Kinetic and Dynamic Models of Diving Gases in Decompression Sickness Prevention," Clinical Pharmacokinetics, 41, no. 6 (2002): 390.

[80] Richard H. Strauss, M.D., ed., Diving Medicine, 69.

[81] Ibid., 69.

[82] Cheryl Hall, "Richardson Company Reaches Heights With Portable Underwater Computers," The Dallas Morning News, 4 February 2001: pars. 1, 25 [article online], accessed 8 October 2003; available from http://www.divecochran.com/press_clippings/Dallas_Morning_News/020401.html.

[83] Melissa Rodriguez, "Diving History Time Line," 1 October 1998, [article online], accessed 28 October 2003; available from http://scuba.about.com/library/weekly/aa100198.htm.

[84] Cheryl Hall, "Richardson Company Reaches Heights With Portable Underwater Computers," par. 46.

[85] James T. Joiner, ed., NOAA Diving Manual, 5-42.

[86] Bruce Wienke, "Decompression Theory," 64.

[87] James T. Joiner, ed., NOAA Diving Manual, 5-42.

[88] Peter B. Bennett and David H. Elliot, ed., The Physiology and Medicine of Diving, 30.

[89] James T. Joiner, ed., NOAA Diving Manual, 5-42.

[90] Bruce Wienke, "Decompression Theory," 104.

[91] George Lewbel, Ph.D., Multi-Level Diving: Computer Assisted Multi-Level Diving Work Book, 6.

[92] James T. Joiner, ed., NOAA Diving Manual, 5-43.

[93] Jan Neal and Bret Gilliam, Nitrox: A User Friendly Guide to Enriched Air Mixtures, (Underwater Dynamics, Inc., 1997), 4.

[94] Christopher Wayne Dueker, M.D., Medical Aspects of Sport Diving, 165.

[95] Richard H. Strauss, M.D., ed., Diving Medicine, 75.

[96] Jan Neal and Bret Gilliam, Nitrox: A User Friendly Guide to Enriched Air Mixtures, 6.

Works Cited

Baker, Erik C., P.E. "Understanding M-values," [paper online]. Accessed 16 September 2003. Available from ftp://ftp.decompression.org/pub/Baker/Understanding%20M-values.pdf.

Ball, Robert and Sorell L. Schwartz. "Kinetic and Dynamic Models of Diving Gases in Decompression Sickness Prevention." Clinical Pharmacokinetics 41, no. 6 (2002): 398-402.

Bennett, Peter B. and David H. Elliot, ed. The Physiology and Medicine of Diving. 4th ed. London: W.B. Saunders Company Ltd, 1993.

DAN. Report on Decompression Illness, Diving Fatalities and Project Dive Exploration: The DAN Annual Review of Recreational Scuba Diving Injuries and Fatalities Based on 2001 Data 2003 ed. [Report Online]. Durham: Divers Alert Network, 2003. Accessed 6 November 2003. Available from https://www.diversalertnetwork.org/medical/report/2003/2003DANReport.pdf.

Department of the Navy, U.S. Navy Dive Manual, Naval Sea Systems Command, 2001.

Dueker, Christopher Wayne M.D. Medical Aspects of Sport Diving. Cranbury, NJ: A.S. Barnes and Co., Inc., 1970.

Edmonds, Carl, Christopher Lowry, and John Pennefather. Diving and Subaquatic Medicine. 3rd ed. Oxford: Butterworth-Heinemann Ltd, 1992.

Hall, Cheryl. "Richardson Company Reaches Heights With Portable Underwater Computers," The Dallas Morning News. 4 February 2001. pars. 1, 25 [article online]. Accessed 8 October 2003. Available from http://www.divecochran.com/press_clippings/Dallas_Morning_News/020401.html.

Joiner, James T. ed. NOAA Diving Manual: Diving for Science and Technology, 4th ed. Flagstaff: Best Publishing, 2001.

Lewbel, George, Ph.D. Multi-Level Diving: Computer Assisted Multi-Level Diving Work Book. Carlsbad, CA: Sea Quest, Inc., 1988.

Neal, Jan and Bret Gilliam. Nitrox: A User Friendly Guide to Enriched Air Mixtures. Underwater Dynamics, Inc., 1997.

Oliver, Peter and Mike Williams, ed. NAUI Scuba Diver. National Association of Underwater Instructors, 2000.

Rodriguez, Melissa. "Diving History Time Line." [article online]. 1 October 1998. Accessed 28 October 2003. Available from http://scuba.about.com/library/weekly/aa100198.htm.

Strauss, Richard H., M.D., ed. Diving Medicine. New York: Grune and Stratton, 1976.

Wienke, Bruce. "Decompression Theory." [paper online]. Accessed 16 September 2003. Available from ftp://ftp.decompression.org /pub/Wienke/deco.pdf.