SPECIAL COMMUNICATION

The U.S. Navy Decompression Computer

F. K. BUTLER and D. SOUTHERLAND

Naval Special Warfare Command, Detachment Pensacola and Navy Experimental Diving Unit Panama City Beach, Florida

Butler FK, Southerland D. The U.S. Navy decopression computer. Undersea Hyper Med 2001; 28(4):213–228.—The U.S. Navy has recently approved the Cochran NAVY decompression computer (DC) for use in Naval Special Warfare diving. This action represents the first approval of a diver-worn DC for use in the U.S. Navy. This paper reviews the development and testing of both the decompression algorithm and the hardware chosen for the Navy's DC. The decompression software in the Cochran NAVY is the VVAL 18 algorithm developed at the Navy Experimental Diving Unit (NEDU) by Captain Ed Thalmann. A discussion of the relative conservatism of the VVAL18 algorithm in comparison to the U.S. Navy Standard Air Tables and the basis for the differences between the two is provided. The initial guidelines establishing DC diving practice for the Navy SEAL community are outlined as are plans for future research efforts in U.S. Navy DC diving.

U.S. Navy, decompression computer, decompression models, decompression table testing, dive computer

BACKGROUND

In the late 1970s, the U.S. Navy Special Warfare community was developing a new underwater breathing apparatus (UBA) for use by its SEAL (Sea-Air-Land) commando teams. The MK 16 is a closed-circuit, mixed gas rebreather that uses a microprocessor to control the partial pressure of oxygen at 0.75 atm abs. (Fig. 1) The higher partial pressure of oxygen at shallower depths has the advantage of extending the shallow no-decompres-sion limits and shortening shallow decompression stops. (1)

This new gas mix required the development of new constant partial pressure of oxygen decompression tables. In addition, since SEAL operations entail the use of open submersible SEAL Delivery Vehicles (SDVs) launched from submarines, the dives are typically multi-level and may be many hours in length. An SDV is shown in Fig. 2. These factors prompted the SEALs to request that the Navy develop a diver-worn decompression computer (DC). The request was first made in 1978, 23 yr ago. Why has it taken the U.S. Navy (USN), with all of its resources and diving expertise, 23 yr to develop a DC?

New diving technology and procedures for the U.S. Navy are developed and approved in a well-established manner. The diving commands in the fleet—SEALs, Explosive Ordnance Disposal, ships husbandry, salvage, and saturation divers—request new hardware and procedures as needed to perform their respective missions. The office of the Chief of Naval Operations (N773) has oversight for diving activities in the Navy, but authority to approve new diving equipment and procedures is delegated to the Supervisor of Diving and Salvage at the Naval Sea Systems Command (NAVSEA OOC). NAVSEA's primary testing facility is the U.S. Navy Experimental Diving Unit (NEDU) in Panama City, FL. The Naval Medical Research Institute (NMRI, now renamed the Naval Medical Research Center) has also been historically involved in diving physiology research and has acted as an advisor to NAVSEA. The Bureau of Medicine and Surgery's Director of Undersea Medicine (BUMED Code 21) is likewise a source of advice .to NAVSEA on diving physiology issues. Typically, NEDU evaluates new diving equipment and procedures and, based on its findings, makes recommendations to NAVSEA about their suitability for fleet use. NAVSEA seeks additional input from NMRI and BUMED Code 21 if needed, then makes a decision on approval.

The development of the new constant partial pressure of oxygen nitrox tables (called hereafter the MK 16 tables) was undertaken at NEDU in 1978 with then-Commander Ed Thalmann as the primary investigator. His model was named the VVAL series with numbering used to designate successive versions. By 1980, testing was complete and the new decompression software was ready (2–4). The MK 16 tables were first published in 1981 and are still contained in the U.S. Navy Diving Manual (5). The Naval Ocean Systems Center in San Diego had been developing the DC hardware in a parallel effort, but this prototype computer failed testing at NEDU. It was then proposed that the NEDU algorithm developed by CDR Thalmann be incorporated into one of

FIG. 1—Mk 16 Underwater breathing apparatus.

the first commercially available decompression computers, the Deco-Brain. Before negotiations were complete, however, the factory that produced this DC was destroyed in a fire.

Shortly after this event, the first operational use of a new SDV support system, the Dry Deck Shelter (DDS), took place in the waters near Subic Bay in the Philippine Islands. The DDS is a transport compartment for SDVs that is attached to a fast-attack or ballistic missile submarine (Fig. 3). Since the DC was not yet ready, Thalmann and Butler developed the Combat Swimmer Multi-Level Dive (CSMD) procedures as an interim measure to calculate decompression for multi-level dives pending the completion of the Navy DC (6). NEDU medical personnel supporting the first operational use of the DDS observed that SEALs piloting the SDVs breathed both compressed air and from the MK 16 during the course of their dives. A decompression algorithm designed to calculate decompression for a constant PO_2 breathing mix could not be used for divers breathing a combination of air and mixed gas. When this was pointed out in the NEDU after-action report (7), the NSW community decided that SEALs needed to be able to breathe both air and MK 16 to achieve the dive durations required. This was communicated to NEDU and dive trials designed to incorporate an air capability into the new algorithm were begun.

Commander Thalmann's model was initially calibrated to produce the no-decompression limits and decompression times contained in the U.S. Navy Standard Air Decompression Tables developed in 1955 at NEDU. Dive trials revealed that the deeper No-Decompression (No-D) limits contained in the Standard Air Tables were safe to dive, but that some of the decompression schedules for long bottom time dives resulted in an unacceptable incidence of decompression sickness (DCS) (8). Appropriate adjustments to the VVAL model were begun and eventually resulted in the version called VVAL18, but work on the combination air/nitrox algorithm was not completed before CDR Thalmann's departure in 1985 for a 3-yr tour at the Institute of Naval Medicine in the United Kingdom. The SEALs became increasingly comfortable using the CSMD procedures and work on the DC stopped.

At about the same time, a radically new decompression model was being developed by Weathersby, Flynn, Survanshi, and their colleagues at NMRI. (9–11) Theirs was a probabilistic model which sought to predict the likelihood of DCS after any given hyperbaric exposure. The tables generated by this model, therefore, were determined by the level of predicted risk that one is willing to accept. The NMRI model was eventually very well received by the scientific community in that it predicts a progressive increase in the probability of DCS as decompression stress increases, rather than attempting to establish a single arbitrary threshold below which the diver is safe and above which he or she will be bent.

FIG. 2—SEAL Delivery Vehicle (SDV).

When now-Captain Thalmann returned to the United States in 1988, he was assigned to NMRI and became involved in the continued development of the NMRI probabilistic model. With a renewed interest in the DC project by the newly established NSW Biomedical Research Program, funding was obtained to finish the required testing for a Navy DC algorithm, but the focus now was shifted to a real-time version of the NMRI probabilistic model. Testing was resumed at both NMRI and NEDU in 1991. By 1993, both NMRI and NEDU agreed that this model was mature enough and sufficiently well tested to be recommended to NAVSEA for approval. This work has been described in a number of subsequent reports (12–21). The recommended acceptable levels of risk of DCS (as calculated by the NMRI probabilistic model) were 2.5% for the No-D limits and dives with small amounts of decompression, increasing to 5% for longer decompression dives and 10% for exceptional exposure dives. (CAPT Paul Weathersby, NAVSEA briefing, 1993) Although this risk level may seem high, the tables that it generated were overall more conservative than the Standard Air Tables currently used by the Navy. NEDU and NMRI's recommendation was endorsed by BUMED Code 21 and the tables were given preliminary approval by NAVSEA in 1993. Work was then begun on rewriting the air and nitrox decompression sections of the U.S Navy Diving Manual, and the search was begun anew for a suitable DC into which to incorporate the Navy's new decompression model. An interim laptop computer-based version of this model was designated the Naval Special Warfare Dive Planner and approved for computation of decompression obligation on SDV/DDS operations (22).

Captain Thalmann proposed that the Navy enter into a cooperative research and development agreement (CRDA) with one or more manufacturers of commercially available DCs (of which there were many by this time). This would enable the Navy to get its algorithm incorporated into an established DC and thus avoid development costs. In addition, the civilian diving world would get the benefit of the newly approved and well-tested Navy decompression algorithm. With the assistance of the Diving Equipment Manufacturer's Association, a meeting was convened at the Naval Special Warfare Center in Coronado, CA, in November 1993 to present this proposal to all interested DC manufacturers. The meeting was well-attended, but no DC manufacturers decided to sign a CRDA with the Navy for this project. Among the reasons expressed for this decision were: 1) the microprocessors in their DCs could not handle the computational requirements of the NMRI probabilistic model; 2) if a company fields a computer with new decompression software, what does it do about all of its DCs already in use with the old decompression software?; 3) there were concerns that the USN algorithm was too conservative on repetitive dives and would be commercially unpopular on that basis; 4) there were concerns that the Navy No-D limits were not conservative enough;

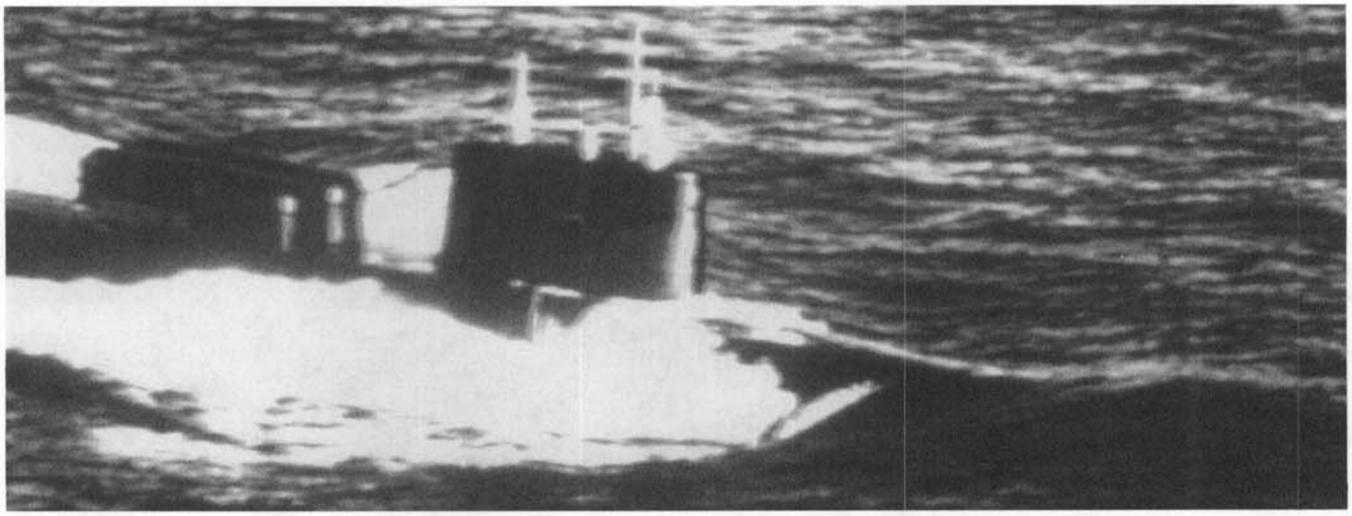

FIG. 3—Dry Deck Shelter (DDS).

5) manufacturers were uncomfortable with fielding a decompression algorithm that is stated to result in an estimated DCS risk of 2.5% and higher; and 6) the perceived marketing benefits of a "Navy-approved" decompression model were not felt to be worth the expense of incorporating it into an existing DC.

The attempt to establish a CRDA was therefore abandoned and funding to develop another prototype Navy DC was obtained through the Special Operations Special Technology (SOST) program at the U.S. Special Operations Command. This project was successful and by 1995, the Navy had a nearly finished prototype of a DC capable of handling the computational requirements of the NMRI algorithm.

In the summer of 1995, however, the project suffered another major setback. A new Supervisor of Diving and Salvage had taken over at NAVSEA and he received input from the ship's husbandry divers that the 40 ft No-D limit in the new tables was too conservative. The NMRI probabilistic model would have reduced the 40 ft No-D limit from 200 min to 144 min. The ship's husbandry divers contended that they had a great deal of experience with the 200-minute No-D limit and had had no trouble with it. At a meeting held at NAVSEA on 23 August 1995, this problem was presented to the researchers and it turned out that this particular profile had not been retested in the recent manned trials. The Supervisor of Diving and Salvage decided to reverse the decision of his predecessor and the implementation of the new Navy air tables was suspended indefinitely.

The NSW sponsor responded to the 23 August 95 decision by proposing that if the Navy was not going to implement the new tables, presumably a DC that was equally conservative or more conservative in comparison to the decompression tables currently in use should be acceptable to NAVSEA from a safety standpoint if it were acceptable to the diving community involved. NAVSEA agreed and attention was subsequently re-directed to CAPT Thalmann's VVAL18 model, which had been used to generate the current MK 16 tables approved and used by the Navy. This algorithm is able to compute decompression schedules for either air or a constant partial pressure of 0.7 atm abs of oxygen in a nitrox mix. VVAL18 is a modified Haldanian model with nine tissue compartments (half times 5–240 min) that produces No-D limits that are intermediate between the Standard Air Tables and USN 93 in the shallow range, but is increasingly more conservative than as Total Decompression Time (TDT) increases.

On 1 November 1995, representatives from NEDU, NSW, NAVSEA, and NMRI agreed that the VVAL 18 algorithm was the best choice for a Navy DC.

USN DECOMPRESSION COMPUTER—ALGORITHM

In reporting the development, testing, and approval of the U.S. Navy DC, the authors do not suggest that the VVAL18 decompression algorithm is optimized or that it is superior to other algorithms or tables in use. There is no single right answer in this area nor are there any completely "safe" decompression schedules. Rather, each diver and each organization of divers must answer for his/her/its own purposes the question: "How safe is safe enough?" The decision to use VVAL18 takes into account both the results of manned dive trials and many years of fleet experience with the U.S. Navy Standard Air Decompression Tables.

Appendix 1 provides a comparison of the No-D limits in the Thalmann VVAL18 algorithm with the No-D limits in the Standard Air Tables. Appendix 2 shows the differences in the total decompression stop times found in the two tables. (23).

Civilian divers have largely discontinued using the USN No-D limits in favor of more conservative limits. (24) The Navy No-D limits have an average predicted DCS incidence of 2.3% as calculated by the NMRI Probabilistic Model (23), but have been in use for many years in the Navy and been found to be safe as used by operational diving units. The VVAL18 algorithm is more conservative in the shallow range than the Standard Air Tables (23), despite the fact that these tables have recently been changed to call for more conservative No-D limits at shallow depths. Previous versions of the Standard Air Tables allowed unlimited time without decompression at 30 ft and shallower (6). Studies at the Naval Medical Research Center have demonstrated that DCS can occur at depths shallower than 30 fsw on air saturation exposures (25). The 30-ft No-D limit has been shortened to 405 min in the current version of the Standard Air Tables (5) and further shortened to 372 min by VVAL18 (23). The VVAL18 algorithm is also more conservative than the Standard Air Tables at 35, 40, and 50 ft. An analysis of the predicted DCS rate of the Standard Air Tables No-D limits found that the 35- and 40-ft limits had estimated DCS probabilities of 5.5 and 4.0%, respectively (26). These were the highest estimated rates for any of the No-D limits in the Standard Air Tables. Ball and Parker (27) reported 91 exposures on a 40 ft for 200 min air dive profile. They found only two cases of DCS in this series, but the second was a cerebral event that resulted in residual neuropsychiatric deficits. The investigators had planned to do 260 expo-sures on this profile to determine as precisely as possible the true incidence of DCS, but the series was terminated after the severe hit noted above. Although the incidence of DCS reported from fleet use of this schedule was only 0.11% (28), these data include many dives that are shorter or shallower than the limits of the schedule, lowering the risk accordingly. At 60 fsw and deeper, the No-D limits in VVAL18 are equivalent to or somewhat less conservative than the Standard Air Tables. There is data to support these extensions in NEDU testing (8). No-D dives were done for 66 min at 60 ft (29 man-dives), 30 min at 100 ft (20 man-dives), 24 min at 120 ft (19 man-dives), 14 min at 150 ft (20 man-dives), and 10 min at 190 ft (19 man-dives.) No episodes of DCS were seen following any of these dives, despite the fact that these trials were conducted using test conditions designed to produce maximal decompression stress (29). The divers were immersed in the wet chamber of the NEDU ocean simulation facility (OSF), the water was cold, and the divers were exercising while at depth (8).

The VVAL18 algorithm becomes significantly more conservative than the Standard Air Tables as dive profiles move into the decompression range. This conservatism increases with total decompression time (appendix 2). The need for additional decompression on at least some of the long bottom time dives is shown dramatically in work done at NEDU (8). The 60 fsw for 180-min profile requires 56 min of decompression in the Standard Air Tables. Thalmann found that decompressing for 70 min after this profile produced three cases of DCS in 10 dives. Adding 40 more minutes of decompression resulted in four cases of DCS in 10 man-dives. Another 42 min of decompression reduced the DCS incidence to one case in 20 man-dives (8). The Thalmann VVAL18 algorithm now requires 197 min of total decompression time after a 60 fsw for 180-min dive—3.5 times more decompression than the Standard Air Tables.

Further evidence of the need for additional decompression on long bottom time dives is found in the research done by Kelleher at NEDU in 1991 (30). The Combat Swimmer Multi-Level Dive Procedures were developed at NEDU by Thalmann and Butler in 1983 as mentioned previously (6). The CSMD procedures are based on the Standard Air Tables but facilitate decompression calculation on multi-level SDV dives by dividing the dive into "transits" of 30 fsw and shallower and "excursions" deeper than 30 fsw. SEALs performing SDV missions have used the Combat-Swimmer Multi-Level Dive Procedures safely for many years. Kelleher, however, found that multi-level dive profiles performed using air and a constant transit depth of 30 fsw produced DCS rates of up to 11% (30). SEALs' safe use of the CSMD procedures for many years probably results from the fact that the divers often breathe from the MK 16 or the MK 25 closed-circuit oxygen UBA during the dive (both of which have higher PO_2 than air at shallow depths) and from the fact that the transit phases of the dive are usually performed at depths shallower than 30 fsw. Both practices will continue once the DC is introduced and will add an additional margin of safety to these dives as well.

Since the decompression software found in many commercially available dive computers is proprietary, comprehensive comparisons are not yet available. Occasional reviews in the sport diving literature provide an estimate of relative conservatism (31). A comparison of the VVAL18 with the decompression computations provided by a number of commercially available dive computers on selected profiles is planned for the near future at NEDU.

Is a computer that contains VVAL18 suitable for use by sport divers? Since most recreational divers do not

Table 1: Decompression Computer Specifications

Specifications	Min. Required
Decompression algorithm	VVAL18
Computational Accuracy (as compared with PC FORTRAN program)	
Remaining No-D time	±5% or ± 1 min
Remaining decompression time	±10% or ± 5 min
Operating Temperature	
Water	−2 to 35°C
Air	−10° to 60° C
Max design depth (no damage)	200 fsw
Depth accuracy:	± 2 fsw
Depth range	0–200 fsw
Time accuracy	$\pm 1\ s \cdot h^{-1}$
Storage temperature	−10° to 65°C
Battery duration:	24 h
Compatible with SDV/ SPECWAR environment (EMI) (Evaluated during Field Test)	Yes
Audio alarms	can disable
Non-magnetic	not necessary
Display format	(may scroll)
Depth	displayed
First stop depth	displayed
Total remaining decompression time	displayed
No-D time remaining	displayed
Visual Alarms	
Too shallow	yes
Low battery	yes
Program verification (self-test on startup)	yes
Ruggedness,3' drop test all surfaces onto concrete in boot, resistant to mud and sand pack	yes
Battery change without loss of memory	yes
Battery—user replaceable, commercially available.	yes
Reprogrammable (via ROM/EPROM replacement)	yes
Data logging (Depth/Time profile) Log each 2 fsw depth change or every 2 s for 10 h [Worst case: assume depth changes 2 fsw every 2 s for 10 h]	yes
Data log transfer to PC in ASCII format	yes
Display readability	at least 18" in air
Size	less than 6" × 4" × 3"
Weight	less than 1.5 lb.

by sport divers? Since most recreational divers do not routinely make decompression dives, the extra safety incorporated into those areas of the DC software is unlikely to benefit them. The air No-D limits found in the VVAL18 algorithm are less conservative, at least for some depths, than those in many commercially available dive computers (24). Navy divers have, however, used less conservative shallow No-D limits than those found in VVAL18 for many years with a very low incidence of DCS. In the deeper No-D range, as mentioned above (8), additional testing of these limits resulted in no DCS cases in the 107 experimental dives performed at NEDU. These trials were performed under worst-case conditions with divers immersed in cold water and exercising strenuously on the bottom. The currently approved Navy DC described in the next section assumes that the divers breathing the higher PPN_2 of the MK 16 at depths greater than 78 ft. (*Note*: At depths shallower than 78 ft, air has a higher PPN_2 than the MK 16; at depths greater than 78 ft, the MK 16 has a higher PPN_2 than air.) If this assumption were left unchanged in a civilian version, it would result in more conservative decompression calculations at depths deeper than 78 feet. The 3- to 5-min safety stop that has become common in recreational diving practice would also add a significant measure of safety to these limits. Still, recreational divers should know that the VVAL18 algorithm is probably more aggressive on No-D profiles than most, if not all, recreational dive computers currently in use.

USN DECOMPRESSION COMPUTER—HARDWARE

In 1996, NSW requested that NAVSEA task NEDU to identify, procure, and test a commercial dive computer (DC) modified to incorporate the Navy-approved VVAL18 decompression algorithm (32).

At the time of the tasking, no commercial dive computer used the VVAL18 decompression algorithm, so NEDU advertised in the Commerce Business Daily for a commercial DC manufacturer to place the VVAL18 decompression algorithm in one of its DCs. The specifications in Table 1 were used to rank the proposed bids. These specifications were based on those created during the CRDA meeting described earlier in this paper and represented the minimum design requirements that the attendees felt would be necessary for a DC designed for military use. Since the specifications would be applied to a commercial product rather than a military development item, some flexibility in the requirements was possible. Cochran Undersea Technology (Richard-son, TX) was awarded the contract and delivered five modified Commander DCs containing the VVAL18 decompression algorithm. The manufacturer named the modified DC the "Cochran NAVY".

The initial NEDU evaluation revealed several problems in both the DC hardware and software that had to be corrected by the manufacturer before testing could proceed. Eventually, the DCs successfully passed NEDU testing and were deemed suitable for evaluation by the SDV teams. During 1998 and 1999, SDV Teams One and Two performed operational testing on the DC and identified several problems. The major issues were: 1) the PC software used to communicate with the DCs was difficult to use; 2) there was uncertainty about the DC depth accuracy; 3) there were three floodouts in 440 dives; 4) the color of the DC case was gray instead of the operationally preferred black; 5) the computer had been programmed to assume that the diver was breathing air, which meant that the MK 16 could not be used deeper than 78 ft; and 6) a change in the DC illumination function to a 10-s light on demand was requested (33).

The Navy Experimental Diving Unit then contracted with the manufacturer for modifications to change the DC case color to black, to add tamper-resistant features to the DC pressure housing, and to respond to the other concerns raised during the operational testing. The decision was made to configure the DC to assume air as the breathing gas when the DC depth was shallower than 78 fsw and the MK16 MOD 0 UBA when deeper. This allowed the diver to shift between the MK16 UBA and open circuit air breathing. NEDU received five newly modified NAVY DCs in March 2000. These new DCs not only included the desired modifications, but also software and hardware enhancements that the manufacturer was adding to its newest generation of dive computers, which included longer battery life and better backlighting control. Since these DCs had multiple software and hardware changes, new unmanned testing was performed.

The Navy Experimental Diving Unit tested the modified NAVY DCs during April–August 2000 to verify their proper operation. This testing has been described in detail (34) and will be discussed only briefly here.

The pressure transducer was tested at depths down to 200 fsw. The overall average depth error was 0.7 fsw with a standard deviation of 0.2 fsw.

Profile tracking was tested first on the No-D limits down to 200 fsw. Readings for the DCs were consistent for each test. The DC predictions were all within the predictions based on the DC being 2 fsw shallower to 2 fsw deeper, which corresponds to an error of 1% of the scale depth.

Three additional profiles were tested with similar results:

a) 60 fsw No-D Stop Repetitive Profile
 60 fsw for 60 min
 60-min surface interval
 60 fsw for the displayed No-D stop limit
 60-min surface interval
 60 fsw for the displayed No-D stop limit
 60-min surface interval
 60 fsw for the displayed No-D stop limit

b) 80-fsw Decompression Dive Repetitive Profile
 80 fsw for 60 min
 60-min surface interval
 80 fsw for 60 min
 60-min surface interval
 80 fsw for 60 min

c) SDV Mission Profile
 50 fsw for 50 min
 20 fsw for 180 min
 50 fsw for 30 min
 20 fsw for 180 min
 50 fsw for 50 min

One DC failed on the third profile due to a mechanical defect, for which the manufacturer has subsequently instituted quality assurance measures to prevent future occurrences. For the other DCs, the displayed times were all within the predicted limits.

The last feature tested was the switchover function. The switchover from air to MK 16 at 78 ft was confirmed on a series of dives by noting the differences in remaining No-D stop times as the DC shifted from using one gas mix to the other for decompression calculations

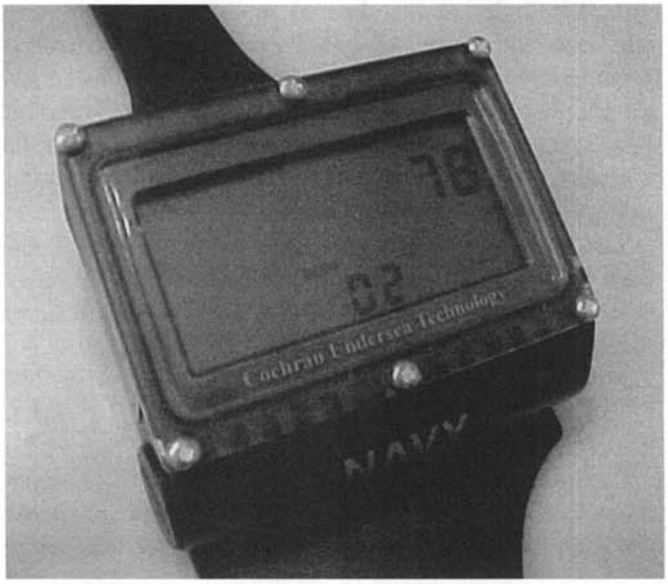

FIG. 4—The Cochran NAVY.

as the switchover depth was passed. Proper switchover was observed in all NAVY DCs. The Cochran NAVY DC is shown in Fig. 4.

U. S. NAVY DC DIVING PRACTICE

After the testing described above, NEDU recommended approval of the Cochran NAVY for NSW diving operations (34,35). The Naval Sea Systems Command approved the use of the DC by selected SEAL units on 25 January 2001 (36).

The delays and setbacks encountered in the development of the Navy's first DC seem Olympian in proportion, especially when contrasted to the proliferation of civilian dive computers that has ensued during the last two decades. The problems encountered in both DC hardware and decompression philosophy, outlined above, help to explain the prolonged duration of this effort. The USN is not alone among naval services in its slow progress in the area of DC diving. For the transition to DC diving to be made smoothly and safely, initial guidelines for DC diving practice had to be established by the Naval Sea Systems Command (36) and the Commander of the Naval Special Warfare Command (37). During the preparation of these guidelines, a survey of the decompression practices of other countries was conducted to see what guidance other navies that were diving DCs provide to their divers. This survey found no other countries that had a DC accepted for use by their navies (personal communication, Dr. Lee Greenbaum, Undersea and Hyperbaric Medical Society). The initial guidelines provided to USN divers using the Cochran NAVY are as follows (36,37):

a) Navy divers using a DC must read and become familiar with the manufacturer's Operation and Maintenance Manual, must complete the SEAL DC training course, and must pass the post-course test before being allowed to use the DC on dives.

b) Individual divers and units are not currently required to use the profile download function on the Cochran NAVY. To analyze data from the DCs correctly, however, NEDU researchers must have an accurate record of the gas mixes breathed during the dive. The times of all gas switches made during the dive are recorded by SEAL divers using DCs.

c) Every diver will have his own DC. In the event of a DC failure (blank screen or obviously inaccurate display data), both members of the dive pair will use the remaining computer to determine decompression status.

d) Divers making repetitive dives with the Cochran NAVY should obviously use the same NAVY DC used on the previous dive(s). In addition, however, to maintain the ability for a diver to use his buddy's computer as a backup decompression device, the buddy pair must be the same for repetitive dives to ensure that both divers have approximately equal tissue nitrogen loading. If one member of the buddy pair is unable to make the repetitive dive and a new (clean) diver is substituted, the new diver will use the same NAVY DC as the diver for whom he is substituting.

e) Divers who have made dives using other methods to calculate decompression must wait a minimum of 24 h before making a dive with the Cochran NAVY to ensure that nitrogen offgassing is complete. In addition, divers who have made dives using the Cochran NAVY must wait at least 24 h before making a subsequent dive on which another method of decompression calculation is to be used.

f) All DC divers decompressing together on DDS/SDV and Advanced SEAL Delivery System (ASDS) operations will be decompressed according to the DC that shows the longest total decompression time.

g) Since the NAVY DC is configured for constant F_{O_2} of 0.21 at 78 feet and shallower and a constant P_{O_2} of 0.7 atm abs deeper than 78 ft, divers may breathe any combination of air, Mk 16, and closed-circuit oxygen and still be assured of adequate decompression.

h) Divers are restricted to the maximum depth of either their UBA or their qualifications, whichever is less.

i) All programmable options on the Cochran NAVY DCs are preset by the manufacturer. NSW units and individual SEAL operators and units have been directed not to attempt to change these settings. It is possible to change the options chosen based on user feedback, but when changes are made, they will be made consistently

Table 2: Programmable Option Settings for the Cochran NAVY

1	Time to Zulu time (Universal and Greenwich Mean Time)
2	Imperial units
3	Profile storage period to 2 s
4	Predive planning max depth to 150 ft
5	Ascent rate bar as "fixed"
6	Ascent rate alarm to 60 ft $\cdot min^{-1}$
7	Ascent rate responsiveness to 3
8	Remaining time responsiveness to 3
9	Max depth alarm to 150 ft
10	Decompression time display on "both"
11	Taclite on "off"until demanded, then on for 10 s
12	Audible alarm beeper on "off"
13	Decompression conservatism to 0
14	Max Po_2 alarm at 1.6
15	Gas mix:
.	Air from 0–78 ft
	Constant PPo_2 of 0.7 atm abs 79 ft and deeper

throughout the force and all DCs will be modified to reflect the change. The options selected for the Cochran NAVY are shown in Table 2.

j) All Cochran NAVY DCs procured by NSW units will go to NEDU first to confirm proper configuration and function. Any units that do not pass this confirmation testing will be returned to the manufacturer. Once this testing is complete, the units are forwarded to the purchasing NSW command.

k) Any DCs that develop problems during field use will be returned to NEDU with a full description of the nature of the problem and the circumstances that preceded it. This allows a single central location to maintain a record of the reliability of the DC hardware and to identify and remedy any patterns of malfunctions. Factors that may contribute to the malfunctions can also be identified and addressed.

l) In a similar vein, any cases of DCS that occur on dives during which the Cochran NAVY is used to calculate decompression status will be reported using standard Navy reporting guidelines. The computer worn by the diver with DCS will be sent to NEDU so that the profile can be downloaded.

m) Although the Cochran NAVY will sense altitude and will calculate decompression status for altitude diving, diving at altitudes above 1,000 ft on the VVAL18 algorithm has not been tested with manned dive trials and is not authorized at present.

n) The Flying after Diving guidelines found in Chapter 9 of the U.S. Navy Diving Manual are based on Repetitive Group designators (5). Since the Cochran NAVY does not provide Repetitive Group designators, divers using the Cochran NAVY must wait 24 h before flying.

o) Divers breathing closed-circuit oxygen must continue to observe the oxygen exposure limits found in Chapter 18 of the U.S. Navy Diving manual to avoid CNS oxygen toxicity.

U. S. NAVY DC DIVING—FUTURE DIRECTIONS

The first 20 Cochran NAVY units all passed the NEDU quality control check and were delivered to SDV Team ONE in January 2001. Decompression computer training was conducted on 30 January, and the Navy's first decom-pression computer dive took place on 31 January 2001. NAVSEA authorization to use the Cochran Navy estab-lished a requirement to conduct a 6-mo safety and reli-ability survey (36). This survey was completed on 1 August 2001 and a final decision about DC use for both NSW and the entire U.S. Navy diving community is pending at this time. Preliminary analysis of the data from this reliability survey reveals no computer failures and one questionable case of DCS observed in approximately 250 DC profiles (unpublished data). This diver was on a long (6+ h), multi-level profile with an average depth of 25 fsw and a maximum depth of 31 fsw. He began to have left axillary pain during a 20-ft stop to accomplish DDS hangar complex draindown. He was found to have a positive modified Romberg sign on neurologic examination and recompressed on a USN Treatment Table Six without improvement of his pain. The positive Romberg's test had resolved by the end of treatment, and the pain resolved spontaneously approximately 6 h after treatment.

Recommendations from users regarding changes in the Cochran NAVY hardware or software or DC diving practice will be reviewed by the newly established NEDU Decompression Computer Configuration Management Board. This board will also monitor DCS episodes and DC hardware failures that occur during Navy use of the DC and recommend changes in hardware and software to NAVSEA when appropriate. (36,37).

Now that the Cochran Navy has been introduced into Navy diving units, dive profile data from all operational Navy DC dives can be collected using the unit's download software, once it has been made more reliable on a variety of computer operating systems. The methodology is similar to that used by the Diver Alert Network's Project Dive Exploration (http://www.diversalertnetwork.org) and allows research quality decompression data to be collected outside of the laboratory setting. This data will be invaluable in refining the VVAL18 decompression algorithm based on operational experience. Areas of the model in which multiple episodes of DCS are documented can be targeted for focused revision when and if required. Updated software would then be provided for the DCs so that DC diving becomes safer in a stepwise fashion as experience is gained. One unique benefit of collecting these data from a military diving population is that the information obtained can be published and incorporated into the diving medical literature. The fear of loss of competitive advantage and potential litigation has largely prevented open analyses of DCS data from being performed on dives using civilian dive computers.

Another possible improvement in diving safety that may result from the analysis of DC data is the ability to better identify and quantify risk factors for DCS. It is interesting that some commercially available computers offer the ability to customize the desired conservatism of their model, but provide no guidance on how exactly to calculate the appropriate adjustments. If, for example, one considers increasing age to be a risk factor for DCS, how much extra conservatism should be planned for each 10 yr of age? If cold water is considered a risk factor, how much extra conservatism is required for each 10° drop in water temperature? The Navy Standard Air Decompression Tables are also not much help in this regard. Divers on profiles with a perceived increased risk of DCS are decompressed on deeper or longer schedules based on the personal experiences of the diving supervisory personnel involved. More precise recording of dive profile data may bring about better knowledge regarding DCS risk factors. In some cases, even the direction of the risk modification, much less the magnitude, is not clearly understood. One example of observations from diving experience being in contradiction to the conventional wisdom was the TWA 800 recovery, where the use of hot water suits was associated with an unexpectedly high incidence of DCS (38). Fourteen dives over 50 min in length using the prescribed USN surface decompression with oxygen schedule resulted in five cases of DCS and forced the divers to extend the decompression time beyond that shown in the Diving Manual. The U.S. Navy Diving Manual, however, states that a decrease in core temperature causes increased gas absorption (39) and calls for selection of a deeper or longer schedule for dives in *cold* water rather than hot water (39,40). Better-focused research efforts to define the effects of risk factors for DCS may be an added benefit of DC use in the Navy.

An updated version of the NSW Dive Planner that uses the same VVAL18 algorithm as the DC has already been developed and is now being field tested with the SEAL teams. This will allow operational commanders to download dive profiles from the DCs into a laptop and to calculate No-D limits and decompression requirements as a planning aid for contemplated additional dives.

Appendix 1

Air No-Decompression Limits: VVAL18 vs. Current USN Standard Air Decompression Tables (min)

Depth, fsw	USN Air DC Tables	VVAL18
20	Unlimited	Unlimited
30	405	372
35	310	232
40	200	163
50	100	92
60	60	63
70	50	49
80	40	40
90	30	34
100	25	29
110	20	26
120	15	23
130	10	19
140	10	17
150	5	14
160	5	12
170	5	11
180	5	10
190	5	9
200	Not allowed	8

Appendix 2

Total Air Decompression Stop Time: VVAL18 vs USN Standard Air Decompression Tables
(VVAL18 Delta: + longer; - shorter)

Depth, fsw	Time, min	USN Air DC Tables TST, min	VVAL18 Delta, min
40	210	2	45
40	230	7	57
40	250	11	78
40	270	15	97
40	300	19	122
40	360	23	164
40	480	41	245
40	720	69	413
50	100	0	0
50	110	3	17
50	120	5	24
50	140	10	60
50	160	21	84
50	180	29	105
50	200	35	135
50	220	40	167
50	240	47	191
60	60	0	0
60	70	2	14
60	80	7	30
60	100	14	55
60	120	26	97
60	140	39	130
60	160	48	159
60	180	56	197
60	200	70	226
60	240	81	289
60	360	139	449
60	480	192	609
60	720	265	781
70	50	0	4
70	60	8	30
70	70	14	53
70	80	18	73
70	90	23	84
70	100	33	107
70	110	43	129
70	120	51	151
70	130	58	171
70	140	64	188
70	150	70	209
70	160	85	224
70	170	98	239
80	40	0	0
80	50	10	36
80	60	17	68
80	70	23	89
80	80	33	99
80	90	46	123
80	100	57	151
80	110	66	177
80	120	73	201
80	130	82	221

Appendix 2, *continued*

Total Air Decompression Stop Time: VVAL18 vs USN Standard Air Decompression Tables
(VVAL18 Delta: + longer; - shorter)

Depth, fsw	Time, min	USN Air DC Tables TST, min	VVAL18 Delta, min
80	140	95	240
80	150	109	260
80	180	120	341
80	240	178	465
80	360	279	718
80	480	353	862
80	720	454	1017
90	30	0	0
90	40	7	28
90	50	18	69
90	60	25	97
90	70	37	112
90	80	53	131
90	90	66	161
90	100	75	194
90	110	85	221
90	120	100	242
90	130	115	270
100	25	0	0
100	30	3	-1
100	40	15	56
100	50	26	94
100	60	37	120
100	70	56	126
100	80	71	163
100	90	83	200
100	100	96	242
100	110	116	270
100	120	131	301
100	180	201	535
100	240	282	722
100	360	415	928
100	480	502	1058
100	720	612	1193
110	20	0	0
110	25	3	-3
110	30	7	24
110	40	23	80
110	50	34	117
110	60	54	131
110	70	72	156
110	80	87	206
110	90	106	254
110	100	124	290
120	15	0	0
120	20	2	-2
120	25	6	7
120	30	14	46
120	40	30	100
120	50	46	132
120	60	69	144
120	70	87	200
120	80	105	258

Appendix 2, *continued*

Total Air Decompression Stop Time: VVAL18 vs USN Standard Air Decompression Tables
(VVAL18 Delta: + longer; - shorter)

Depth, fsw	Time, min	USN Air DC Tables TST, min	VVAL18 Delta, min
120	90	130	310
120	100	148	365
120	120	174	472
120	180	282	760
120	240	394	915
120	360	549	1092
120	480	652	1193
120	720	771	1315
130	10	0	0
130	15	1	-1
130	20	4	-3
130	25	10	28
130	30	21	66
130	40	35	120
130	50	61	142
130	60	84	174
130	70	101	252
130	80	129	317
130	90	152	378
140	10	0	0
140	15	2	-2
140	20	6	8
140	25	16	45
140	30	26	85.
140	40	44	134
140	50	74	151
140	60	95	230
140	70	123	303
140	80	153	379
140	90	164	454
140	120	238	652
140	180	384	921
140	240	509	1061
140	360	682	1212
140	480	799	1294
140	720	922	1401
150	5	0	0
150	10	1	-1
150	15	3	-1
150	20	9	17
150	25	21	61
150	30	32	99
150	40	57	142
150	50	86	181
150	60	110	274
150	70	144	366
150	80	171	438
160	5	0	0
160	10	1	-1
160	15	5	3
160	20	14	28
160	25	27	75
160	30	38	111

Appendix 2, *continued*

Total Air Decompression Stop Time: VVAL18 vs USN Standard Air Decompression Tables
(VVAL18 Delta: + longer; - shorter)

Depth, fsw	Time, min	USN Air DC TST, min	VVAL18 Delta, min
160	40	69	148
160	50	96	232
160	60	130	331
160	70	164	417
170	5	0	0
170	10	2	-2
170	15	7	11
170	20	19	39
170	25	32	87
170	30	43	123
170	40	79	158
170	50	107	278
170	60	150	383
170	70	181	480
170	90	244	677
170	120	354	884
170	180	533	1105
170	240	679	1216
170	360	871	1343
170	480	1005	1402
180	5	0	0
180	10	3	-3
180	15	9	18
180	20	23	51
180	25	37	99
180	30	50	132
180	40	90	202
180	50	125	321
180	60	165	430
190	5	0	0
190	10	4	1
190	15	13	24
190	20	28	61
190	25	41	112
190	30	60	138
190	40	100	243
190	50	144	368
190	60	180	490
200	5	1	-1
200	10	5	5
200	15	15	26
200	20	37	69
200	25	46	121
200	30	70	151
200	40	109	282
200	50	158	414
200	60	196	546
200	90	321	895
200	120	470	1054
200	180	682	1235
200	240	839	1329
200	360	1055	1428

—*Manuscript received June 2001; accepted April 2002.*

REFERENCES

1. Butler FK, Smith DJ. United States Navy Diving Techniques and Equipment. In: Diving Medicine, Bove AA ed. Philadelphia, W.B. Saunders, Third Edition; 1997; 372-387
2. Thalmann ED: Computer algorithms used in computing the Mk 15/16 constant 0.7 ata oxygen partial pressure decompression tables. U.S. Navy Experimental Diving Unit Report 1-83, 1983.
3. Thalmann ED, Buckingham IP, Spaur WH: Testing of decompression algorithms for use in the US Navy underwater decompression computer. U.S. Navy Experimental Diving Unit Report 11-80, 1980.
4. Thalmann ED: Phase II testing of decompression algorithms for use in the US Navy underwater decompression computer. U.S. Navy Experimental Diving Unit Report 1-84, 1984.
5. US Navy Diving Manual. Volume 4, Chapter 17. Naval Sea Systems Command Publication 0910-LP-100-3199. Revision 4, Change A; March 2001.
6. Thalmann ED, Butler FK: A Procedure for doing Multi-Level Dives Based on Repetitive Groups. U.S. Navy Experimental Diving Unit Report 13-83, 1983.
7. Butler FK: Medical Support of Dry Deck Shelter Operations. NEDU Memorandum 6 Dec 83.
8. Thalmann ED: Air-N2O2 decompression computer algorithm development. U.S. Navy Experimental Diving Unit Report 8-85, 1985.
9. Weathersby PK, Homer LD, Flynn ET: On the likelihood of decompression sickness. J Appl Phys 1984; 57: 815-825
10. Weathersby PK, Survanshi SS, Homer LD, Hart BL, Nishi RY, Flynn ET, Bradley ME: Statistically based decompression tables I: Analysis of standard air dives 1950-1970. Naval Medical Research Institute Technical Report 85-16, 1985.
11. Weathersby PK, Hays JR, Survanshi SS, Homer LD, Hart BL, Nishi RY, Flynn ET, Bradley ME: Statistically based decompression tables II: Equal risk air diving decompression schedules. Naval Medical Research Institute Technical Report 85-17, 1985.
12. Survanshi SS, Parker EC, Thalmann ED, Weathersby PK: Statistically based decompression tables XII, vol 1. Repetitive decompression tables for air and constant 0.7 ata O2 in N2 using a probabilistic model. Bethesda, MD: Naval Medical Research Institute, 1997. Report No. 97-36 (Vol 1)
13. Survanshi SS, Parker EC, Thalmann ED, Weathersby PK: Statistically based decompression tables XII, vol II. Repetitive dive tables: air. Bethesda, MD: Naval Medical Research Institute, 1997. Report No. 97-36 (Vol. II)
14. Survanshi SS, Parker EC, Thalmann ED, Weathersby PK: Statistically based decompression tables XII, vol III. Exceptional exposure tables: air. Bethesda, MD: Naval Medical Research Institute, 1997. Report No. 97-36 (Vol III)
15. Survanshi SS, Parker EC, Thalmann ED, Weathersby PK: Statistically based decompression tables XII, vol IV. Repetitive dive tables: 0.7 ATA PO2 in N2. Bethesda, MD: Naval Medical Research Institute, 1997. Report No. 97-36 (Vol. IV)
16. Survanshi SS, Parker EC, Thalmann ED, Weathersby PK: Statistically based decompression tables XII, vol. V. Exceptional exposure tables: 0.7 ATA PO2 in N2. Bethesda, MD: Naval Medical Research Institute, 1997. Report No. 97-36 (Vol. V)
17. Weathersby PK, Survanshi SS, Homer LD, et al: Predicting the time of occurrence of decompression sickness. J Appl Phys 1992; 72: 1541-1548
18. Thalmann ED, Parker EC, Survanshi SS, Weathersby PK: Improved probabilistic decompression model risk predictions using linear-exponential kinetics. Undersea Hyperbaric Med 1997; 24: 255-274
19. Survanshi SS, Weathersby PK, Thalmann ED: Statistically based decompression tables X. Real time decompression algorithm using a probabilistic model. Bethesda, MD: Naval Medical Research Institute, 1996. Report No. NMRI 96-06
20. Survanshi SS, Weathersby PK: Rational decompression trials produce biased data. Undersea Hyperbaric Med 1998; 25(suppl):25
21. Thalmann ED, Kelleher PC, Survanshi SS, et al: Statistically based decompression tables XI. Manned validation of the LE probabilistic model for air and nitrogen-oxygen diving. Bethesda, MD: Naval Medical Research Institute, 1999. Report No. NMRC 99-01.
22. Valaik DJ, Parker EC, Survanshi SS: Calculating decompression in Naval Special Warfare SEAL Delivery Vehicle operations using the Real Time Dive Planner. Naval Medical Research Institute Report 96-54; 1996
23. Thalmann ED: Suitability of the USN MK 15 (VVAL 18) decompression algorithm for air diving. Durham, F.G. Hall Laboratory Report, 30 March 1997
24. Lewis JE, Shreeves KW: The Recreational Diver's Guide to Decompression Theory, Dive Tables, and Dive Computers. Santa Ana: PADI, 1990.
25. Temple DJ, Ball R, Weathersby PK, Parker EC, Survanshi SS: The dive profiles and manifestations of decompression sickness cases after air and nitrogen-oxygen dives. Naval Medical Research Center Report 99-02; May 1999
26. Gerth WA, Thalmann ED: Estimated DCS risks of reverse dive profiles. In, Proceedings of Reverse Dive Profiles Workshop. Washington DC ; Smithsonian Institution; 1999: 145-161
27. Ball R, Parker E: A trial to determine the risk of decompression sickness after a 40 feet of sea water for 200 minute no-stop air dive. Aviat Space Environ Med 2000; 71: 102-108
28. Flynn ET, Parker EC, Ball R: Risk of decompression sickness after shallow air diving: analysis of U.S. Navy Safety Center data 1990-1994. Bethesda, MD: Naval Medical Research Institute, 1998. Report No. NMRI 98-08.
29. Vann RD, Thalmann ED: Decompression Physiology and Practice. In: Bennett PB, Elliott DH, eds. The Physiology and Medicine of Diving, 4th ed. London: WB Saunders, 1993: 376-432.
30. Kelleher PC. Air-N2O2 algorithm phase 1(b) – results of testing no-decompression repetitive and combat swimmer multilevel air dives. Navy Experimental Diving Unit Technical Memorandum TM92-08. April 1992
31. Hardy J. Is your computer safe? Rodale's SCUBA Diving. March 1999: 78-85
32. Decompression risk using the VVAL18 NITROX decompression algorithm. COMNAVSEASYSCOM Task 96-20; 7 April 1996
33. Cochran NAVY decompression computer. Naval Special Warfare Command message of 050007Z Oct 99
34. Southerland DG: NAVY diver computer evaluation. NEDU Report TR 10-00 of Oct 2000
35. Cochran NAVY decompression computer. NEDU letter 3963 Ser 02/0408 of 20 Oct 2000
36. Cochran NAVY decompression computer. Naval Sea Systems Command letter 3150 Ser OOC34/3019 of 25 Jan 2001
37. Cochran NAVY Decompression Computer. Commander, Naval

Special Warfare Command letter 6000 Ser N9/0168 dated 4 April 2001.

38. Leffler CT, White JC: Recompression treatments during the recovery of TWA Flight 800. Undersea Hyperbaric Med 1997; 24: 301-308

39. US Navy Diving Manual. Volume 1, Chapter 3. Naval Sea Systems Command Publication 0910-LP-100-3199. Revision 4, Change A; March 2001: page 3-46

40. US Navy Diving Manual. Volume 2, Chapter 9. Naval Sea Systems Command Publication 0910-LP-100-3199. Revision 4, Change A; March 2001: page 9-6