# DEVELOPING THE *NEW* US NAVY TABLES

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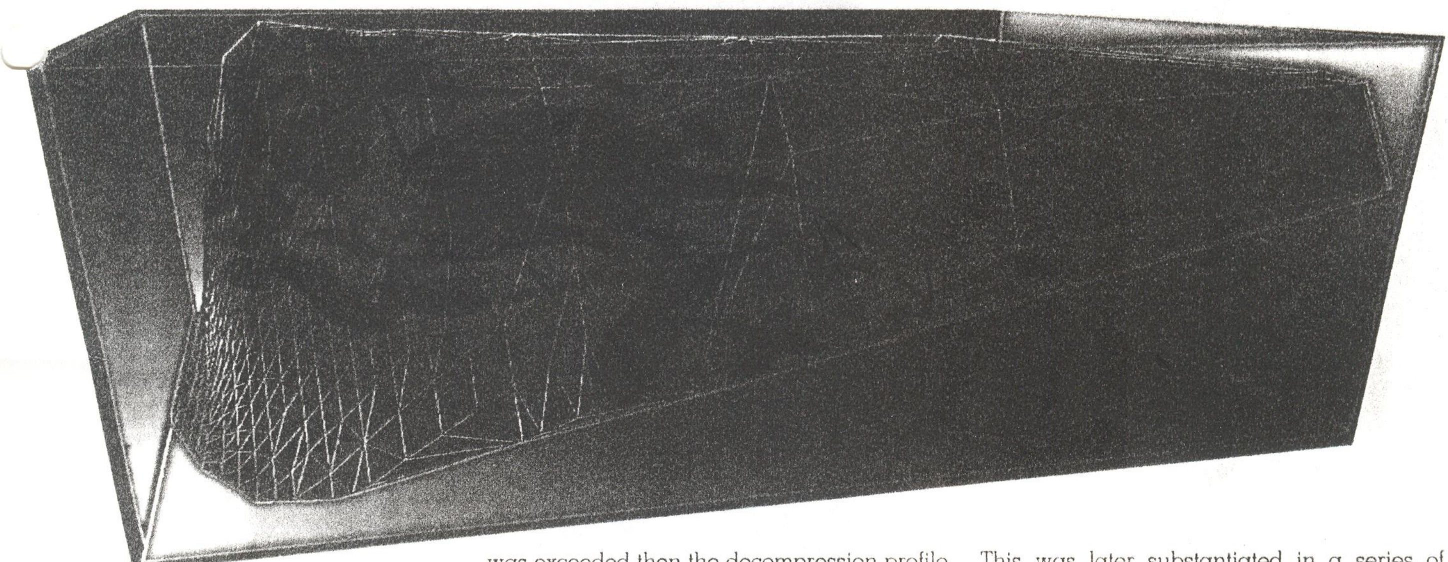
The U.S. Navy is about to revise its air decompression tables which have been in use since 1956. In revising these tables the Navy has formulated a fundamentally new approach to diving decompression safety; not just new tables, but a different approach to the underlying principles of the risk of decompression illness (DCI).

The 1956 revision of the U.S. Navy Air tables was accomplished over a two year period and employed mathematical methods that had been used in its 1930 revisions. These followed the principles laid out by Haldane in the development of the 1908 Royal Navy tables. In Haldane's approach, the human body was assumed to be composed of several "tissues" in which nitrogen uptake and elimination could be described by an exponential function. So long as the partial pressure of nitrogen in these tissues did not exceed the ambient water pressure by more than a certain amount, then decompression illness would not occur and the decompression profile was considered to be "safe." If this critical nitrogen partial pressure



was exceeded then the decompression profile was "unsafe." Models under which decompression profiles are classified as "safe/unsafe" are referred to as deterministic models.

Testing for the 1956 USN Air tables was done by first computing a set of some 300 decompression schedules, then testing only 40 representative schedules, giving no direct indication of the safety of the remaining 260. The untested schedules were considered to be acceptable since they were derived from the same criteria as the tested and accepted schedules. There were on average, fewer than six test dives per schedule on those tested. Acceptance rules dictated that a tested schedule which resulted in "zero bends out of four dives" be regarded as "safe". If schedules were found to be "unsafe", the decompression model was revised and further tests done until the zero DCI in four dives criteria was met. The model used to compute the schedules was revised twice during the trial. During the later portion of testing, only the "unsafe" profiles were manually modified to increase stop times. At the end of testing, a complete set of air tables was produced but not all of the schedules could be calculated from the decompression model.

In the 1956 approach to testing, each decompression schedule had to be considered as an independent event, that is, that only dives conducted on a specific schedule could be used to estimate the actual DCI risk. Statistics indicate that in accepting a schedule based on the 0 out of 4 rule, the true underlying incidence of DCI could be anything from 0 to 60%, possibly resulting in the acceptance of many very risky schedules. In the current atmosphere of risk regulation and management this level of uncertainty is just not acceptable. In addition, a 1980 analysis of available information on U.S. Navy Air diving suggested that schedules were regularly being "jumped"—using a schedule for a deeper depth or longer bottom time than was actually dived—presumably for the benefit of the diver. If the tables were not being followed as intended, then the Navy's overall good diving safety record might not be indicative of the underlying safety of the tables as they were written. This was later substantiated in a series of experimental dives in which a standard Air 60 fsw/18 msw for 180 minutes schedule produced three cases of DCS in ten divers. (The only 60 fsw/18 msw schedule tested in 1956 was for 90 minutes.)

In 1973, engineers at the then Naval Ocean Systems Center (NOSC) in Hawaii proposed building a small wrist worn device for constantly monitoring a diver's depth and computing decompression schedules. At about the same time the Navy was developing a new closed circuit rebreather which used an oxygen-nitrogen mix in which the partial pressure of oxygen was electronically controlled to a constant level of 0.7 atm. The task of developing new decompression tables for this system fell to the Navy Experimental Diving Unit (NEDU) which had been developing a comput-

***Editors note: I have substituted the term "decompression illness", or DCI, in this article in place of the traditional name, decompression sickness, DCS, to reflect changing terminology. For more information see, "Goodbye Decompression Sickness. Hello Disorders: A New Approach To Classification" by T.J.R. Francis, D.J. Smith, and J.J. W. Sykes, aquaCorps Journal, N5, "BENT."***

er program to compute air decompression schedules based on Workman's method. Their approach was to extend the 1956 Air Tables to a constant partial pressure model.

Initial manned testing of these tables was carried out from pre-computed schedules in 1977, but the many problems of using pre-computed schedules (e.g. adjusting for holds during descent due to ear squeezes) coupled with the high DCI incidence for 175 fsw/54 msw test dives caused suspension of this effort.

NEDU personnel developed a real-time version of the constant partial pressure algorithm which allowed schedules to be calculated from actual chamber depth as the dive progressed. The subsequent test dive series in 1978 marked the first time U.S. Navy divers decompressed using schedules computed in real-time. The algorithm was modified as testing progressed, and only after the final version was determined, were the printed tables computed. NEDU's efforts were still based on deterministic models and relied on the same "safe/unsafe" approach to determine the safety of decompression schedules. A set of test schedules was devised, with each schedule subjected to 10 to 30 dives. The only difference from earlier tests was the larger number of exposures required before deciding on the safety of a particular profile. The incidence of DCI for all dives during any given series was used as an estimate of overall safety but the statistical confidence limits on DCI incidence for individual profiles ranged from 0-17%. Changes to the algorithm were based on the judgement of experienced investigators, but there was no way to quantify the overall safety of the final version of the tables. The breakthrough which heralded the beginning of a new approach to decompression management came from the investigators at the Naval Medical Research Institute (NMRI).

NMRI approached the problem of DCI risk as a probabilistic event. The hypothesis that any decompression exposure involves some degree of risk, and that neither individual divers nor identical exposures have the same bends outcome, was clearly established in hypo-baric, or aviation, bends trials in the 1940s. Based on this idea, a mathematical approach was adopted that related a dive profile to the probability of occurrence of bends, or P(DCI), breaking with the approach of defining a profile as "safe/unsafe." Another fundamental change in approach was the emphasis on dive data as the basis for model development. Rather than assigning model parameters based on approximations of physiological variables, or by "fitting" a model to pre-existing tables of uncertain or unknown quality, the model was to be fitted to a large and varied data set derived from accurately recorded, carefully supervised experimental dive trials using accepted statistical methods. The usefulness of the resulting model would then ultimately be a direct reflection of the quality and diversity of the calibration data set.

Earlier use of test dive "data" to adjust an algorithm relied on large numbers of dives done on exactly the same profile. Not only did this restrict the sources of data which could be used, but there was no objective, or statistical, methodology available for estimating the precision with which parameters in the algorithm could be determined. The NMRI approach could use data effectively even if there was only one exposure on a particular profile, and could also calculate the precision to which model parameters were estimated. This opened up many more sources of data, with the only restrictions being that the actual dive profile used must be precisely known, and that trained medical personnel observe the divers for symptoms of DCI.

In what is now viewed as a landmark paper in this effort, the viability of the P(DCI) approach was first successfully demonstrated by using heliox upward excursion data from saturation dives in 1984. In the next several years refinements of this probabilistic approach were successfully applied in a number of analyses involving standard air bounce dives, no-stop nitrox dives, and saturation dives. These studies demonstrated that the probabilistic method could satisfactorily predict the DCI risk of dives ranging from less than one minute to more than one day in duration. The important question of whether such diverse types of dive data can justifiably be combined under a single model was also explicitly addressed.

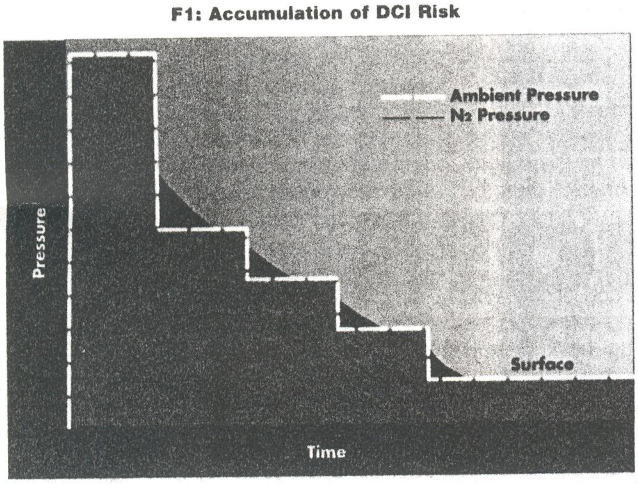
The usefulness of the technique was further demonstrated by computing, for the first time, a set of single dive tables that had a consistent probability of bends throughout. These preliminary tables would later be revised based on models calibrated to a much larger data set. The 1956 U.S. Navy Air Tables were analyzed for uniformity of DCI risk, and compared to UK and Canadian Air Tables. This analysis indicated that the schedules in the 1956 USN Air tables have a tremendous range of DCI risk, from approximately 1-7% for shallow and/or short dives, to as much as 40-45 % for some extreme exposures. The UK tables were found to be marginally less risky than the USN tables, and many of the schedules in the Canadian tables were far less risky than their counterparts in either the UK or USN tables, due largely to their greater required decompression times. An important point noted in this study was that longer decompression times do not always lead to lower risk, emphasizing the importance of finding the optimal distribution of decompression time among the available stop depths.

In 1988, the U.S. Navy Supervisor of Salvage gave the go ahead for development of a new set of air and constant 0.7 atm $PO_2$ nitrox tables based on the new NMRI probabilistic approach. It was furthermore decided that a real-time version of the decompression algorithm would be tested for approval and the same underlying model would be used to compute printed tables for air and constant PO2 nitrox tables. Before progress could be made on these projects, several remaining concerns had to be addressed.

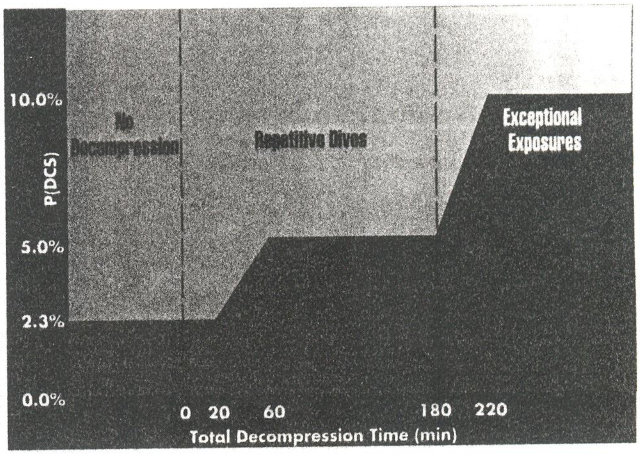
One concern was that the 1985 version of the algorithm was calibrated on dive data up to 35 years old, some of which may have been carried out under different diagnostic standards than others. In particular, this may have resulted in some cases of divers scored as safe that would have been diagnosed and treated as having bends in more recent trials.

A second concern was whether the individualized decompression schedules computed in real-time were believable. Through the

**F1: Accumulation of DCI Risk**




**F2: DCI Risk "Slide"**



1980s, probabilistic models were calibrated using data which indicated only whether DCI occurred, or did not occur, following a dive. The application of the model during a dive requires more detail with regard to the time course of DCI risk in order to make reliable decisions regarding decompression requirements as the dive progresses.

A third concern was the enormous amount of computer time required to calculate the NMRI constant risk tables. This resulted from the need to evaluate literally thousands of possible decompression profiles in an exhaustive "global search," in order to meet the competing demands of an acceptable risk level and minimum decompression time. While decompression tables can be calculated with this method given enough time, the desire to apply this probabilistic algorithm to real-time decompression calculations required a more efficient solution to the decompression time distribution problem.

A fourth concern arose because the Navy still wanted a set of traditional printed tables in addition to the real-time capability. Single dive table calculation is straightforward, but repetitive dive tables presented some unique challenges. If a P(DCI) limit of 5% is chosen and a single dive profile from such a 5% risk table is followed, the diver cannot make any subsequent dives until declared "clean," usually considered to be the next day. This restriction comes about because, after completing the initial dive, the diver has accumulated the allowed 5% DCI risk, and any further dives will only add to that risk. After enough time has passed for the diver to be considered "clean," his accumulated risk is reset to 0%. The solution would be either to know the exact repetitive sequence in advance and stick to it, or to allow higher, maybe much higher, risk for the second and following dives. The former option leads to unacceptably long decompression times (or short no-stop limits) for repetitive dives, so that the dive sequence as a whole comes in under the 5% allowed risk, and the latter leads to unacceptably high levels of DCI risk for the sequence.

The data problem was addressed by the accumulation of over 4,000 carefully collected and thoroughly verified air and nitrox dives from U.S., UK and Canadian Navy labs. The oldest of these dives dated to 1977, recent enough to be certain of the quality and consistency of the data. Also for consistency, wherever possible only cold, wet and working dives were chosen for use in model calibration, since that was the application that the algorithm was intended for. Each reported case of DCI was reviewed, going back to original dive records where necessary. Those responsible for conducting the dives were also consulted to resolve inconsistencies. In addition, a significant piece of information was now included which had not previously been considered; the specific time at which bends occurred. This additional information addressed the concern over the reliability of real-time results. A probabilistic model which could incorporate the time of DCI occurrence into its calculations would be capable of reliable DCI risk estimates on a scale of minutes or hours, rather than just whether DCI is likely sometime after the dive.

The statistical techniques developed at NMRI provided powerful tools for calibrating model parameter values with dive data, and investigators could then concentrate on developing those details of the models which relate pressure exposure to DCI risk. Since 1985, all models have been based on a risk or hazard function. Definitions of instantaneous risk have used either instantaneous inert gas supersaturation, or the time history of supersaturation.

Of several candidate gas kinetic models tried, earlier work at NEDU coupled with the new time of DCI data, provided the best fit to the calibration data set.

The kinetic component of this model is comprised of three parallel, independent compartments, with DCI risk accumulated proportional to the area under the nitrogen "tissue" over-pressure curves in all compartments. Figure F1 illustrates the accumulation of DCI risk for one compartment on a typical decompression dive. On each pull to a shallower stop depth, the "tissue" pressure exceeds the ambient pressure and the risk accumulated while this overpressure persists is proportional to the shaded area under that curve. The total DCI risk for the dive is then proportional to the sum of each of these areas for the three compartments. Since risk exists only when there is an overpressure, the model parameters must be adjusted so that an overpressure exists, and hopefully is "high" at the time of each recorded DCI occurrence.

In the gas exchange section of the 1993 U.S. Navy model, nitrogen pressure follows single-exponential kinetics for uptake, and allows for mixed linear and exponential kinetics for off-gassing, potentially resulting in a flexible asymmetric inert gas wash-in/wash-out. In the best fitting version of this model, only one of the three kinetic compartments takes advantage of this asymmetry, the other two use symmetric exponential-only kinetics. Similar models, which used only symmetric exponential wash-in/wash-out kinetics, were unsuccessful in fitting some of the time of occurrence data. In particular, some bends cases occurring several hours post-dive lead to model failure, since no calculated overpressure was present at the time of occurrence. The extended wash-out provided by these asymmetric gas kinetics allows all DCI cases in the calibration data set to be fit. The 1993 model is able to accurately predict the overall level of DCI as well as the time of occurrence in a wide variety of air and nitrox dives, both within the calibration data set and among data not used for fitting.

The massive computer time requirement was eliminated by a novel "local search" method. Rather than wait until the end of a dive's bottom time to begin searching for an optimal decompression schedule, this "local" method searches a much smaller set of candidate schedules several times a minute as the dive progresses. Each search is usually limited to about five candidate schedules, beginning with the schedule found to be optimal as a result of the most recent search. This method will be successful as long as the required decompression time varies in a reasonably smooth manner as bottom time and/or depth increase. Since this method requires a recently optimal schedule in order to continue the search, it must begin at the start of a dive, when the optimal schedule is known—no decompression for no exposure. The schedule that is eventually selected at the end of the bottom time, differs insignificantly from the schedule selected by the "global" search used earlier but uses only a fraction of the computer resources.

The fourth problem, regarding repetitive diving, was solved by application of "conditional" probability. Incorporating the time of bends information in the data set into the probabilistic model allowed the algorithm to predict not just the level of risk of DCI for a given profile, but also when DCI was most likely to occur. Knowing the time course of DCI risk allows the risk incurred in the past to be progressively ignored, assuming the diver has survived without DCI up to the present. In other words, the diver need only be concerned with the risk to be incurred in the future. This idea is illustrated in Figure F1, in which a diver who has followed this profile, and is now at the later part of the last decompression stop, has already survived the risk associated with the first three risk accumulation periods. This diver now only needs to be concerned with the risk of travelling from the last stop depth to the surface. This allows a diver to follow a profile calibrated to 5% DCI risk, then, assuming she survives without DCI during the following surface interval, she can dive another 5% profile, and so on for multiple repetitive dives. The calculated nitrogen tension levels need to be followed throughout the sequence. If the surface interval is not long enough to restore normal, pre-dive, nitrogen levels, second and subsequent dives will be progressively restrictive, but only slightly so compared to the "non-conditional" approach discussed earlier.

In order to produce decompression tables with this algorithm, a calculated risk level must be chosen. While it may at first seem desirable to simply choose the lowest possible risk level, say 1% or less, it quickly becomes apparent that such conservative limits lead to unacceptably long decompression times (conversely very short no-stop times). In addition, not all dive environments are equal; no-stop and short decompression dives are not only done more often, but also under circumstances in which a recompression chamber and diving medical personnel may not be readily available. A lower allowed DCI risk level may be appropriate for these conditions, while for longer, deeper dives, leading to longer decompression times, a higher risk level might be more appropriate. In U.S. Navy diving, these type of dives require the rapid availability of recompression facilities and trained medical personnel.

These factors have lead to the development of an innovative "sliding risk" scheme, illustrated in Figure F2. In this system, a dive's acceptable risk starts at a low level, and is then linked to the required decompression time so that as decompression time increases, so does the acceptable risk level. F2 shows the shape of this risk slide with the risk-limits as chosen for the new decompression tables. This arrangement allows no-stop dives and those with short decompression obligations to be calculated at a stringent risk level, while allowing a relaxation of the risk limit for more extended dives. For repetitive diving, the "risk slide" returns to the low initial level during the surface interval between dives at a rate governed by the nitrogen wash-out kinetics. Depending on the length of the surface interval, the DCI risk level used to calculate the next dive's decompression schedule might be anywhere between the upper and lower limits of the "risk slide." For dives designated as "exceptional exposures" *(To only be conducted in an operational emergency according to the USN—ed.)* a second step is added to raise the acceptable risk level again as decompression time becomes very long. No further diving is to be allowed for several days following an exceptional dive. The sliding risk scheme allows the algorithm to flexibly adapt to the demands of a variety of diving situations, while maintaining a common probabilistic approach. The U.S. Navy has filed a patent application on the final form of this algorithm, which incorporates all of these advances.

In 1991, the algorithm was tested in a prospective dive trial involving 571 dives. The profiles in this trial were chosen to be different from those in the calibration data base as a test of the flexibility of the algorithm. These dives included single air, multiple repetitive air and multilevel air dives, and about 25% of the tested schedules used a combination of air with oxygen during decompression or shallow transits. This trial had a bends outcome very close to that predicted by the algorithm whether the trial was looked at as a whole, as dives grouped by type of profile, or according to predicted risk level. The success of this trial verifies the model's applicability to an even wider variety of air and nitrox dives.

Decompression tables based on the tested algorithm were computed for both air and the constant 0.7 atm PO2 nitrox mixes (closed circuit diving). A single repetitive dive procedure allows a diver to use both types of breathing gas; for example, a nitrox second dive can follow an air dive. Tables for other nitrox mixes could be calculated, but the two gasses mentioned above are the only nitrogen based mixes currently used by the USN. The tables contain a separate complete set of schedules for each of 26 repetitive groups (A-Z), with A representing a "clean" diver. A "clean" diver beginning a sequence of dives uses the A table, and at the end of the dive the table lists the diver's new repetitive state code. These repetitive states are a condensation of the infinite number of possible states which could result from a repetitive dive. Similar to the current tables, a surface interval credit table tells the diver what her new state is at the end of the surface interval. However, there is no longer any residual nitrogen time table. For second and subsequent dives, the diver simply flips to the complete set of tables for her current repetitive state and follows the appropriate decompression schedule for the next dive. Although they are far larger than the existing tables, these new tables are much easier to use, requiring the diver only to keep track of her current repetitive state in order to follow even the most complex sequence. Calculations of equivalent bottom time are no longer required, simply follow the schedule as listed for the actual dive in the appropriate state's table.

Schedules in the new air tables will be different from their counterparts in the 1956 USN tables. At present, only a few generalizations can be made about the nature of these differences; the range of DCI risk will be much smaller than the 1 to 45% of the 1956 tables, most required decompression times will be longer for a given dive and most decompression schedules will be safer. A more detailed analysis of specific differences will have to wait for the public release of the new tables scheduled in 1994.

Three significant PC compatible computer programs have resulted from this work, and were demonstrated at the Undersea and Hyperbaric Medical Society meeting in July 1993 *(Note that the developer, Automation Counselors Inc. Frederick, MD holds the copyrights—ed.)*.The simplest of these is a schedule look-up program designed to assist in planning a table-based dive, whether single or repetitive, no-stop or decompression, utilizing air or constant 0.7 atm PO2 nitrox tables. One advantage this program offers over using the paper tables is simply in bulk. The program and all tables can be carried on one 3.5" floppy disk, while the equivalent paper tables run to several hundred pages. The program also logs the selected dive sequence and allows great flexibility in exploring "what-ifs," such as extending bottom time or the surface interval, switching between air and nitrox tables, extending bottom depth to the next tabulated depth, and several different scenarios can be compared quickly and easily.

A second program evaluates any dive profile for DCI risk level. The user simply enters a desired profile, including travel rates, bottom time and depth, and decompression stops (or lack thereof), to any level of complexity. Up to three different gas mixes (one is always air) may be used on any one profile, and are defined by the user prior to entering the depth/time information of the dive. The program processes the profile input and provides an estimate of DCI risk, with confidence limits that depend on the nature of the dive. The only limitation that the user should keep in mind is that the algorithm as presently implemented may underestimate the DCI risk on dives utilizing oxygen decompression. A dive trial planned for early 1994 will address this specific problem. The reported analysis show; that this program's estimates of DCI risk for most other types of air or nitrox dives are reliable.

The third program is a versatile dive planner, designed around the same front-end as the above estimator program. Rather than providing the risk level of a pre-determined profile, the planner provides a decompression schedule for any selected risk level and allows the risk slide limits to be modified to include a wider range of DCI risk. Similar to the estimator program, up to three user-defined gas mixes may be used on any one dive scenario, with the same limitation regarding oxygen decompression.

Tools are now available which can objectively evaluate the DCI risk of any decompression profile, and for the first time a method of calculating decompression requirements exists which has a documented and verified accuracy of DCI prediction throughout a wide range of air and nitrox applications, backed up by over 4,000 experimental dives. It is hoped that these tools will bring a new level of confidence to dive safety. The ability to select an acceptable level of DCI risk, including the capability to vary the risk according to the severity of the dive, allows for great flexibility in dive planning, while retaining the confidence of the underlying methods.

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# Visualizing Decompression Risk:

## A Comparative Analysis of the U.S. Navy, British, and DCIEM Tables

by David Story

The U.S. Navy has been doing ground-breaking decompression research in order to create new tables and dive computers which can predict decompression illness (DCI) risk. As part of their research, the team at the Naval Medical Research Institute (NMRI) has also analyzed the decompression risks of the three best known tables in the world.[1] This article uses 3-D *visualization* techniques to change their results from a ream of numbers into an easily-understood pictorial representation. Visualization techniques provides the densest possible presentation of the datasets in question, allowing us to "see" the trends of a large data-set in a single image.

Figures F1, F2, and F3 present estimates of DCI risk for each depth/time entry in the U.S. Navy, Royal Navy, and DCIEM tables, respectively. The risk estimates are shown starting with the no-decompression limits of each table. Dive depth and bottom time are combined with the resultant decompression risk to create a *risk surface*. This three dimensional surface lies over the risk data points like a colored tablecloth. A *wire-frame* surface has been added to give a better sense of the shape of the figure. The colors on the surface correspond to the estimated DCI risk at each point, and are coded to match Figure F2 shown in The New Navy Tables, by Parker et al, pg. 52 in this issue of the Journal: green for risks up to 2%, yellow for risks up to 5%, and red for risks beyond 10%.

For comparison, the boundaries of the U.S. Navy Table visualization (F1) are indicated on F2 and F3 as a thin, blue wire-frame box. Note how much larger the Navy risk volume is than the other tables. It would appear that the DCIEM tables offer less risk than the USN Tables for comparable profiles though they cover a smaller set of possible profiles.

Table T1, presents the limits of each table. Clearly, simply reducing a table's maximum depth or increasing total decompression time is not sufficient to increase safety.

There are two important patterns which recur in each of the tables. The first might seem counter-intuitive: mild decompression dives are actually safer than dives to the no-decompression limits. You can see this from the "trough" created as the risk surface of each table dips upon entering decompression. This dip indicates that the NMRI model considers a safety stop a wise precaution.

The second trend reminds us of the limits of our theoretical models, no matter what kind. Examine risk figures F1-F3 and note how rapidly risk rises as a function of total decompression time. All three tables show an extremely steep climb in risk as decompression times get longer. This surprisingly consistent result indicates that although all three tables use very different theoretical models, none is safe enough for long decompressions; other methods must be utilized.

***T1: Comparison of Table Limits***

| *Source* | *Max Depth* | *Max Dive Time* | *Max Risk* | *Max Deco Time* |
|---|---|---|---|---|
| *U.S. Navy* | *300 fsw* | *12 hours* | *45.1%* | *1109 minutes* |
| *Royal Navy* | *200 fsw* | *11 hours* | *44.9%* | *240 minutes* |
| *DCIEM* | *240 fsw* | *8 hours* | *18.0%* | *301 minutes* |

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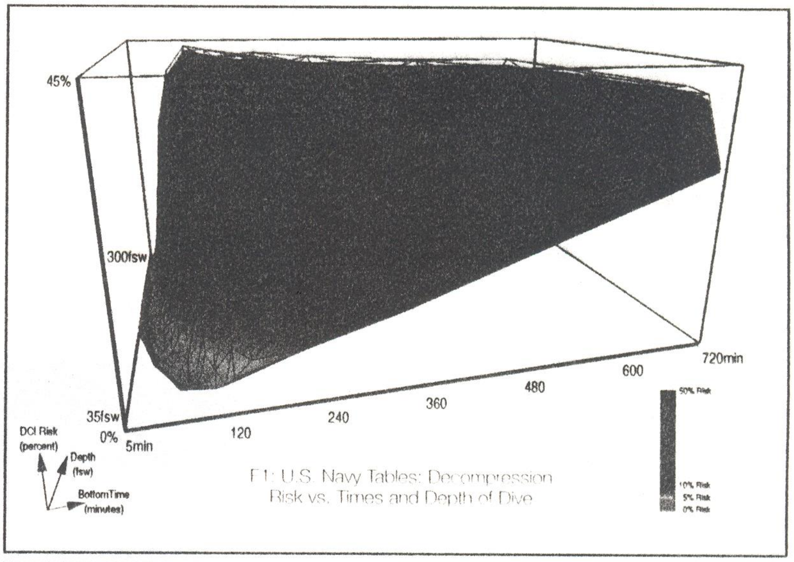
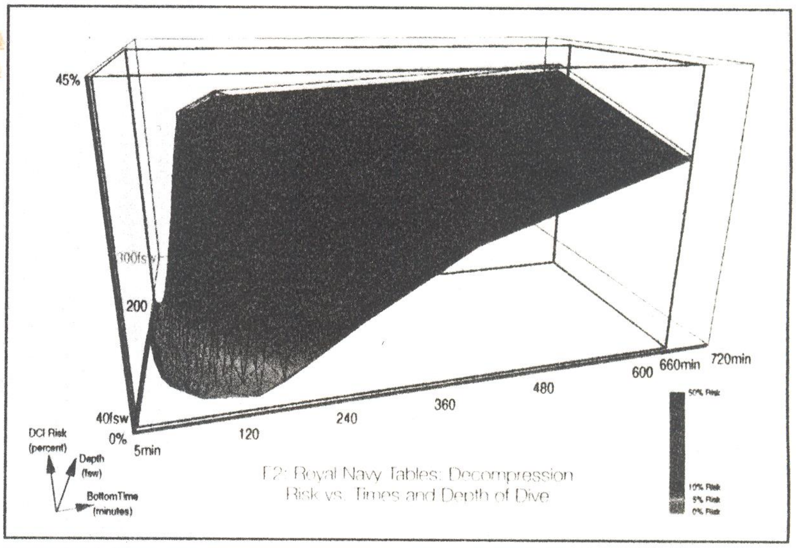
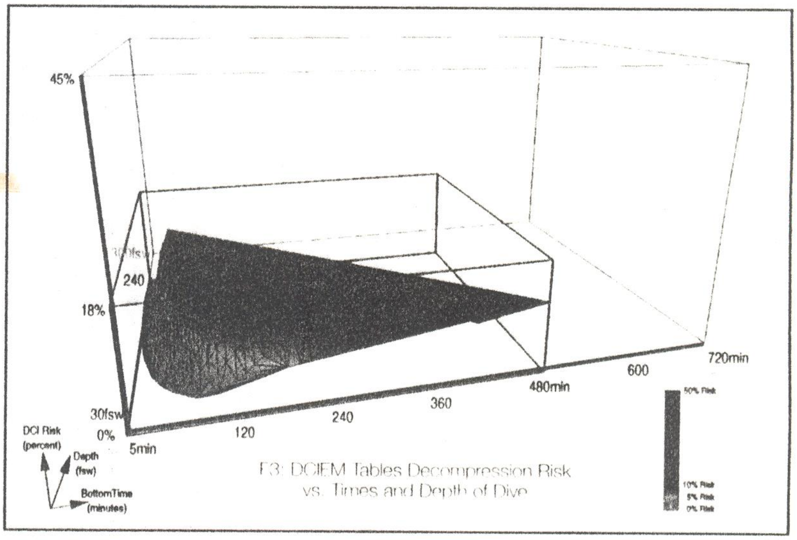


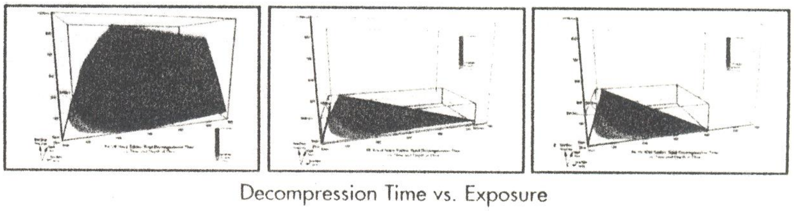
F1: U.S. Navy Tables: Decompression Risk vs. Times and Depth of Dive



F2: Royal Navy Tables: Decompression Risk vs. Times and Depth of Dive



F3: DCIEM Tables Decompression Risk vs. Times and Depth of Dive


Decompression Time vs. Exposure