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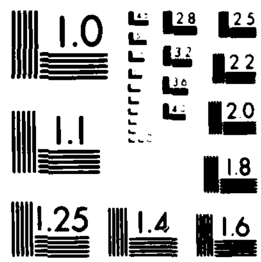

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NAVY EXPERIMENTAL DIVING UNIT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Diving Systems International Superlite 17B helmet underwent manned failure-mode testing at simulated depths of 30 and 856 feet of seawater during air bounce dives and a helium-oxygen saturation dive in the Ocean Simulation Facility. Twenty-three graded exercises (50-150 watts) were performed by seven subjects with either the helmet in normal configuration or with the one-way oronasal valve removed to simulate a worst case single failure. There was no significant difference in maximum end tidal CO_2 between the two configurations.

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Abbreviations

CO_2	carbon dioxide
C	celsius
cmH_2O	centimeters of water
cc	cubic centimeters
$P_{ET}CO_2$	end tidal partial pressure of carbon dioxide
F	Fahrenheit
FSW	feet of seawater
mmHg	millimeters of mercury
min	minutes
NEDU	Navy Experimental Diving Unit
N	number
OSF	Ocean Simulation Facility
PCO_2	partial pressure of carbon dioxide
psi	pounds per square inch
psig	pounds per square inch gauge
ΔP	pressure differential
STP	standard temperature and pressure
SL 17	Superlite 17B
SEV	surface equivalent volume (SEV = percent by volume of a gas x atmospheres absolute)

Abstract

The Diving Systems International Superlite 17B helmet underwent manned failure-mode testing at simulated depths of 30 and 856 feet of seawater during air bounce dives and a helium-oxygen saturation dive in the Ocean Simulation Facility. Twenty-three graded exercises (50-150 watts) were performed by seven subjects with either the helmet in normal configuration or with the one-way oronasal valve removed to simulate a worst case single failure. There was no significant difference in maximum end tidal CO_2 between the two configurations.

KEY WORDS: open-circuit
saturation
helium-oxygen
exercise
carbon dioxide
breathing resistance
underwater breathing apparatus
oronasal valve
Test Plan 83-60

I. INTRODUCTION

The Superlite 17B (SL 17) is a commercially available open-circuit surface supplied diving helmet produced by Diving Systems International (425 Garden Street, Santa Barbara, California). The Navy Experimental Diving Unit (NEDU) was given the task of evaluating the SL 17 for possible use in the Navy's Deep Diving Systems. The NEDU has done both unmanned (1) and manned testing (2) and has shown that the SL 17 meets standardized NEDU performance goals (3) and was able to support a working diver breathing a helium oxygen mixture at a simulated depth of 850 feet of seawater (FSW).

The proper function of the helmet depends on a demand regulator which supplies fresh breathing gas to a tight fitting oronasal mask. Exhaled gas passes out the demand regulator and into the water. A free flow valve may be used to admit gas to the helmet cavity where it first passes over the faceplate to clear it of fog if necessary, then enters the oronasal mask through a one way valve, finally leaving through an exhaust valve in the demand regulator. The free flow valve is not used in normal operations except to clear the faceplate, and was not used at all during the previous manned study. During that study the CO_2 level in the helmet rose significantly to 4.5% surface equivalent volume (SEV) but the helmet gas did not interchange appreciably with oronasal gas. That the diver did not inhale the high helmet CO_2 is due to the general design of the SL 17 which has a small volume and a neckdam with low compliance, and is additionally kept low by careful attention to fit of the foam filled headliner, which takes up much of the free space in the helmet. However, a situation in which the one way valve in the oronasal mask failed in the open position is believed to be a worst case condition, potentially allowing rebreathing from the helmet cavity. Inspired gas containing a PCO_2 of 4.0% SEV causes dyspnea at shallow depths. The effects at greater depths are not known but could lead to severe dyspnea or even unconsciousness.

This report describes the results of a series of manned tests of the SL 17 at 30 FSW, and at 856 FSW during a helium-oxygen saturation dive, Deep Dive '84 (NEDU Test Plan 83-60), at the NEDU Ocean Simulation Facility (OSF). Graded exercise studies were done both with the helmet in normal configuration and with the one way oronasal valve removed to simulate failure of the valve, with the helmet instrumented to study breathing characteristics under various work loads.

II. MATERIALS AND METHODS

The studies were carried out during the workup for the saturation dive and during two days of a 31 day helium-oxygen saturation dive in the OSF. The SL 17, serial number 2181, described elsewhere (2), was checked to meet specifications. The chest level of the diver-subject in the wet chamber of the OSF was at an equivalent depth of 30 FSW or 856 FSW. Water temperature was 35°F (1.7°C) and the diver-subjects wore non-return valve hot water suits. A 30-minute graded exercise was used to assess ability of the SL 17 to adequately support a working diver. Diver work rate was provided by a specially designed electronically braked pedal mode ergometer (Warren E. Collins, Braintree, Mass.) modified for submerged use (4, 5). Studies were done with the diver in a 45° head-up position. Graded exercise consisted of a 4-minute rest period followed by 6-minute work periods of 50, 100, and 150 watts, each separated by a 4-minute rest period. The helmet was supplied with air at 30 FSW or with a breathing mixture of 98.5% helium and 1.5% oxygen at 850 FSW. Previous studies using similar methods showed an estimated oxygen consumption while pedalling at 150 watts of approximately 3 liters per minute (6).

III. SUBJECTS

The diver-subjects were six well trained, experienced U.S. Navy divers. All were physically pre-conditioned for three weeks by a 5-day a week program of calisthenics, runs up to 4 miles, and 30 minute graded exercises on a bicycle ergometer. During the training period the diver-subjects made test pool dives using the SL 17 for familiarization. All diver-subjects did graded exercises at 30 FSW during the training period, but two of them did so using a different diving apparatus than the SL 17.

IV. INSTRUMENTATION

Gas samples from the oronasal and helmet cavities were obtained by capillary sample lines with micrometering valves to give sampling rates of 500 to 2100 cc/min (STP). The gas samples were analyzed by one or two mass spectrometers (Perkin-Elmer modified model MGA-1100). The delay time from the helmet to the mass spectrometer was less than 3 seconds which provided rapid response to variations in gas composition without significant mixing in the sample line. Breath-by-breath curves were recorded on a Gould 8-channel stripchart. End tidal PCO_2 ($P_{ET}CO_2$) was measured during the last 30 seconds of each test or work period. This value approximates alveolar PCO_2 (7).

The inspiratory/expiratory pressure differential was measured in the oronasal mask and in the helmet cavity by differential pressure transducers (Validyne DP-9 with 1.25 psi diaphragms) referenced to ambient water pressure at approximately eye level. These transducers were calibrated by a water manometer before each study.

V. EXPERIMENTAL PROCEDURES

Before each dive the diver-subject filled the helmet liner with open cell foam inserts to give a snug helmet fit and a tight oronasal seal. During the initial rest period in the water the diver-subject adjusted the demand regulator dial-a-breath to comfortable breathing effort but no other attempt was made to standardize regulator setting. Diver-subjects were instructed not to turn on the free-flow defogger valve except in an emergency. Following the exercise, the diver-subject was interviewed for his subjective evaluation of breathing effort during work, comfort, and oronasal fit. For the studies simulating failure of the one way oronasal valve in the open position, the valve was simply removed from the oronasal mask.

The bounce dives done at 30 FSW were done during the workup for the saturation dive and were considered to be training dives. As a result drills took precedence over data collection in some instances.

VI. RESULTS

Table 1 summarizes the CO_2 levels in mmHg partial pressure taken from either the oronasal or helmet cavity for the 30 FSW graded exercises during the last 30 seconds of the rest or work cycle. Five graded exercises were done with the oronasal valve in place, although one run was stopped after 5 minutes of the 150 watt work cycle due to a planned drill. Five graded exercises were completed with the oronasal valve removed. The oronasal $P_{ET}CO_2$ and helmet PCO_2 both increased slightly when the oronasal valve was removed but there was no subjective change noted by the diver-subjects and there was no change in their ability to exercise.

Table 2 summarizes the pressure differentials from full inspiration to full expiration (ΔP) during the graded exercises at 30 FSW. Oronasal ΔP is a quantitative measurement of breathing resistance and can be compared to ΔP measurements taken under similar conditions of gas density where flow measurements were also taken. In this way actual breathing resistance can be estimated. There were no significant differences between the tests done with and without the oronasal valve.

Table 3 is similar to Table 1 but summarizes the CO_2 levels during the graded exercises at 856 FSW. Nine graded exercises were begun with the oronasal valve in place but only two were completed. One diver-subject stopped work during the 100 watt exercise, and six others stopped during the 150 watt exercise due to dyspnea. The differences in $P_{ET}CO_2$ or helmet PCO_2 between those who completed the exercise and those who did not, fell within overlapping standard deviations and therefore the results are not considered to be significantly different. Four graded exercises were done with the oronasal valve out, and two were completed, but two diver-subjects stopped during the 150 watt exercise due to dyspnea. One diver-subject who did not complete the exercise ventilated his helmet while pedalling at 150 watts so the helmet data collected during that period is not included. The average $P_{ET}CO_2$ and helmet PCO_2 was slightly higher in the tests done with the oronasal valve out, but did not manifest itself in any change in diver exercise capability, or result in increased dyspnea of other symptoms of carbon dioxide retention.

Table 4 is similar to Table 2, and summarizes the average ΔP in the helmet and oronasal during the graded exercises at 856 FSW.

The diver-subjects were interviewed following each graded exercise. In those seven cases when the exercise was not completed with the one-way oronasal valve in place, the reason for stopping was dyspnea in four cases, fatigue in two cases, and could not be specified in one case. In the two cases not completed with the one-way oronasal valve out, the reason given for stopping was fatigue.

Several system adjustments and changes were made during the study to correct what was perceived to be inadequate equipment performance after the first three divers failed to complete graded exercises. Following dive number three, with oronasal valve in, the gas supply pressure was found to be low, approximately 70 psig overbottom pressure, instead of the intended 165 psig. The gas supply pressure was readjusted and raised to 185 psig for all subsequent dives. A 50 foot umbilical was substituted for the 300 foot umbilical in dive numbers five through eight. A 72 cubic foot tank connected by a tee to the gas supply regulator served as a volume tank for dive number seven and all subsequent dives. The configuration used for each dive is listed in Table 5.

VII. DISCUSSION

The primary purpose of the present study was to predict the result of failure of the SL 17 one way oronasal valve in the open position. Such a failure could cause increased ventilation, hypercarbia, and decreased work capacity due to rebreathing from the helmet dead space. End tidal PCO2 provides a good estimate of ventilation and there was only a slight increase in this parameter at both 30 FSW and 856 FSW when the oronasal valve was removed. The average values at the end of the work periods in the previous study at NEDU (2) using the SL 17 (51.1 mmHg CO_2 ± 6.5 at 50 watts, 51.4 ± 6.7 at 100 watts, and 55.2 ± 5.9 at 150 watts) compare closely with the values from the present study. The slight increase in end tidal CO_2 did not decrease a diver-subject's work capacity in this study. Thus, although an oronasal valve failure is not normal to the SL 17, should it occur, it does not represent a severe hazard to the diver.

In the previous study at NEDU all 4 divers were able to complete graded exercises including exercise at 150 watts at 850 FSW using the SL 17. In the present study, a number of similar graded exercises at 856 FSW were halted due to dyspnea at 150 watts. Comparing the results of both studies shows that the average $P_{ET}CO_2$ and helmet PCO_2 levels were virtually identical at all work rates. However, the average ΔP was markedly elevated in the present study, being 38.5 ± 8.4, compared with 15.5 ± 3.3 at 150 watts. Diver-subject five completed exercises at 856 FSW both with and without the oronasal valve in place, with no subjective trouble breathing, and with a low ΔP on each run which was very close to the average ΔP of 19.5 ± 6.4 cm H_2O seen during the previous study. The remaining Diver-Subjects did not complete all or some of the graded exercises.

When a diver-subject using an open circuit demand breathing apparatus is unable to complete a graded exercise and there is evidence of a high ΔP, there are two possible explanations. One explanation is poor performance of the breathing apparatus, and the other is inadequate diver conditioning leading to overbreathing of the demand valve. The data from the dives was examined to see if the failures could be explained by either mechanism.

We first considered poor performance of the breathing apparatus as a possible cause. The one dive in which this possibility was evident was the first dive by diver-subject three during which the gas supply pressure dropped from 165 psig to as low as 70 psig. In the dives following that failure and because of the failure of the first two divers to complete graded exercises, the changes listed in Table 5 were made in the configuration of the gas supply system. These changes were intended to improve gas supply to the demand regulator of the SL 17. The various configuration changes did not result in any definite improvement in the ability to complete graded exercises and suggests that the problem lay in the divers exercise capability at depth. The low ΔP's seen during both graded exercises completed by diver-subject five is evidence that the performance of the breathing apparatus was satisfactory.

The other possible explanation for failure to complete graded exercises in this study is inadequate conditioning of the diver-subjects. An underwater pedal mode ergometer setting of 150 watts causes a diver to expend about 225 to 250 watts pedalling due to the additional resistance of suit and water, and is close to and may exceed maximum capability in some individuals at or near the surface. At deep depths a diver experiencing fatigue may begin a rapid respiratory rate with a demand for peak flow rates beyond the capacity of the regulator to supply (9). This overbreathing of the regulator is more likely to occur with a diver who is not fully conditioned or who is not well-experienced in a diving apparatus. Most diver-subjects who failed to complete exercise at 150 watts reported dyspnea or leg fatigue. Analysis of pressure recordings indicate a large increase in helmet differential pressure and respiratory rate just prior to stopping work. Previous experience at NEDU with other breathing apparatus shows a similar pattern of breathing change when a diver exceeds his exercise capacity. Moreover, some diver-subjects stated that they were not as well trained physically as they had been for past dives. These observations suggest that the divers were unable to complete work at 150 watts due to inadequate training and that the subsequent high differential pressures observed in this study but not in a previous study are due to diver-subject overbreathing of the SL 17 demand regulator.

VIII. SUMMARY

The SL 17 was tested at 30 FSW and at 856 FSW in a failure mode simulating failure of the oronasal one-way valve. Potential problems with CO_2 rebreathing from such a failure did not occur. A number of graded exercises at 856 FSW were not completed due to dyspnea or fatigue of the diver-subject.

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TABLE 1

CO_2 LEVELS WITH AND WITHOUT ORONASAL ONE WAY VALVE

Depth 30 FSW

Mean Value in mmHg ± Standard Deviation

Work Rate (Watts)	End Tidal in Oronasal: Oronasal Valve In (N = 5)	End Tidal in Oronasal: Oronasal Valve Out (N = 5)
Rest	33.6 ± 2.6	35.8 ± 3.0
50	33.2 ± 4.5	37.6 ± 5.7
100	33.8 ± 3.9	39.4 ± 5.3
150	34.5 ± 3.7	39.2 ± 3.8

Work Rate (Watts)	Helmet Mean: Oronasal Valve In	Helmet Mean: Oronasal Valve Out
Rest	19.8 ± 2.4	21.8 ± 7.0
50	22.4 ± 4.3	26.2 ± 7.7
100	22.6 ± 5.9	27.2 ± 7.4
150	25.5 ± 5.7	26.8 ± 6.3

TABLE 2

PRESSURE DIFFERENTIAL (ΔP) WITH AND WITHOUT ORONASAL ONE WAY VALVE

Depth 30 FSW

Mean Value in cmH_2O ± Standard Deviation

Work Rate (Watts)	Oronasal Mean	
	Oronasal Valve In (N=5)	Oronasal Valve Out (N=5)
Rest	13.4 ± 4.4	12.2 ± 2.9
50	14.0 ± 3.5	15.0 ± 3.2
100	16.2 ± 2.5	15.0 ± 2.6
150	16.5 ± 4.1	17.0 ± 2.1

Work Rate (Watts)	Helmet Mean	
	Oronasal Valve In	Oronasal Valve Out
Rest	14.4 ± 4.4	14.4 ± 3.2
50	16.4 ± 3.3	17.2 ± 4.1
100	17.6 ± 1.7	18.0 ± 4.6
150	18.8 ± 1.5	20.0 ± 3.1

TABLE 3

CO_2 LEVELS WITH AND WITHOUT ORONASAL ONE WAY VALVE

Mean Value in mmHg ± Standard Deviation

Depth 856 FSW

Work Rate (Watts)	End Tidal in Oronasal: Oronasal Valve In (N = 9)	End Tidal in Oronasal: Oronasal Valve Out (N = 4)
Rest	37.9 ± 4	38.5 ± 3.0
50	47.8 ± 4.1	51.5 ± 3.4
100	50.7 ± 5.9	53.5 ± 5.0
150	(N=8) 50.8 ± 4.9	55.5 ± 8.4
Diver-Subjects Who Completed 150 Watt	N=2 51.5 ± 6.4	N=2 60.0 ± 11.3

Work Rate (Watts)	Helmet Mean: Oronasal Valve In	Helmet Mean: Oronasal Valve Out
Rest	16.4 ± 5.2	17.5 ± 1.9
50	23.9 ± 6.8	26.3 ± 3.4
100	25.3 ± 7.5	29.8 ± 3.8
150	(N=8) 25.1 ± 7.8	(N=3) 29.3 ± 7.0
Diver-Subjects Who Completed 150 Watt	N=2 26.5 ± 6.4	N=2 33.0 ± 4.2

NOTE: Not all subjects completed 100 Watt and 150 Watt work. Data was taken during the last 30 seconds of actual work.

TABLE 4

PRESSURE DIFFERENTIAL (ΔP) WITH AND WITHOUT ORONASAL ONE WAY VALVE

Depth 856 FSW

Mean Value in cmH_2O ± Standard Deviation

	Oronasal Mean	
Work Rate (Watts)	Oronasal Valve In	Oronasal Valve Out
Rest	13.2 ± 2.4	13.5 ± 3.4
50	21.7 ± 9.0	19.3 ± 2.2
100	27.4 ± 7.2	23.0 ± 5.8
150	37.6 ± 7.8	24.5 ± 3.9
Diver-Subjects Who Completed 150 Watt	N=2 31.0 ± 7.1	N=2 22.0 ± 4.2
Diver-Subjects Who Did Not Complete 150 Watt	N=6 39.8 ± 7.1	N=2 27.0 ± 1.4

	Helmet Mean	
Work Rate (Watts)	Oronasal Valve In (N = 9)	Oronasal Valve Out (N = 4)
Rest	13.7 ± 2.1	16.3 ± 6.8
50	22.2 ± 10.4	21.3 ± 2.5
100	27.6 ± 9.9	26.3 ± 6.7
150	38.5 ± 8.4	29.3 ± 4.3
Diver-Subjects Who Completed 150 Watt	N=2 33.5 ± 9.2	N=2 27.5 ± 6.4
Diver-Subjects Who Did Not Complete 150 Watt	N=6 40.2 ± 8.3	N=2 31.0 ± 1.4

NOTE: Not all subjects completed 100 Watt and 150 Watt work. Data was taken during the last 30 seconds of actual work.

TABLE 5

INDIVIDUAL DIVE ORONASAL PRESSURES AND EQUIPMENT CONFIGURATIONS
Depth 856 FSW

DIVER	ORONASAL VALVE	Last 30 seconds of work: P cmH_2O	EXPIRATORY PRESSURE cmH_2O	INSPIRATORY PRESSURE cmH_2O	UMBILICAL LENGTH	OVERBOTTOM PRESSURE psig	VOLUME TANK	RESULT
1	IN	33	+11	-22	300 ft	165	No	Stopped at 4::15 of 150 watts
	IN	40	+ 7	-33	300 ft	185	Yes	Stopped at 5::41 of 100 watts
	OUT	25	+ 7	-18	50 ft	185	Yes	Completed
2	IN	44	+14	-30	300 ft	165	No	Stopped at 3::00 of 150 watts
	IN	45	+20	-25	50 ft	185	No	Stopped at 4::08 of 150 watts
3	IN	39	+11	-28	300 ft	70	No	Stopped at 3::00 of 150 watts
	IN	30	+12	-18	300 ft	185	Yes	Stopped at 3::14 of 150 watts
	OUT	28	+12	-16	300 ft	185	Yes	Stopped at 3::48 of 150 watts
4	IN	48	+14	-34	300 ft	185	No	Stopped at 1::46 of 150 watts
5	IN	26	+13	-13	50 ft	185	No	Completed
	OUT	19	+ 9	-10	300 ft	185	Yes	Completed
6	IN	36	+11	-25	50 ft	185	Yes	Completed
	OUT	26	+13	-13	300 ft	185	Yes	Stopped at 2::48 of 150 watts

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