Electronic Diving Data Collection during Monitor Expedition 2001

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Abstract—The USS Monitor is a famous iron-clad ship that fought in the American Civil War and sunk during a storm off the coast of North Carolina in 1862. Since 1973, when its location was identified, several organizations have surveyed the wreck and recovered artifacts. In the summers of 2000 and 2001, the U.S. Navy participated with the National Oceanic and Aeronautics Association (NOAA) in a set of historical preservation dives on the Monitor. The U.S. Navy used recently modified Surface Supplied Helium Oxygen Decompression Tables. The modifications reduced the in-water oxygen exposure because several incidents of oxygen toxicity had been reported by operational users. The modified tables had not been man-tested. In 2000, permission was given to dive those tables operationally if the data collection system makes use of the data logging ability of a dive computer (DC) or other electronic data logger, along with selected manually-recorded dive logs. The information is then placed into an electronic database for further analysis.

B. Monitor Expeditions

In the summers of 2000 and 2001, the U.S. Navy participated with the National Oceanic and Aeronautics Association (NOAA) in a set of historical preservation dives on the wreck of the USS Monitor. The USS Monitor was a famous iron-clad ship that fought in the American Civil War and sunk in about 230 feet of seawater (fsw) during a storm off the coast of North Carolina on New Year’s Eve, 1862 [2]. It was located in 1973, and several organizations have been active in surveying the wreck and recovering artifacts.

For the Monitor dives, the U.S. Navy used recently modified Surface Supplied Helium Oxygen Decompression Tables [3]. The modifications reduced the in-water oxygen exposure because several incidents of oxygen toxicity had been reported by operational users. The modified tables had not been man-tested. In 2000, permission was given to dive those tables operationally if the data collection system was used. The system would capture dive data in research quality detail that could be used to determine the success of the tables, and could also be used to modify the tables if necessary. The system was successfully used during Monitor 2000 Expedition. The decompression tables were used again in the Monitor 2001 Expedition, and data collection of those dives was again required.

This paper describes that diving data collection effort performed during the Monitor 2001 Expedition. The main goal of the Monitor 2001 Expedition was to recover the Monitor’s engines.

I. INTRODUCTION

A. Operational Dive Data Collection Background

Decompression table development in the U.S. Navy has required relatively large numbers of experimental dives at research facilities. These studies have been very expensive to perform, and with the current and projected fiscal situations, are becoming prohibitively expensive.

One method to decrease number of laboratory dives is to supplement them with appropriate operational dives. The Navy Experimental Diving Unit (NEDU) has been tasked with developing and implementing a data collection system useful for collecting operational dive data of sufficient quality for research purposes [1]. This system makes use of the data logging ability of a dive computer (DC) or other electronic data logger, along with selected manually-recorded dive logs. The information is then placed into an electronic database for further analysis.

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C. Surface Supplied Helium Oxygen Decompression Procedure

Before one can make sense of the dive data collection process required during the Monitor Expeditions, one needs to understand how those dives are performed. Surface decompression with oxygen is typically used with the Surface Supplied Helium Oxygen Decompression Tables to avoid long in-water decompression times. For a typical dive, two divers are dressed in the diving gear (hard hat, hot water suit, harness, weights, and umbilical). The initial breathing gas with the dive rig is air. The divers then proceed to a dive stage where they are lowered by a small crane to 20 fsw. After completing all in-water checks, the divers are switched to a helium-oxygen (He\textsubscript{2}O\textsubscript{2}) breathing gas mixture, known as the bottom mix. For the Monitor dives, this mixture would have about 14\% oxygen (known as an 86/14 He\textsubscript{2}O\textsubscript{2} mix). Then the divers are lowered to the bottom, where they get off the stage, and work. When ordered, the divers return to the stage and the stage then ascends. The stage will stop at certain depths and stay for set times as determined by the decompression tables. At the 90 fsw stop, the divers will be shifted from the bottom mix to a 50/50 He\textsubscript{2}O\textsubscript{2} breathing gas mixture for decompression. Once the divers have completed the 40 fsw stop, they are surfaced, stripped of the dive gear, and herded quickly into a recompression chamber where they are pressed to 50 fsw. (The divers have only five minutes from the time they leave the 40 fsw top in the water until they are at 50 fsw in the chamber; otherwise, they are in an omitted decompression status and have to undergo a Treatment Table 6, which is almost five hours long.) In the chamber, the divers wear a face mask and breathe 100\% oxygen with a five minute air break every 30 minutes. The decompression tables determine the number of in chamber oxygen breathing cycles and the required chamber depth. Upon completion of the required oxygen breathing cycles, the divers are surfaced, and the dive is considered complete. The progress of the dive is logged on paper and is known as a Dive Chart. The Smooth Log is a summary of all dives performed for the day.

II. METHODS/MATERIALS

Ten Cochran NAVY DCs (Cochran Consulting Inc., Richardson, TX), developed for another purpose [4], were provided in the study. These commercial DCs had been previously evaluated and found adequate for data collection [5]. The DCs record depth every second for 550 hours of dive time. Prior to the start of the expedition, all DCs were tested dived to 200 fsw at NEDU to build accurate (+1 fsw accuracy) depth correction curves for each DC. Previous experience has shown that the DC depth error is linear at the deeper depths and so any depth corrections required deeper than 200 fsw could be extrapolated with minimal error.

The DCs were also configured for at least a 50\% oxygen mixture with at least 90\% oxygen for a decompression gas. These values were arbitrary, and were selected to keep the DC from going into an omitted decompression mode as the diver would be surfacing more rapidly because of the surface decompression than if all of the decompression were performed in the water. In addition, the DC was not designed for He\textsubscript{2}O\textsubscript{2} diving or surface decompression diving and was not to be used for monitoring decompression. Its sole use was to record the dive profile.

Onsite, the authors monitored the DCs and performed periodic data archiving of the paper and DC logs; usually this work was performed by D.L.D. alone.

The standard Dive Chart was modified to allow the logkeeper to record the DC serial number being used by each diver, along with the two in-water breathing gas switch times. Since the dive logs and the DC clocks are not exact, an easily identifiable point near the gas switch times was identified as a synchronization point to align the dive logs and the DC recording. For the first switch, the time when the diver left 20 fsw to descend to the bottom was selected since previous experience had shown that that point was easily recognized and logged quickly with little error. For the second gas switch, the time when the diver left the 90 fsw decompression stop was chosen as the synchronization point for the same reason as before. The time when the divers left the surface at the beginning of the dive was considered, but was unreliable since the DC did not begin recording until the depth as between 5-8 fsw. The divers could spend some time in the water at the surface while the diver's rig was examined for leaks and the DC may or may not have been deep enough to have begun depth logging. In addition, for surface supplied He\textsubscript{2}O\textsubscript{2} diving, the time spent between the surface and shifting to the bottom mix at 20 fsw counts as dead time and so logging accuracy by the logkeeper during that period can be quite lax.

While the diver was being dressed for the dive, a DC was selected and logged in the Dive Chart, and then strapped to chest strap of the diver's harness. The Dive Supervisor ensured that the DC was secure and that it had been turned on prior to start of the dive. The diver was instructed not to removed the DC during the dive, nor to use it for any decompression advice. During the expedition the divers almost always dived in dive pairs. This allowed the profile for a diver whose DC failed to have that dive reconstructed using the dive partner's DC, assuming that both divers were at the same depth during the dive.

Upon surfacing, the diver was quickly stripped of the dive gear including the DC. The DC was handed to the diver before the diver entered the recompression chamber. The diver then placed the DC in a small bucket containing sufficient water to submerge the DC's depth transducer,
since the pressure transducer was not designed to be pressurized in air.

Since previous experience has shown that the chamber Dive Supervisor is very meticulous in the timing of the required five minutes air breaks in the chamber, and the DC has no way of knowing what gas mixture the diver is breathing, the study did not require any special logs to be maintained to determine the air break time and duration. By design, those air breaks would be reconstructed post facto when the data were reduced at NEDU after conclusion of the expedition.

Upon surfacing from the chamber, the diver was queried about problems and then returned to work. Due to the remoteness and close working environment of the expedition, the study assumed that at least one of the authors would be aware of any medical problems that resulted from the diving. Therefore, 24 and 48 hour follow-ups were not formally performed.

Daily, the electronically logged dive profiles in the DCs were copied to a personal computer using Analyst, a program supplied by the manufacturer. Smooth logs were created based on the input of the Graph Charts, and copies of both were made.

At the end of the expedition, the DCs, computer files, and copies of the Dive Charts and smooth logs were delivered to NEDU. Since the computer files containing the DC data were stored in a proprietary format used only by the Analyst program, Analyst was used to export each dive profile as a text file in DL-7 format that could be more easily used. DL-7 was created by Dr. Petar Denoble at DAN to provide a common method for storing dive profiles amongst dive computer manufacturers [6]. The data were then reduced and analyzed using several utility programs were written in Perl (ActivePerl 5.6.1.626, ActiveState Tool Corp., Vancouver, BC), Microsoft Visual Basic 6 (Redmond, WA), and S-Plus 2000 (Insightful Corp., Seattle, WA).

III. RESULTS

There were 387 man-dives recorded during the diving operations of 17 July 2001 – 24 August 2001. All dives except one were performed with two divers. The exception used a single diver whose dive partner's diving rig had communications problems. There were an additional 12 aborted dives, which were commonly due to difficulty equalizing ear and sinus pressure in one of the two divers descending on the dive stage at the start of the dive.

There was one case of decompression sickness Type II which was successfully treated with a Treatment Table 6 with extensions. The diver's symptoms were decreased sensation in the fourth and fifth fingers bilaterally and left elbow pain. The elbow pain, which awoke him, was ultimately diagnosed as mechanical in origin. The diver's dive profile was unremarkable. He did operate a chain fall during the dive, but was experienced with its use.

Four divers were treated on a mandatory Treatment Table 6 for having had excessive delays due to ear squeezes while being compressed for the in-chamber phase of the tables. Only two divers actually had ear squeezes; the other two divers were the dive partners.

On the Dive Charts, six man-dives had mislabeled DC serial numbers and 19 man-dives did not have a DC serial number recorded. For 30 man-dives, at least one of the gas switch times was omitted. In such cases, the missing values were expected to be imputed from the other dives. The majority of the missing gas switches occurred during the first three days of diving.

Only six NAVY DCs were used for the dives. The other four other DCs were available as backups. The DCs appeared to work well, but four dive profiles were not recoverable from one DC. These failures were most likely due to attempting to transfer the dive profiles before the DC had written the dive profile to storage memory.

During the rush in recovering two divers from the water, removing the divers' dive gear and moving the divers into the recompression chamber, DCs were left behind four times on the surface. Fortunately, the other diver's DC was placed in the chamber in all cases. Since both divers followed the same decompression profile in the recompression chamber and both DCs were placed in the same bucket, the in-chamber portion of the in-chamber DC's dive leg could be appended to the DC left behind to give a full dive profile for the diver forgetting his DC.

Fig. 1 shows a typical expedition dive where the diver spent most of the time on the bottom at a relative constant depth. The divers stay on the dive stage during the in-water stops. Fig. 2 shows another dive. One can see where the dive stage stopped, the diver dropped to the sea floor, and then climbed up on top of the Monitor's armor belt, which is about 9 feet above the sea floor. After working on the armor belt, the diver dropped to the sea floor again, and then ascended to the dive stage, where some time was spent in recovering the diver umbilical. In Fig. 3 the diver's dive stage was again stopped above the sea floor. The diver then spent about half of the remaining bottom time on the sea floor. The diver only spent a few minutes on the sea floor during the dive of Fig. 4. The remainder of the bottom time was spent on the stage or the 30 foot scaffold used to recover the Monitor engines.

IV. FINDINGS/DISCUSSION

Currently in the U.S. Navy, the decompression schedule used is determined by assuming that the diver
spent all of the bottom time at the maximum depth attained. In addition, both time and depth are rounded up to the next higher schedule in the decompression tables. For example, consider a diver that descends to 200 fsw and remains there to work, except for a one minute round trip to 232 fsw to pick up a dropped tool. The diver continues to work at 200 fsw until 31 minutes have elapsed since leaving surface (or 20 fsw in the case of the a surface-supplied HeO2 diver). This diver will decompress on a 240 fsw for 40 minute schedule, since the maximum depth attained (232 fsw) falls between 230 fsw and 240 fsw in the decompression table, and so is rounded up to the next higher table depth of 240 fsw. Likewise, the 31 minute bottom time falls between 30 and 40 minutes in the schedule for a 240 fsw dive, and so the higher 40 minute bottom time is selected. While this method of schedule selection is conservative, it does not very accurately describe the dive, and therefore is not useful for decompression modeling.

Figs. 1-4 demonstrate this variation in bottom depths and times, and thus show the usefulness and power of electronic data collection for such operational dives. While the dive of Fig.1 could potentially be used for decompression modeling without having the electronically logged profile, attempting to do the same with Fig. 4 would be very unwise. The Dive Chart and Smooth Log, which are manually recorded on the surface and are the only resources available to an investigator, do not distinguish between these two dives, so the only way to know how depth changes during such dives is to place a pressure transducer on the diver and electronically record the depth. Thus if one is going to use operational dive data to support or criticize a decompression method, accurate electronically-logged data is essential; otherwise the profile is too suspect.

To be successful, operational dive data collection requires an individual whose primary responsibility is to
ensure that the data are collected properly. Without such a
case, the demands of meeting the mission requirements
for the operational dives typically cause data collection to
be set aside. In this study, the data collection person did
not have the data collection effort as his primary
responsibility. Although he was highly motivated and did
a superb job, there were still data losses since his primary
focus as the Dive Supervisor was on the safety of the divers
and not on data collection. For operational dive data
collection, there is typically a compromise required for data
collection personnel, since space is typically too limited to
allow a nondiving individual aboard solely to collect the
dive data.

It is essential to synchronize the DC real time clock
with the local time logged at the dive station for each dive.
This is required to allow matching of the electronically
stored dive profiles in the DC with the Dive Chart and
Smooth Log records that were reviewed after completion of
the expedition. Such synchronization becomes even more
important when the DCs are used around the world where a
nonsynchronized DC clock time can differ by more than a
day from the local time. However, differences of several
minutes are tolerable, since the main purpose of the local
time clock is to match the paper logs for a dive with the DC
used. Once that is done, then all gas switch times are
determined based on relative times within the dive, so local
time is unimportant.

As mentioned earlier, whenever a DC did not follow
the diver into the recompression chamber, the missing
portion of the profile could be taken from the dive partner's
DC. However, this situation has required a change to the
database design to allow the profile of a single dive to be
constructed from selectable portions of dives recorded on
different DCs. The previous database design assumed that
a single man-dive would be recorded as a single
electronically logged dive by a single DC. Additional
changes to the database design are also required to allow
the user to know which missing data have been imputed.

Software tools for data reduction and analysis are
essential for this project. Most of the data reduction
software was originally written in Microsoft Visual Basic.
However, this platform requires major software
rewrites every two to four years, thus making the tools too
unstable for long-term (a decade or more) use. Other tools
that appear to offer more stability are being evaluated.
Several software data reduction programs have been
rewritten in Perl, which appears at this time to be more
stable from a long-term coding maintenance view.

Due to changes required in the database structure, the
data have not been entered into a Microsoft SQL Server
2000 (Redmond, WA) database as originally planned, but
instead are stored as ASCII files in an ordered Microsoft
Windows based directory structure. Other database
solutions are also being examined, since a concern has been
raised about the portability ease between newer versions of
SQL server. Until the database design and the database
platform are finalized, the study will continue to use the
ASCII file structure, since it has proven to be both
functional, portable, and flexible so far.

In conclusion, electronic dive data collection for
operational dives appears both useful and feasible,
especially if there is an onsite investigator to ensure the
data are collected properly. Procedures have been
developed to provide data fusion of written dive logs and
the DC electronically stored dive profile. While such data
collection is expected to reduce the number of expensive
laboratory dives required for decompression modeling
efforts, it cannot be expected to eliminate all laboratory
dives. Experimental laboratory dives will still be required
to test diving regions in which there is no experience or
there is concern that such testing may be too hazardous to
be performed in the operational setting, where there is
much less control of the diver and dive than in the
laboratory setting. However, even the design of laboratory
dives can directly benefit from the data collection by
documenting the diving methodology actually performed in
the operational setting so that the investigators can
determine if the investigator's assumptions about
operational diving methodology are indeed correct. If not,
then the laboratory dives can be designed with those
differences in mind.

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