DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
321 BULLFINCH ROAD
PANAMA CITY, FLORIDA 32407-7015

IN REPLY REFER TO:
3963/FT00-03B
Ser 06/ 064
1 Jun 09

From: Commanding Officer, Navy Experimental Diving Unit
To: Dr. Michael L. Bates, State of Florida District Fourteen Medical Examiners Office, Panama City, Florida

Subj: REPORT OF INVESTIGATION FOR RICHARD L. MORK

Encl: (1) Report of Investigation dtd 4-20-09
(2A) Air Analysis Report dtd 9-24-08
(2B) Air Analysis Report dtd 9-24-08
(2C) Air Analysis Report dtd 10-7-08
(2D) Air Analysis Report dtd 10-7-08
(2E) Air Analysis Report dtd 10-7-08
(2F) Air Analysis Report dtd 10-7-08
(3) *NEDU Gas Analysis Laboratory Results*
(4) NEDU Memo *Output levels from three R-22D oxygen sensors* dtd 9-23-08
(5) 2005 Teledyne Analytical Instruments, Diving Oxygen Sensors, Diving Sensor Specifications
(6) Suunto Dive Manager 2.6.0, Information from Dive Computer, dtd 9-19-08
(7) Figures 1-6 of the Equipment tested

1. This letter responds to your request that Navy Experimental Diving Unit (NEDU) evaluate the equipment involved in a fatal diving accident on September 19, 2008 at Blue Springs Recreational Park, Marianna, FL. The decedent was Richard L. Mork.

2. NEDU received and investigated a Megalodon rebreather, dive computers, and various gas bottles. The full report of this investigation, NEDU Case number 08-08, is found in Enclosures.

3. There were two primary faults with the rebreather: excessive age and resulting significant nonlinearity in the oxygen sensors, and improper assembly of the solenoid controlled oxygen add-valve.

4. When the above faults were corrected, the submitted equipment operated satisfactorily.

REPORT OF INVESTIGATION

04/20/09
Rebreather Accident Investigation – Richard Mork, Megalodon UBA, NEDU tracking number EDF #08-08

1. Initial Contact
On Friday, September 19, 2008, Navy Experimental Diving Unit's (NEDU) Scientific Director, Dr. John Clarke, was contacted by Dr. Michael Bates, the Director and Chief Investigator for State of Florida, District Fourteen, Medical Examiners Office, regarding an hours-old fatality on a Megalodon underwater breathing apparatus (UBA) at Jackson Blue Springs (a fully submerged cave system) in Jackson County near Marianna, FL. Dr. Clarke put the Medical Examiner (ME) in contact with NEDU's Lead Accident Investigator, Mr. David Cowgill.

2. Receipt of Equipment
On Saturday, September 20, approximately 18 hours after the rebreather was recovered from the dive site, Dr. Bates delivered the Megalodon UBA, 4 scuba cylinders with regulators, wrist worn Liquivision X1 and Suunto "Dive Manager" dive computers to NEDU. Mr. Cowgill observed that the three oxygen (O_2) sensor values shown on the Megalodon primary display read an average of 0.7 ata partial pressure of oxygen (PO_2). The heads-up display (HUD) was flashing red in a pattern of three short flashes, a code also indicating a PO_2 of ~0.7 ata. Mr. Cowgill was able to secure most of the electronics on the rebreather to conserve battery power but he was unable to immediately turn off the secondary display. While he directed the unit to enter the "sleep" mode, he did not actually observe the display go blank; thus the time at which the display finally turned off is not known. He preserved the integrity of the breathing loop for later gas sampling by confirming that all breathing loop valves were closed. It had been reported anecdotally that these valves were closed at the scene of the accident.

3. Background on the Rebreather
The Megalodon is a fully closed-circuit UBA (rebreather) manufactured by Innerspace Systems Corp (ISC). Unlike open-circuit UBAs (i.e., scuba), a fully closed-circuit rebreather does not release gas into the water with each breath but rather, the exhaled gas flows through an absorbent canister where the CO_2 is removed. Also unlike open-circuit scuba, a rebreather normally has two gas bottles. One contains pure oxygen, the other, contains diluent, either air or a mixture of helium and oxygen. When a diver breathes on the UBA, his exhaled breath has its CO_2 absorbed by the scrubber canister. Oxygen sensors measure the oxygen partial pressure in the gas leaving the canister. The UBA control electronics and firmware operate a solenoid controlled oxygen add-valve to raise the oxygen concentration (PO_2) back to the desired value (to make up for the oxygen that is metabolized by the diver). According to the US Navy Dive Manual, a hypoxic condition occurs at a PO_2 level below 0.16 ata and hyperoxic condition at a level above 1.5 ata. Both conditions can lead to unconsciousness and death. Most rebreathers are designed to maintain PO_2 between 0.75 and 1.3 ata.

The Megalodon is normally equipped with two visual displays (primary and secondary) that allow the diver to monitor the PO_2, battery life and gas cylinder pressures. There is also a Heads-Up Display (HUD) that provides a visual alert, prompting the diver to check the detailed data on his primary and secondary displays. In the event of failure of the electronic controlled oxygen add-valve, the diver would be able to manually add oxygen, while monitoring his primary and secondary displays. In this UBA, all oxygen monitoring and controlling functions were managed by an APECS digital controller (firmware version 2.06). The rebreather had a non-ISC primary display made by Rebreathersolutions, Ltd., presumably added by the diver. The secondary display was the standard ISC secondary display. A HUD consisting of a colored light system for monitoring average PO_2 within the rebreather breathing loop was also included (Figure 1, enclosure 7).

4. <u>Evaluation</u>

The two gas bottles used as components of the rebreather were Faber 23 cu.ft. steel cylinders with a 3L floodable volume. One cylinder was marked for oxygen service, the other, the diluent bottle, was for mixed gas (oxygen and nitrogen) or air. Both Faber bottles were attached to the rebreather by Tiger mounts. The pressure of the rebreather oxygen cylinder was 1900 psi (enclosure 2A) and that of the diluent 1850 psi (enclosure 2B). The contents of the two bottles were analyzed by the Naval Surface Warfare Center Panama City Chemistry Laboratory. Their report (enclosure 2B) indicates the diluent bottle contained 26% oxygen mixed with 74% nitrogen. They determined the oxygen concentration of the oxygen bottle to be ~92% (enclosure 2A); however, limitations in their analysis instruments prevent them from accurately determining the actual concentration of oxygen for values greater than ~90%. This bottle was reanalyzed by NEDU's gas analysis laboratory and was found to contain nominally 99% oxygen (enclosure 3, cylinder 05-8749). No significant concentration of harmful contaminants was found in either cylinder.

In addition, there were two brushed aluminum 40 cu.ft. Luxfer cylinders. One of these was marked for trimix (23% oxygen/23% helium/balance nitrogen). Its pressure was measured to be 200 psi while its contents were analyzed to be nominally 22.4% oxygen and 76.9% nitrogen, not the indicated trimix (enclosure 2C). The second bottle, marked with a green cylinder valve as oxygen, contained 2550 psi. As above, the preliminary analysis indicated ~93% oxygen (enclosure 2D) while the reanalysis by NEDU determined the gas was nominally 100% oxygen (enclosure 3, cylinder LS8273). No significant contaminants were found in either cylinder.

The two remaining gas cylinders were 80 cu.ft. brushed aluminum cylinders containing nitrogen and oxygen mixes. The first cylinder, marked 32% oxygen, had a pressure of 2600 psi and was found to contain 31% oxygen with the balance nominally nitrogen (enclosure 2E). The second, marked 34% oxygen, also had a pressure of 2600 psi and was found to contain 30.9% oxygen with the balance nominally nitrogen (enclosure 2F).

On Monday, September 22, 2008, NEDU personnel powered up the rebreather displays and checked the readings on both the primary and secondary displays of the three

Teledyne R-22D oxygen sensors. Both displays indicated approximately 0.65 ata partial pressure of oxygen within the UBA. Two gas samples were taken from a port on the automatic diluent add-valve, which were considered to be representative of the gas within the UBA's breathing loop. The two samples were measured to contain 59.7% and 65% oxygen (0.597 ata and 0.65 ata PO_2 at the surface, respectively; enclosure 3, section 2). The variability in these two readings is unremarkable given the sampling technique that was used. These measurements also were comparable to the average PO_2 value shown on the UBA's primary display at the time of sampling; i.e. 0.65 ata.

Following gas sample extraction, the breathing loop was opened, inspected, and the oxygen sensors removed for testing. Nothing appeared out of the ordinary within the unit head, which houses the oxygen sensors, oxygen injection solenoid valve, primary and secondary electronics modules, and separate primary and secondary batteries (Figure 2, Enclosure 7). The carbon dioxide absorbent canister and its contents were dry. The absorbent was composed of fine granules that were similar in appearance to commercially available *Sofnolime* ™ *812* absorbent material. The granules were packed in the canister in a manner consistent with proper operation. There were small water droplets in the vicinity of the O_2 sensors, but no sign of overt flooding. While the absorbent material was removed from the canister and sealed in plastic bags, no further analysis of this material was attempted.

Linearity of the three Teledyne R-22D oxygen sensors was checked over the PO_2 range from 0.21 to 1.68 ata (enclosure 4). Two of the sensors were manufactured in August 2006, and one in September 2006. The sensor manufacturer's warranty period is 24 months, thus 2 were expired while the third was in its last month (enclosure 5).

Note that the sensor specification sheet states that the usable PO_2 range of the sensors is 0 to 1.0 ata. However, almost all rebreather manufacturers successfully use those sensors over the range of 0 to 2.0 ata, as long as the sensor output voltage remains linear over that range.

When functioning properly, oxygen sensor voltage output increases in a linear relationship with the partial pressure of oxygen in the gas monitored. All three sensors were relatively linear up to about 1.0 ata PO_2, but one sensor actually declined in voltage output as PO_2 was *increased* from that level. The other two sensors were not able to correctly read PO_2 above ~1.5 ata, and in fact declined in output as PO_2 was *raised* above that value. This situation would cause the average PO_2 value determined by the UBA's three sensors and shown on the UBA's displays to be less than the actual value when in the range ~1.0–1.5 ata, with a maximum displayed value of ~1.5 ata, even for PO_2 values greater than 1.5 ata. This performance is not typical of fresh, properly operating sensors, but is an indication that aging sensors have exceeded their useful life.

Because of the sensor's age-related degraded performance, it is unlikely that the rebreather's target PO_2 would have been accurately maintained. If the PO_2 in the UBA was dangerously high, above 1.6 ata, then the voting logic rules for the APECS controller would have voted out the one low sensor. The two handset displays would have indicated to the user that the sensor had been voted out. The displayed average PO_2 would have reflected the mean of the other two sensors, both of which decreased in value as PO_2 exceeded 1.5 ata. In summary, there would have been no warning of a catastrophically high PO_2.

Two isolation valves (Figure 1, enclosure 7) were attached to the high-pressure lines coming from the diluent and oxygen bottles' regulators, respectively. It is not known when they were closed. When both the oxygen isolation valve and the oxygen cylinder valve were opened, oxygen flowed freely into the UBA's breathing loop, demonstrating that the O_2 solenoid controlled oxygen add-valve was failed in the "open" position—even with the electronics and solenoid power turned off. The normal condition of the valve is to be "closed" when the solenoid is de-energized, which is the case when the electronics are turned off.

During disassembly of the solenoid controlled valve, the plunger and integrated valve seat were found to be installed incorrectly (i.e., inverted from the correct orientation; Figures 3-5, Enclosure 7). Small amounts of corrosion were also observed but not considered enough to affect the functioning of the valve. With the electronics turned off and the plunger and valve seating surface reinstalled correctly, the free flow of oxygen through the valve into the breathing loop no longer occurred. When the electronics were turned on, however, the solenoid controlled valve did not open. This is anomalous behavior, since the rebreather has a solenoid valve self-check procedure that should fire the solenoid, thereby opening the valve three times when the electronics first are turned on. Replacement of the battery pack installed in the UBA as received by NEDU with a new battery restored the solenoid controlled oxygen add-valve to its proper functioning. While the original battery pack voltage read 5.0 volts on the rebreather's primary display, it apparently could not provide the current required to activate the solenoid valve even after it had been properly assembled. Since some of the energy stored in the battery would have been dissipated from the time of the accident on Friday until Monday when all electronics were turned off, we cannot comment on the state of the battery's charge level during the accident dive. The secondary display and the HUD are powered by a second battery pack, separate from that of the primary handset display and solenoid valve. This battery's voltage read 6.4 volts on the secondary display and had adequate power to operate both that display and the HUD.

The data downloaded from the Suunto dive computer are included in enclosure 6. The recorded dive data show that the diver quickly descended to about 12 meters (m) depth after entering the water, and remained at that depth for about 10 minutes. He then descended directly to ~28 m depth and maintained depth between 27-30 m for approximately 12 minutes. The diver then began a slow ascent and finally reached ~20 m depth after ~35 minutes. At this point, ~60 minutes after the start of the dive, the depth remained fixed at ~20 m and the consumption of oxygen (the default label "AIR" on the dive computer printout actually represents the pressure in the oxygen cylinder since the diver computer transducer was located in that cylinder) ceased. About 85 minutes later, the depth again increased to ~29 m and then decreased to the surface—this most likely represents the depth changes that took place during recovery of the body since oxygen consumption never resumed.

The Liquivision dive computer was unresponsive when NEDU attempted to activate it to examine its data. Since the data from the Suunto dive computer appeared to accurately characterize the depth-time profile of the entire dive and did not show any erratic or anomalous data, no further attempt was made to download the data stored in the Liquivision unit.

5. Summary

There were at least two faults with the rebreather: 1. excessive age and resulting significant nonlinearity in the oxygen sensors. 2. improper assembly of the solenoid controlled oxygen add-valve. The first fault could have caused the UBA's displays to report lower than actual oxygen levels when PO_2 values rose above ~1.0 ata. The second fault precluded *normal* automatic functioning of the rebreather at *any* time during the accident dive.

The relatively large amount of oxygen remaining in the rebreather O_2 bottle (1900 psi) implies that the solenoid valve was *not* free-flowing oxygen throughout the approximate hour-long dive. Since the solenoid controlled valve was failed in the open position due to its improper assembly, the O_2 supply to the valve would have had to be turned off, most likely via the oxygen isolation valve that is located on the chest mounted counter lung. This configuration would have required the diver to manually add O_2 via the manual oxygen add-valve (also mounted on the counter lung), bypassing the solenoid valve, and to monitor the PO_2 readings on his HUD, and primary or secondary handset displays to keep the oxygen level from becoming hypoxic or hyperoxic. This is an accepted *emergency* procedure that can allow a diver to abort and safely recover from a dive following a solenoid valve failure; however, it is neither recommended nor accepted practice to use that technique as a normal procedure for initiating or continuing a dive. It is our opinion that the oxygen isolation valve was intentionally closed in order to prevent gas from free flowing through the nonfunctional solenoid controlled add-valve into the breathing loop.

With one of the oxygen sensors incapable of accurately indicating PO_2 values greater than 1.0 ata, and the other two unable to indicate values above ~1.5 ata PO_2, the PO_2 reading on the HUD, primary and secondary displays would have been lower than was actually present in the breathing loop. It is our assessment that the actual PO_2 was higher than normal during the dive.

The positioning and functioning of the isolation valve makes it relatively easy to move it from its "closed" to its "open" position (Figure 6, Enclosure 7). If the valve had been inadvertently opened during the dive, the PO_2 in the breathing loop could have increased rapidly to a toxic level. Deep scratch marks on the oxygen isolation valve may have been made while the diver was in the narrow passage in the cave and might have opened the valve. It is our opinion that the isolation valve may have been accidentally opened during the dive.

Although inadvertent movement of the isolation valve could have led to a rapid rise in PO_2, a hyperoxic condition may have already existed due to the faulty sensors. Changes in depth and exertion level can alter the PO_2 in the breathing loop. Keeping the PO_2 at safe levels under manual control with faulty O_2 sensors would have been difficult. High PO_2 levels can lead to convulsions and unconsciousness, which when occurring in a diver without a full face mask, results in the loss of the breathing mouthpiece and drowning.

Important!
This Megalodon UBA has been returned by NEDU partially disassembled and **must** *be fully serviced by a qualified technician before it is used again.*

Test Facility:		**Report To:**
Naval Surface Warfare Center Panama City Chemistry Lab, Bldg#414 110 Vernon Avenue Panama City, FL 32407 850-235-5505	**Oxygen Analysis Report** **Report Date:** 9/24/2008	Dave Cowgill NEDU 321 Bullfinch Road. Panama City, FL 32407

Date and time of sample collection:	N/A
Date of receipt of sample:	9/23/2008
Condition of sample:	Scuba cylinder #05-8749 filled to 1900 psig. Tested as received.
Date(s) of testing:	9/23/2008 to 9/24/2008
Time of sample preparation and/or analysis:	1200 on 9/23/2008
Reference to sampling plan and procedures used:	Reference NSWCPC-S-GAF-SOP13: Air Sampling.

Sample Description: Analysis of oxygen from accident investigation. Case #08-08. Scuba cylinder #05-8749.

Room Temperature: 75°F

In accordance with your request, the gas sample delivered to the gas analysis lab was analyzed and found to contain:

Standard Components

COMPONENT (Ref#7)	ABSOLUTE MEASURED LEVEL	ANALYSIS METHOD	REPORTING LIMIT (Ref#6)	SURFACE ALLOWED LIMIT (Ref.)
Oxygen 7782-44-7	92%	SOA NSWCPC-S-GAF-SOP11	19.9%	99.5% (3)
Carbon Dioxide 124-38-9	<7 PPM	CO2-IR NSWCPC-S-GAF-SOP2	2 PPM	10 PPM(3)
Total Hydrocarbons	11.2 PPM	GC-FID and GC/MSD2 NSWCPC-S-GAF-SOP6,26	5 PPM	25 PPM(1,5)
Carbon Monoxide 630-08-0	<1 PPM	CO-IR NSWCPC-S-GAF-SOP2	1 PPM	0 PPM(3)

ENCLOSURE (2A)

Methane 74-82-8	11.2 PPM	GC-FID NSWCPC-S-GAF-SOP6	10 PPM	50 PPM(3)
Acetone 67-64-1	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	40 PPM	200 PPM(2)
Acetylene 74-86-2	<0.1 PPM	GC-FID NSWCPC-S-GAF-SOP6	0.02 PPM	0.1 PPM(3)
Benzene 71-43-2	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	0.2 PPM	1 PPM(2)
Chloroform 67-66-3	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	0.2 PPM	1 PPM(2)
Ethanol 64-17-5	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	20 PPM	100 PPM(2)
Ethylene 74-85-1	<0.1PPM	GC-FID NSWCPC-S-GAF-SOP6	0.08 PPM	0.4 PPM(3)
Ethane & other Hydrocarbons	<1.2 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	1.2 PPM	6.0 PPM(3)
Refrigerant CFC-113 76-13-1	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	20 PPM	100 PPM(2)
Refrigerant CFC-11 75-69-4	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	20 PPM	100 PPM(2)
Refrigerant CFC-12 75-71-8	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	20 PPM	100 PPM(2)
Refrigerant CFC-114 76-14-2	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	20 PPM	100 PPM(2)
Halogenated Refrigerants	<0.4 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	0.4 PPM	2.0 PPM(3)
Halogenated Solvents	<0.04 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	0.04 PPM	0.2 PPM(3)
Isopropyl Alcohol 67-63-0	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	0.2 PPM	1 PPM(2)
Methanol 67-56-1	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	2 PPM	10 PPM(2)
Methyl Chloroform 71-55-6	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	6 PPM	30 PPM(2)
Methyl Ethyl Ketone 78-93-3	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	4 PPM	20 PPM(2)
Methyl Isobutyl Ketone 565-61-7	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	4 PPM	20 PPM(2)

Methylene Chloride 75-09-2	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	5 PPM	25 PPM(2)
Toluene 108-88-3	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	4 PPM	20 PPM(2)
Trimethyl Benzenes 25551-13-7	<0.008PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	0.6 PPM	3 PPM(2)
Xylenes 1330-20-7	<0.011 PPM	GC/MSD2 NSWCPC-S-GAF-SOP26	10 PPM	50 PPM(2)
Odor	pass	nose/smell Ref#3	pass/fail	Odor Free(3)

Other Components

Note: The estimated measured level for other components is calculated based upon the instrument response to Benzene

COMPONENT (Ref#7)	ESTIMATED MEASURED LEVEL	ANALYSIS METHOD	REPORTING LIMIT (Ref#6)	SURFACE ALLOWED LIMIT (Ref.)
None				

Test results are only applicable to the sample identified in the sample description. The sample showed no appreciable contamination. All components were not within their specified limit. The Oxygen level was too low at 92%.

[1]Expressed as methane equivalents.
[2]Limits taken from Navy Dive Manual; Rev. 5, Table 15-5.
[3]Limits taken from Navy Dive Manual; Rev. 5, Table 4-3.
[4]Section F6-C of P9290 Rev A(pg F-20). Limit is equal to:

A). One-tenth the lowest allowable exposure limit established by OSHA or ACGIH, or

B). The 90 day limit specified by the Nuclear Powered Submarine Atmosphere Control Manual, or

C). The appropriate mission day limit specified by NASA JSC 20584 Spacecraft Maximum Allowable Concentration for Airborne Limits.

[5]Limits taken from Navy Dive Manual; Rev. 5, Table 4-1.

[6]The reporting limit is the lowest concentration (sensitivity) to which each component must be analyzed. The reporting limit should be not less than 1/5 the SEV corrected allowable exposure limit. Where the SEV corrected allowable exposure limit is less than or equal to the instrument sensitivity, the reporting limit shall be specified as instrument detectability. The minimum instrument detectability shall be equal to the SEV corrected allowable exposure limit, or if greater, a value acceptable to cognizant medical department personnel.
[7]Chemical Abstract Service number (CAS).

THIS TEST REPORT SHALL NOT BE REPRODUCED EXCEPT IN FULL, WITHOUT THE WRITTEN APPROVAL OF THE LABORATORY

Ken Watford 9-24-08
Ken Watford, Date
Analyst.

Hugh B Orr 9-24-08
Hugh Ben Orr, Date
Test Director.