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REPORT NO. 8-89

EX 19 PERFORMANCE TESTING AT 850 AND 450 FSW

LCDR M.E. KNAFELC, MC, USN

JUNE 1989

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The EX 19 is a self-contained closed-circuit underwater breathing apparatus (UBA) capable of controlling the PO_2 at a specified level. Previous testing conducted in February 1988 reported that EX 19 could support a hard-working diver breathing a 0.7 PO_2 in nitrogen to a depth of 150 FSW. The present evaluation was conducted at 450 and 850 FSW during an HeO_2 saturation dive at the Navy Experimental Diving Unit, Panama City, FL. A series of graded exercises were performed on a bicycle ergometer modified for underwater use. The work protocol involved 6 minutes of work at 50, 100, and 150 watts each preceded by 4 minutes of rest. While performing 150 watts at 850 FSW the mean ΔP was 27.3 ± 1.7 cm H_2O and the $P_{ET}CO_2$ was 57.1 ± 4.4 mmHg). At 450 FSW the ΔP was 22.7 ± 3.9 cmH_2O and the $P_{ET}CO_2$ was 56.5 ± 4.3 mmHg. The PO_2 was maintained at 0.7 ATA ± 0.1. There were no primary electronic failures during the
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testing of the EX 19. However, water leaked into the cable and connector between the electronic sensing unit and the O_2 addition valve. The cause for the leak was the poor bonding between the metal connectors and the potting material allowing helium intrusion and then expansion during decompression from 850 FSW. In conclusion the EX 19 met the NEDU performance goals at 450 and 850 FSW. The overall design can support deep diving operations and deep saturation diving. If the EX 19 is to be used for helium saturation diving the cable and connectors will require redesign.

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I. INTRODUCTION

The EX 19 is a self-contained closed-circuit underwater breathing apparatus (UBA) capable of controlling the partial pressure of oxygen (PO_2) at a specified level. The Naval Coastal System Center (NCSC) prototype underwent manned evaluations in February 1988 and was accepted for continued development. In addition, it was found that the overall design could be adapted to an expanded mission requirement (1). This potential retains the perspective that was outlined in the operational requirement for the Conventional Dive System (OR #102-02-87) in which the EX 19 is the designated UBA. Reference (1) contains a complete description of the NCSC EX 19.

The initial study performed on the prototype design was at a depth of 150 feet of seawater (FSW) using a PO_2 of 0.7 ATA in nitrogen. The divers reported low dyspnea scores and had no difficulty performing their work cycles. When evaluating performance with respect to gas density, the 150 FSW study is more difficult for the diver when compared to a 1000 FSW dive using HeO_2. It was concluded that the EX 19 had an overall breathing resistance that would support a working diver at a deeper depth.

The purpose of this study was to perform a manned evaluation of the advanced design model (ADM) of the EX 19. Due to the engineering constraints of the ADM, the maximum test depth was 850 FSW. The EX 19 was also tested at 450 FSW.

II. METHODS

A. SUBJECTS

The subjects were seven U.S. Navy trained saturation divers participating in a 20-day HeO_2 saturation dive at the Navy Experimental Diving Unit's Ocean Simulation Facility (OSF). Their age, height, weight, and % body fat was determined prior to the dive and are listed in Table 1. All divers participated in an 8-week physical training program designed to increase their aerobic and anaerobic thresholds for bicycle ergometry.

TABLE 1

DIVER'S PHYSICAL CHARACTERISTICS

Diver	Age	Height (cm)	Weight (kg)	% Body Fat
1	28	180	81	15
2	28	183	83	12
3	28	185	87	13
4	31	183	72	8
5	31	183	84	15
6	30	178	82	18
7	25	175	87	16

The divers were trained to report a dyspnea score. This scale was developed at the Navy Experimental Diving Unit and found useful as a subjective measure of breathing comfort when testing diving apparatus (4). The scale was as follows:

0 - No air hunger
1 - (Mild) A sensation of air hunger but does not impede the divers' ability to exercise
2 - (Moderate) A very strong sensation of air hunger although not severe enough to cause the subject to doubt his ability to complete the exercise period
3 - (Severe) A sensation of air hunger sufficiently distressing to have nearly forced cessation of exercise

The divers were trained to consistently reproduce the feeling of breathlessness by exhaling to residual volume, and holding their breath for 20 seconds. They practiced equating the feeling of the breathlessness at 0, 5, 10, and 15 seconds of the breath-hold with the dyspnea score of 0 to 3 respectively.

B. EX 19 INSTRUMENTATION

The oronasal mask was penetrated with two lines of teflon tubing. One line with an internal diameter of 0.078 inch was attached to the positive side of a differential pressure transducer (Validyne DP15 with a 0.8 psi diaphragm, Northridge, CA). The negative side of the transducer was referenced to the diver's suprasternal notch. The transducer was calibrated at depth using a U-type water filled manometer (Meriam Instrumentation Co., Cleveland, OH). The pressure range was 0 to $\pm$ 50 cmH_2O.

The other teflon line with an internal diameter of 0.032 inch was connected to a microvalve and then to the trunk gas sampling line. Gas flow was controlled at depth between 2000 and 2500 cc/min at the surface. This flow rate was determined to give the optimum mass spectrometer response time, 230-270 msec, for breath-to-breath analysis from the wet chamber of the OSF (2).

The EX 19 was equipped with a data communications cable connected to a microcomputer on the medical deck. This allowed the principle investigator and UBA engineers to observe all the electronic functions of the EX 19.

C. MASS SPECTROMETER

A mass spectrometer (Perkin-Elmer, MGA 1100, Pomona, CA) was used for this study. A breath-to-breath analysis of P_{O2} and P_{CO2} was performed during each set of graded exercises. The mass spectrometer was calibrated prior to each dive and the calibration was checked upon completion of each study.

D. STRIP CHART RECORDER

A strip chart recorder (Gould, ES 2000, Cleveland, OH) continuously monitored the divers end-tidal P_{CO2} ($P_{ET}CO_2$), PO_2, oronasal peak-to-peak differential pressure (ΔP) and ECG. The first 30 seconds of the last minute of work was plotted for data analysis. The chart speed was 10 mm/sec.

E. PROCEDURE

A calibrated bicycle ergometer (Collins Pedalmate, Braintree, MA) modified for underwater use was placed in a horizontal position within the wet chamber of the OSF. Because the breathing bags were not insulated or heated, the water temperature was maintained at 45°F (7.4°C). This temperature reduced the possibility that the breathing gas temperature would affect the diver's performance. The divers wore hot water suits.

The EX 19 was set up daily and its operation checked prior to each dive set. A 97/3% HeO_2 gas mix was used as the diluent gas for the 850 FSW study. A 95/5% HeO_2 mix was the diluent gas for the 450 FSW study. The diluent was supplied through a gas umbilical to the diluent high pressure regulator to compensate for the gas lost when sampling the diver's breath. The CO_2 absorbent canister was packed with LiOH prior to the diving evolutions. Proper functioning of the UBA and instrumentation was verified before each study began.

After entering the water the diver properly positioned himself on the ergometer. He filled the breathing bags to a level comfortable for him to take deep inhalations, yet not exhaust gas upon exhalation. Prior to the exercise sequence the diver held his breath after an exhalation which allowed measurement of the UBA's static pressure. In addition, the diver's resting $P_{ET}CO_2$ was recorded prior to the start of exercise.

Each 6-minute exercise sequence was preceded by 4 minutes of rest. The diver worked at 50, 100, and 150 watts as indicated on the ergometer controller. When in-water work is performed the fluid resistance can increase the energy expenditure by 33 to 42% (3). Though the controller may read 150 watts, the diver's work level may be 200 to 210 watts. Upon completion of each work sequence, the diver reported his level of breathlessness based on a 4-point dyspnea score.

F. <u>DATA ANALYSIS</u>

The strip chart recordings of the last 30 seconds of each work cycle was analyzed for the ΔP, $P_{ET}CO_2$ and PO_2. The mean and standard deviations for the ΔP and $P_{ET}CO_2$ and the average PO_2 were reported.

G. <u>RISKS</u>

The risks of using a closed-circuit UBA while working at depth are hypercapnea, hyperoxia, and hypoxia. Unconsciousness can result from any of these conditions. These risks were minimized by the continuous monitoring of the diver's breathing gas and by preparing to abort the dive if the $P_{ET}CO_2$ exceeded 70 mmHg or the PO_2 decreased below 0.2 ATA. The amount of physiological stress on the diver was monitored with an ECG.

III. RESULTS

Only four graded exercises with the EX 19 were performed at 850 FSW due to a mechanical failure of the UBA. Three divers completed the graded exercises at 150 watts with a mean ΔP of 27.3 ± 1.7 cmH_2O , and a $P_{ET}CO_2$ of 57.1 ± 4.4 mmHg. One diver stopped after completing the 100 watt load complaining that the gas was too cold for him to continue and that his chest was feeling congested. All divers reported a dyspnea score of 0 for inhalation and exhalation after all the exercise periods.

The mechanical failure of the EX 19 on the second day of testing at 850 FSW was due to water leaking into the cables and connectors from poor bonding between the potting material and the metal in the connectors. The potting material allowed helium intrusion and then expansion within the cable during decompression that occurred after the first day of testing at 850 FSW. With the space created, water was able to short circuit the oxygen addition valve and give inconsistent oxygen bottle pressure readings. If the EX 19 were to be used for helium saturation diving, the cables and connectors will require redesign to prevent such a reoccurrence. The electronics within the EX 19 were reliable during all testing.

Six dives were successfully performed at 450 FSW. The mean ΔP for the 150 watt work cycle was 22.7 ± 3.9 cmH_2O and $P_{ET}CO_2$ was 56.5 ± 4.3 mmHg. Four divers reported a dyspnea score of 0 for their graded exercise, and two divers reported a 1 after the 150 watt cycle. All the test results for both depths are in Table 2.

The static load within the EX 19 varied with the diver and ranged between 0 and +14 cmH_2O.

While the diver was performing heavy exercise, 150 watts, at 850 FSW the EX 19 maintained an average PO_2 of 0.68 ATA. At 50 and 100 watts the average PO_2 was 0.63 and 0.61 ATA respectfully. The minimum PO_2 observed during exercise was 0.59, the maximum was 0.78 ATA. At 450 FSW, the averaged PO_2 for 50, 100 and 150 watts were 0.69, 0.69, and 0.65 ATA respectively. The minimum PO_2 observed during exercise was 0.61 ATA, the maximum was 0.77.

There were no primary electronic failures during the testing of the EX 19 at 850 or 450 FSW.

TABLE 2

BREATHING CHARACTERISTICS OF THE EX 19 AT 450 FSW

Diver		Rest	WATTS 50	100	150
1	$P_{ET}CO_2$ (mmHg)	43	49.3±1.3	48.4±1.1	50.6±1.0
	ΔP (cmH_2O)		16.7±1.0	20.7±1.4	24.0±1.4
	static load (cmH_2O)	+2			
2	$P_{ET}CO_2$ (mmHg)	46	55.8±1.7	56.6±2.1	55.8±1.2
	ΔP (cmH_2O)		21.1±1.8	24.6±2.3	28.7±1.7
	static load (cmH_2O)	+14			
3	$P_{ET}CO_2$ (mmHg)	40	58.5±1.6	57.4±1.1	62.1±1.4
	ΔP (cmH_2O)		15.6±1.9	16.9±1.1	18.4±0.9
	static load (cmH_2O)	+10			
4	$P_{ET}CO_2$ (mmHg)	39	52.6±1.2	53.5±1.9	57.5±1.1
	ΔP (cmH_2O)		18.9±2.3	21.8±2.0	23.6±1.6
	static load (cmH_2O)	+6			
5	$P_{ET}CO_2$ (mmHg)	45	50.2±0.9	54.5±1.5	59.8±2.1
	ΔP (cmH_2O)		16.0±0.0	19.6±0.8	23.6±1.3
	static load (cmH_2O)	+8			
6	$P_{ET}CO_2$ (mmHg)	45	51.0±1.4	52.2±1.6	53.0±2.3
	ΔP (cmH_2O)		16.2±1.3	16.2±0.7	18.2±1.1
	static load (cmH_2O)	+4			

BREATHING CHARACTERISTICS OF THE EX 19 AT 850 FSW

Diver		Rest	50	100	150
6	$P_{ET}CO_2$ (mmHg)	44	51.0±2.2	55.6±3.2	61.0±2.4
	ΔP (cmH_2O)		15.6±2.1	18.7±2.6	29.2±3.8
	static load (cmH_2O)	0			
7	$P_{ET}CO_2$ (mmHg)	36	47.1±1.3	51.6±1.8	52.3±1.1
	ΔP (cmH_2O)		28.0±2.7	31.1±2.5	26.8±3.9
	static load (cmH_2O)	+8			
3	$P_{ET}CO_2$ (mmHg)	45	54.4±2.3	62.6±2.1	(a)
	ΔP (cmH_2O)		17.6±1.8	24.6±1.9	
	static load (cmH_2O)	+3			
4	$P_{ET}CO_2$ (mmHg)	37	50.6±1.1	54.2±1.5	58.0±1.4
	ΔP (cmH_2O)		18.5±1.4	20.9±2.0	26.0±2.1
	static load (cmH_2O)	+4			

(a) Dive aborted upon request by the diver.

IV. DISCUSSION

When evaluating a diving apparatus several variables must be examined. First, the UBA's breathing resistance must not impair the diver's ability to perform work. Second, the $P_{ET}CO_2$ generated by the diver should not exceed 70 mmHg. CO_2 peaks above this level have been associated with cerebral dysfunction (5). Third, the static load should be between 0 and +10 cm.H_2O. Fine and Flynn (1987) reported that positive static loads were preferred. Some individuals in that study preferred +10 cmH_2O to 0 cmH_2O, and others preferred +20 to +10 cmH_2O. Finally, the oxygen set point of the EX 19 must be verified that it was delivering the proper breathing mix to the diver.

At 850 and 450 FSW all divers were able to complete their graded exercises reporting a 0 or 1 as their dyspnea score. Overall the EX 19 did not impair the diver's ability to perform work. The $P_{ET}CO_2$ did not exceed 65 mmHg for any diver, averaging 56.5 mmHg for the 150 watt cycle. The static load, which is volume dependent, was between 0 and +14 cmH_2O. The EX 19 design appears to allow the diver to set his preferred static load by varying the amount of gas in the breathing bags. The EX 19 maintained the PO_2 within the design parameters of 0.60 and 0.90 ATA. This advanced design model of the EX 19 was primarily built for 450 FSW, and at this depth the PO_2 was maintained near 0.7 ATA for all work loads.

The expected operational depth for the EX 19 ADM is 450 FSW. The engineering design allowed testing at 850 FSW while maintaining an acceptable safety margin. By testing at both depths the performance of the EX 19 using HeO_2 was determined. The compliance of the UBA, its static load and internal resistance combine to allow the diver adequate ventilation (6). This capability was evidenced by the safe levels of end-tidal CO_2 seen during the work loads at the test depths. Applying the maximum likelihood approach to tolerance as developed by the Naval Medical Research Institute (7), to the measured differential pressure, it can be projected that the EX 19 will support a hard working diver at 1000 FSW, gas density of 5.86 g/l, (figure 1). Figure 1 contains all the manned oronasal differential pressure data with the EX 19 measured at NEDU.

Because one diver aborted his run at 850 FSW complaining of cold gas, a method warming the breathing gas must be addressed when using the EX 19 at that depth. This could be readily accomplished by shunting hot water through a shroud over the breathing bags.

This evaluation confirmed the acceptability of the EX 19 for deep diving operations to 450 FSW. In addition, it projected that such a design may be applicable to deep saturation operations.

ORONASAL DIFFERENTIAL PRESSURE FOR THE EX 19

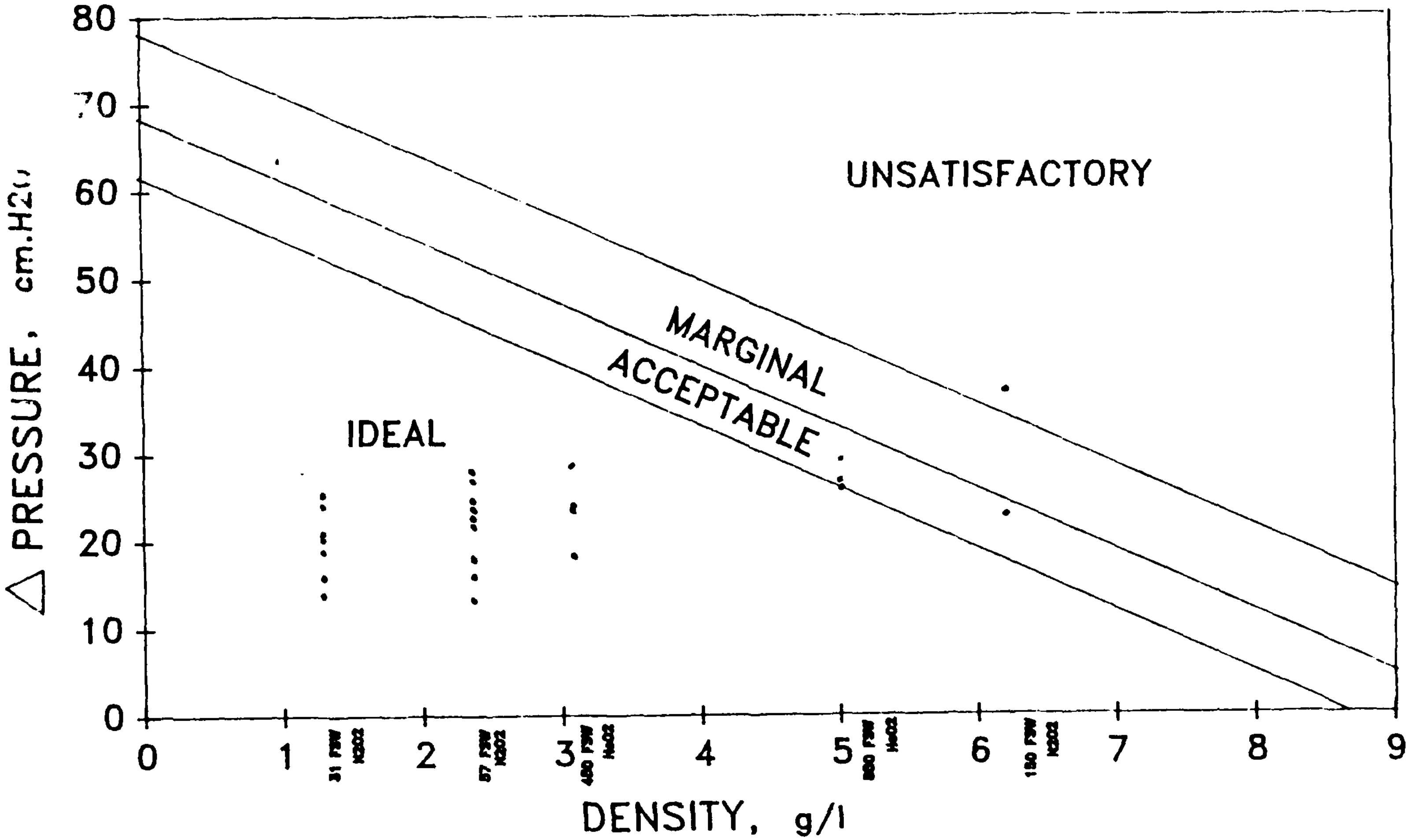

figure 1

V. CONCLUSION

A. The advanced design model of the EX 19 has met the NEDU breathing performance goals at 450 FSW using HeO_2. The electronics package worked reliably.

B. The EX 19 meets the NEDU breathing performance goals at 850 FSW. The overall design can support deep saturation diving to at least 850 FSW. The electrical connectors and cables must be redesigned if the EX 19 is to be used in saturation operations.

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